Sustainable potentiality of achieving thermal comfort in vernacular Ladakhi dwellings in cold desert of India: Case study of Ladakhi houses in Leh, Ladakh

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Abstract

A vernacular dwelling represents the culmination of knowledge, skills, and techniques honed over years of practical experience, serving as a means to sustain life. The sustainable approach entails the capacity to sustain for longer period of time, climatically, ecologically and socially. The vernacular built environment demonstrates its ability to sustain humans and structure over the years. This endurance is achieved through the application of techniques and practices that have been acquired and refined over many years of practical experience. These accumulated skills and knowledge enable vernacular architecture to withstand the test of time, addressing the unique challenges posed by different environments, climates, and societal needs. The external climatic threats of cold desert such as gust and squalls, high altitude and extreme cold are dealt architecturally to sustain high altitude anthropology. Any architectural form's precedent can be summarized in three ways: man as user, building as structure, and environment as context. Man being the primary, he requires comfort environmentally as well as spatially, to work efficiently and to sustain life. With growing concern on safeguarding energy and bridging the gap between vernacular wisdom with modern lifestyle, this research focuses on the findings based on the same traditional wisdom used in vernacular dwelling units of Ladakhi region.

The vernacular housing units in cold regions have been able to achieve thermal comfort, by utilising simple strategies like increasing the thermal mass of walls and reducing the extent of openings in architectural typology along with spatial organization. This paper will describe the ‘thermal comfort’ provided in vernacular dwellings as potentially sustainable approach. The study assesses and evaluates thermal comfort along of Ladakhi dwellings which helped to ensure survival at high altitude of cold desert and identifies the contribution of existing design criteria using case study of documented dwelling units. The research includes questionnaire survey, spatial organisation analysis and simulations of the selected cases to achieve thermal comfort. The study infers the quantified design interventions done to achieve thermally acceptable dwellings using sustainable approach.

Thus, in case of a cold desert, the quantitative conclusions will find the sustainable parameters. These can be used as guiding factors to build thermally comfortable and sustainable dwellings in modern times.

Keywords: Thermal Comfort, Cold Desert, Cold and Dry Climate, Vernacular Dwellings, Ladakhi Houses, India.

1. Introduction

There are essentially three core requirements for human survival: sustenance through food, access to clean water, and shelter for protection. A shelter, in turn, evolves into a dwelling unit that goes beyond mere survival and aims to offer a sense of comfort for living. Consequently, dwelling units are adapted and customized to meet individual needs. As a fundamental principle, these units should create a pleasant and accommodating environment that enables individuals to carry out their daily tasks with ease and efficiency, even in the presence of external challenges. The dwellings should be able to sustain the comfort to dwell to be productive and stay healthy. 'Comfortable environment' or Comfort is the state of feeling satisfied with surrounding. The thermal dynamics of human body with its surrounding is one of the main aspects that affects comfort of an individual. (Dinal Mehta, 2021)

As cities continue to transform into urban environments, the demands for comfort have grown significantly. Nowadays, thermal comfort is often treated as a product of engineering, relying on external technologies for heating, lighting, and ventilation. Although the economic argument is in favor of mechanical comfort suggesting that evolving technology makes such products more efficient and thus sustainable. However, mechanical comfort through HVAC systems is raising concerns about its environmental impact, as it contributes to the production of greenhouse gases and global warming. Additionally, it can lead to a decline in people's ability to adapt to temperature variations. Globally, this approach consumes a significant portion of energy resources, accounting for a quarter of the total. The future would have double the emission of carbon dioxide. So even if the equivalent scenarios are first accessed in computers (software) which provides the 'maximum acclimatization' and 'energy efficient' designs; the heat stress would increase leading into increment of global temperature creating seasonal problems. (Auliciems & Szokolay, 2007) Therefore, whatever maybe the argument, these systems are not sustainable as it has huge negative impact on environment as well as on the human adaptability and quality of life.

The vernacular homes, shaped by generations of practical wisdom, represent enduring and climate- responsive designs. Vernacular architecture defined as an architecture that encompasses the peoples' dwellings and other constructions, relating to their respective environments and resources, usually built by the owners or the community, using traditional techniques. (Paul Oliver, 2006) They are a product of local materials, innovative construction techniques and optimum planning that offer shelter and comfort while minimizing the impact on the environment. These traditional structures excel in providing thermal comfort tailored to the local climate, displaying remarkable adaptability and versatility. Structures, that are often precisely designed, symbolically executed, and more carefully fitted to the local environment than so-called "professionally" planned structures. Too often we view the products of a past pioneer technology as primitive and crude when they are in fact quite complex and exacting (Noble, 2007). These lessons are even more meaningful in the contemporary Indian context with low energy resources and the unremitting escalating needs of an exploding population. Moreover, learnings from the Indian vernacular have also established their effective thermal performances with respect to existing environments especially in the hot-dry and warm-humid climates (Gulati & Pandya, 2014). The approach of vernacular dwelling which has sustained life for years showcases its potentiality of being sustainable.

The word 'sustainable' come from amalgamation of two words 'sustain' meaning for longer period of time and 'able' meaning the quality to perform. Thus the literal meaning of sustainability would be that it is able to perform for over longer period of time with minimal hazard to the environment and ecosystem or livelihood in general. The Sustainable architecture is an approach to architectural design and construction that seeks to create buildings and spaces that are environmentally responsible, energy-efficient, and socially and economically viable. The goal is to minimize the negative impact of the built environment on the natural world while enhancing the quality of life for its inhabitants. Henceforth, the decisions and attributes at each stages, from thinking to construction, which helps the building to last over longer period of time with minimal negative impact on quality of life and environment, is define as sustainable approach in this paper. Finding these attributes and approaches will result in finding the sustainable potentiality of the dwellings.

This paper centers on the cold climatic region of Ladakh, located in the northern part of the Indian subcontinent. In 2019, Ladakh was declared a Union Territory, with Leh as its capital. This shift has led to significant urbanization in Leh, with a sudden influx of residents, increased military activities, and a surge in tourism. The population increase has triggered a rise in construction activities, placing stress on conventional building practices and raising concerns about energy and resource consumption. The harsh weather conditions in Ladakh have also compromised the thermal comfort within these conventional buildings. Consequently, the pursuit of comfort in this context relies heavily on "mechanical" or "artificial" means. In the twentieth century, comfort is more a 'product' produced by machines and run on cheap energy. In a world where fossil fuels are becoming ever scarcer and more expensive, and the climate more extreme, the challenge of designing comfortable buildings today requires rethinking (Nicol, et al., 2012). The Traditional Ladakhi Architecture of Leh can provide the answers to alarming situation.

The paper aims to analyze the thermal comfort performance of vernacular Ladakhi dwelling to draw down the different approaches used to provide comfort and discomfort of Ladakhi dwellings. These approaches have provided the comfort or discomfort over a long period of time with vernacular knowledge showcasing the potentiality of sustainable. The empirical data of the analysis may provide different sustainable parameters that can be used in today's scenario to attain naturally thermal comfortable dwelling.

2. Thermal Comfort

Thermal Comfort is the condition of thermal environment under which a person can maintain a body heat balance at normal body temperature and without perceptible sweating (National Building Code Sectional Committee, 2016). It is that condition of mind that expresses satisfaction with the thermal environment (ASHRAE, 2017). Human is at comfort by his cognize when the skin and core of body, and the environment are at thermal equilibrium. Man's energy, health and comfort mainly depends on the effect of his environment (Victor Olgyay, 1963). Creating a comfortable indoor atmosphere that promotes thermal contentment, resulting in enhanced productivity, increased efficiency, and a lively mind coupled with a healthy body is defined as thermal comfort.

There are primarily three factors on which thermal comfort is dependent: environmental, personal and physiological. The personal and physiological factors are dependent on personal choice whereas the environmental factors can be dealt through climate responsive strategies using sustainable approach. Architectural elements such as thermal mass, spatial arrangement, facade design, and other factors contribute to achieving thermal comfort while using energy efficiently and sparingly. Table 1 provides an overview of the factors that impact thermal comfort in a cold desert climate zone.

Table 1: Factors of thermal comfort and Architectural Parameters affecting thermal comfort
Source: Author

Factors		Dependency and Parameter
Personal Factors	Metabolic rate	Body type, Body Mass Index (BMI)
	Clothing Insulation	Type of cloth Number of Layers of cloth
Physiological Factors	Activity performed	Personal Choice
	Function of the space	
Climatic or Environmental Factors	Air Temperature	Dry bulb temperature
	Mean radiant Temperature	Radiation
	Relative Humidity	Precipitation
	Air Velocity	Direction and Altitude
Architectural Factors	Context	Surroundings: buildings, vegetation Topography: slope, hill, valley Local climate: micro-climate Reflectivity of surrounding surfaces
	Orientation	Climate Function of space: Living room in south, storage in north etc.
	Form and Envelop	Volume exploration, Facades, Opening and fenestrations
	Material and Construction	Thickness of material, Insulation properties, Thermal properties, Bridging of materials.
	Spatial Organization	Position of spaces within, Interrelate-ability of spaces depending on activities

3. Cold Desert

The cold desert is climatic classification where the annual average temperature is below 25°C and the rate of evaporation is greater than the rate of precipitation, making it dry. The atmospheric condition is cold and dry. The Cold desert is classified as Bwk by Koppen Geiger in their climatic classification chart where 'B' means dry (little or no precipitation), 'w' represents Desert and 'K' as cold. The National Building Codes (NBC) 2005 India classifies the similar climatic condition as cold and sunny. The climatic zone was updated by National Building cold in 2016, resulting it to fall under Cold 'CD' Climatic zone. The Cold (cold desert) climatic zone is marked by specific traits, including an annual average temperature below 25°C, fluctuating relative humidity levels without a fixed value, and approximately 80% of the year characterized by sunny or clear skies.

Located at an elevation of 3500 meters above mean sea level, Leh is classified as having a Cold climate or cold desert of India. The distinctive features include its arid terrain, chilly winds, and snow-caped Himalayan peaks of higher altitude, which are indicative of its climate. The region exhibits limited rainfall, resulting in a barren landscape. Cold winters prevail from November to early March, with snowfall occurring at higher altitudes than Leh itself. The cold season typically spans from November to early March, with snowfall occurring at peaks of higher altitudes than Leh. The windy spring season prevails from March to early May, with peak wind-speed reaching 6 m/s. May to July are summer months where the intense direct sunlight falls due to the high altitude. There are approximately 320 days of clear sky and sun annually. Monsoon falls from July to September with limited precipitation as the region falls on the leeward side. Leh experiences light precipitation year-round, with autumn occurring from October to early November.

The annual average air temperature in Leh remains at 4.9°C, with a minimum average of -2.6°C and a maximum average of 11.4°C. The lowest temperatures are observed in January, reaching as low as -20.8°C, while the highest temperatures occur in July, peaking at 24.5°C. This variation in temperature throughout the year amounts to 52.7°C. The prevailing wind direction of Leh is from the southwest, accounting for approximately 14.12% of all wind directions. The average wind speed is 1.4 m/s, with the maximum wind speed reaching approximately 6 m/s. Annual average relative humidity hovers around 38%, varying from 26% to 51%. Winter months see higher relative humidity levels due to snowfall. The average annual snowfall in the mountainous regions is 60 cm, with a 12 mm variation in precipitation between the driest and wettest months. August records the highest precipitation levels, while November experiences the lowest, resulting in an average annual rainfall of 106.5 mm. All of this climatic data has been collected from the Indian Meteorological Department.

4. Sustainable Approaches to achieve Thermal Comfort in Cold Desert.

Air temperature and wind velocity are crucial factors influencing thermal comfort, particularly in cold desert regions like Leh. In such cold climates, effectively managing heat gain while blocking cold winds is vital to maintain comfortable indoor temperatures within dwellings. The extent of heating or heat gain within a building depends on the season and outdoor temperatures. Thus, achieving the optimal balance between harnessing solar heat and minimizing cooling effects from the breeze is determined by the specific function and thermal requirements of the space.

The heat exchange process is of utmost importance in this context. Heat exchange occurs at various stages: between humans and the surrounding indoor air, between the indoor air and the building surfaces, among different building surfaces, and between the building's outer surface and the outdoor environment. Therefore, heat flux is a critical consideration at every stage of this exchange. One significant source of natural heat gain is through solar radiation, commonly referred to as solar heat gain. Cold and sunny climates, such as cold deserts, can effectively harness solar gain due to the high percentage of clear skies throughout the year. In passive solar heating buildings, four interconnected components work in unison to enhance building efficiency: Collection, Storage, Release, and Insulation.

There are numerous sustainable approaches in architectural design to address heat gain in cold and dry climates. This can be approached on multiple scales, including the contextual scale, building scale, and element scale. At the site level, considerations encompass site development, context, macro and microclimates (including sun and wind direction), among others. Building-level parameters include the form, envelope, structure, compactness and aspect ratios, double facades, and fenestration. Passive techniques, such as thermal mass, 'trombe' walls, water walls, sunspaces, greenhouses, and earth berms, serve as crucial parameters at the element level. Elements like openings, walls, and roofs are also integral to heat management strategies. Additionally, internal layout and planning significantly impact the overall effectiveness of these measures. These approaches have sustained over years and yet function efficiently when used correctly with the right sequence understanding the space, functionality and needs.

5. Vernacular Ladakhi Dwellings

The Ladakhi dwelling is often called as "Khangpa" in their local language. The dwelling represents their culture and tradition, climate and environment and resource availability. In the Ladakh region, known for its cold desert climate, a prevalent architectural feature of most houses is their two-level construction. The ground level serves as a dedicated space for housing animals and storing essential supplies like wood and fodder for the harsh winter months. In contrast, the upper level is designated for human habitation. A typical design within these houses comprises a single, spacious room with a stove placed in one corner, fulfilling a dual purpose of cooling and heating the interior spaces. The dwellings usually have two to three storey where the ground one is for animals and fodder, the first is known as winter floor and the second as summer floor. The first floor has *Chansa*, which is a spacious single room functioning as living, dining and kitchen. Along with that it has toilet pit and storages. The second floor has prayer room, guest room and verandah. The figure 1 shows the diagrammatic representation of the different levels, its function, wall thickness and size of fenestration.

The critical season in this region is winter, and the primary requirement is natural heating. The sole source of this natural heating is the sun. To combat the challenging climate, the settlement layout is strategically planned as the initial line of defense. Entire settlements are situated on the southern face of hillocks, employing an open settlement pattern that maximizes solar exposure to harness heat and effectively shields against cold winds from the North-East, a result of meticulous site selection. The primary frontage of these houses, characterized by larger openings, faces south to optimize the capture of sunlight and direct light. Typically, the entrance is positioned on the east side, and the absence of openings on the north or west sides serves the dual purpose of preventing cold winds from penetrating and minimizing heat loss.

The reliance on sunlight to maintain comfortable climatic conditions is complemented by traditional building materials and construction techniques in the region. The primary construction materials consist of locally available earth and timber, which have been utilized for centuries not only in the construction of houses but also in the creation of magnificent monasteries and palaces throughout the area. The construction materials predominantly comprise mud, including sun-dried bricks made from alluvial soil typically found along the banks of the Indus River. Additionally, stone and timber are employed due to the limited availability of vegetation. These trees, mainly poplars and willows, are utilized for wood, serving both as structural elements, such as sills and lintels, and as connectors, particularly crucial in an earthquake-prone zone rated at level 5 . Typically, roofs in the region are constructed using a combination of mud and thatch, with less emphasis on precipitation protection. The material usage nd construction is displayed in figure 2. Walls are constructed using techniques like rubble stone masonry, rammed earth, or sun-dried mud bricks. The locally found material not only showcases the potentiality of being sustainable but also the construction method and techniques exploiting the material and its properties to the extend.

6. Research Methodology

The study was conducted in two parts, the physical observation and simulation through software to analyses the thermal comfort and draw down the parameters to find out the sustainable potentiality. The primary survey of selected case study was carried out with physical observations, photographic documentations and questionnaire survey of the selected cases. The parameters of thermal comfort are examined with the use of software simulation. Later these parameters are studied to look for sustainability in vernacular Ladakhi dwelling in achieving thermal comfort.

The questionnaire was developed following a review of the existing literature and was subsequently employed as a self-administered survey. Furthermore, it was ensured that the sample survey encompassed both respondents and occupants of the chosen case study. The questionnaire had five major parameters; house criteria, occupancy, heating criteria, thermal comfort personal factors and thermal comfort rating based on thermal sensational scale by Franger. The objective of the survey was to gather data on thermal comfort conditions within Vernacular Ladakhi houses and to distill information regarding the most optimal conditions that best meet the needs of the occupants. This data was used for analysis as well as simulation.

The case study was subjected to analysis using Energy Plus Design Builder 6.0 software simulation. This investigation involved the simulation of parameters such as the Predicted Mean Vote (PMV) index and the Predicted Percentage of Dissatisfied (PPD) individuals based on Franger's thermal-sensation scale and the Adaptive Comfort model following the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) standard 55. Additionally, the study calculated the ambient indoor operative temperature, air temperature, and mean radiant temperature using outdoor climatic data. These data and values, specific to each case, were input into the software to generate simulated values and corresponding graphs, as detailed in Table 2.

Table 2: Input Values of Parameters and Output of the Simulation
Source: Author

Sr. No	*Input Parameters*	*Input Values*	*Output*
1.	Metabolic Rate	1.2 met	Temperature Graphs
2.	Clothing Insulation	Summer: 1.3 clo. Winter: 2.5 clo.	
3.	Environmantal factors	Leh Weather File	Humidity and PPD
4.	Construction Material	As per case	
5.	Thickness of Material	As per drawings	PMV Index
6.	Layers of Material	As per drawings	

Thermal comfort levels differ among individuals based on their geographical regions. In hilly and cold areas, people have naturally adapted to lower temperatures, resulting in a comfort temperature range that is lower compared to regions with different climate classifications. "People in India also use warm clothing (sweater, jacket, inner thermal, socks, cap) in winters as compared to 0.9 clothing [sweater, long sleeve shirt, heavy slacks]. (ASHRAE, 2017). Thus a higher inside temperature need not to be created by the heating systems as recommended 22.7°C. (S.S. Chandel, 2012). The resultant output will be compared to this framework to establish empirical and logical insights. The established criteria for thermal comfort will serve as a framework for analyzing the results of the simulation and drawing conclusions from the questionnaire. These standards, have been derived from a comprehensive review of literature focused on cold climates and are synthesized from various codes relevant to the study. For instance, in cold desert or cold climate areas, the Indoor Comfort Operative Temperature, as stipulated by both ASHRAE and the Indian Society of Heating, Refrigerating, and Air-Conditioning Engineers (ISHRAE), is 22.7°C. According to the Energy Conservation Building Codes (ECBC) of India, the recommended indoor operative temperature for Leh is 19.42°C, falling within a range of 15.78°C to 22.7°C. Additionally, as per the National Building Codes (NBC) of India, the indoor comfort range spans from 21°C to 26°C nationwide, with colder regions having a lower comfort temperature. These standards, as detailed in Table 3, are employed as reference points for the analysis of the case studies.

Table 3: Thermal Comfort Standards used as Framework for analysis
Source: Author

Sr. No.	*Data*	*Comfort Standards*	*Range*
1.	Indoor Comfort Operative Temperature	21°C	19.34 °C to 22.7°C
2.	Comfort sensation: Franger's scale sensation (Predicted Mean Vote Index)	0.0	-0.5 to +0.5
3.	Predicted People Dissatisfaction (PPD) Percantage	10%	0% to 20%
4.	Relative Humidity	40%	20% - 60%

7. Analysis

The cases selected for analysis were based on four criteria mainly. It should be traditional vernacular dwelling with floor area ranging between 175m^2 to 250 m^2. The dwelling should be at least 50 years old or more and the modification done shall be at least 50 years prior. The four such cases were studied, simulated and analyzed to draw down the findings and sustainable potentiality of these dwellings. In this paper the Khirze house will be analyzed in detail to show the method and comparative analysis of Norbu house, Skiltang house and Hanugan house along with Khirze house will be done.

The Khirze house, situated in Leh old town at an altitude of 3,509m, is a 150-year-old double-storey dwelling with a rectangular plan and an aspect ratio of 1.4. The house features a mud roof with hay insulation, supported by stone mason walls with mud plaster comprising mud, limestone, and husk. Poplar wood is used for structural elements like beams, purlins, lintels, and tying members. The thermal mass decreases with increase on height. The ground floor serves as a cowshed, stable, storage, and kitchen as shown in figure 3, while the first floor accommodates the kitchen-cum-living room and a sleeping room facing south around a central area called the "yab." The upper floor has glass-fitted windows, and the ground floor has smaller openings resembling ventilators.

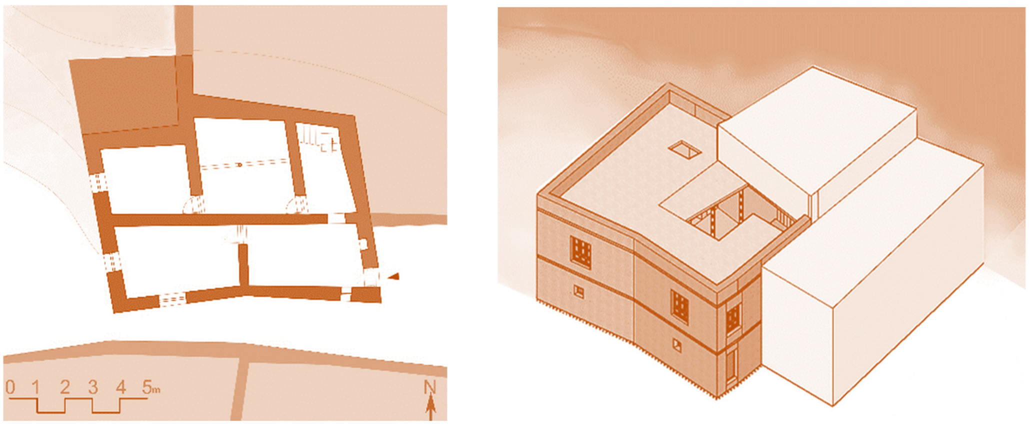

Figure 2: Khirze house plan and simulation model.
Source: Author.

Using design builder, the simulation graphs were produced as shown in figure 4. Simulation results indicate indoor operative temperatures in the Khirze house ranging from 16.8°C to 21.3°C throughout the year, with an annual average of 19.1°C. The lowest temperatures are in January (16.8°C), and the highest in June (21.3°C). The difference between indoor and outdoor temperatures, attributed to the building's architecture, ranges from 11 °C in summers to 15°C in winters. The Predicted Mean Vote (PMV) Index falls below the comfort range of -0.5 to +0.5, with an annual average of -0.9, indicating slightly cooler indoor conditions. Consequently, the Predicted Percentage of Dissatisfied (PPD%) is 27.6%, with 7.6% of occupants falling outside the comfort zone. The ground floor has an annual average indoor operative temperature of 18.27°C, a PMV index of -0.98, and a PPD% of 27.9%. In contrast, the first floor has an average indoor temperature of 20.13°C, a PMV index of -0.8, and a PPD% of 25.5%. This suggests that the ground floor is slightly cooler than the first floor.

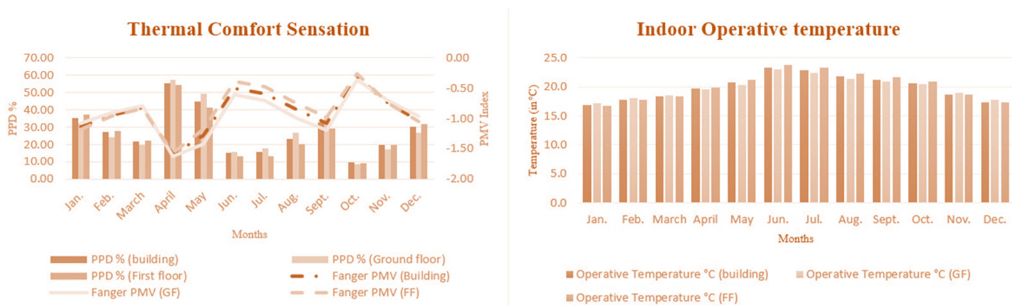

Figure 3: Thermal sensation (PMV and PPD%) and Indoor operative temperature Graph from Simulated analysis data. Source: Author

From the simulation analysis, it is inferred that the building's design is influenced by three major factors: thermal mass leading to heat lag, direct solar gain through windows, and spatial organization creating a veranda-like structure. These factors display the potential of being sustainable in case of Khirze house. The rate of heat gain through radiation is higher than conduction, with stone masonry walls on the ground floor and a thick roof contributing to heat exchange; whole system acting as thermal mass. The ground floor has a low window-to-wall ratio (WWR) of 7.78% and serves as thermal insulation due to its function as a cattle shelter and storage area. The first floor has a higher WWR of 13.11%, with 40% of it located on the south side, contributing to solar heat gain. The veranda-like structure on the first floor creates a wind tunnel effect, particularly in winter when it receives minimal sunlight. Warm air from inside the room creates higher pressure, while the veranda, enclosed on all sides, has lower pressure. This pressure difference causes air to flow from the veranda into the room, creating a draft and a sensation of windiness in winter. To address this issue, the veranda could be opened on one side to allow wind passage or eliminated entirely, possibly repurposed as a gathering space with a skylight for indirect heating.

Table 4 :Comparative Analysis table of case studies of Vernacular Ladakhi Dwellings
Source: Author

Sr. No.	Case Study	1	2	3	4
1.	*Name*	*Khirze House*	*Hanugun House*	*Norbu House*	*Skltang House*
4.	*Age of House (in years)*	150	70	200	150
5.	*Floor area (in m^2)*	189	250	218	210
6.	*Construction Material used*	Stone masonry + mud mortar + wood and mud roof	Sundried Mud bricks + mud mortar + wood and mud roof	Stone masonry + mud bricks + mud mortar + wood and mud roof	Stone masonry + mud bricks + mud mortar + wood and mud roof
7.	*Form of the House*	Rectangular	Rectangular	Rectangular	Rectangular (Human Habitable)
8.	*Sustainable potentiality of Design Attributes*	*Yab*[1] in northeast, Thermal mass, Shared wall	Glass widows, Thermal mass, Orientation of openings	Earth berm, Glass room, Thermal mass, WWR%	Thermal mass, Form/aspect ratio, WWR%
9.	*Aspect Ratio*	1.4	1.38	1.35	1.17
10.	*Number of storey*	Ground + 1	Ground + 2	Ground + 3	Ground + 2

11.	*Temperature (in °C)*	19.1	20.02	17.41	19.9
12.	*Franger's PMV** *PMV Index ()*	-1 -0.91	0 -04	-0.5 -0.3	0 0.1
13.	*PPD% (in %)*	27.60	16.90	9.25	14.30
14.	*Wall thickness (in mm)* *Ground Floor* *First Floor* *Second Floor* *Third Floor*	600 400 - -	700 400 350 -	700 500 325 230	735 400 350 -
15.	*Floor Height (in mm)* *Ground Floor* *First Floor* *Second Floor* *Third Floor*	2300 2500 - -	2200 2250 2700 -	2500 2570 2650 2800	2300 2500 2600 -
16.	*Wall Window Ratio (WWR) (in %)* *North/North West* *East/North East* *West/South West* *South/South East* *Total (complete building)*	0.00 4.48 11.5 12.6 9.93	02.41 07.96 12.70 11.74 08.70	00.00 04.47 06.87 14.73 12.13	00.95 00.80 04.56 10.00 04.56
17.	*Most used space in the house and its direction*	*Chansa* (Kitchen cum family room)	*Chansa* (Kitchen cum family room)	*Chansa* (Kitchen cum family room)	*Chansa* (Kitchen cum family room)

Similarly, the analysis of Norbu, Hanugan and Skiltang houses were and the simulation data is formatted in the table 4. In Norbu house, the main attributes which helps to achieve the thermal comfort are thick wall for thermal gains, envelope design, earth berm technique and solarium. The thickness of mud brick wall in ground floor is 700mm having thermal transmittance (U-value) of 0.57 W/m^2K. With increase in number of storey the wall thickness decreases. The first floor has 500mm thickness whereas the second floor has 325mm thickness of mud brick wall with U-value of 1.72 W/m^2K. With increase in height of the structure, the wall thickness decrease but the size of fenestration increase. The upper floor, designed for summer use, features substantial windows on the southwest side. In winter, these windows help insulate the room, while in summer, their orientation allows for comfort by aligning with prevailing wind directions. The earth- covered floor contributes to temperature regulation within the building. The lower temperature on the floor is due to limited solar heat gain, as only the south-facing side receives direct radiation. This minimizes heat loss and direct solar heat gain. The building's window-to-wall ratio (WWR) is optimized for human comfort, with the floor primarily used for storage and cattle shelter. The first and second floors are designated for human habitation. In the summer, the thinner walls help reduce indoor temperatures, and the windows' orientation toward the south-east or south-west aligns with prevailing winds in Leh, providing an evaporative cooling effect. ‘L’ shape building envelope helps to lock the south west wind, provide greater surface area for solar radiation and heat gain.

Figure 4: Norbu house simulation model, ground floor plan and first floor plan.
Source: Author

From the analysis of Hanugan house, the potential factors that contributes to achieve thermal comfort for habitants are the fenestration placement and size, thermal mass and usage of construction materials. The analysis data reciprocate the fact that the house has greater WWR ratio and the large size of glass windows as compare to others along with the surface area. The WWR on the first floor is 11.81% and on the second it is 15.34%. The southwest and southeast walls help in maximum gain. Another sustainable design manifestation in the house is that the north east receiving minimal solar radiation has thick wall of 700mm throughout the building so to reduce the heat loss. The table 4 directs that the wall thickness reduces to half as we reach to second floor and the wind direction that is south west has greater WWR than South east, showing that the west will stay warmer for longer time and will also help in regulating the indoor temperature and maintaining ventilation for summer.

Figure 5: Hanugan house ground floor plan, first floor plan and simulation model.
Source: Author

The Skiltang house being the oldest and situated at the higher altitude amongst the others. The sustainable parameters from the analysis can be inferred as the planning of spaces, its spatial organization as per the usage, thermal mass, fenestration sizes, placement and orientation and the construction material used. The locally available material mainly stone and mud are good insulator and helps to achieve thermal comfort. The house was constructed using locally available materials such as rocks quarried from the neighboring mountains, pagbu (mud blocks) from their fields and wood from the trees such as Poplar or Willow. the WWR and U value along with the volume works very efficiently. The higher U value and smaller openings helps in retaining he heat, whereas higher WWR and lower U value helps in gaining and losing heat to create comfort equilibrium inside. The chance of excessive heat loss is from North and thus it has same thickness of 735mm throughout all the floors with minimal opening for accessibility and ventilation.

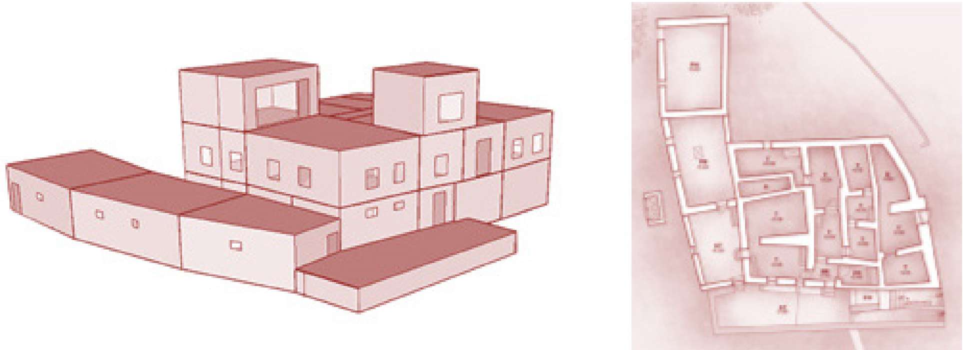

Figure 6: Skiltang house simulation model and plan.
Source: Author

8. Findings and Discussions

Based on the case study analysis, it is observed that the vernacular dwellings showcase the potential of being a sustainable approach to achieve thermal comfort in case of cold desert, that is Leh region, of India. It is observed that the sustainable approach is seen from the thinking process itself till the construction stage. The planning of the spaces to compact the overall size yet design the envelope to increase its surface area optimizes the aspect and compactness ratio which eliminates the risk of heat loss. The design approach includes the orientation of spaces in accordance to its functionality and usage as per their lifestyle. It also includes the size and placement of fenestration such that the heat gains vs heat loss if efficiently catered inside in accordance to the temperature outside. The following sustainable parameters are found to play pivotal role in achieving thermal comfort in Ladakhi dwellings and can be used effectively even today:

- The parameters such as aspect ratio, compactness ratio, window to wall ratio and thermal mass and dependent on the size, orientation, topography, context and function of the space. Variables are the material and its thickness, aperture position and dimensions and the opening to depth of space.
- Traditionally, the solar direct and indirect gains remain the essential of thermal comfort in cold desert. Thus the orientation plays a major role. Orientation of spaces based on activity and usages receiving source of direct and indirect solar gain are the prime considerations.
- Generally, a most used spaces such as chansa has arrangement of openings not greater than two in the south east or south west side and has greater openings in the south than that of south east or south west in case of a space consisting of corner walls exposed to solar angles.
- The fundamental of retaining thermal comfort by maintaining ambient temperature is in the balance of heat gain and heat loss. Consequently, the harmony in between the thickness and bridging of construction material and technique, and the size of opening (glazing for solar gain) is obligatory.
- It is evident from the case study analysis that the averaged wall thickness of ground level, first floor and second storey is 700mm, 400mm, and 250mm respectively. It also provided the fact that the traditional material and construction technique is used.
- Thermal mass is present in the outer planes as well as the inner planes. The vertical planes of outer and inner surface have same thickness to avoid heat loss and maintain the temperature. Thus the wall thickness of interior walls as well as the exterior wall shall be same for better result. Depending on the orientation, the thermal mass thickness can be change for good performance to achieve thermal comfort. Preferably, the north facing walls shall have greater thickness than that of south and shall remain of same thickness throughout the building that is on all level.
- For better results, the height of the room is kept constant along with the window to wall ratio and thermal transmittance. The planar dimensions of the space/ room are the variables along with plane surface (that is wall, roof and floor) thickness and the size of openings.

- Usually the sill level is constant and dependent on the context. It is calculated from solar angle on that particular coordinates of the size. The sill level, broadly sought to be at 200mm and 500mm for winter floor and summer floor respectively to optimize the solar heat gain according to their working region and space inside.
- It is suggestive to follow the WWR percentage for better and effective thermal comfort The window to wall ratio percentage for ground floor, first floor and second floor is 1% to 2%, 10% to 12% and 15% to 18% respectively for effective direct solar heat gain. It will enhance the controlled wind inside to maintain the ambient indoors.

9. Conclusions

The research suggests that the variables employed in Ladakhi dwellings adhere to traditional design techniques commonly found in vernacular regions with similar environmental conditions. This alignment is also consistent with the thermal comfort performance observed in traditional buildings within the cold desert climatic region of India. The study underscores the pivotal role of climate, human activities, and the human body in determining thermal comfort. Effective heat transfer mechanisms and limited or negligible air movement within the space emerge as crucial factors in achieving thermal equilibrium.

The findings suggest practical applications for achieving thermal comfort in residential dwellings within the cold desert region, leveraging the empirical insights garnered from traditional Ladakhi dwellings. The empirical data shows the potentiality of being sustainable and thus it can e used in current scenario. The utilization of software such as Design Builder proves valuable in evaluating the thermal comfort performance of both spaces and dwellings, making it a viable tool for the context of the cold desert. Consequently, ensuring consistent thermal comfort in residential dwellings in the cold desert hinges on factors proving to be sustainable parameters such as thermal mass (wall, roof, and floor thickness), materials used (thermal transmittance U value), spatial dimensions (depth, breadth, and height), compactness ratio (surface area to volume), aspect ratio (length, breadth, or depth), orientation, and openings (size, material, and wall-to-window ratio percentage).

This research has not only validated the relevance of vernacular design principles but has also its potentiality of being sustainable design and illuminated possibilities for informed decision-making in new development endeavors, facilitated by software tools. The lessons derived from the exploration of vernacular design ideas remain pertinent in the current context.

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