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Environmental Adaptations for Achieving Sustainable Regeneration: A Conceptual Design Analysis on Built Heritage Fujian Tulous

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Abstract: Environmental adaptation is essential for maintaining a building's indoor environmental quality and performance. This paper is focused on heritage regeneration research of the sustainable paradigm of Fujian Tulous in China. These earthen dwellings were built hundreds of years ago and were proven to be conventional green buildings today. However, few researchers have clarified or specified regenerative approaches for Tulous in response to realistic demands and sustainable concerns. Our study surveyed 10 non-world-heritage Tulou cases in Nanjing County, Fujian Province, China. Environmental adaptation in the Tulou archetype was analysed through an intensive review and field investigation to explain how they interacted with local climatic conditions. This article analysed the green effects of building components on five passive design strategies—thermal comfort, solar shading, natural lighting, ventilation, and waterproofing—and then proposed conceptual design strategies based on three aspects: reshaping building envelopes, reorganising spatial layouts, and using innovative construction materials and techniques. The conclusions indicated that, to realise the sustainable generation goals of non-world-heritage Tulous, environmental, socioeconomic, and cultural issues have to be considered, among which environmental adaptation should be a primary approach.

Keywords: Fujian Tulou; passive design strategy; indoor environment; heritage regeneration; adaptation; green effect

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1. Introduction

In recent decades, modern building performance has undergone significant development through active design strategy and advanced technology. Large quantities of artificial and manufactured products like curtain walls and air conditioning are applied to modify indoor environments to make them more comfortable and controllable [1]. However, such progress has led to rising energy consumption, carbon emissions, and pollution. To meet the needs of housing sustainability, another conventional paradigm, passive design [2] incorporates environmental factors of wind [3], sunlight [4], humidity [5], and heat [6] into house design in the early planning stage. Some traditional dwellings have been found to contain ancient generations' worth of wisdom in conforming to a climate and creating a suitable micro-environment for human habitation [7]. They have similarities to passive design and green buildings [8] because they rely primarily on building components, rather than air conditioning and other facilities, to control the indoor environment [9]. Specifically, great importance was attached to a building's shape, materials, and other construction details to strengthen its ability to interact with natural conditions. In earlier times, some rural Chinese located their dwellings and arranged living spaces to adapt to local climatic and geographical conditions so that they could survive natural threats and meet the basic needs of safety, durability, and liveability. One of the typical dwelling prototypes is the

UNESCO World Heritage Tulou [10,11], a physical representation of the local historical construction system in Fujian, China.

Heritage regeneration is considered to be an important source for the shaping of culture, society, and architecture [12] because it brings an ecological worldview to a mechanistic way of thinking [13]. Yung et al. [14] analysed the major factors of sustainable development of built heritage and found that challenges to the adaptive use of built heritage remain unsolved. For built heritage exposed to the outdoors, the natural environment is seen as both a threat and an opportunity. However, reconnecting human activities with the natural system [15] will take more than merely incorporating advanced technology into built heritage regeneration; otherwise, the elements of built heritage might not strengthen a building's performance but could possibly reduce it. Coombes et al. [16], who introduced the integration of natural-based solutions [17] and built heritage conservation, believe that it is necessary to understand building performance as being driven by the instinctual "gene" of built heritage and to promote its interaction with nature [18].

As far as the Tulou is concerned, it is a specialised dwelling that enables locals to survive in a particular environment in ancient times. As time went by, human requirements changed, but the Tulous remained. Without exceptional conservation efforts, Wang et al. [19] said that it was impossible to protect and kept intact other non-world-heritage Tulous (NWHTs). Ma et al. [20] discussed the assessment of non-World Heritage Tulous by using the analytic hierarchy process (AHP) to focus on funding and community participation. Some arguments against the adaptation of historical buildings said that coping with the complexity of environmental and socioeconomic factors was difficult [21]. However, considering the environmental benefits of climate adaptation, low-carbon emissions, material recycling, and intensive land use, the regeneration of built heritage Tulous is still important for sustainability [22,23]. Previous studies have analysed critical points of conservation and regeneration for built heritage Tulous, but environmental adaptation has not been clearly articulated.

This article is divided into four parts. Section 2 presents an overview of the current conditions of heritage Tulous in Fujian based on a field survey conducted in Nanjing County from May 2021 to March 2022. The complex requirements of sustainable on-site regeneration are described from multiple perspectives. In Section 3, the conventional sustainability paradigm of heritage Fujian Tulous is interpreted through 10 Tulou case studies. In addition, the passive design techniques of Tulou settlements are reviewed and illustrated to reveal traditional green building strategies. In Section 4, practical issues of regenerative design and construction are analysed. The transition from conventional sustainability to regeneration has three aspects: reshaping building envelopes, reorganising space layouts, and innovating materials and techniques. Section 5 is a summary of the conceptual design workflow of non-world-heritage Tulous. In short, this study fundamentally proposes an adaptative environmental framework for the sustainable regeneration of historical dwellings.

2. Overview of Tulou Heritage Regeneration

2.1. Context of Regeneration

Tulou refers to one or a cluster of earthen dwellings built in southern China between the 15th and 20th centuries. "Tu" means earth, and "lou" refers to a dwelling of 1–4 floors. Fujian Province has thousands of Tulous, and in 2008, UNESCO recognised 46 Fujian Tulou buildings as world heritage sites. Since then, they have been protected by the local Chinese government [24], and Fujian Tulous have become the cornerstone of the local economy through the tourism industry.

However, these 46 Tulous account for a mere 1.5% of the total. Thousands of non-world-heritage Tulous are distributed across rural mountain areas. Although they embody the historical records of family culture and local construction techniques, most are currently abandoned and dilapidated. One reason is that these earthen houses that were built over 100 years ago could no longer meet the needs of residents living in the 21st century. As a result, most historical Tulou groups are largely deserted and left to the elements to deteriorate [25]. A primary goal of heritage conservation and sustainability is an architectural regeneration route toward a response to the further development of common Tulous.

The term "regenerative" is interpreted as a design and management strategy of reusing, recycling, and rebuilding heritage structures from a long-term perspective [26] to maximise their value and stimulate their vitality, and this leads to green design [27]. The concept of sustainability has been around in the architecture industry for decades, and sustainable conservation is intended to fulfil the current society's demands while considering future generations' needs [28]. However, some members of current or future generations may be willing to overlook the values behind the non-world heritage Tulous [29]. A resident in Nanjing County stated: "I was born in a Tulou and currently live in an urban area. What impresses me most about Tulou is that it is a dirty, messy place with much inconvenience. I could not imagine moving back to a Tulou."

This episode demonstrated that a successful Tulou regeneration will entail not only physical refurbishment but also a shift in public attitudes toward non-world-heritage Tolous [30].

2.2. Research Methodology

First, this study constructed an environmental adaptation framework for passive house strategies for Tulous to examine how conventional Tulous interacted with environmental factors and residents' living needs. The building data came from an on-site field survey that provided architectural-scale details of Tulou building components. The mapping data were collected and compared to validate the typological features of Tulous. Then, we extracted correlations among building components and their environmental performance as "green genes", which guided the transition from a conventional green paradigm to a sustainable regeneration paradigm. Based on the idea of regenerating green building performance, we chose 10 non-world-heritage Fujian Tulous in Nanjing County as studying subjects. The study had three inclusion criteria:

1. The Tulous were distinct representations of Fujian Tulous and were of different building types;
2. The regenerative project should first be active in the sustainable adaptation of the neighbourhood;
3. The regeneration process must be a joint effort among local government, professionals, villagers, and investors.

However, finding an agreement among the four parties increases the difficulty of working out a regeneration plan. The Nanjing County government requires that these non-world-heritage Tulou groups be activated effectively and sustainably, but there is little experience in promoting traditional village vitality or environmentally sound buildings. The local owners inherited their Tulous over hundreds of years, but the younger generations have little knowledge of traditional construction techniques or financial support for heritage protection and renovation. Therefore, professional planners and scholars are expected to take responsibility for construction suggestions and proposals.

2.3. Study Area

Nanjing County is located at 24°52′ E and 117°37′ N in a remote mountain area in southern Fujian. It is home to the world-famous Tianluokeng Tulou group, which is 12 km from the county centre. Apart from this World Heritage Site, there are other non-world-heritage Tulou settlements, including Gaobei, Hekeng, and Yunshuiyao (Figure 1), most of which have been developed and managed as tourist spots by the Nanjing County Government. Because they are non-world-heritage Tulous, they are not famous; most of them have not been commercialised for development and have kept their original shapes, which are slowly decaying. The local government initiated a general survey of Tulou settlements in early 2021—before the regeneration project—to establish a digital archive so that the current conditions of every Tulou could be monitored and stored. The previous survey results showed that numerous historical Tulous have become empty shells since few villagers want to live in or refurbish them, so the planning of revitalisation and the design for thousands of historical Tulous is a challenge.

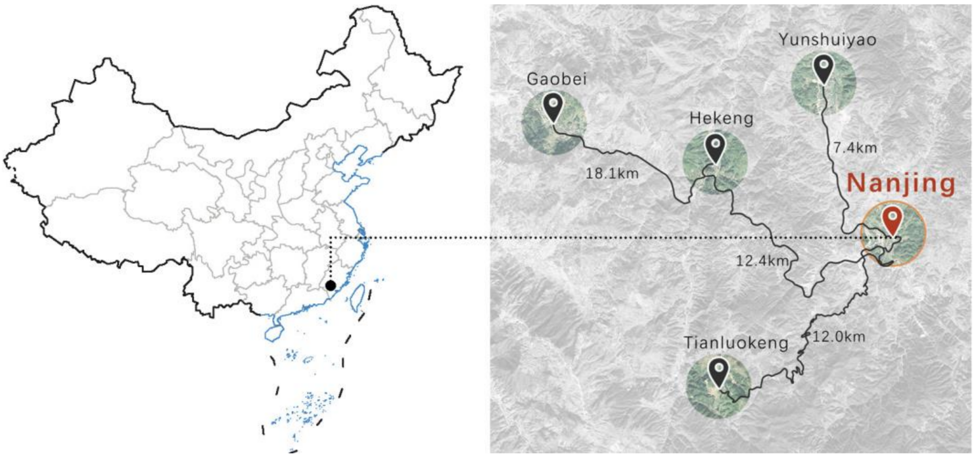


Figure 1. Locations of world heritage sites in Nanjing County, Zhangzhou City, Fujian Province, China.

2.4. Study Cases

During the field survey, 10 Tulou cases were selected for architectural mapping and investigation (Table 1). They were situated in different historical villages in the towns of Shuyang, Meilin, Chuanchang, and Hexi. Except for Yanshan-lou and Jing-lou, the other cases have the prominent feature of an enclosed inner courtyard. Built during the Ming and Qing dynasties (1368–1912), those dwellings initially served as private homes and detached castles for large families. Typically, three or four generations lived under one roof, but now, all of them are deserted.

Table 1. Study cases of Tulou dwellings.

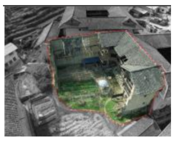
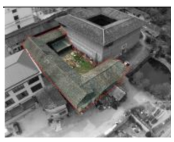
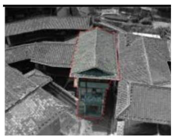
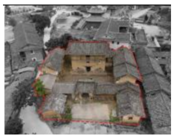
Photo [1]	Name of Tulou	Location	Date Built	Number of Floors	Building Height (m)	Reusing Purpose
	Yupian-lou	Nanou village, Shuyang town	1770s	3	10.00	business and office
	Guifang-lou	Shuyang village, Shuyang town	1890s	3	10.35	hospitality
	Ao-lou	Tianzhong village, Shuyang town	unknown	2	7.15	hospitality
	Yanshan-lou	Taxia village, Shuyang town	unknown	2	7.32	cultural

Table 1. *Cont.*

Photo [1]	Name of Tulou	Location	Date Built	Number of Floors	Building Height (m)	Reusing Purpose
	Junyuan-lou	Taxia village, Shuyang town	1925	3 (partly 2)	9.90 (partly 7.27)	hospitality
	Dexing-lou	Xiafan village, Shuyang town	1950	3	11.50	commercial
	Jing-lou	Meilin village, Meilin town	1716	3	11.40	cultural
	Gong-lou	Xikeng village, Chuanchang town	1600s	2 (partly 1)	9.08 (partly 3.95)	hospitality
	Chunshan-lou	Cunya village, Nankeng town	unknown	4	14.82	business and office
	Longde-lou	Linfan village, Hexi town	1662	4	16.75	hospitality

[1.] Photos were taken and provided by the Nanjing Government.

Though the first regeneration project of non-world-heritage Fujian Tulous has been officially selected, the paradigm and design of the regeneration are unclear because they place heavy demands on cooperation among green design strategies during adaptation. On the other hand, functional repurposing is specific and pragmatic, and it can include structural reinforcement, interior decoration, and refurbishment.

3. Conventional Sustainable Design Strategies

3.1. Environmental Adaptation

"Adaptation" is the fitting of organisms to their environments. In the context of natural selection, the most superior genotypes are developed in the evolution process of offspring generations. Similarly, dwellings have to be adapted to their environment—solar heat, sunlight, wind, air temperature, humidity, and rainfall must be considered [31]. Current studies have shown the need to adapt by learning from past environmental threats and low-tech habitats [32,33].

Nanjing County has a subtropical monsoon climate, and both monsoon circulation and mountainous terrain have a substantial impact on the local climate. The average temperature of the coolest month is a mild 10.0–15.0 °C, and that of the warmest is 25.0–30.0 °C. The average annual precipitation is 1795 mm, resulting in year-round high humidity that averages 82% [34]. While the winter is relatively warm, the summer is hot and humid, with heavy rainfall.

The specific objectives of Tulou adaptation are thermal comfort, solar shading, ventilation, and waterproofing, especially in summer. Most relatively passive strategies for

Tulous have been examined in response to heat and rainfall. In such cases, the architectural patterns have been interpreted in terms of human-environment correlations:

- Native people first built shelters to protect themselves from the macro-climate threats of rain, wind, and sunlight, which they could not control;
- They then adapt to the meso-environment by selecting a location according to geographic conditions and natural resources;
- Finally, they started to build Tulous, especially to create an indoor micro-environment for comfort, safety, and durability.

Their conventional adaptive strategies are reflected in architectural patterns, such as exterior shapes, interior spaces, materials, and construction techniques. The first two aspects are the physical expressions of green ideas, which are supported and realised through particular materials and construction techniques. Specifically, the exterior shape refers to the overall three-dimensional form and its exterior envelope, and it is regarded as the first and most significant interface with the environment. Correspondingly, interior spaces refer to the room layouts and interior envelopes, directly connecting with people's living needs and preferences. The environmental adaptations of Tulou were reviewed under an environment-oriented framework (Figure 2).

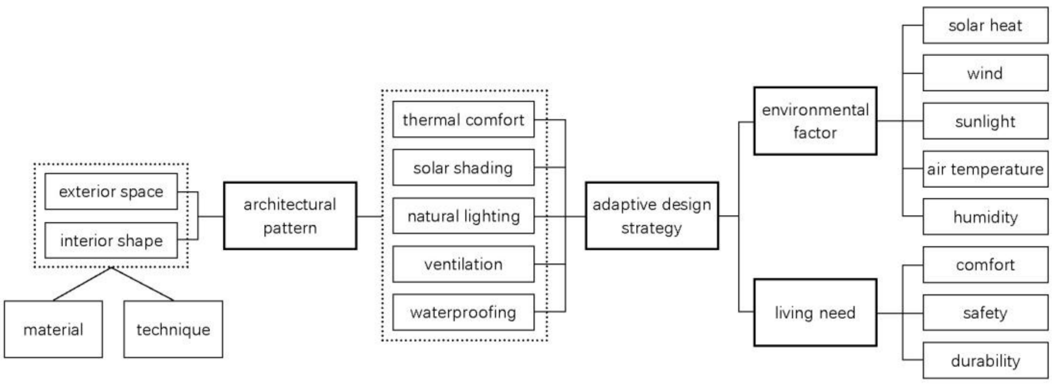


Figure 2. Framework for the climate-oriented adaptation of a conventional Tulou developed through a review of the literature.

3.2. Passive House Strategies

3.2.1. Thermal Comfort

Heat is transferred between buildings and the environment through conduction, convection, and radiation. A characteristic of Tulous is that their thick, sturdy exterior walls and double-slope roof keep heat out in the summer and retain heat in winter (Figure 3). The massive walls are made of rammed earth and are covered by 20 mm of protective mud on each side. The heat transfer coefficient of a 1.2 m thick wall is about 0.831 $W/(m^2 \cdot K)$ [35], and this earth-based material requires more heat to change its temperature than low-density materials like wood [36]. Low thermal insulation and large thermal mass that the rammed-earth walls provide create a stable indoor environment [37]. In fact, indoor temperature fluctuations in a Tulou are more moderate than the outdoor temperature and are even lower than those in a modern rural building constructed with concrete or brick. According to an investigation by Li et al. [38], when the outdoor temperature ranged from 23.0 to 35.0 °C on 4 August 2011, the indoor temperature in a Tulou was 26.0–28.0 °C, whereas, in a modern building, it was 25.1–31.0 °C. Residents of a Tulou enjoy thermal comfort in hot weather without the need for fans or air conditioning [39]. Furthermore, the windows in the earthen walls are small, which controls the amount of sunlight entering the rooms. Most windows are on the third floor, and hardly any are on the ground or second floor.

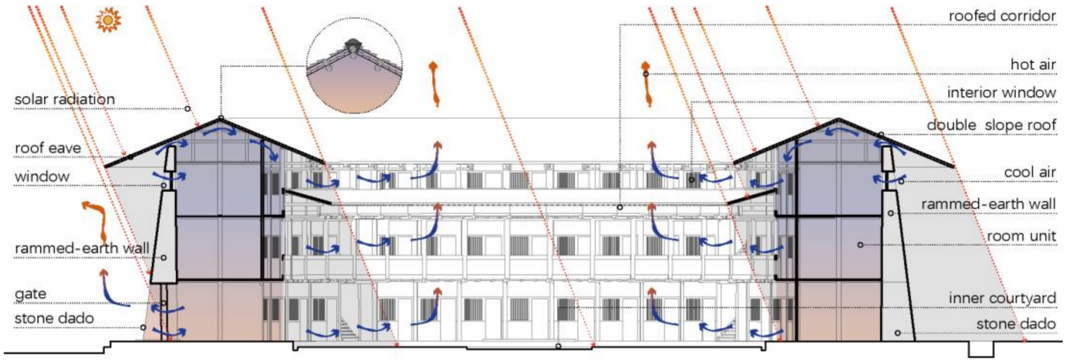


Figure 3. Schematic section of the Dexing-lou's environmental adaptation in summer daylight.

Another important component is the roof, which is made of wood and covered with grey Chinese tiles. Li et al. [40] calculated the average heat transfer coefficient of the roof [40] at 3.4 $W/(m^2{\cdot}K)$ since both woods and tiles have weaker thermal performance than the earth. Local people improved thermal comfort by using double-layer roofs and tile shingles. Specifically, the tiles were piled up with small cavities to allow air to flow through, taking away the heat. Additionally, the roof is not tightly attached to the top of the walls but sits on wooden pillars. The gap between the upper roof and wall provides thermal insulation in summer daylight. In the evening, heat is gradually released from the roof cavity, which cools the building down [41]. According to an investigation by Yang [42], the temperature on the top floor is the lowest.

3.2.2. Solar Shading

In contrast to the exterior envelopes, which are made of earth and are the first line of thermal prevention, the interior envelopes—walls, pillars, windows, and doors—are made of wood and act as the second line. This solar shading is another way to adjust the temperature in the indoor environment, which, strictly speaking, refers only to the interior space enclosed by the earth walls, since there is still open space in the inner courtyard.

Corridors and eaves are the two main sunshade components on the internal building envelopes of the walls and roofs. They act as uneven surfaces to create shadows for living spaces under direct sunlight. The semi-indoor corridors around the inner courtyard on each floor have the particular function of connecting every room with public walking space, and they partially block sunlight. The long overhanging eaves shade the tops of the corridors, leaving the facade open to the air.

Although the corridors and eaves decrease the amount of sunlight radiation entering a Tulou, some indirect light does enter. In this case, adjusting room layouts is a micro-scale strategy. For example, a room unit (width × depth) in Guifang-lou is 2.87 × 2.64 m; in Dexing-lou, it is 2.12 × 3.78 m; in Chunshan-lou, it is 2.68 × 3.00 m. The width-depth ratio of a regular room fluctuates from 56.08% to slightly over 100%. Because the depth is greater than the width, indirect sunlight is largely blocked, keeping the indoor space pleasantly cool in summer.

3.2.3. Natural Lighting

Because sunlight was the primary light source [43] when Tulous started to be built, windows in the exterior earth wall were limited in their amount and size (the window-wall ratio). For example, the windows in Longde-lou are 0.70 m wide and 1.15 m high, so the light from the exterior windows is not enough. Therefore, an inner courtyard was designed in the centre of some large Tulous. It is the main entrance of a Tulou that allows natural light to come into the dwelling. Its shape is always the same as that of the building; if the building footprint is square, so is that of the inner courtyard. Its size is relatively large and accounts for 27.97–46.38% of Tulou's footprint. Due to the high courtyard-footprint ratio, almost every room could be illuminated through wooden windows and doors on the internal side. The older generations who farmed during the day rose with the sun and rested after sunset, so their demand for light was lower.

3.2.4. Ventilation

Particularly for the high-density population in Tulous, efficient ventilation ensures clean and fresh air and is beneficial for thermal dispersion. Natural ventilation consists of both wind and thermal pressure ventilation. The former depends on monsoons to bring wind mainly through the gate and inner courtyard [44] since the low window-wall ratio allows little wind ventilation. Therefore, the building orientation of Tulou is important for wind ventilation.

The inner courtyard contributes to the chimney effect. In summer, when solar radiation heats the air in the inner courtyard, the heated air begins to rise and pull the wind like a chimney. The thermal pressure ventilation takes heat away from the house. Since rooms on the same floor are connected, air flows freely and equally across the round corridor. For example, an interesting phenomenon is that residents are accustomed to enjoying leisure activities in the shaded space near the gate on the ground floor, which is a passage between the gate and the inner courtyard. According to architectural physics, when the air close to the ground is heated, it creates air pressure between the inner passage and the outdoor, which causes a draught through the passage. Deng [40] conducted a wind field simulation through applications of computational fluid dynamics and found that the wind speed near the inner courtyard and gate was higher than that in other places.

3.2.5. Waterproofing

Strategies to deal with the water environment are summarised along two lines in a Tulou. First, preventing water sources in the natural environment, mainly rain. Second, taking away the indoor water quickly through draining and ventilating. The exterior envelope has three key features that improve the rainproofing efficiency (Figure 4):

- The plinth walls on the ground floor made of rocks create a durable and waterproof building base so that the earthen wall is lifted above the stone plinth wall and kept dry when raining. It is said that the height of stone dados should be above the highest flood level to prevent the rammed earth from soaking [45];
- The double-pitched roof drains rainwater. The pitch is calculated as the ratio of the roof height to the horizontal distance. Gong-lou has the steepest pitch at 77.50%, while Ao-lou has the shallowest at 34.95%. The bigger the figure, the sharper the slope;
- The eaves drain rainwater from the roof. Their deep width guarantees that after the rainwater is drained, the eave keeps leading it away from the Tulou. The eave width refers to the horizontal distance between the edge and the wall surface. The figures in Table A1 show that the width of an overhanging eave at Ao-lou is over 0.75 m, and this width reaches 2.18 m at Dexing-lou. After the rain falls to the ground, it is collected and led quickly away by drainage ditches [46].

Figure 4. Schematic section of the Dexing-lou's environmental adaptation to rain.

Considering that high humidity can easily cause dampness and bacteria growth [47], a Tulou relies on ventilation to carry away indoor air moisture. In addition, the organic materials of both mineral-laden soils and wood have bio-based dehumidification performance [48], which is conducive to discharging wall moisture through its "breathability". Ueda [41] conducted a field test to collect the relative humidity data of Chengqi-lou, and the results showed that the moisture records in the inner courtyard varied from 63% to 97% in 24 h, whereas the indoor humidity remained relatively constant at 85% on the first floor and 76% at the second floor. His investigation showed that indoor humidity on the upper floors was lower but more variable than that on the ground floor.

4. Transition from Convention to Regeneration

4.1. Strategic Planning at the Early Stage

Before working out alternative design solutions for the regeneration of non-world-heritage Fujian Tulous, a deep understanding of the past is in order. We constructed a comprehensive correlation between Tulou's architectural components and environmental adaptation to show the core principles of the green effect that every functional component should have. As summarised in Table 2, the five passive strategies of Tulous depend on the cooperation of multiple building components: walls, roofs, windows, corridors, et al. Not only do those components provide proper spaces for crowded households, but they also create interactions between the indoor environment and the external climates.

Table 2. A summary of Tulou building components and their related environmental adaptations.

Strategy	Environmental Adaptation	Architectural Component	Architecture Patterns				Supportive Literature or Data
			Exterior Shapes	Interior Spaces	Materials	Techniques	
Thermal comfort	Keeping thermal performance	Earthen walls	○ [1]	/ [2]	• [3]	○	Li [35], Sun et al. [37], Li et al. [38],
	Reducing insulating weakness	Small windows	•	/	/	○	Table A1
	Strengthening roof insulation	Double-layer roofs	•	/	•	•	Deng [40]
Shading	Sheltering rooms from the sun	Long overhanging eaves	○	•	/	○	Yang [31]
	Sheltering residents from solar radiation	Roofed corridors	/	•	/	○	
	Stopping sunlight from entering a room	Rooms with narrow width and deep depth	/	•	/	/	Table A2
	Controlling light's entry into rooms	Interior window	/	○	○	•	
Lighting	Allowing light to enter the building	An inner courtyard	•	•	/	/	Table A2
	Allowing light to enter rooms	Interior windows	/	○	/	•	
Ventilation	Causing a draught across the gate	Building orientation	•	○	/	/	Su et al. [44]
	Pulling wind like a chimney	An inner courtyard	/	•	/	○	Deng [40]
	Improving air ventilation	Interior windows	/	•	/	○	Li et al. [39]
Waterproofing	Sheltering building from rain	Long overhanging eaves	•	○	/	•	Table A1
	Serving as a waterproof base	Stone dadoes on the ground floor	•	/	•	○	Frangedaki et al. [45]
	Sheltering rooms from rains	Roofed corridors	/	•	/	•	Table A1
	Organising raindrainage	Ground drain	○	•	/	•	Wu [46]
	Bio-based breathability	Earthen walls	○	○	•	○	Su et al. [48]
	Taking away the moisture	An inner courtyard	/	•	/	/	Ueda [41]

[1] ○ minor factor; [2] / irrelevant factor; [3] • main factor.

At this point, the conceptual design for Tulou regeneration involves the reapplication of the green principles of responsive and efficient adaptation to the environment.

First, each component may have multiple effects on environmental adaptation, which reflects past integrative thinking to maximise the construction resources and environmental efficiency of Tulous. The inner courtyard, for example, is used for family activities, and it provides natural lighting, ventilation, and dehumidification. This single design feature in the centre of a Tulou, therefore, deals with light, heat, wind, and moisture. Similarly, the corridor not only functions as a physical connector but also shelters the interior rooms. Thus, its environmental adaptation involves solar shading and waterproofing.

Second, each passive strategy is carried out through the cooperation of different building components. For example, the components, from top to bottom—-roofs, walls, corridors, dadoes, ground drains, inner courtyards—-keep out rain and moisture.

4.2. Conceptual Design for Sustainable Regeneration

4.2.1. Reshaping Building Envelopes

Because of the historical Tulou conservation regulations in Fujian [49], the exterior shape of a Tulou cannot be altered very much. In this case, the design of the envelopes should be seen as a breakthrough point for reshaping environmental adaptations. Especially given the fact of climate change. In 2022, abnormal climate phenomena worldwide have been reported to be frequent and destructive. Zhuang et al. [50] monitored climate change in Nanjing County from 1981 to 2010 and found that the temperature rose by 0.32 °C and evaporation rose by 134.2 mm every 10 years. Therefore, since Tulous are directly exposed to the elements, preventive measures toward shifting climate patterns must be taken.

In green ecological architecture design, there have been many eco-friendly envelope inventions to interact with climatic factors. We proposed the Trombe wall [51] as one of the conceptual strategies for equipping existing rammed-earth walls with additional top-down envelopes, especially on the southern side of dwellings. The Trombe wall enacts its green effect on thermal and solar adjustment automatically through blinds and glazed cavities. It is supposed to protect the old rammed-earth walls as indoor components [51]. Relevant cases using double skins in the William Farrell Building project were discussed by Ueda [41]. In addition, Badarnah suggested biomimetics [52], a new style of architecture in which a structure is built to blend in organically with the environment [52]. In other words, the building envelope mimics the characteristics of the environment. However, it is not easy to find suitable and proper forms and patterns that fit the Tulou's adaptive envelopes, so more imagination and exploration are needed.

4.2.2. Reorganising Space Layouts

The conventional Tulou layout is intended to be reorganised according to the preferences of residents, the government, and investors. It is not a simple matter of replacing interior components, furniture, and decorations. There are three attributes of a regenerative space that must be satisfied. First, it must be fully used and defined with a specific social function, such as reception, catering, or entertainment. Second, it must maintain a green indoor environment through passive and environmentally friendly strategies. Third, the space must maintain sociocultural connections with the past. For example, during the renovation of the Tsingpu Tulou Retreat [53], the central room on the ground floor was conserved for family spirits out of respect for the locality and social customs.

One means of satisfying these attributes is through sunlight [54]. In a Tulou, the entrance where sunlight enters and the indoor channel through which it passes are under precise control through windows, the inner courtyard, and corridors. In spatial design, light is even regarded as a building material [55] because it creates a comfortable physical and psychological atmosphere for the residents, as it triggers the movement of air and moisture. Therefore, attention should be paid to the bridging effort of sunlight between indoor spaces and the green effect.

4.2.3. Innovating Construction Materials and Techniques

The Tulou was initially built out of local materials from the rural mountains: earth, stone, wood, and bamboo. Using rammed earth to build the exterior walls had five advantages. First, it is easily accessible and cheap. The raw earth could be sourced from Tulou's foundation pit and used on-site, thus reducing the costs of transporting other construction materials. Second, the construction is environmentally friendly, since physically ramming the earth using local labours does not involve any direct energy consumption or chemicals. Third, the constructive technique is simple and efficient because the earthen walls simultaneously serve as the body structure [56] and envelopes. Fourth, it is environmentally adaptative, which means that its low thermal resistance keeps indoor spaces cool or warm during times of extreme temperature [57,58]. It also improves indoor air quality because it is breathable [59]. Fifth, after it reaches the end of its lifespan, the earth can be recycled and reused as a construction material or soil fertiliser.

The technique of Tulou construction shows how materials can be rationally evaluated from ecological, social-economic, and cultural perspectives. In recent years, research into green chemistry and alternative materials has been expanded to the renovation and repair of historical and heritage buildings. Turo et al. [28] suggested using innovative chemical products for material conservation because of their durability, compatibility with existing materials, transparency, and easy synthesis. For non-world heritage Tulous, there are extra practical issues to consider during their life cycle: environmental performance, accessibility, and degradability. Bricks and concrete are two common materials for the construction of modern dwellings in rural villages in Nanjing County, and although they are more durable than natural materials (earth, wood, and bamboo), they are less eco-friendly. In a neighbourhood in Nanjing County, yellow-coloured concrete walls [60] have been introduced to imitate the rammed-earth walls, but these are poor imitations.

Similarly, priority is given to low-tech construction using local materials and resources in vernacular dwellings. If regeneration is cheap, low-tech, and green, it is easy for it to be accepted by the stakeholders. However, that does not mean avoiding high-tech equipment. It is reasonable to suppose that smart sensors, automatic shades, and photovoltaic panels could be used in the regeneration of non-world heritage Tulous. In that case, the cost, maintenance, management, and circulation of building waste might be challenges for the residents.

5. Conclusions

In this study, a field survey was conducted in the non-world-heritage Tulous in Nanjing County, Zhangzhou City, Fujian Province, China, to investigate environmental adaptation in heritage regeneration. From the research on the correlation between architectural pattern and their green effects on environmental adaptations, five passive strategies—-thermal comfort, solar shading, natural lighting, ventilation, and waterproofing—-were reviewed. It is clear that a Tulou is like an organism in a rural ecosystem: There is close cooperation among all of the building components, which have multiple functions, and such specialisation was reached through long-term incremental interaction with the environment. Regarding environmental adaptation, possible regenerative ideas were proposed based on a strategic analysis of local non-world-heritage Tulous (Figure 5). Lessons learned from the past are incorporated into the building envelopes, space layouts, and construction. In this study, environmental adaptation was taken as a primary approach or a chief trigger for the sustainable regeneration of non-world-heritage Tulous. However, sociological, economic, and cultural attributes should also be taken into consideration.

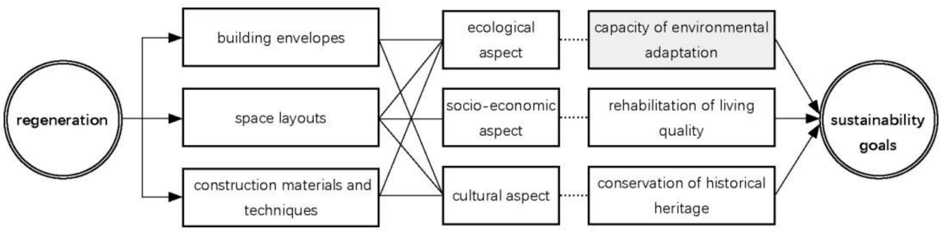


Figure 5. Framework for the design of sustainable Tulou regeneration strategies.

Further follow-up visits and investigations are planned to develop and detail the design of the regeneration and construction process. Assessing a Tulou's regeneration is another essential step after implementing the relevant design. We will use centuries-old wisdom not only to meet current needs but also to stimulate today's wisdom to respond to future requirements.

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Appendix A

The list of building component sizes of the 10 Tulou cases is provided in the table below.

Table A1. List of exterior elevation factors.

Variables	Yupian-lou	Guifang-lou	Ao-lou	Yanshan-lou	Junyuan-lou	Dexing-lou	Jing-lou	Gong-lou	Chunshan-lou	Longde-lou
Wall thickness(m)	0.60	1.05	0.40	0.60	0.60	0.80	0.45	0.60	1.37	0.70
Window area (m^2)	1.53	7.41	2.98	0.00	6.85	9.39	4.08	1.09	4.18	12.86
Sidewall area (m^2)	233.00	220.34	236.56	106.85	220.52	1003.05	123.00	82.75	347.75	498.72
Window-wall ratio (%)	0.66	3.36	1.26	0.00	3.11	0.94	3.32	1.31	1.20	2.58
Gate area (m^2)	× [1]	2.97	11.25	2.46	5.70	7.73	14.94	3.43	5.51	3.51
Main wall area (m^2)	×	205.97	240.63	110.03	127.49	1003.05	123.00	82.75	391.95	498.72
Gate-wall ratio(%)	×	1.44	4.68	2.24	4.47	0.77	12.15	4.15	1.41	0.70
Roof pitch (%)	×	42.42	34.95	49.40	59.30	46.00	33.20	77.50	44.70	48.30
External eave width (m)	1.00	2.03	0.75	0.92	1.05	1.69	1.49	0.90	1.97	2.18

[1] × unmeasurable.

Table A2. List of interior elevation factors.

Variables	Yupian-lou	Guifang-lou	Ao-lou	Yanshan-lou	Junyuan-lou	Dexing-lou	Jing-lou	Gong-lou	Chunshan-lou	Longde-lou
Window and door area (m^2)	15.56	28.61	29.32	13.02	18.84	97.02	/ [2]	/	45.88	46.42
Wall area (m^2)	206.00	147.29	240.63	112.31	108.56	692.70	/	/	260.65	339.83
Window-wall ratio(%)	7.55	19.42	12.18	11.59	17.35	14.01	/	/	17.60	13.66
Room width (m)	1.97	2.64	3.75	2.25	2.86	2.12	2.43	2.25	2.68	3.82
Room depth (m)	3.42	2.87	4.55	3.65	2.81	3.78	2.82	3.30	3.00	3.92
Width-depth ratio(%)	57.60	91.99	82.42	61.64	101.78	56.08	86.17	68.18	89.33	97.45
Inner courtyard areas (m^2)	× [1]	133.30	324.80	/	95.29	313.66	/	129.89	315.22	319.94
Building footprint areas (m^2)	×	476.60	700.30	/	404.00	786.46	/	426.62	723.41	991.50
Courtyard-footprint ratio(%)	×	27.97	46.38	/	23.59	39.88	/	30.45	43.57	32.27

[1] × unmeasurable; [2] / absent.

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