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Exploring the Implementation Path of Passive Heat-Protection Design Heritage in Lingnan Buildings

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Abstract: To achieve indoor thermal comfort via natural ventilation, traditional buildings in South China's Lingnan region have evolved distinct features tailored to the hot and humid climate conditions, involving site planning, function layout, and construction techniques. This study delves into the influences of these features on aspects such as sun-shading, ventilation, and heat insulation. By analyzing over ten Lingnan buildings in both the traditional and modern forms, several representative standardized models have been developed. Through a hybrid approach of combining qualitative and quantitative methodologies, including simulations, quantifications, and comparisons, several passive heat-protection measures commonly employed in Lingnan buildings were examined and evaluated. The effectiveness of shading, ventilation, and heat insulation in both traditional and modern buildings was assessed, resulting in the compilation of design principles for passive heat protection in buildings located in similar climatic zones. Key findings include (1) Shading: traditional methods reduce sunlight by 54.55%, while modern buildings enhance shading by applying new materials; (2) ventilation: traditional design achieves an outdoor wind speed of 1.5 m/s, improving thermal comfort, while modern Lingnan buildings optimize these principles; (3) insulation: traditional techniques maintain indoor temperatures below 26.0 °C, and modern buildings introduce innovation solutions for improved thermal insulation. In summary, traditional Lingnan design effectively addresses the challenges of the hot and humid climate by employing passive strategies for thermal comfort. Modern Lingnan buildings, in turn, preserve these principles while introducing innovative approaches.

Keywords: Lingnan buildings; thermal comfort; passive design; architectural design; heat protection

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1. Introduction

The construction sector plays a pivotal role in global energy consumption, accounting for roughly 30% of total energy usage and more than 50% of electricity demand worldwide [1]. In China, buildings alone contribute to 25% of the country's total energy consumption [2]. While the operational phase of maintaining indoor thermal conditions and basic services constitutes the majority of building energy consumption [3,4], the energy efficiency of a building is predominantly shaped by the design decisions made during the initial planning phase [5]. This implies that designers have the opportunity to select optimal design solutions that can significantly enhance energy efficiency and promote the development of environmentally friendly buildings [6]. To achieve this, extensive efforts are being made to identify both active and passive strategies aimed at improving building energy efficiency [7–11].

However, it is noteworthy that heatwaves have become more frequent, long-lasting, and increasingly intense, especially after the 1990s [12]. By the year 2022, heatwaves in China had doubled in both magnitude and frequency compared to the level of the 1990s, with Southern China experiencing the most significant increases [13,14]. Under a 1.5 °C warming limit, it is projected that the average number of heatwave days and their duration across China will increase by 10.8 days and 3.9 days, respectively [15]. The co-occurrence of drought and heatwave is also on the rise, with a notable increase at a rate of 7–11% per decade from 1990 to 2022. This co–occurrence further intensifies heatwaves [16]. During the summer, the indoor thermal environment is primarily influenced by the absorption and transmission of thermal radiation through the building envelope and the penetration of solar radiation through openings. Simultaneously, the outdoor thermal environment is affected by direct solar radiation and stagnant heat in the absence of wind. Traditional passive energy-saving design techniques for Lingnan buildings aim to physically separate the indoor and outdoor environments, thereby reducing overall energy consumption [17,18]. During the operational phase, significant heat exchange occurs, resulting in the transfer of outdoor heat into the indoor environment, which can lead to what is often referred to as the "oven effect" in hot climates. This effect significantly reduces the thermal comfort of occupants. However, passive energy-efficient design strategies can effectively minimize heat gain into the interior space, leading to lower indoor temperatures and enhanced thermal comfort for occupants. Therefore, the passive thermal design of buildings has a substantial impact on both energy efficiency and indoor environmental quality [19,20].

Currently, cities are confronted with the dual challenges of global warming and the urban heat island (UHI) effect, with buildings playing a significant role as both contributors to and sufferers of urban overheating. Researchers have proposed that the concept of a GB-based UHIM system, or "zero UHI impact building", or "zero-heat building", or "microclimate neutral building", aiming to achieve a zero-heat impact on surrounding environments through reasonably designing and operating buildings, or depending on innovative techniques to eliminate the excessive heat, on the basis of GB's goals [21]. Studies on natural ventilation in building atria have demonstrated its ability to lower indoor temperatures, remove humidity, and reduce air conditioning energy consumption while providing a healthier and more comfortable indoor environment [22]. Dehghani-sanij [23] has proposed the use of a "wind tower," which is a vertical ventilation design leveraging the "chimney effect". This design is particularly effective for natural ventilation under hot and humid conditions, thereby reducing cooling energy consumption. Furthermore, researchers and engineers have recognized the potential of enhancing building thermal insulation by modifying the characteristics of building envelopes. In recent years, optimization models combined with building energy simulation techniques have been developed to assist architects in identifying optimal design solutions [24,25]. For instance, C.K. Cheung et al. [26] demonstrated a remarkable 31.4% energy saving by adding extruded polystyrene insulation to the walls of selected high-rise apartments in Hong Kong. Balaras et al. [27] found that the insulated buildings in Greece consume 20–40% less energy compared to the uninsulated buildings, while low-permeability structures use 20–40% less energy than their uninsulated counterparts.

The warming trend in Chinese cities has shown an accelerating pace, with the average temperature of Chinese cities in the last two decades reaching its highest point in at least one century (CSIRO, 2015). The urban heat island effect compounds this issue, presenting a significant challenge. Wang [28] conducted an analysis of various mitigation strategies and technologies within the natural and built environment. These strategies include urban greenery, green roofs and walls, water-based technologies, cool roofs, and cool pavements. The aim is to assist local governments in mitigating the impact of rising temperatures on their communities and residents. Li [29] proposed a risk assessment framework for urban heat exposure. This framework works to identify the factors influencing the risk of excess or potentially unsafe heat exposure for individuals, locations, and the environment. To adapt to the hot and humid climate of the Lingnan region, traditional Lingnan architecture incorporates various thermal design measures for indoor and outdoor spaces [30,31]. The primary objective is to offer users optimal thermal comfort through effective strategies involving shading, ventilation, and thermal insulation. In recent decades, passive energy-saving technologies, such as external shading systems, natural ventilation, lightweight concrete wall insulation, and green roofs, have been widely implemented in architectural design (Figure 1) [32–35]. The fusion of technology and art within traditional Lingnan architecture has also influenced modern Lingnan building design to a certain extent. Therefore, it is crucial for contemporary architectural design to not only reflect local culture but also to thoroughly consider the unique regional climate characteristics [36].

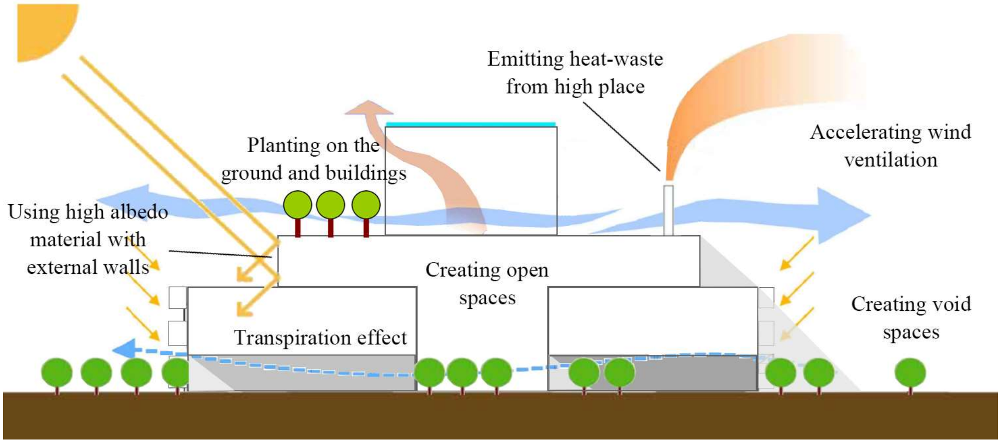


Figure 1. Summary of passive strategies for architectural design.

This paper provides a brief overview of the design characteristics and development trends of Lingnan buildings at the beginning. It then conducts an in-depth analysis of the spatial features of Lingnan buildings, employing simulation and quantitative analysis as research methods to establish a scientific basis for climate-adaptive design approaches. Subsequently, the impact of specific design variables on the thermal environment of buildings is explored, considering factors such as site space, building layout, and construction techniques. The study concludes that shading, ventilation, and insulation are effective design strategies for Lingnan buildings and also summarizes the findings from these three aspects to formulate a comprehensive thermal design strategy tailored specifically to Lingnan buildings.

Furthermore, the study presents the results of simulations and verifications, emphasizing the impact of passive thermal design on both traditional and modern Lingnan buildings. The applied simulation-quantification-comparison analysis method visually demonstrates the scientific rationale of passive technologies for heat protection in Lingnan buildings. The proposed passive thermal design approach, which encompasses shading, ventilation, and insulation, provides valuable insights and technical references for decision makers and architects involved in construction projects within the Lingnan region.

2. Description of the Study Area

2.1. Study Area

This study focuses on the Lingnan region, which is situated to the south of the Five Ridges in South China. The Five Ridges, specifically Yue Cheng Ling, Du Pang Ling, Meng Zhu Ling, Jie Tian Ling, and Dayu Ling, extend from west to east and naturally serve as watersheds between the Yangtze River Basin and the Pearl River Basin. Consequently, the Lingnan region is distinguished by its distinct geographical features when compared to the northern central plains. In a broader context, the Lingnan region, as depicted in Figure 2, encompasses Guangdong, Guangxi, Hainan, Hong Kong, Macao, and the South China Sea islands. It shares borders with Fujian to the east, Yunnan to the west, the South Ridge to the north, and the South China Sea to the south [37]. Guangzhou, a representative city within the Lingnan climate zone, exhibits specific climatic attributes detailed in the accompanying table. All these climatic characteristics play important roles in shaping the features of traditional Lingnan buildings. Figure 3 shows the design features of a typical

Lingnan vernacular dwelling. It is worth noting that all the selected cases discussed in this paper are situated in Guangzhou.

Figure 2. Schematic representation of the extent of the Lingnan region in China.

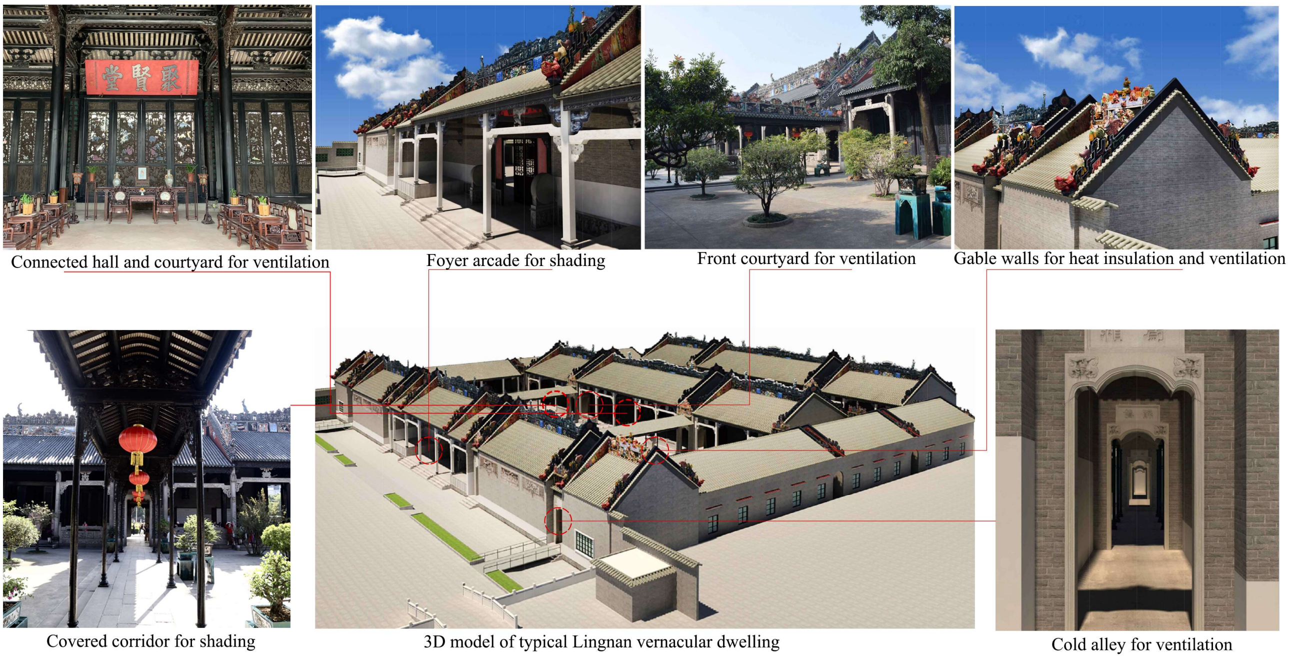


Figure 3. Typical representative of Lingnan architecture: arcade building.

2.2. Climatic Conditions

According to China's Thermal Code for Civil Buildings (GB50176-2016) [38], the Lingnan region falls within the category of hot summer and warm winter climate zones. This climate zone is characterized by a wide temperature range, intense heat radiation, strong solar exposure, and abundant sunlight. The region experiences annual solar radiation hours ranging from 1900 to 2200 h, with an annual solar radiation percentage exceeding 40%. Total annual average solar radiation levels vary from 4500 to 5500 MJ/m^2 [39]. The climate of Guangzhou, a representative city within the Lingnan region, is significantly influenced by its geographical location and natural surroundings. Prevailing winds throughout the year primarily originate from the north and southeast directions, as illustrated in Figure 4. Wind speeds in Guangzhou peak in December, with an average of 3.79 m/s, while September records the lowest wind speeds, averaging at 1.94 m/s. For a more comprehensive understanding, climatic data for Guangzhou City are outlined in Table 1 and illustrated in Figure 5.

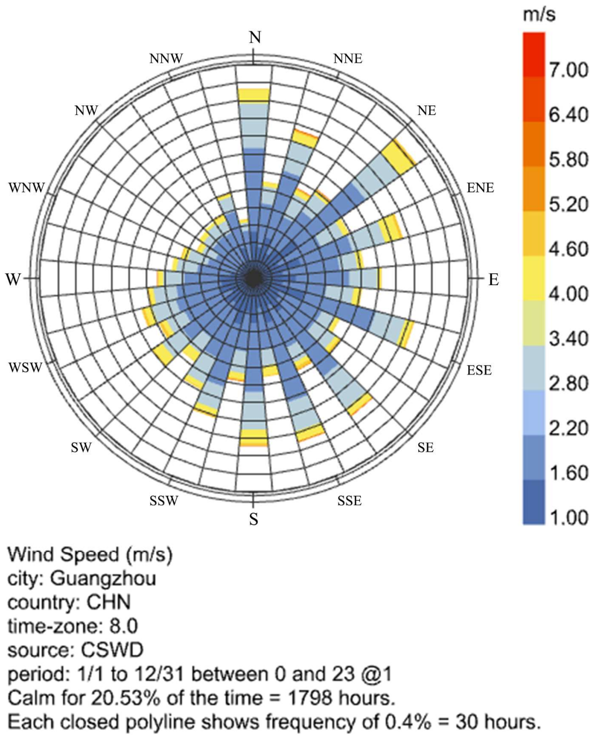


Figure 4. Annual wind rose of Guangzhou.

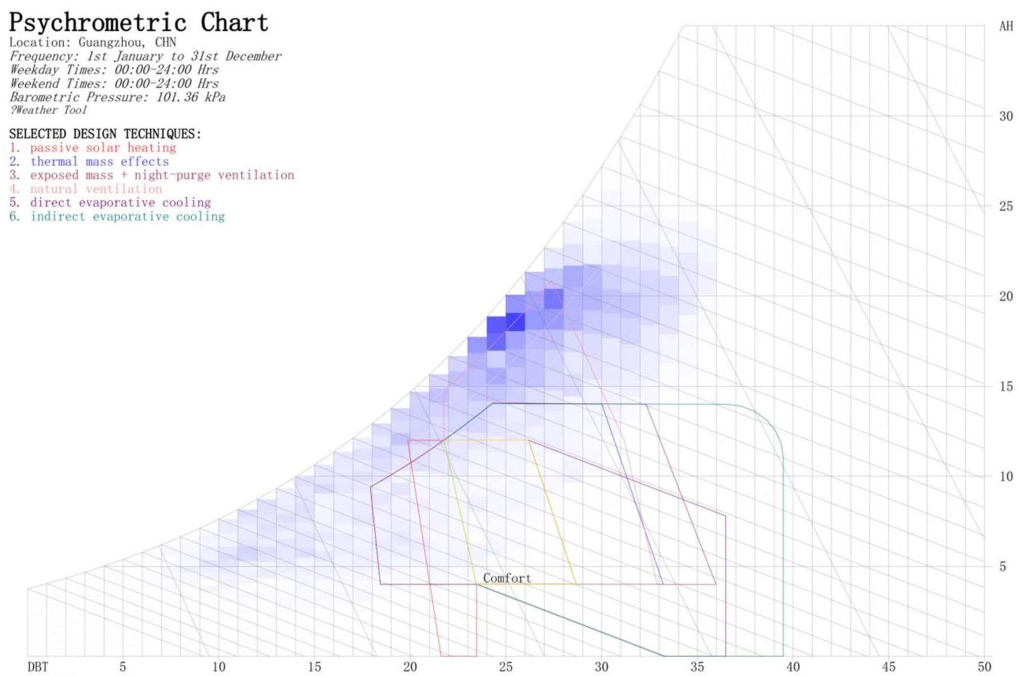


Figure 5. Enthalpy–humidity diagram generated by Weather Tool based on the meteorological data of Guangzhou city.

Table 1. Monthly weather data in Guangzhou city (Source: http://www.cma.gov.cncma.gov.cn, accessed on 23 June 2023).

Months	January	February	March	April	May	June	July	August	September	October	November	December
Average temperature °C	13.8	14.1	18.3	22.3	26.0	27.1	28.8	28.0	27.3	24.3	20.0	15.3
Maximum temperature °C	24.6	22.7	29.7	28.2	32.8	32.9	34.7	34.6	34.9	32.3	28.9	24.2
Minimum temperature °C	6.1	4.7	11.3	17.1	19.4	22.6	22.0	24.0	22.5	18.6	13.0	8.6
Rainfall (mm)	40.9	69.4	84.7	201.2	283.7	276.2	232.5	227.0	166.2	87.3	35.4	31.6
Number of days of rainfall	7.5	11.2	15.0	16.3	18.3	18.2	15.9	16.8	12.5	7.1	5.5	4.9
Average wind speed (m/s)	2.58	3.26	2.54	2.63	2.14	2.67	2.51	2.25	1.94	3.22	2.57	3.79
Average daily solar radiation (kWh/m^2)	3252	2614	2279	2834	4070	3676	4541	4692	4676	5092	4745	4361

Monthly temperature averages in Guangzhou indicate that July and August are the warmest months, with an average monthly peak of 28 °C, while December and January are the coolest, with temperatures averaging around 15 °C. In terms of rainfall, May receives the highest volume, with an average of 283.7 mm, while December sees the lowest, with an average of 31.6 mm. Regarding daily solar radiation duration, October records the highest average daily solar radiation, while March experiences the least, as shown in Figure 6. For a comprehensive overview, Table 1 compiles climatic data, including temperature, rainfall, wind speed, and solar radiation, for Guangzhou.

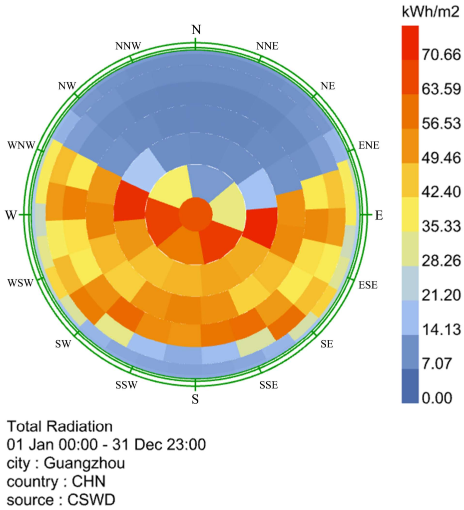


Figure 6. Distribution of solar radiation in Guangzhou.

3. Methodology

3.1. Case Selection

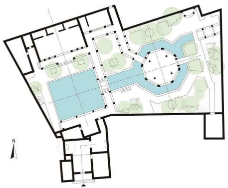
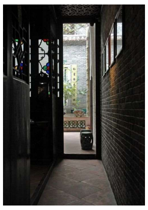
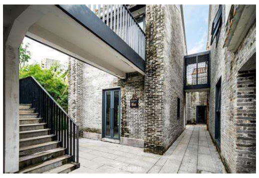
This study focuses on the architectural design in the subtropical region of China, with a specific emphasis on Lingnan architecture. Within the sub-tropical architectural regions of China, the Pearl River Delta area stands out for its distinct climatic characteristics and rapid architectural development. In this context, a series of Lingnan buildings exhibit advanced design concepts and a diverse range of design techniques, showcasing strong typicality and orientation.

Accordingly, a total of 12 typical Lingnan buildings, including 6 traditional and 6 modern Lingnan buildings, were selected to examine their unique passive design features, as shown in Table 2. These cases are geographically centered around Guangzhou, with building completion dates spanning 30 years from 1988 to 2018. These architectural samples are characterized by well-thought-out designs and high technological standards, offering a comprehensive reflection of the development of Lingnan architecture.

Table 2. Selected typical Lingnan buildings.

Ground-Level Elevated for Shading		**Overhanging Roof for Shading**	
Arcade along Guangzhou Ensi Road	The main entrance of Guangzhou Urban Planning Exhibition Center	The main gate of Xiguan Dawu	The main entrance of Guangzhou Baiyun Airport terminal
			

Table 2. *Cont.*

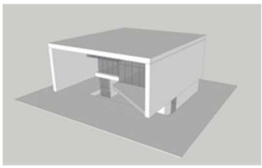
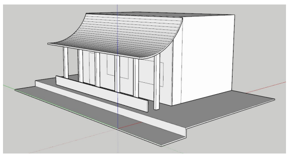
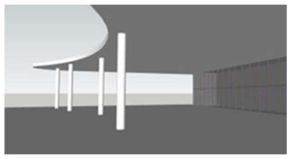
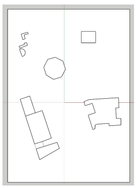
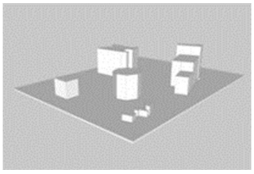
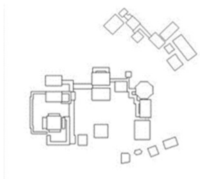
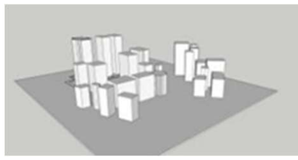
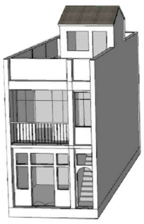
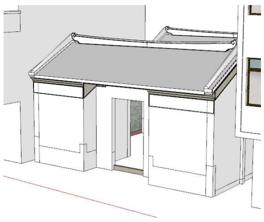
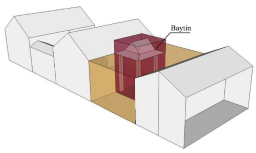
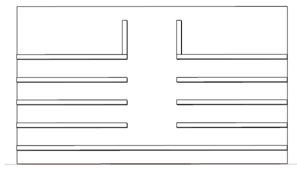
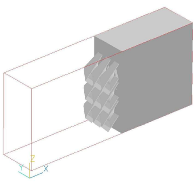
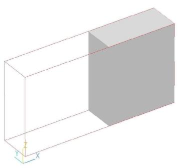
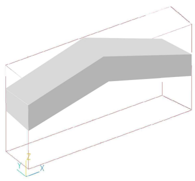
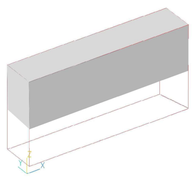
Ground-Level Elevated for Shading		**Overhanging Roof for Shading**	
Building complex arrangement for site ventilation			
Site plan of Yu Yin Shan Fang		Site plan of Cantonese Opera Art Museum	
			
Climate space for building ventilation			
Courtyard of Bamboo tube house	Patio of Chongdeli residence	Courtyard of vernacular with three rooms and two corridors	Atrium of Library at GDUT
			
Special wall material for thermal insulation		Special roof structure for thermal insulation	
Oyster shell wall of vernacular house in Siu Chau village, Haizhu district	Masonary wall of Guangzhou Library	Terracotta roof of vernacular house in shawan town, Panyu district	Green roof of Wengyuan meteorological station, Guangzhou
			

3.2. Simplified Models

The essence of this study lies in its utilization of simulation data extracted from simplified models for quantitative analysis, which defines our quantitative research approach. This approach departs from relying on simulation results based on specific building examples and instead utilizes simplified models based on representative traditional and modern Lingnan buildings located in Guangzhou, as illustrated in Table 3. These selected buildings epitomize the unique architectural style of Lingnan, designed to adapt to the local natural climate, and encompass a diverse range of architectural types. Notably, these buildings are of a moderate scale and hold significant research value. Furthermore, the simulations are conducted based on the assumption of ideal experimental conditions. Key climate parameters, such as temperature, wind speed, and solar radiation, are derived from authoritative scientific data published in reputable sources to ensure the accuracy and reliability of the findings.

The development of the simplified model aims to optimize and simplify the form and dimensions of the cases to meet the research requirements. In accordance with the environmental characteristics division of the primary spaces found in Lingnan architecture, this study primarily focuses on three fundamental objects: the external site space, the spatial volume of the building, and the internal building spaces. Accordingly, several representative cases from both traditional Lingnan architecture and modern Lingnan architecture are selected. Consequently, corresponding simplified models are derived. These two types of simplified models are built using professional software, such as Ecotect, Phoenics, and Ladybug. These software enable researchers to control variables in simulation and generate results for analysis that are scientifically grounded. Subsequently, these analyses facilitate the exploration of how specific thermal protection measures influence the thermal comfort of users.

Table 3. Simplified models of the selected typical Lingnan buildings.

Ground-Level Elevated for Shading		**Overhanging Roof for Shading**	
Arcade along Guangzhou Ensi Road	The main entrance of Guangzhou Urban Planning Exhibition Center	The main gate of Xiguan Dawu	The main entrance of Guangzhou Baiyun Airport terminal
			
Building complex arrangement for site ventilation			
Site plan of Yu Yin Shan Fang		Site plan of Cantonese Opera Art Museum	
			
Climate space for building ventilation			
Courtyard of Bamboo tube house	Patio of Chongdeli residence	Courtyard of vernacular with three rooms and two corridors	Atrium of Library at GDUT
			
Special wall material for thermal insulation		Special roof structure for thermal insulation	
Oyster shell wall of vernacular house in Xiaozhou village, Haizhu district	Masonry wall of Guangzhou Library	Terracotta roof of vernacular house in Shawan town, Panyu district	Green roof of Wengyuan meteorological station, Guangzhou
			

3.3. Combining Quantitative and Qualitative Analysis

The results of the environmental simulations consist of two primary components: the data distribution map and quantitative data. The distribution map provides an overview of the general environmental trends in the study area, while the analysis of sampled quantitative data offers a precise examination of factors such as wind patterns, solar radiation levels, and temperature fluctuations. Building upon this foundational data and considering real-world conditions, a qualitative analysis of individual design variables is conducted to assess whether specific design measures enhance a building's adaptability to hot and humid climates. The study consolidates critical technical aspects related to shading, ventilation, and insulation. Subsequently, it summarizes passive heat-protection design strategies within these three domains to offer practical guidance. By employing a combination of quantitative and qualitative methodologies, the study ensures the objectivity of its conclusions. It also equips architects with a means of rapidly assessing the effectiveness of design measures related to shading, ventilation, and thermal insulation during the early stages of building planning.

3.4. Simulation-Quantification-Comparison Analysis

To comprehensively assess passive thermal design in both traditional and contemporary Lingnan buildings, this study introduces a hybrid approach that seamlessly integrates simulation, quantification, and comparative analysis. By combining building simulation analysis with visualization techniques, this method offers a compelling demonstration of the scientific validity behind these design practices. As depicted in Figure 7, this conceptual framework outlines the proposed building simulation visualization method, which consists of three key steps: typical case selection, the development and validation of simplified models, and building simulation analysis. This method Leverages simulation tools such as Ecotect, Phoenics, and the Grasshopper-based Ladybug plug-in to facilitate scenario simulations based on the adaptability of the building and site characteristics. The resulting simulation data are carefully processed to mimic real-world conditions, leading to a detailed analysis. This analysis, in turn, yields specific passive heat-protection design strategies meticulously tailored for Lingnan buildings. Through this approach, the study effectively conveys the effectiveness of heat protection in Lingnan buildings, providing valuable insights for architects and researchers engaged in sustainable design practices.

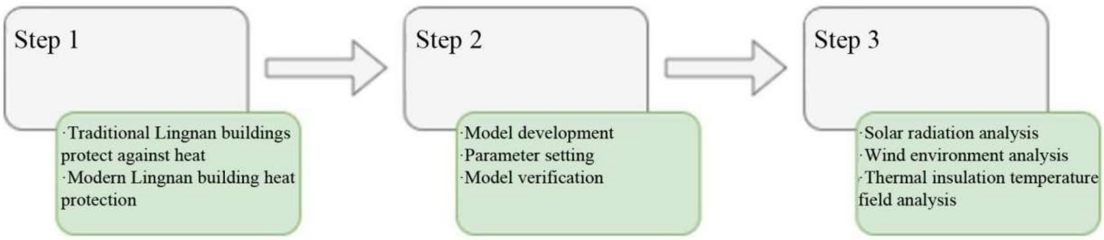


Figure 7. Flow of the proposed building simulation visualization method.

3.5. Detailed Configurations for Simulations

3.5.1. Solar Radiation

In this study, the typical meteorological year (TMY) weather data of Guangzhou served as the benchmark weather file. The shading scenario was parameterized using the Rhino platform, and the weather file was imported by utilizing the Ladybug tool (source: https://www.ladybug.tools/epwmap/, accessed on 26 June 2023). for solar radiation simulations. The threshold was set at 300 kWh per unit. The noon time of 12:00 on the summer solstice (22nd June) was selected as the simulation time. The analysis area included the ground-level elevated space and street space, which were divided into a grid with a resolution of 0.2 m × 0.2 m for simulations. The solar radiation simulations were conducted based on four cases: Shops along Ensi Road, Xiguan Dawu, Guangzhou Baiyun Airport Terminal (GBAT), and Guangzhou Urban Planning Exhibition Center (GUPEC).

3.5.2. Outdoor Wind Environment of Building Complexes

The WinAir plug-in from the Ecotect platform was used to simulate the site wind environment of the building complex cases by applying the TMY weather file of Guangzhou. The results were observed at a height of 1.5 m above the ground level. The noon time of 12:00 on the summer solstice (22nd June) was also selected as the simulation time. The site area was divided into a grid with a resolution of 1 m × 1 m for simulation. The wind direction was set to south with a speed of 2.7 m/s. The wind simulation was applied to two cases: Yu Yin Shan Fang and Cantonese Opera Art Museum. To assess the impact of variations in building height, façade dimension, block shape, and orientation of Lingnan buildings on the external wind environment, this study focused on the layout of building groups in the external wind environment. The wind shadow area was determined with a wind speed threshold of 0.2 m/s. Table 4 lists the impact of wind speed on people's work and activities [40].

Table 4. Evaluation of wind speed perception.

Wind Speed (m/s)	Impact on Work and Activities
0~0.25	Imperceptible
0.25~0.5	Pleasant
0.5~1.0	Generally pleasant
1.0~1.5	Unpleasant
1.5~7	Extreme unpleasant

3.5.3. Indoor Wind Environment of Individual Building

The simulations in this group were conducted based on 4 scenarios: bamboo tube house, Chongdeli residence, vernacular with three rooms and two corridors, and the library at Guangdong University of Technology (GDUT). They were simulated by applying the incoming wind with a speed of 1.5 m/s at a reference height of 10 m above the ground level, and 13:00 pm on the summer solstice (22nd June) was set as the simulation time. The wind vector diagram at key sections was analyzed to identify the patterns in wind pressure and thermal pressure ventilation. The simulation results on two sections were selected for indoor wind environment evaluation. One section was within a cold lane, allowing for the observation of horizontal airflow in it, while the other was in a patio, enabling the observation of the updraft in it. Four profiles were selected as follows.

3.5.4. Heat Transfer through Building Envelope

In this section, one-dimensional steady-state heat transfer simulations for various building elements of the selected cases were conducted by using Phoenics. These elements involve the oyster shell wall of a vernacular house, the masonry wall of Guangzhou Library, the terracotta roof of a vernacular house, and the green roof of Wengyuan meteorological station. Some detailed configurations are listed as follows (Table 5).

(1) For convective heat transfer between the air, wall/roof, wind speed, direction, and atmospheric temperatures were specifically set at 0.25 m/s, southeast, and 31 °C;
(2) Temperature differences were considered between the inner and outer surfaces of the wall and roof. The outer surface temperature was set at 31.86 °C, while the inner surface temperature was set at 28.19 °C.
(3) Heat convection effects between the air and the wall/roof were taken into account, with heat radiation between the surfaces being neglected.
(4) The thermal parameters and thickness of the materials used in the simulations are presented in Table 5. The total thickness of the wall was 0.06 m, while the total thickness of the roof was 0.10 m.

Table 5. Thermal properties settings of the materials.

Materials	Thermal Conductivity (w/m^2·K)	Specific Heat Capacity (J/(g·K))	Density (Kg/m^3)	Thickness (m)
Oyster shell	0.12	155	1870	0.6
Concrete	1.74	1680	1900	0.6
Terracotta roof	1.433	920	2100	0.6
Green roof	1.35	740	2000	0.6

4. Passive Shading in Lingnan Buildings

Solar radiation from the sun is the primary driver of temperature increase, introducing heat into both the interior and exterior of a building through transparent and non-transparent surfaces. Consequently, effective shading is crucial in blocking or mitigating the impact of direct solar radiation, with the creation of shadows being a fundamental technique to achieve this objective. Hence, shading stands as a critical element in the heat-protection design of Lingnan buildings. Tables 6 and 7 provide a comprehensive overview of traditional shading techniques employed in Lingnan buildings. These include riding tower shading, roof shading, partition fan shading, and stained-glass shading. These time-tested techniques have demonstrated their efficacy in providing shade and serve as valuable references for contemporary shading practices in Lingnan buildings. The calculation process and results of solar radiation for both traditional and modern Lingnan buildings are shown in Figure 8, Figure 9, and Table 8. The "Xia's sun shading" method has set a precedent for contemporary Lingnan building window and roof shading, making it an essential practice in heat-protection strategies. The in-depth examination of shading techniques presented in this study offers architects valuable insights into addressing solar heat gain in Lingnan buildings, aiding in the design of energy-efficient and sustainable structures.

Table 6. List of shading techniques in traditional Lingnan buildings.

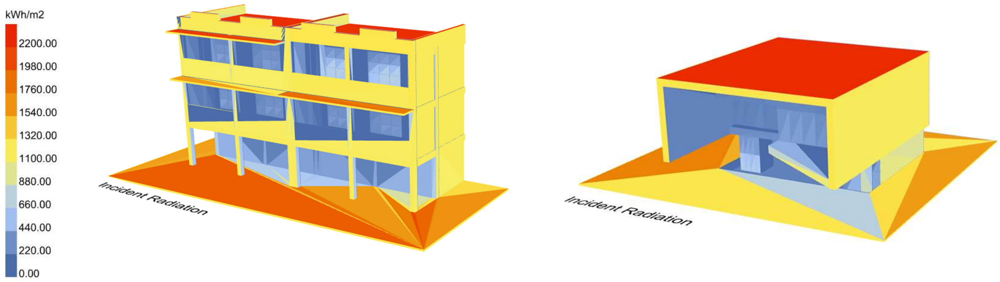
Category	Practice	Technical Description	Scope of Application
Arcade	Partial elevation of the ground floor	The ground floor is occupied by stores on the inner side, sidewalks on the outer side, and residences above.	Vernacular dwelling
Roof	Roof structure shading	With sunshade, rain prevention, lighting and other environmental maintenance comprehensive efficiency.	Vernacular dwelling
Partition	Window and door elements shading	Partition doors and windows, generally a group of four, by the child mullion, frame, wipe head, skirt plate four parts.	Vernacular dwelling
Stained-glass	Glass reflective shading	Inlaid colored glass or stained glass.	Vernacular dwelling

Table 7. List of shading techniques in modern Lingnan buildings.

Category	Practice	Technical Description	Scope of Application
Localized overhead shading	Partial elevation of the ground floor	The ground floor contains the main functional rooms on the inner side and the sunken plaza on the outer side.	Modern public buildings
Metal sunshade elements	Roof shading elements	Shading elements made of metal materials, commonly in the form of eaves shading formed by metal roofs, and façade and roof shading formed by metal frames.	Modern public buildings

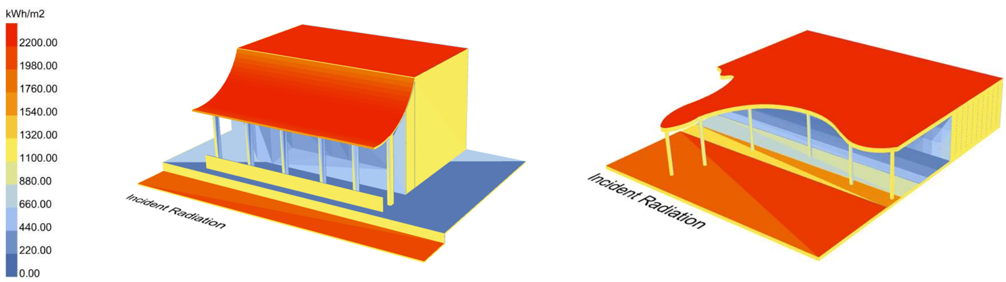
Table 7. *Cont.*

Category	Practice	Technical Description	Scope of Application
Electronically controlled color-changing glass sunshade	Glass reflective shading	By laminating the existing glass with dimming film or installing electronically controlled dimming glass, and adjusting the light transmission capacity of the glass through a control system.	Modern public and residential buildings
Vegetative shading	Plant reflective shading	Plant shading is the use of some kind of plant to block the excessive light that we do not need, and at the same time has the functions of heat preservation and heat insulation.	Modern public and residential buildings



(**a**) (**b**)

Figure 8. Comparison of solar radiation results between traditional and modern volume shading. (**a**) Arcade along Ensi Road. (**b**) Main entrance of GUPEC.



(**a**) (**b**)

Figure 9. Comparison of solar radiation results between traditional and modern roof shading. (**a**) Xiguan Dawu. (**b**) Main entrance at GBAT.

Table 8. Comparison of solar radiation between traditional and modern Lingnan buildings.

Form	Average Solar Radiation without Shading (KWh)	Average Solar Radiation with Shading (KWh)	Solar Radiation Reduction Rate (%)
The arcade shaded the sun	1109	504	54.55%
Sunken Plaza Shade	1692	497	70.63%
Floating eaves shade the sun	1208	901	25.41%
Large roof shading	1238	727	41.28%

4.1. Building Volume Shading

The concept of self-shading design in architectural form involves the purposeful utilization of architectural elements such as concavity, convexity, external projections, and the resultant shadows they create [41]. Traditional Lingnan architecture often incorporates partial building elevation as a prevalent form of self-shading, effectively blocking direct solar radiation. A prime example of this self-shading technique can be found in the riding towers commonly seen in Lingnan towns, where transportation, shading, and ventilation seamlessly merge to provide efficient cooling. In this study, the Ensi arcade was selected as a representative case of self-shading in traditional Lingnan buildings. Considering the hot and humid climate, Ladybug Tools software v1.4.0 was employed for radiation simulation analysis and visualization of the cyclorama by applying the hourly weather data from the past decade for Guangzhou City (source: EPW Map (ladybug.tools)). The results, as outlined in Table 8 and Figure 8, highlight that the concave space on the first floor of the cyclorama received 504.64 kWh of solar radiation, while the unshaded street space received 1109.82 kWh, resulting in an average solar radiation reduction of 54.55%. This measure not only provides pedestrians with a comfortable open space and effective sunshade but also offers shelter from rain. It exemplifies a successful integration of climatic adaptation design into the building.

The concept of concave–convex architectural design is a recurring technique in modern Lingnan architecture. It involves creating suspended architectural designs with voids at lower levels and solid structures at upper levels. An excellent example of this design approach can be observed at the main entrance of the GUPEC, drawing inspiration from the space beneath the riding towers in Lingnan. This design seamlessly bridges the gap between indoor and outdoor spaces. At the GUPEC, a three-story suspended volume, combined with a sunken plaza, generates a substantial shaded area at the entrance. Solar radiation analysis and visualization using Ladybug software, as shown in Table 8 and Figure 8, reveal that the sunken space at the main entrance received 497.74 kWh of solar radiation, while the unshaded street space received 1692.61 kWh, resulting in an average solar radiation reduction of 70.63%. This design approach effectively provides shade and mitigates heat, carrying forward traditional Lingnan shading practices while improving the indoor thermal environment. This approach not only prevents the building envelope from overheating but also reduces the indoor heat load caused by secondary radiation and convection, creating a more comfortable and energy-efficient indoor space.

4.2. Shading of Building Elements

Traditional Lingnan buildings are distinguished by their low and expansive structures, which effectively provide shelter from the sun and protection from rain. A notable example is the renowned ancient residential building known as "Xiguan Dawu". Solar radiation analysis and visualization were conducted using Ladybug software. The results, detailed in Figure 9, reveal that Xiguan Dawu received 901.23 kWh of solar radiation, while the unshaded street space received 1208.95 kWh, resulting in an average solar radiation reduction of 25.41%. This ingenious design utilizes eaves and gable corridors to create shaded areas for indoor–outdoor transition spaces. It not only enhances overall environmental efficiency but also ensures structural stability. Furthermore, it introduces a transitional gray space to the traditional building or courtyard gateway, providing effective sunshade benefits. Additionally, traditional Lingnan architecture incorporates waist eaves to compensate for the absence of roof shading. Robust eave roof structures are commonly employed to fulfill the requirements of single large spaces while providing sunshade, rain protection, and natural light. The design of doors and window sunshades is of paramount importance. The concave shape of doors and windows, achieved through wall thickness, offers comprehensive sun-shading benefits. Floating eaves above windows and doors serve as horizontal shades. Furthermore, the distinctive colored door and window glass used in Lingnan architecture boasts a low shading coefficient, efficiently offering sunshade and creating a distinctive indoor color landscape. The combination of roof, windows, and doors effectively prevents solar radiation heat from directly infiltrating the interior.

While modern roofing materials may differ from traditional tiled roofs, contemporary Lingnan architecture still incorporates features like eaves and outer corridor spaces in roof design to mitigate sun exposure. Take the GBAT as an example, where solar radiation analysis and visualization were conducted using Ladybug software. The results, presented in Table 8 and Figure 9, reveal that the Airport terminal in Guangzhou received 727.85 kWh of solar radiation, while the unshaded street space received 1238.14 kWh, resulting in an average solar radiation reduction of 41.28%. This example illustrates how the roof shading technology of traditional Lingnan buildings has evolved into gable porch shading space created by substantial metal roof eaves and sturdy columns in modern Lingnan architecture. This innovative design not only provides shade for pedestrians but also meets requirements for wind and rain protection. Furthermore, it exhibits characteristics such as lightweight construction, thermal insulation, noise reduction, lightning protection, and innovative aesthetics. Modern Lingnan buildings retain the sunshade considerations of traditional Lingnan architecture while adding a distinctive Lingnan touch [42]. In various modern residential areas and public buildings, the influence of "Xia's sunshade" can still be observed, as seen in Building 14 at South China University of Technology and the outpatient clinic building at Sun Yat-sen University of Medical Sciences. Regarding window shading, modern Lingnan buildings take into account the sunlight angle and building orientation in Guangzhou [6]. They incorporate prefabricated sunshade panels that create staggered projection lines. The combination of different materials, structural forms, and shapes in the shading components of modern Lingnan buildings showcases a more integrated and distinctive Lingnan characteristic compared to the past.

5. Passive Ventilation in Lingnan Buildings

The Lingnan region is known for its "hot and humid" climate, emphasizing the need for a robust ventilation strategy in the area [43]. Tables 9 and 10 provide an overview of the traditional ventilation methods employed in Lingnan architecture, encompassing both group layouts and individual climate spaces. From a holistic layout perspective, it is important to note that the prevailing wind direction in the Lingnan region usually comes from the southeast during the summer. Ensuring unobstructed airflow from this direction has become the primary method for achieving natural ventilation in Lingnan buildings. Additionally, the significance of local ventilation systems that create a "micro-environment" with cooling effects should not be underestimated. This underscores the important role of ventilation as a fundamental aspect of Lingnan architecture. It not only addresses the challenges posed by the region's hot and humid climate but also promotes thermal comfort and sustainability.

Table 9. List of ventilation techniques in traditional Lingnan buildings.

Form	Practice	Technical Description	Scope of Application
Outdoor ventilation	Group layout ventilation	The building complex adopts a decentralized overall layout and the space pattern of low south and high north to obtain good natural ventilation to achieve passive cooling of the building.	Landscape architecture in the Lingnan region
Climate space ventilation	Patio ventilation Corridor ventilation Cold-stream ventilation	Typical "climate spaces" of traditional Lingnan buildings include cold alleys, courtyards, patios, corridors, and so on. Various architectural climate spaces do not exist in isolation, but have a mutual linkage effect, which can work together to solve the thermal comfort problem of the indoor environment of the building.	Landscape architecture in the Lingnan region

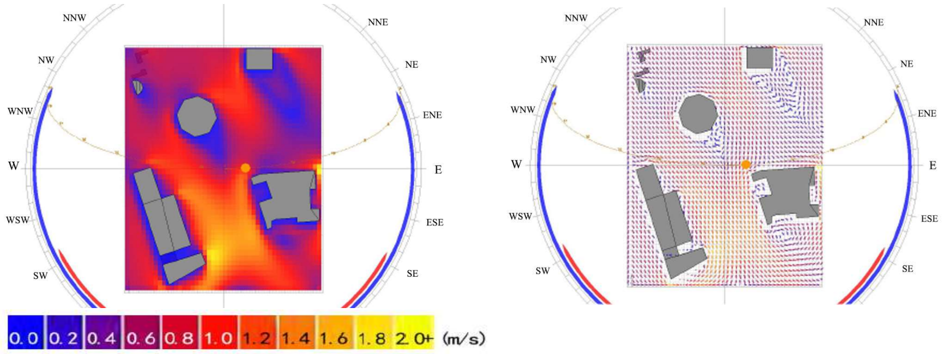
Table 10. List of ventilation techniques in modern Lingnan buildings.

Form	Practice	Technical Description	Scope of Application
Outdoor ventilation	Group layout ventilation	The complex adopts the spatial pattern of low south and high north to obtain good natural ventilation and forms an organic ventilation system of patios, courtyards, and corridors to enhance the cooling effect.	Modern public and residential buildings
Localized room ventilation	Atrium ventilation	Ventilation in the atrium is mainly vertical ventilation, and the unique "greenhouse effect" and "chimney effect" of the atrium are conducive to inducing ventilation problems in the atrium and even in the whole building.	Modern public and residential buildings

5.1. Decentralized Group Layout

In situations where a building site is congested and building orientation options are limited, adopting a garden-style building layout, as referenced in [44], can serve as an effective solution to address indoor ventilation and lighting challenges. Traditional Lingnan houses have ingeniously utilized a decentralized overall layout and spatial organization to achieve natural ventilation, facilitating passive cooling. This design approach effectively eliminates indoor humidity and stuffiness, thereby providing occupants with a healthy and comfortable indoor environment. Under similar conditions, if buildings can be spaced apart, additional gap spaces can be incorporated, allowing for the infiltration of natural air into the buildings or facilitating wind circulation between them. Moreover, many large-scale Lingnan building complexes exhibit a notable trend of having lower structures in the south and taller structures in the north. The lower southern side welcomes the entry of summer southeast winds, creating favorable conditions for the wind to enter the rooms and enhancing ventilation through open gardens. Conversely, the higher northern side acts as a barrier against winter northwest winds, preventing them from encroaching on the gardens. It is worth noting that in some Southern villages, a comb ventilation layout is employed, aligning the main village lanes with the dominant wind direction during summers, which leads to excellent ventilation [45]. These architectural strategies emphasize the significance of adapting the building layout to local climate conditions to ensure effective passive cooling and maintain a comfortable indoor environment.

Taking the Lingnan garden-style building Yu Yin Shan Fang in Guangzhou as an example, designed to accommodate the dominant summer wind direction from the south-east, it features an overall layout characterized by "two east–courtyards with sun-shading partitions," "south-facing halls with cleverly designed corridors", and "distinct main and secondary areas with shading for secondary spaces". Through analysis using WinAir software v4 and wind environment simulations, it is evident that the comprehensive utilization of wind pressure ventilation and thermal pressure ventilation within the courtyard, patio, and corridor settings results in an average wind speed of 1.25 m/s, creating a cool and comfortable environment (Figure 10a). The concept of having lower structures in the south and higher structures in the north allows for summer winds to easily flow directly into the building area through open courtyards in the south. Furthermore, due to the denser arrangement of buildings and separate blocks, these gaps serve as natural ventilation "corridors", facilitating accelerated airflow. The thermal pressure ventilation effect becomes apparent as the temperature difference between the top and bottom of the buildings, along with the varying air density, contributes to a cool and comfortable environment. The open courtyard at the front of the building receives prolonged sunlight exposure, causing air temperatures to rise rapidly and resulting in upward airflow. In contrast, the shaded area at the back of the house mitigates the influence of solar radiation, leading to relatively lower air temperatures and downward airflow, which complements the front courtyard. Yu Yin Shan Fang exemplifies the typical layout featuring open and spacious courtyards with large water surfaces, referred to as a sparse front and dense back layout. The wind environment simulation analysis validates the significant positive impact of this layout, as detailed in Figure 10.



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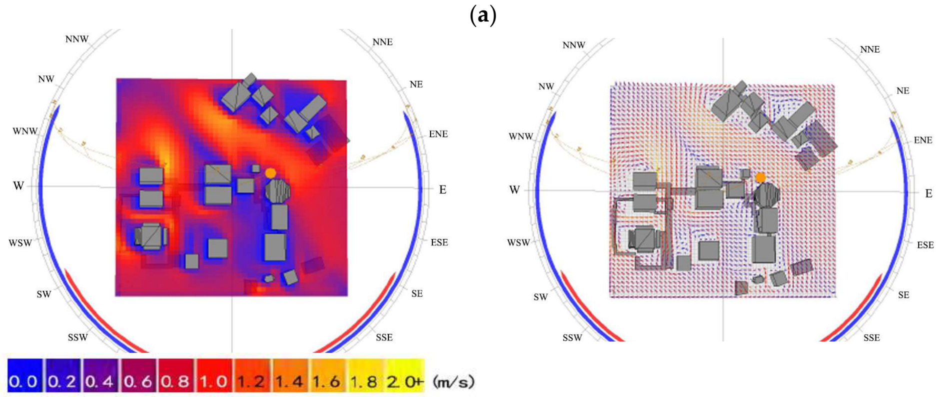

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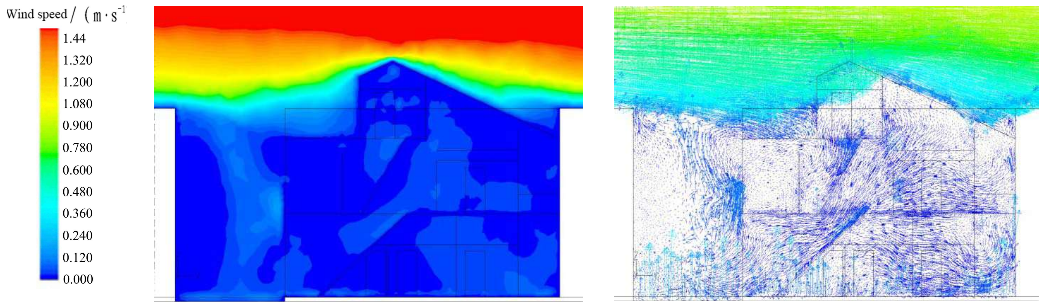
Figure 10. Wind simulation results of Yu Yin Shan Fang and Cantonese Opera Art Museum. (**a**) Wind speed and vector distributions in Yu Yin Shan Fang. (**b**) Wind speed and vector distributions in Cantonese Opera Art Museum.

This spatial arrangement has also been inherited by contemporary architecture, where an organic ventilation system is integrated through the use of patios, courtyards, and porches. These architectural elements vary in scale and serve as both air inlets or outlets, facilitating favorable indoor–outdoor airflow and heat exchange. For instance, the Cantonese Opera Museum is designed to harmonize with the surrounding historic buildings. Inside the museum, a multi-level patio–courtyard–corridor system is implemented. The highest point, Bawo Pavilion, is located in the northwest corner of the garden, while the lower pavilions are staggered on the southeast side and connected by corridors. This results in a general layout of lower structures in the southeast and higher structures in the northwest. Wind environment simulations, conducted using WinAir software, demonstrate effective natural ventilation, with an average wind speed of 1.32 m/s (Figure 10b). Along with wind induction from Liwan Chong and the central water court, the museum successfully creates a favorable overall wind environment in the old urban area. Furthermore, when planning residential areas in the Lingnan region, buildings are ideally oriented to face south. Additionally, architectural designs incorporate a sawtooth arrangement to increase the windward surface area of the buildings [46], resulting in improved ventilation effects.

5.2. Monolithic Building Climate Space

Traditional Lingnan buildings provide ample space designed to regulate the microclimate environment [47]. These buildings incorporate various architectural climate spaces that are interconnected, enhancing indoor and outdoor air convection through techniques like thermal and wind pressure ventilation. This approach aids in heat dissipation and improves thermal comfort. A common feature in traditional Lingnan architecture is the combination of a front courtyard and a back patio. The three-room and two-corridor layout, representing a typical plan form of traditional Lingnan buildings, comprises a main building with three rooms, two corridors, and a front patio connected to three courtyards. This layout exhibits characteristics of external closure and internal openness. The patio serves as a crucial inlet and outlet for air, enabling airflow driven by wind and thermal pressure to enter the rooms. Simulations using Fluent v2021 R1 were conducted to assess the indoor wind environment in the patio. The results, detailed in Figure 11c, indicate that in completely calm outdoor conditions, areas such as building corridors and halls are affected by natural convection ventilation, resulting in airflow rates of approximately 0.6~1.0 m/s. The patio serves a dual purpose by effectively inducing and extracting wind. During periods of strong external wind, the patio functions as a wind pressure vent, while it generates its own thermal pressure ventilation when external wind speeds are low. Consequently, the patio's ventilation efficiency surpasses that of simple air inlets and outlets. Thermal pressure ventilation is particularly significant in this spatial configuration. The relatively small scale of the patio creates cold zones during the day, shielded by surrounding buildings or walls, preventing direct sunlight. This leads to naturally cooler air and lower temperatures. In contrast, the larger courtyard exposed to sunlight becomes a heat source. The interplay between these two sources allows for cold air from the back patio to complement the front courtyard, resulting in cooling through airflow.



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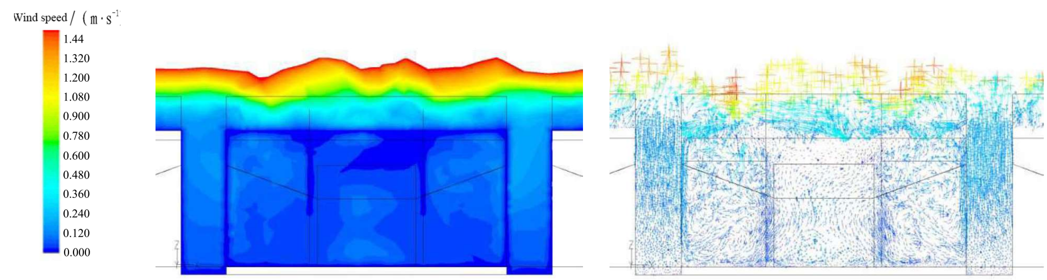

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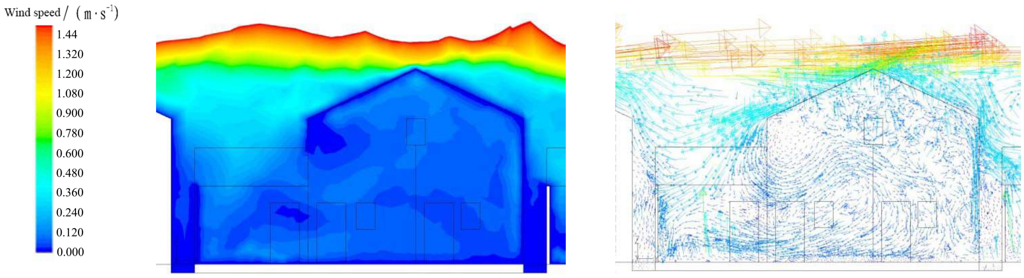
Figure 11. *Cont.*



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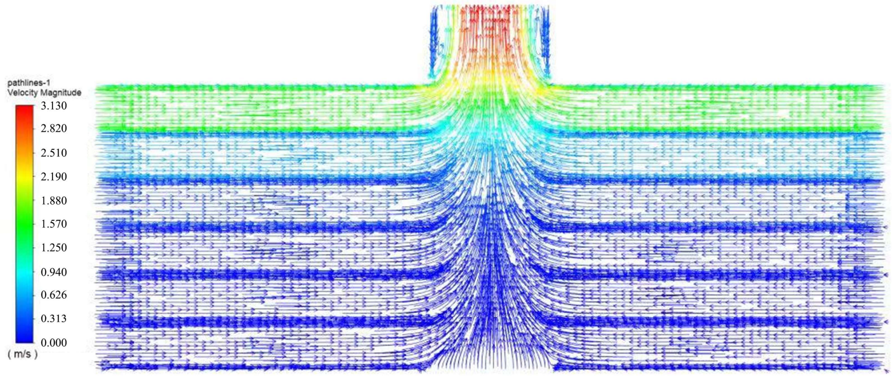

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Figure 11. Wind simulation results in traditional and modern Lingnan buildings. (**a**) Wind velocity and vector distribution in the cold alley of bamboo tube house. (**b**) Wind velocity and vector distribution in the patio of Chongdeli residence. (**c**) Wind velocity and vector distribution in the patio of the vernacular with three rooms and two corridors. (**d**) Wind velocity and vector distribution in the atrium of the library at GDUT.

In addition to the back patio, traditional Lingnan buildings also feature a unique architectural element known as the "cold alley" within the house. Cold alleys play a central role in climate regulation in Lingnan architecture and are particularly prominent in bamboo houses. The Fluent software simulation results reveal that in completely calm outdoor conditions (Figure 11a), areas like building corridors and halls experience natural convection ventilation, resulting in airflows of approximately 0.6~1.0 m/s. Cold alleys serve not only as passageways within the house but also as the principal air ducts for the internal ventilation system. They facilitate the movement of airflow within the house through what is known as the "Venturi effect." When air from open halls or patios enters the confined space of the cold alley, the air mass cannot accumulate significantly, leading to an increase in wind speed within the cold alley. The long, narrow, and tall configuration of the cold alley, oriented in a north–south direction, restricts the penetration of sunlight from the east–west direction. This natural shading effect cools the air within the alley, creating a cold source. Together with other heat sources, such as open and spacious courtyards, this configuration facilitates thermal pressure ventilation. Additionally, the elongated shape of the cold alley promotes wind pressure ventilation, accelerating air movement and enhancing both indoor and outdoor ventilation.

The ventilation elements that are inherent in traditional Lingnan architecture, such as courtyards, patios, and cold alleys, have found a renewed purpose in modern Lingnan architecture. Contemporary Lingnan architectural designs prioritize spatial openness and frequently employ techniques that promote multi-directional openness and excavation, staying true to the inherent spatial permeability of traditional architecture. The integration of cold alleys and patios within modern Lingnan architecture serves as a means to organize and stimulate ventilation, gradually extending a sequence of courtyard spaces from the internal building areas to the external environment. This open layout creates favorable conditions for ventilation. Simulations and analyses conducted by the Chongdeli residence in Guangzhou using Fluent software demonstrate that in the afternoon of midsummer and in completely calm outdoor wind conditions, the air flow rate in building corridors, halls, and other areas is approximately 0.3~0.8 m/s due to natural convection ventilation (Figure 11b). The inclusion of cold alley spaces in these designs establishes connections between outdoor environments and internal open halls, facilitating the introduction of cool air and inducing ventilation. Furthermore, the integration of cold alleys with courtyards and open halls contributes to comfortable natural ventilation in courtyard spaces and blurs the boundaries between indoor and outdoor environments. This results in the creation of pleasant public spaces for relaxation and interaction. The unique spatial configuration of patios remains an irreplaceable component of traditional architecture's sustainable design wisdom. Hence, when incorporating ventilation elements like courtyards and patios into building atriums of varying scales, it is common to position a tall courtyard at the center of the structure. This design approach can be viewed as a modern variation of the traditional deep wells, vertically connecting spaces to create a "big chimney" that spans from the top to the bottom, bridging the indoor and outdoor environments. This "big chimney" functions as a natural wind extractor. Elevating the base of the building allows for the formation of a wind-through hall. For example, the library at GDUT serves as a case study(Figure 11d), where Fluent software is utilized to simulate and analyze the indoor sectional wind environment. The results demonstrate that in the afternoon of midsummer and in completely calm outdoor wind conditions, the air flow rate in building corridors, halls, and other areas is basically 0.8–1.5m/s. The design blends traditional architectural wisdom, creating a modern "climate space system" that reduces the need for artificial climate control, ultimately achieving energy-efficient design. By adhering to Lingnan's natural climate patterns and understanding the appropriate scales for "climate space," a green building space layout strategy tailored to the climatic conditions of the Lingnan region is developed. The building's profile incorporates principles from Lingnan architecture's patio, allowing for vertical ventilation through wind chimneys extending from the first floor to the roof. This organized airflow circulation is achieved through internal interactions, facilitating the smooth exchange of indoor and outdoor airflows. These techniques, reminiscent of the traditional "courtyard-tenjing" in Lingnan houses, can be combined to enhance air circulation.

6. Passive Insulation in Lingnan Buildings

In the Lingnan region, the use of eco-efficient insulation materials and advanced wall masonry techniques in Lingnan buildings serves to facilitate the exchange of heat between the indoor and outdoor environments. The building envelope in Lingnan architecture functions like a living, self-regulating biological skin, adapting to changing environmental conditions. Among the envelope components, the thermal insulation performance plays a pivotal role in determining the overall thermal efficiency of the building. Notably, both the roof and walls are crucial elements of the envelope structure, contributing significantly to thermal insulation and heat preservation. In the context of modern Lingnan buildings, special attention must be given to the arrangement of material layers, as well as the incorporation of double roofs and diverse facades, to maximize the insulation's effectiveness. As elaborated in Tables 11 and 12, various insulation techniques utilized in traditional Lingnan buildings, including roof insulation and façade insulation, provide valuable insights for insulation practices in contemporary Lingnan buildings. These findings offer essential technical guidance for achieving superior insulation performance in modern Lingnan architecture.

Table 11. List of heat insulation techniques in traditional Lingnan building.

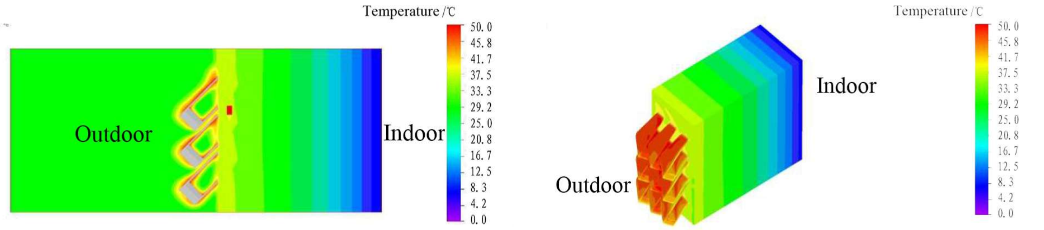
Form	Practice	Technical Description	Scope of Application
Roof	Ceramic tile double layer Insulated Roofs	Ceramic tile double-layer heat-insulated roofing is a kind of roofing that takes heat-insulating measures to prevent the sun from directly irradiating the upper surface of the roof. By the upper and lower two layers of roof composition, the lower roof is the main ventilation roof, the upper roof is generally used in the lighter materials, and difference in height of the upper and lower two layers is generally 200mm.	Vernacular dwelling
External wall	Oyster shell wall	Lingnan oyster shell wall is made of local materials, is ecological and environmentally friendly, and its heat transfer coefficient is small, with excellent thermal insulation properties, adapted to the hot and humid climate of Lingnan. The main component of oyster shells is calcium carbonate, which is resistant to erosion and insects, and has the function of wind and moisture protection in the coastal areas of Lingnan.	Vernacular dwelling

Table 12. List of heat insulation techniques in modern Lingnan buildings.

Form	Practice	Technical Description	Scope of Application
Roof	Green roof	Roof greening refers to green planting on the roof, with green plants as the main cover, with nutrient soil layer, water storage layer, etc., together to form a roof system.	Modern public and residential buildings
External wall	Modern insulation	Enhancement of wall thermal insulation and heat preservation performance by using thermal insulation materials	Modern public and residential buildings

6.1. Material Insulation

The walls of traditional Lingnan buildings are often constructed using water-worn and red bricks, which offer excellent insulation and heat preservation properties. In terms of masonry, the gap left in the middle of the brick walls in traditional Lingnan architecture acts as an effective air barrier, enhancing heat preservation and insulation while reducing the need for bricks, mortar, and labor. Modern Lingnan buildings predominantly use wood for doors and windows, which provides outstanding heat preservation capabilities. In particular, black lacquer wood is employed to absorb heat radiation from the environment, contributing to the building's ventilation, heat insulation, and lighting performance. Various styles of window splicing are employed to create partitions between spaces that are both aesthetically pleasing and functionally ventilated for efficient heat dissipation. Furthermore, Guangdong's folk architecture takes a pragmatic approach, emphasizing adaptation to local conditions and the use of locally sourced materials. This approach has resulted in unique craftsmanship, such as the oyster shell walls found in traditional Lingnan architecture. Oyster shells, primarily composed of calcium carbonate, are resistant to erosion and insects, effectively preventing wind and moisture penetration in Lingnan's coastal areas. Through a case analysis of oyster shell houses in Xiaozhou Village, Guangzhou, temperature analysis using Phoenics [48] revealed (Figure 12a) that the outer cavity of the oyster shell wall has a certain heat resistance ability, which reduces the outer boundary temperature of the wall from 45.8 °C to 33.5 °C. The lower the temperature of the oyster shell wall, the higher the temperature drop rate, and 63.4% of the low-temperature field is within the oyster shell wall. Plain white oyster shell walls have higher reflectivity compared to bricks and other ancient building materials. This reduced absorption of solar radiant heat and the irregularly distributed protuberances on the walls minimize direct sunlight exposure. Additionally, the external cavity of oyster shell walls provides a certain degree of heat resistance, reducing the temperature at the outer boundary of the wall. The temperature drop rate increases as one moves towards the interior of the oyster shell wall, creating a larger low-temperature zone within the internal temperature field. This low-temperature zone, similar to an air interlayer due to the presence of air within the oyster shell, exhibits a low coefficient of heat transfer, enhancing its thermal storage capacity and contributing to thermal insulation.



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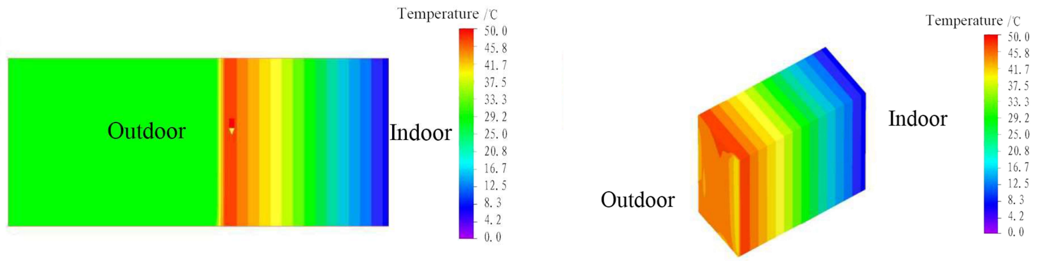


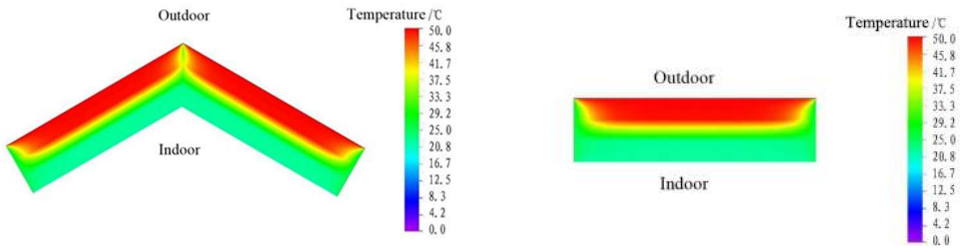
(**b**)

Figure 12. Simulation results for the thermal insulation of different wall materials. (**a**) Temperature distribution across the oyster shell wall. (**b**) Temperature distribution across the masonry wall of Guangzhou Library.

In the past decade, rapid urbanization in China has brought significant advancements in climate-adaptive design in the Lingnan region [49]. The introduction of green building materials, including thermally dimmable glass and heat-insulating wall materials, has revolutionized the heat insulation capabilities of modern Lingnan buildings, surpassing those of traditional materials like oyster shell walls and Manchurian windows. These innovative materials have become essential in the design of contemporary Lingnan buildings. For example, modern Lingnan building facades often incorporate light-colored finishes, reflective coatings, and facade tiles to effectively reduce radiation heat. Vertical greening of building facades has emerged as a crucial ecological compensation measure in green buildings. It not only enhances aesthetics but also contributes to cooling, noise reduction, reduced energy consumption, and decreased carbon emissions. A noteworthy case is the Guangzhou Library, which features Low-E glass windows and doors, providing abundant natural lighting, heat insulation, and comprehensive energy-saving benefits. The library's facade is constructed using light-colored stone with a textured concave and convex design. Temperature field analysis of the library's profile wall using Phoenics reveals (Figure 12b) that the textured facade generates numerous small shadows, significantly reducing solar radiation absorbed by the wall. The temperature of the outer boundary of the wall is reduced from 46.8 °C to 12.8 °C. Moving to the inside of the wall, the temperature drop rate increases, forming a large low-temperature zone in the internal temperature field, effectively achieving a substantial thermal protection effect. This contemporary heat-protection design exhibits similarities to the traditional oyster shell walls of Lingnan architecture. In building design, it is imperative to make thoughtful choices in selecting suitable materials and construction practices to meet green and energy-saving objectives [50].

6.2. Tectonic Insulation

The roofs of traditional Lingnan houses are often adorned with flowers and trees, and sunshade pergolas are constructed to enhance heat insulation. An illustrative example is the use of bamboo trellises on roofs to support climbing plants, which, through transpiration and photosynthesis, dissipate heat and provide effective insulation. Ceramic tiles are a common insulation material used for the roofs of folk residential buildings in Lingnan [51]. Typically, traditional residential architecture features a double-layer tiled roof structure. By conducting temperature field simulations using Phoenics, it becomes evident (Figure 13a) that the combination of bottom and surface tiles forms an active air layer, allowing for ventilation and heat dissipation between the two layers of the roof. This double-layer design offers superior heat insulation compared to a single-layer tiled roof. It not only shields the roof surface from direct sunlight exposure but also utilizes airflow to facilitate heat dissipation. The undulating shadows created by the pitched tiles further contribute to reducing the temperature at the outer boundary of the roof. As can be seen from the temperature field cloud image, when moving to the interior of the roof, the rate of temperature drop increases, which reduces the temperature of the outer boundary of the roof from 48.6 °C to 14.8 °C, leading to the enlargement of the low-temperature zone of the internal temperature field of the roof. This significantly enhances the thermal insulation performance of the roof and effectively serves as a thermal insulation layer.



(**a**) (**b**)

Figure 13. Temperature distribution across different roofs. (**a**) Temperature distribution across the traditional terracotta roof. (**b**) Temperature distribution across the modern green roof.

In modern Lingnan architecture, there is a growing diversity in roof designs, featuring options such as ventilated roofs, water storage roofs, vegetated roofs, and sloped roofs with attic floors [52]. Among these, vegetated roofs with suitable substrate materials play a pivotal role in enhancing the thermal inertia and thermal resistance of the roof, thus delivering effective insulation. Green roofs offer exceptional thermal and heat insulation properties for buildings while also providing added benefits such as structural protection, water storage capacity, and reduced roof runoff, which collectively contribute to an improved microclimate in the vicinity of the building. Water storage roofs leverage the high heat capacity of water and its evaporative properties, effectively absorbing and minimizing heat conduction. This approach prevents the roof panels from overheating under the scorching summer sun. Moreover, the evaporative cooling effect of the water body consumes a significant amount of heat during vaporization, maintaining the water temperature within reasonable limits and reducing the surface temperature of the roof, thereby achieving the desired heat insulation. Passive thermal insulation evaporation roofs, using moisture-absorbing porous materials as heat storage mediums, offer an efficient insulation method [53]. This approach is especially suitable for Lingnan's hot and humid climate. For instance, the

Guangzhou Wengyuan meteorological station incorporates a large green roof with a variety of plantings. The roofing system integrates layers of nutrient soil, water storage, plant root barriers, drainage, and waterproofing, among others. Simulation results show that the green roof effectively delivers thermal insulation properties for the building. As can be seen from the temperature field cloud map (Figure 13b), when moving to the interior of the green roof, the rate of temperature decline increases, reducing the temperature of the outer boundary of the roof from 49.5 °C to 18.6 °C, resulting in the expansion of the low-temperature area of the temperature field inside the roof. This greatly improves the thermal insulation performance of the roof and effectively plays the role of an insulation layer. It also safeguards the building structure, reduces roof runoff, and enhances the microclimate in the vicinity of the building, contributing to the mitigation of the urban heat island effect.

7. Conclusions

In the pursuit of the green, low-carbon concept, modern Lingnan architectural design methods are evolving and adapting. They have, to varying degrees, drawn inspiration from the experiences and practices of passive heat-protection design in traditional Lingnan buildings, building upon this rich heritage. As a result, the energy-efficient design strategies rooted in traditional Lingnan architecture have left a profound imprint on the design of contemporary Lingnan buildings. This paper has presented a comprehensive argument covering three key aspects: shading, ventilation, and heat insulation. It has introduced a qualitative and quantitative method within a case–model–analysis framework (Figure 14), integrating building simulation analysis and visualization. This approach has been illustrated through the selection of representative traditional Lingnan buildings and modern Lingnan structures, which have been analyzed and validated using building simulation and emulation platforms.

(1) Shading and heat protection: Traditional Lingnan architecture's practice of self-shading, including mutual shading from closely arranged building layouts and techniques such as roofing using doors, windows, external porches, and eaves, proves highly effective. These principles can be directly applied in the design of contemporary Lingnan buildings.
(2) Ventilation and heat mitigation: Given the Lingnan region's prolonged hot climate, the incorporation of air ducts in the "southeast to northwest" direction remains a paramount consideration in the design of modern Lingnan buildings. Additionally, innovative interpretations for creating ventilation and cooling effects within the local spaces of modern Lingnan structures are emerging. This includes the flexible use of atriums and elevated floors, especially by exploiting atrium height.
(3) Heat insulation and mitigation: Traditional Lingnan buildings traditionally use air gaps between layers for insulation. Modern Lingnan architecture extends this practice and incorporates new insulation techniques using modern technology. These innovations include green roofs, water storage roofs, and more to enhance heat insulation performance.

Beyond the rich cultural significance of traditional Lingnan architecture, its adaptation to the hot and humid climate through spatial layout, building volume, openings, structural techniques, and greenery is a topic worthy of further exploration. Architects are urged to build upon the demand for heat protection and insulation in Lingnan buildings. Valuable lessons from traditional structures that can be applied and disseminated should be unearthed and passed on, thereby inspiring new architectural creations that harmoniously adapt to the hot and humid climate of the Lingnan region.

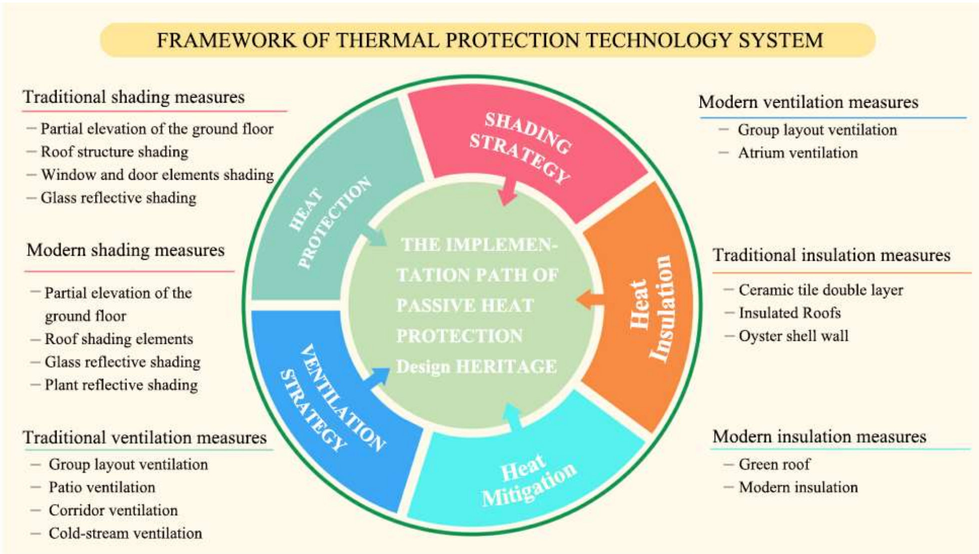


Figure 14. Framework of thermal protection technology system.

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