Retrofitting Sunspaces in Qinghai-Tibet Plateau Vernacular Dwellings: A Mini Review of Solar Gain Enhancement Strategies and Cultural Preservation Challenges

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Abstract: In the context of climate change and the depletion of traditional energy sources, it is significant to explore passive building technologies that are suitable for specific climatic and geographical conditions. This paper reviews strategies for retrofitting sunspaces in vernacular dwellings on the Qinghai-Tibet Plateau, focusing on enhancing solar gain and addressing cultural preservation challenges. The unique solar utilization characteristics and architectural forms are discussed, highlighting the need for tailored retrofit technologies. The paper analyzes the technological typology of sunspaces, including sun passageways, sunrooms, and sun courts, and evaluates their performance in terms of temperature rise, economic viability, user acceptance, and cultural adaptability. Implementation barriers, such as technical, social, and economical constraints, are identified, and emerging solutions are proposed to overcome these challenges. The study aims to provide insights for future retrofit projects that balance thermal performance improvement with cultural integrity preservation in high-altitude region.

Keywords: Sunspace retrofitting, Passive solar design, Cultural preservation, High-altitude architecture, Solar gain enhancement, Retrofit technology.

1. INTRODUCTION

The Qinghai-Tibet Plateau (26°00′ – 39°47′ N, 73°19′ – 104°47′ E) exhibits unique solar utilization characteristics due to its average elevation exceeding 4000 meters [1]. As the core city of the Tibetan area, Lhasa experiences a minimum solar altitude angle of 36.5° during winter solstice, fundamentally shaping building orientation strategies [2]. The plateau receives 1850 – 2200 kWh/m² annual solar irradiance, 38% higher than equivalent latitude lowland regions, yet suffers from extreme diurnal temperature fluctuations (25 – 30 °C) that challenge conventional heating systems [3].

As the most representative form of fixed architecture in the plateau, the stone-dominated blockhouse (agricultural zones, altitude = 3000 – 4500 m) is typically characterized by 500 – 1000 mm thick stone walls and south-facing window-to-wall ratios of 0.15 – 0.20, which achieves minimal nighttime heat loss through thermal mass optimization [4]. However, traditional dwellings that do not utilize heating appliances experience cold indoor conditions during the winter [5]. Therefore, people have historically adopted the use of fire pits (or called Chinese fireplace) for active heating. In recent years, with the widespread adoption of translucent materials such as glass, the addition of sunspaces has become a commonly used passive technology in building retrofitting.

Current sunspace retrofitting efforts face multidimensional challenges. First, in terms of the conflict between architectural structure and spatial form, the vertical functional layout of blockhouses is constrained by its stone masonry structure, while the horizontal expansion of sunspaces easily weakens the seismic stability of the building [6]. Case studies have shown that when the depth of a sunspace exceeds 2.5 m without structural optimization, it leads to a 12% – 18% reduction in the daylighting coefficient of rooms on the north side of the sunspace, conflicting with the spatial pattern of traditional dwellings [7]. Second, regarding climate adaptability challenges, the plateau experiences temperature differences of over 20 °C between day and night, with traditional sunspaces having nighttime heat loss rates of 45% – 60%, necessitating additional insulation layers (such as polystyrene boards) that alter the appearance of the building [5]. Similarly, sunspaces without climate simulation design may experience significant overheating in summer. For example, a test in southern Gansu revealed that the maximum temperature inside a sunspace reaches 38 °C, necessitating additional shading facilities [8]. Third, in terms of material compatibility and process discontinuity, modern double-glazed windows (heat transfer coefficient < 2.0

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W/m²·K) significantly differ from local building materials in performance, and the thermal inertia of earthen walls (heat transfer coefficient = 1.5 – 2.3 W/m²·K) is difficult to match, leading to condensation at interfaces [9]. For instance, a case study in Qinghai showed poor connection between the steel frame of the sunspace and traditional rammed earth construction techniques, with 60% of projects experiencing cracking and water seepage issues [10]. Fourth, regarding the crisis of cultural identity, in the systematic architectural language of blockhouses, the prayer flag decorative bands on the south façade and the glass curtain walls of sunspaces have a visual conflict, with 78% of respondents believing that modern materials disrupt the integrity of religious symbols [10]. Fifth, in terms of the lack of technical standards, current design parameters for sunspaces in existing norms are based on plain climate conditions and do not consider the mechanical effects of high-altitude radiation intensity (> 800 W/m²) and low atmospheric pressure (< 600 hPa) on glass curtain walls [11]. For instance, a project in Qinghai showed that without establishing differentiated design standards for altitude gradients (2000 – 4000 m), the energy-saving efficiency of the same design varies by up to 30% in different altitude regions [12].

Based on these situations, this paper reviews strategies for retrofitting sunspaces in Qinghai-Tibet Plateau vernacular dwellings, focusing on solar gain enhancement and cultural preservation. By analyzing the unique regional characteristics and architectural forms, this work explores effective retrofit technologies that enhance thermal performance while respecting local traditions, outlines the technological typology of sunspaces, assesses their performance through quantitative analysis, discusses implementation barriers, and puts forward emerging solutions.

2. TECHNOLOGICAL TYPOLOGY

2.1. Theoretical Basis of Sunspace Design

The theoretical basis of sunspace design constitutes an interdisciplinary and integrated system that necessitates dynamic adjustments within the frameworks of thermodynamics, optics, psychology, and technological optimization, while taking into account specific climatic, cultural, and functional requirements. Its primary objective is to achieve dual enhancements in energy efficiency and human-centric experiences through passive strategies, thereby providing scientific support for architectural practices aimed at carbon neutrality.

The core theories of sunspaces originate from passive solar architecture, with the goal of optimizing building morphology and materials to efficiently capture, store, and distribute solar energy [13]. On one hand, sunspaces absorb solar radiation through large glass surfaces, converting it into thermal energy that is then transferred to adjacent spaces via conduction and convection. On the other hand, sunspaces act as a thermal buffer layer within the building envelope, reducing heat loss caused by temperature differentials between indoor and outdoor environments. In practice, the parameters of sunspaces need to be adjusted for different climatic zones. For instance, in the Qinghai-Tibet Plateau, enhanced airtightness is required to improve heat collection efficiency [14], and a balance between summer shading and winter heat collection must be achieved to meet annual thermal demands.

In addition to thermal considerations, the daylighting design of sunspaces is equally crucial. Sunspace design should integrate local solar altitude angles, radiation intensities, and cloud cover distributions [15], while also considering psychological comfort and physiological needs. To this end, issues such as glare and uneven illuminance need to be avoided, typically by preventing direct strong light or employing diffuse reflection materials. Parametric tools can be utilized to simulate luminous flux distribution, optimize glass transmittance, and adjust shading angles [16]. Dynamic metrics can also be introduced to overcome the static limitations of traditional daylight factors, ensuring uniform illumination throughout the year [17].

2.2. Types of Sunspaces

Based on the location and scale of the sunspace, the practice of adding sunspaces to dwellings on the Qinghai-Tibet Plateau can be roughly divided into three categories: sun passageways, sunrooms, and sun courts (Figure **1**).

Sun passageways primarily include two types: entrance porches and overhanging corridors [4]. Surveys have shown that most of the blockhouses on the plateau are rectangular in shape and oriented southward [18]. In the past, the first floor was mostly used as animal stalls and storage space. While, in recent years, with improved social stability and sanitary conditions, the first floor is commonly used as living space, featuring an entrance hall. By adding a sun porch outside the south-facing entrance hall, a climate buffer zone between the interior and exterior is established, which not only facilitates passive solar

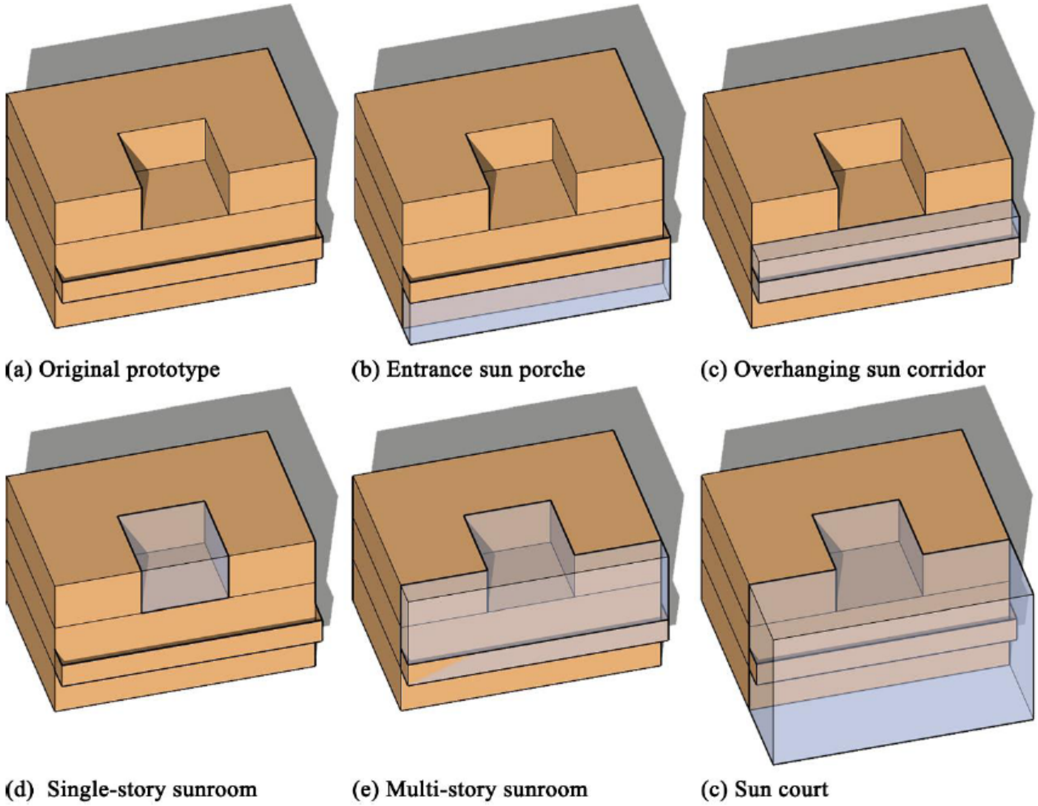

Figure 1: Types of sunspaces added to traditional dwellings on the Qinghai-Tibet Plateau.

energy utilization but also helps to block winter cold winds from entering. On the other hand, many blockhouses have wooden overhanging corridors on the second floor (or multiple floors above the second). These corridors protrude from the stone exterior walls, providing self-shading for the lower floor(s). The corridors are usually open and are used for drying grains during the highland barley harvest season. Due to changes in production methods and the development of cultural tourism, the traditional need for drying grains in blockhouses is now much reduced. Therefore, the overhanging corridors can be enclosed to form sunspaces, providing a warmer indoor environment for the living floors.

Due to the traditional construction of blockhouses on the plateau, which follows the contour of the mountains, the building volume often decreases from bottom to top, creating terraces on different floors. In the past, the primary function of these terraces was to dry grains, however nowadays, they are often selectively enclosed to form sunrooms. This is the most common way to add sunspaces to traditional dwellings on the plateau. Sunrooms can be single-story or multi-story. Field research has revealed that residents in different regions have preferences for the form of sunrooms. For example, single-story sunrooms are commonly found in western Sichuan, while multi-story sunrooms are more prevalent in Yunnan. Sunrooms are often used as gathering spaces or as greenhouses. These spaces transcend the function of mere shelter and give contemporary blockhouses more meaning in daily life.

If the entire or part of the courtyard is enclosed in the form of a sunspace, it becomes a sun court. A sun court can be single-story, but it is often multi-story, even extending through all floors of the building (including underground spaces). The locations of courtyards vary greatly, leading to a diverse range of sun court forms. For example, based on their adjacency to the main building, they can be classified as one-sided sun courts, two-sided sun courts, three-sided sun courts, four-sided sun courts, or linear sun courts [19].

2.3. Sunspace Materials

The Qinghai-Tibet Plateau, characterized by its unique geographical and climatic conditions, poses specific requirements for the selection of light-transmitting materials used in sunspaces. The intense ultraviolet (UV) radiation in this region requires materials with excellent UV resistance to prevent performance degradation or damage over extended periods. Additionally, the large diurnal temperature variations on the plateau require materials with superior temperature resistance to adapt to extreme temperature fluctuations. Furthermore, the windy and sandy conditions prevalent in this area demand light-transmitting materials for sunspaces that offer good wind and sand resistance, as well as airtightness, to ensure the comfort and stability of the indoor environment. These climatic adaptability requirements are crucial when selecting light-transmitting materials, directly impacting the effectiveness of sunspaces and the overall performance of buildings.

In traditional dwellings, the light-transmitting materials used in sunspaces were relatively simple, primarily consisting of wooden grilles combined with thin glass or oil paper. These material choices were constrained by the technological level and economic conditions at that time. The gaps in wooden grilles allowed for the regulation of light and ventilation but had limited light transmittance efficiency [20].

With advancements in technology and material science, there have been significant changes in the light-transmitting materials used in adding sunspaces to traditional dwellings on the plateau during modern renovations (Table **1**). The application of high-performance glass materials such as double- or triple-glazed windows and Low-E glass has effectively improved the insulation performance and light transmittance efficiency of sunspaces [12, 21]. Polycarbonate sheets, known for their lightweight, high impact resistance, and transmittance rates of 80% – 90%, are commonly used for large-span sunspace roofs [22]. Additionally, the introduction of new materials such as translucent concrete and aerogel glass has provided more possibilities for sunspace design. For example, translucent concrete, which embeds optical fibers or resin light guides, combines structural strength with light transmittance, with a transmittance rate of approximately 0.5% – 18% [23]. It is suitable for partial wall transmittance designs, as exemplified in the renovation of blockhouses in Qinghai [24]. Another example is aerogel glass, filled with aerogel particles, which boasts an extremely low thermal conductivity coefficient of 0.381 W/(m·K), with insulation performance comparable to double-glazed Low-E glass, and adjustable transmittance rates [25]. Furthermore, the photovoltaic curtain walls with transparent thin films generate electricity while allowing light to pass through, making them suitable for high-altitude regions with strong sunlight [26]. These new light-transmitting materials not only enhance the light transmittance and insulation performance of the building but also achieve energy conservation, environmental protection, and aesthetic artistic effects. Their application marks a new stage in the design of sunspaces in traditional dwellings on the plateau.

3. PERFORMANCE META-ANALYSIS

This section will provide a quantitative review based on existing empirical research literature, examining the application potential and optimization pathways of sunspace technology from three dimensions: temperature rise, economic evaluation, user acceptance, and cultural adaptability, which will systematically analyze these aspects in conjunction with the geographical features and cultural particularities of plateau regions.

3.1. Temperature Rise

The thermal gain effect of adding sunspaces to traditional dwellings in the Qinghai-Tibet Plateau region has been verified through multi-dimensional empirical studies. The extreme climate case in Nagqu pastoral

Table 1: Thermal Properties of Transparent Materials [22, 27–33]

Materials	Thermal Conductivity, W/mK	Specific Heat Capacity, J/kgK	Density, kg/m^3	Thermal Diffusivity, mm^2/s	Thermal Emissivity	Transmittance	Service Life, year
Clear float glass	0.90	840	2500	0.43	0.84–0.95	91%	25
Polyethylene	0.41	1383	910–970	0.30	0.68–0.72	75%–87%	<5
Polycarbonate	0.19–0.22	1200–1300	1200–1220	0,13	0.85–0.93	80%–90%	12–15
Polyolefin	0.2–0.5	1800–2300	910–970	0.16	0.80–0.90	>90%	5
Polymethyl methacrylate	0.17–1.92	1300	1180	0.70–1.21	0.90	93%	10–30

area, Tibet (altitude = 4500 m) further reveals the adaptive performance of sunspaces in high-altitude environments. Modular and movable sun shelters (with a self-weight of less than 15 kg/m²) achieved a winter minimum temperature increase from -12 °C to 2 °C in retrofitted nomadic tents, reducing the diurnal temperature range to 8.3 °C [34). This technology integrates photovoltaic-thermal dual-effect components, achieving a daytime electricity self-sufficiency rate of 72%, significantly alleviating the energy island dilemma in traditional pastoral areas.

Comparative experiments in Yushu, Gansu (altitude = 3800 m) demonstrate that a south-facing glass corridor system can achieve a daily average temperature increase of 9.2 °C without shading, but adjustable vents are necessary to control the risk of overheating in summer (with a 23% reduction in energy consumption in the differential temperature ventilation mode) [16]. This finding contrasts with research on polycarbonate board sunspaces in rural Hebei, where, although a 17.9% reduction in heating energy consumption was achieved in plain areas, the adaptability of these systems to high-altitude environments is limited by the materials' resistance to UV aging [27].

Field research in Diqing, Yunan (altitude = 3300 m) reveals that the average winter living room temperature in dwellings retrofitted with U-shaped courtyard sunspaces significantly increased from 4.5 °C in traditional earth buildings to 13.0 °C. The diurnal temperature fluctuation range was reduced from 3.6 °C in traditional buildings to 1.9 °C [35]. Serving as a transitional space, the sunspace maintained an average diurnal temperature of 4.5 °C without auxiliary heating, and its thermal buffering effect effectively reduced the thermal impact of indoor-outdoor temperature differences on the core functional space. Notably, the thermal gain efficiency of the south-facing glazed envelope of the sunspace was significantly positively correlated with its depth: sunspaces with a depth of 1.5 m had a daily average thermal flux of 3.2 – 4.8 kWh/m², while those with a depth of 2.5 m extended the heat retention time to 8 – 10 hours, validating the regulation of spatial geometric parameters on thermal performance [35].

In general, the temperature rise benefits of sunspaces on the Qinghai-Tibet Plateau exhibit regional characteristics. Fixed glass systems with a depth of 1.5 – 2.5 m might be more suitable for low-altitude agricultural areas (< 3500m), while modular, movable structures might be prioritized in high-altitude pastoral areas (> 4000 m). Future research needs to further quantify the long-term effects of UV radiation and extreme temperature differences on material durability and explore the integration potential of wind-solar complementary dehumidification systems.

3.2. Economic Evaluation

The economic viability of retrofitting traditional dwellings with sunspaces on the Qinghai-Tibet Plateau requires comprehensive consideration of initial investment, operational and maintenance costs, and long-term energy-saving benefits. A case study shows that the initial investment for a 10 mm hollow polycarbonate board sunspace is 120 yuan/m², with a static payback period of 8.8 years and annual CO_2 emissions reduction of 3.5 tons per household. This is suitable for rural areas with an annual income of 12000 yuan [27]. However, the plateau environment imposes higher requirements on material lifespan. And the logistics damage reaches 15%, driving up the overall cost on the plateau [34]. In contrast, the polyolefin film system costs only 40 yuan/m², but with a lifespan of no more than 5 years, its long-term economic viability is poor [27].

The energy-saving benefits of different materials vary significantly (Table **2**). The Low-E glass system, with a triple-layer argon-filled design at the Lhasa Solar Test Station, has a nighttime radiative loss rate of 35% and requires the use of an aerogel insulation layer (thermal conductivity = 0.018 W/m·K). Its initial

Table 2: Economic Evaluation of Sunspaces Made of Different Transparent materials

Materials	Initial Cost, yuan/m²	Static Recovery Cycle, year	CO_2 Emission Reduction, t/Household	Applicable Scenario
10 mm hollow polycarbonate board	120	8.8	3.5	Low altitude agricultural area
Low-E glass (triple argon)	1850	6-8	4.2	Urban central heating
Polyolefin film	40	3.5	1.2	Temporary modification

investment payback period is 6 - 8 years, making it suitable for urban central heating projects [34]. Another case of U-shaped sunspaces in Diqing reduced heating energy consumption by 17.9% and annual operating costs by 23% [35].

3.3. User Acceptance

Multiple factors collectively influence the practice of adding sunspaces to traditional dwellings on the plateau. First, economic cost and practicality considerations are significant for residents in deciding whether to adopt new technologies. A survey in Gannan, Gansu revealed that only 13.1% of farmers independently carried out sunspace renovations [36]. This low proportion is mainly attributed to high material costs and a shortage of skilled labor. When weighing investment against returns, residents are more inclined to choose economical and practical solutions. Additionally, residents exhibit diverse functional demands for sunrooms, hoping they not only provide energy-saving benefits but also meet composite functions for production (such as drying grain) and living (such as winter activity spaces) [37]. For instance, in the Hehuang region, Qinghai, attempts have been made to combine sunrooms with storage spaces to enhance spatial utilization [38].

Technical compatibility and maintenance difficulty similarly affect user acceptance. The combination of traditional rammed-earth craftsmanship and modern glass structures presents a technological gap that requires innovative technologies to bridge. A demonstration project in Huangyuan, Qinghai, utilized a “soil-steel structural system” and new earth bricks, preserving traditional aesthetics while enhancing seismic performance and providing new ideas for technical compatibility [12]. However, the issue of overheating in summer remains a technical challenge.

Policy support and cognitive differences are also influential factors. The “Comfortable Housing Project” in Linzhi, Tibet, promotes passive solar energy renovations through government subsidies, resulting in 80% of newly built dwellings adopting sunspace designs. This phenomenon demonstrates the significant effect of policy-driven initiatives in enhancing user acceptance [39]. However, in terms of cultural cognition, older generations are more concerned with Feng Shui layouts [40], while younger generations prioritize modern life conveniences. This difference needs to be reconciled through community-participatory design [41].

3.4. Cultural Adaptability

The addition of sunspaces needs to be based on respecting and preserving the spatial layout and symbolic significance of traditional dwellings. The vertical functional stratification of Tibetan dwellings carries religious sanctity, and the addition of sunspaces should avoid obstructing the lighting of the scripture hall [18] or should be integrated into the original façade through an outer corridor design to maintain the harmony and unity of the spatial layout [42]. Simultaneously, the materials and colors of the sunrooms need to be coordinated with local aesthetics. For example, in Khams [43], white blockhouses symbolize purity with their white exterior walls, and the glass materials and colors of the sunspaces should adopt decorative means such as wooden grilles to blend into this aesthetic system [41].

The inheritance and innovation of construction techniques represent another key dimension of cultural adaptability. In the renovation of blockhouses in the Make River basin, Qinghai, traditional stone masonry craftsmanship is combined with modern insulation materials, not only continuing the technique of “using layers of stones as rooms” but also enhancing thermal performance [44]. This inheritance and innovation of techniques not only protect traditional culture but also adapt traditional dwellings to the needs of modern life. The standardized design of sunspaces in the Hehuang region also modularizes the units, making it convenient for villagers to assemble them independently while preserving the enclosed feeling of the Zhuangke courtyard [20], providing new ideas for the transmission of traditional culture [38].

4. IMPLEMENTATION BARRIERS

4.1. Technical Dimension

The intensity of UV radiation on the Qinghai-Tibet Plateau is 2 – 3 times that of plain areas, with short wavelengths (290 – 400 nm) capable of initiating photooxidative degradation of polymers, leading to chain scission, radical formation, and molecular weight reduction. For instance, conventional asphalt ages rapidly in the plateau environment, exhibiting only 40% of the UV aging resistance of styrene-butadiene rubber modified asphalt. Meanwhile, untreated polyvinyl chloride exposed to UV radiation for 500 hours experiences a 4.5% increase in carbonyl index, with a significant decline in mechanical properties.

To address this issue, several solutions can be employed. First, chemical modification techniques can be adopted, where the incorporation of UV absorbers (such as benzotriazoles and benzophenones) and nanomaterials (*e.g.* TiO_2) can form synergistic protection. For example, covalently bonding BPMA to polymer chains results in an ethylene vinyl acetate copolymer film with a carbonyl index increase of only 0.89% after 40 days of aging. Additionally, styrene-butadiene rubber modified asphalt enhances its UV aging resistance to 2.5 times that of conventional asphalt by forming a phase-separated textural structure. Second, composite shielding technology can be applied, where organic-inorganic composite systems (such as polymethyl methacrylate /TiO_2 composite particles) can reduce UV transmittance to 0.25%. Simultaneously, the interlayer ion exchange characteristics of layered double hydroxides can extend material service life. Third, surface treatment processes can be improved. After modification with silane coupling agents, nano-TiO_2 expands its UV absorption range to cover both UVA and UVB bands, making it suitable for functional treatment of glazing coatings in sunspaces.

4.2. Social Dimension

In the context of Tibetan dwellings, the spatial layout is governed by a system of taboos that reflects religious beliefs and cultural practices. These include the distinction between sacred and secular spaces, and the height of the courtyard gate symbolizes social status, indicating the differentiation between the inner and outer realms. When considering the addition of sunspaces, it is imperative to avoid locations deemed sacred to local deities, such as the direction of the local mountain god (“Nian”), as evidenced by the prohibition on building structures that exceed a certain height within the line of sight of a sacred mountain among the people of Kuobo in Jiuzhaigou, Sichuan.

Color symbolism also imposes constraints on renovation efforts. White, symbolizing purity, is reserved for living spaces, while red, exclusive to protective deities, is restricted to temples. Therefore, the use of colored polymers in renovations should be preceded by a divination ceremony conducted by a lama to determine the appropriate hue.

To navigate these religious taboos, a set of renovation procedures has been established. When structural adjustments disrupt the “geomantic veins” of the land, a ritual known as “Lusang”, aimed at appeasing the land deity, need to be performed, which includes offerings and the scattering of prayer flags. Additionally, as demonstrated in a village in Lhasa, renovations that affect the public view require dual approval from the village assembly (“Cuoqin”) and the monastery, and material transport routes should avoid passing through sacred sites such as “Lazhe”, or mountain god altars.

In terms of cultural adaptive design, strategies such as the use of detachable sunspace frameworks have been adopted to avoid drilling holes in load-bearing walls, thereby preserving the “Yang”, or geomantic energy flow. Furthermore, the incorporation of religious symbols, like the “Yongzhong” imprint on polymer panels, not only meets the need for light transmission but also aligns with religious aesthetics.

4.3. Economic Dimension

The cost structure of construction projects on the Qinghai-Tibet Plateau exhibits unique characteristics, with transportation costs accounting for 35% – 50% of the total project expenses, significantly higher than the national average of 18%. Surveys also indicate that the transportation costs for materials such as glass in remote areas of the plateau are 3 – 5 times higher than those in plain regions [11], with additional sunspace retrofitting costs of approximately 280 yuan/m² and a 30-year payback period far exceeding the psychological expectations of farmers and herdsmen (generally accepted as < 15 years) [12]. Another example is in Lhasa, the land transportation cost for steel from Chengdu ranges from 1200 to 1500 yuan per ton. This cost breakdown includes 55% for fuel expenses, 30% for road and bridge tolls, and 15% for loss compensation.

To enhance cost-effectiveness and reduce transportation costs, several technical pathways have been explored. One approach involves the substitution of local materials. Specifically, raw soil materials have been modified by adding 8% – 12% yak wool fibers, which increases their compressive strength to 3.2 MPa, making them suitable to replace 50% of the exterior wall structure. Additionally, the localization of photovoltaic glass production has been implemented. For instance, a highland-type Low-E glass production line has been established in Nagqu, reducing the transportation radius from 1200 km to 300 km. These initiatives aim to optimize the economic dimension of construction projects on the plateau by minimizing transportation costs and leveraging local resources.

4.4. Comparative Analysis of Influencing Factors

During the implementation of the renovation of sunlit rooms in traditional dwellings on the Qinghai-Tibet Plateau, obstacles in technical, social, and economic dimensions interact with each other, but there are significant differences in their weights of influence. Based on horizontal comparisons of multiple cases and data analysis, the economic dimension shows overall dominance, with transportation costs accounting for a much higher proportion of the total project expenses than the national average. In the technical dimension, the high ultraviolet radiation intensity on the plateau leads to a shortened material lifespan. However, through chemical modification and localized production, its constraint on project feasibility can be significantly reduced. Although sociocultural factors directly affect the acceptance of the renovation plans, their intervention costs account for a relatively small portion of the total budget, indicating that they are secondary but non-negligible constraints.

Regional differences further validate the dynamic changes in the primary and secondary relationships: in low-altitude agricultural areas, economic factors have the highest weight, and the static payback period becomes the core decision-making threshold; in high-altitude pastoral areas, the weight of technical factors increases, and the ultraviolet resistance and adaptability to extreme temperature differences of materials become priority optimization targets. This hierarchical system provides a scientific basis for prioritizing technical solutions, which means that transportation costs and material aging issues should be addressed first, followed by avoiding cultural conflicts through modular design, and ultimately achieving multi-dimensional collaborative optimization.

5. EMERGING SOLUTIONS

The future technologies for adding sunspaces to traditional dwellings on the Qinghai-Tibet Plateau may encompass four core directions: coupling of the sunspace(s) with the fire pit, reversible structural design, Building Information Modeling (BIM)-based traditional cultural symbol database, and wind-solar complementary dehumidification system.

5.1. Coupling of the Sunspace(s) with the Fire Pit

The cultural continuation of social functions is an important manifestation of cultural adaptability. Sunspaces can serve as new social spaces, replacing the gathering function of traditional fire pits. For instance, in the demonstration project in Huangyuan, sunspaces are designed as semi-open teahouses, continuing the custom of “discussing matters around the hearth” and enabling the social functions of traditional dwellings to continue in modern life [12]. Tibetan architectural decorations such as the Eight Auspicious Symbols and vermilion window frames can also be incorporated into the components of sunrooms to strengthen cultural identity and ethnic characteristics [45]. Architects can also draw inspiration from the “eccentric fire pit” phenomenon in southwestern Yunnan to optimize the layout between the fire pit and the sunspace(s) [46], preserving cultural symbols while avoiding the impact of direct thermal radiation on residents.

In terms of technology, the fire pit serves as a core heating facility in traditional dwellings on the plateau, with its thermal efficiency and pollutant emissions being key research areas [47]. Future works may optimize the thermal coupling pathway between sunspace(s) and the fire pit through passive thermal circulation designs, such as utilizing the thermal radiation effect of sunspace glass curtain walls in conjunction with fire pit chimneys to form a natural convective circulation system, thereby reducing energy loss. Meanwhile, the introduction of intelligent control systems will enable a dynamic balance between the combustion efficiency of the fire pit and pollutant emissions (such as PM2.5 and CO), achieving “heating on demand”. Furthermore, considering the trend of warming and wetting on the plateau, the development of climate-responsive materials, such as phase change energy storage materials, embedded in the walls surrounding the fire pit, can extend heating duration and mitigate the issue of uneven heat distribution in the traditional fire pit [48].

5.2. Reversible Structural Design

The innovative direction of reversible structural design will provide new ideas for the modernization of traditional dwellings. Designers may draw inspiration from the “reversible damper” technology used in the reinforcement of historic buildings [49] to design detachable modular sunspace components that accommodate the seasonal migration needs of nomads. For instance, lightweight aluminum alloy frames combined with double-layered laminated glass can be employed, facilitating rapid installation and dismantling through standardized interfaces. Additionally, new materials such as shape-memory alloys can be introduced as connection nodes to enhance the structural adaptability.

Regarding culturally protective, reversible design, BIM technology [50] can be integrated to establish a parameterized database of structural nodes in traditional dwellings, enabling newly added sunspace components to achieve "non-destructive docking" with the original buildings. Moreover, a "skin replacement system" can be developed, where the outer layer employs modern insulation materials while the inner layer retains traditional aesthetics, thereby meeting both functional and aesthetic requirements [51].

5.3. BIM-Based Traditional Cultural Symbol Database

The construction pathway of a BIM-based traditional cultural symbol database will be key to achieving the digital preservation and inheritance of cultural heritage. Technological means such as 3D laser scanning and oblique drone photography may be utilized to establish a parameterized model library of decorative patterns and spatial configurations in traditional dwellings [52].

With respect to developing intelligent design assistance platforms, a system that combines semantic search functionality with natural language processing algorithms can be constructed to automatically match user needs and generate combination schemes [53]. Based on historic BIM, a virtual reality interaction platform can be built to incorporate intangible cultural heritage bearers into the design process, allowing them to participate in real-time adjustments and optimizations of sunspace design schemes [50].

5.4. Wind-Solar Complementary Dehumidification System

The technological breakthrough of a wind-solar hybrid dehumidification system will provide a more efficient and environmentally friendly dehumidification solution for traditional dwellings on the plateau [54]. Given the abundant wind and solar resources, future research may focus on addressing the energy storage shortcomings by developing key components such as cold-resistant semiconductor cooling chips to cope with the extreme climate. At the same time, exploring multi-energy coupling modes, such as combining the waste heat from the fire pit with wind and solar power, can drive the regeneration cycle of liquid desiccants [55].

In relation to precise humidity control strategies, zone-specific control technology can be adopted, using partitioned airflow guiding devices to achieve local humidity regulation [47]. Additionally, drawing inspiration from natural biomimetic mechanisms, biomimetic dehumidification materials can be developed to reduce dehumidification energy consumption and improve system stability [55].

5.5. Optimization Design Process Framework

Addressing the complexity of retrofitting sunspaces in traditional dwellings on the Qinghai-Tibet Plateau, this study proposes a multi-stage collaborative optimization design process framework (Figure **2**), aiming to balance the enhancement of solar energy gain with the preservation of cultural adaptability. This

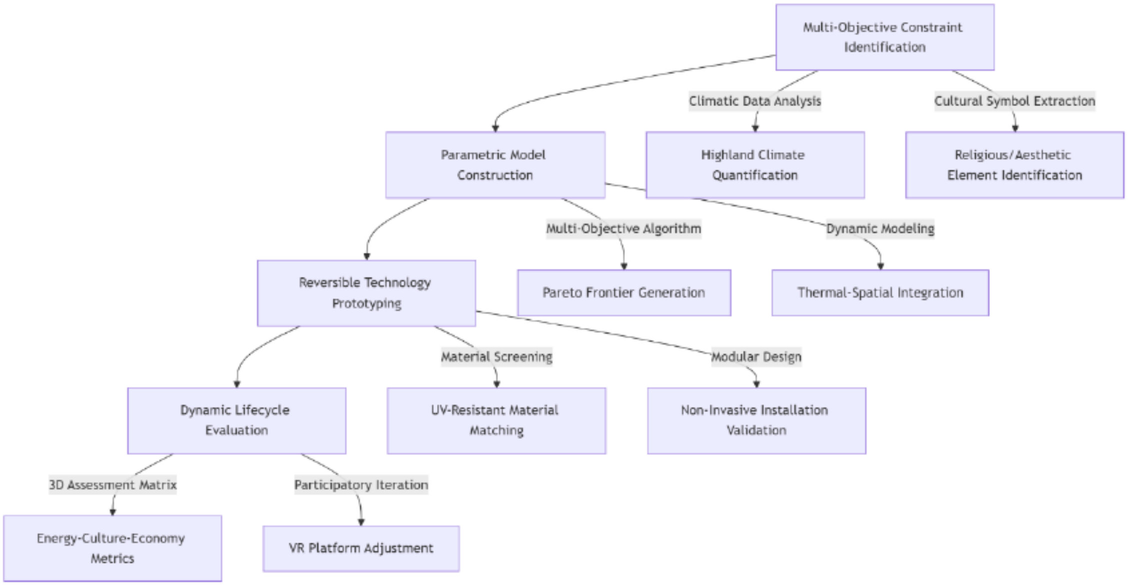

Figure 2: Optimization design process framework.

framework integrates climate data analysis, cultural symbol extraction, parametric modeling, and dynamic evaluation to provide systematic methodological support for subsequent research, avoiding excessive constraints on specific technical parameters.

In the stage of multi-objective constraint identification, the research should quantify climatic characteristics through meteorological station data and field measurements, including diurnal temperature variations, solar irradiance, and ultraviolet intensity. Additionally, a database of traditional decorative symbols constructed using BIM technology can identify immutable religious elements and spatial taboos.

The parametric model construction stage employs multi-objective optimization algorithms, with key variables including sunspace depth, the proportion of glass curtain walls, and spatial hierarchy. A dynamic model can be established by combining material thermal conductivity and ultraviolet resistance properties. Evaluation indicators encompass winter average temperature increase, cultural conflict index, and static payback period, generating an optimal solution.

The reversible technology prototype testing stage involves screening ultraviolet-resistant materials and reversible connection nodes to minimize intervention in traditional structures. Physical model testing in typical villages will validate thermal performance and cultural acceptance, with iterative optimization achieved through feedback loops. For example, the combination of lightweight aluminum alloy frames and double-glazed laminated glass can facilitate rapid assembly and disassembly through standardized interfaces, accommodating the seasonal migration needs of herders.

The dynamic life-cycle assessment stage establishes a three-dimensional evaluation matrix of “energy -culture-economy” to quantify the long-term benefits of retrofitting projects. In the matrix, the energy efficiency dimension focuses on the annual household CO_2 emission reduction as a core indicator; the cultural dimension assesses spatial semantic compatibility through community satisfaction; and the economic dimension emphasizes logistics cost optimization. Combined with participatory design on a virtual reality interactive platform, technical solutions can be dynamically adjusted to adapt to the evolution of sociocultural needs.

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CONFLICTS OF INTEREST

The authors declare no competing interests.

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