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Delphi-AHP-Fuzzy Computational Approach to Sustainability Assessment Model and Indian Traditional Built Forms

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Abstract*: Sustainability is the key issue in a rapidly developing world which has its influence felt in the construction and real estate sectors. Ecological, economic and socio-cultural issues are in the core of planning, construction, and operation of built forms. Developments in today's world pertain to environmental issues, energy, water resource consumptions, pollution and global warming which compel the adoption of sustainable built forms. The national rating system-GRIHA is in force to regulate sustainable developments and LEED has exercised considerable pressure on Indian context. However, it is arguable once if LEED-India and GRIHA are adopted in diverse climatic zones of the country, respective local culture and societies with varying economies, whether these produce the much needed end result; sustainability. Mostly, LEED-India is designed to address environmental concerns and building standards. The national green building rating system GRIHA is following the same model for all climatic zones compromising the local and regional variations. The review establishes that these rating systems mainly focus on the environmental performance assessment. However, these do not effectively address the wider sustainability issues. It will therefore, require an appropriate and pro-active an alternative sustainable built form assessment rating system. Traditional models sustain on their own design and features with acceptable sustainable performance. Research combined three methods to develop a unique model for assessing the sustainability of traditional built forms. Among these methods, the Delphi group decision-making method provides co-design features, the Analytical hierarchy process (AHP) includes Multi-Criteria Decision-Making (MCDM) techniques, and Fuzzy Logic (FL) theory can simplify complex internal and external factors into easy to understand numbers or ratios that facilitate decision-making. In addition to these, an interview-based questionnaire survey is also conducted among vernacular-traditional households to understand their perception of vernacular-traditional buildings and simultaneously recorded physical measurements and climatic data. Adopted methodology and survey interpretation lead to develop an alternative sustainability assessment model for built forms based on local and regional conditions.

Keywords: Sustainability Assessment Model, Traditional Built Forms, Thermal and Energy Performance.

Introduction

Traditional-vernacular built forms are the concretized wisdom of our ancestors that has been developed over centuries without any negative impact over the environment or health. The word 'Vernacular' is derived from the Latin word *'Vernaculus'* which means native. Hence vernacular architecture refers to 'Science of native built forms'. Vernacular architecture is both regionally and socially specific which has been built by the owners and users, or by the community itself, based on their wisdom and knowledge, using locally available building materials. It is therefore, less expensive and gives positive response to climate and socio-cultural factors (Oliver, 2006). Traditional architecture is often referred to as *'Architecture without Architects'* to include structures made by lay-builders (Rudofsky, 1987). These built forms are adapted to the prevailing climate and culture depicting the technological peak of the times. These houses are built appropriately with thermally resistive materials, sizing, positioning of openings and other spaces also minimize needs of cooling or heating. In contrast to energy-intensive modern buildings; they employ passive techniques bringing lowered operational costs and proves thermally efficient.

The relevance of traditional built form is assessed through thermal analysis of mud and stone masonry traditional houses and modern buildings, in the South-West Bengal and Western Maharashtra. Heat transfer analysis is carried out in three types of buildings with different materials; mud, stone and modern building materials. The quantitative results of the analysis indicate that the thermal appropriateness of mud construction with mud walls and thatch roof has a major saving in the energy consumption than contemporary building materials (Alapure et al., 2014). Further, the acceptability of these traditional built forms and traditional technologies are explored through an alternative sustainability assessment model.

Multi-Criteria Decision-Making technique featured in the Analytical Hierarchy Process (AHP), was used to verify the relative importance of each sustainability criterion. Quantification using fuzzy logic technique was used to generate a model that could assess the sustainability of built forms.

This model suggests effective resolution of sustainability issues related to contemporary buildings during early stages of design itself. In addition, the criteria of this model consider social responsibility, attitude towards environmental protection, and long-term energy and cost savings throughout its useful life. This model indicates the importance of each assessment criteria so as to enable professionals for appropriate decision-making.

Methodology

The Delphi method is used to provide implicit expert and objective assistance in research. It is developed by the RAND Corporation, USA, to assist its management in predicting future events. However, its application scope is not restricted to predicting future events only (Lu, et al., 2012; Hsueh, and Yan, 2011). Delphi method is a group decision-making technique that has underlying assumptions, imparting its strengths regarding qualitative research. Effectiveness of the method was demonstrated in a recent national study to develop management audit assessment criteria that can benefit and increases research reliability (Murry, et al., 1995).

The AHP method was first proposed by Saaty and has been extensively used to solve multi-criteria decision-making problems. AHP is also commonly applied to social, policy, planning, and engineering decision-making issues (Saaty, 1990; Saaty, 1994). Cole (1997) studied the development taken place in building assessment tools. He noted that Building Environmental Performance Assessment Criteria (BEPAC) programme of Canada gave 'weighting' to different building environmental criteria to reflect its significance and priority relative to other criteria. CASBEE presents a new concept for assessment that distinguishes environmental load from environmental quality and building performance. He noted that Analytical Hierarchy Process (AHP) can be used to give weightings to environmental criteria.

Fuzzy set theory developed by Professor Zadeh at the University of California, Berkeley, in 1965; is an optimal quantitative for addressing fuzzy phenomena and fuzzy language. Fuzzy logic theory is based on fuzzy sets, primarily used to express and quantify certain fuzzy components that cannot be clearly defined. This theory can provide excellent results when dealing with fuzzy language expressions. Fuzzy Logic can manage vague information in natural human language such as uncertainty, complexity, and tolerance for imprecision (Zadeh, 1976; Zadeh, 1996). Fuzzy Logic theory is extremely suitable for highly complex and difficult to quantify policy evaluations; especially group decision-making issues (Hadi-Vencheh and Mokhtarian, 2011). After determining the model assessment criteria using the Delphi method, Fuzzy Logic is applied to build the model.

The model-building process has a rigorous inference system which should be completed initially to ensure its effectiveness. In addition, an interview-based questionnaire survey is conducted among vernacular-traditional households to understand their perception of vernacular-traditional built forms and physical measurements and climatic data are simultaneously recorded. The survey gathered users' perceptions of thermal comfort and overall performance of vernacular-traditional built forms including comfort vote using five point Rohle's Scale.

Model Development

Developing Criteria and AHP Framework:

The model proposes five major criteria that are to be assessed through opinion survey from traditional households and compared with the provisions of National Building Code (2005; 2010; Draft NBC-2012) and standards valid in India. These five criteria are energy efficiency and thermal performance, environmental aspects, socio-cultural aspects, economical aspects, and service quality aspects. The sub-criteria, namely, energy efficiency and thermal performance: Building layout, physical envelope, operating energy, energy saving, use of renewable energy, and user satisfactory comfort level; environmental aspects: Indoor air quality, daylight and illumination, noise and acoustics. Socio-cultural acceptance: Economical background of the family, use of building materials, spatial arrangement, construction techniques, and acceptability of modern sustainable techniques. Economical Aspects: Life cycle cost, maintenance and operation cost, optimizing life-cycle cost; service quality aspects: Functionality, adaptability, controllability, flexibility, safety, security, and equity during operations. The relative local and global weights assessing criteria can be determined by using Analytical Hierarchy process (AHP). The AHP hierarchy criteria network is required for model building in this research as shown in figure 1.

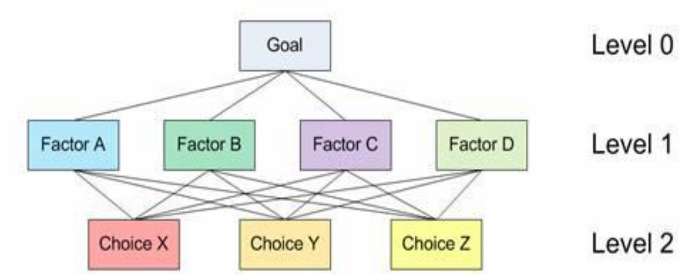

Figure 1: Analytical Hierarchy Process (AHP) Network

Developing Fuzzy Logic Inference System:

The fuzzy logic inference method can be separated into two approaches, that is the Mamdani, and Takagi and Sugeno's approach. Typically, output from the Mamdani approach is continuous; whereas that for the Takagi and Sugeno's approach is discrete.

To understand the change in continuous output, in this study Mamdani approach is adopted. In addition, multiple types of membership functions exist; the membership functions commonly used include triangular functions and bell-shaped functions (Yu, and Skibniewski, 1999; Perng, et al., 2005). Therefore, triangular functions and bell-shaped functions are also adopted in this study for fuzzy set membership functions. Fuzzy Logic belongs to the field of artificial intelligence and can be used to process complex and imprecise semantic meanings in the opinions' of people surveyed. In a fuzzy decision environment, the membership function is used to define the degree of goodness. Fuzzy set theory expands traditional mathematical dichotomy theory (set value is 0 or 1) to an infinite number of continuous set values existing between 0 and 1, to an infinite number of continuous set values (Bellman, and Zadeh, 1970). This also renders fuzzy logic method convenient for processing variables and inferences obtained through linguistic surveys (Zadeh, 1975). In addition, the membership function and fuzzy range for the fuzzy set containing the output the value must also be defined. When the assessing criteria were quantitatively defined in the fuzzy set, the IF-THEN rule base of the Fuzzy Logic Controller is used to perform the appropriate quantification process on the assessing criteria in various scenarios. This is determined by using the Delphi Method, as shown in Figure 2.

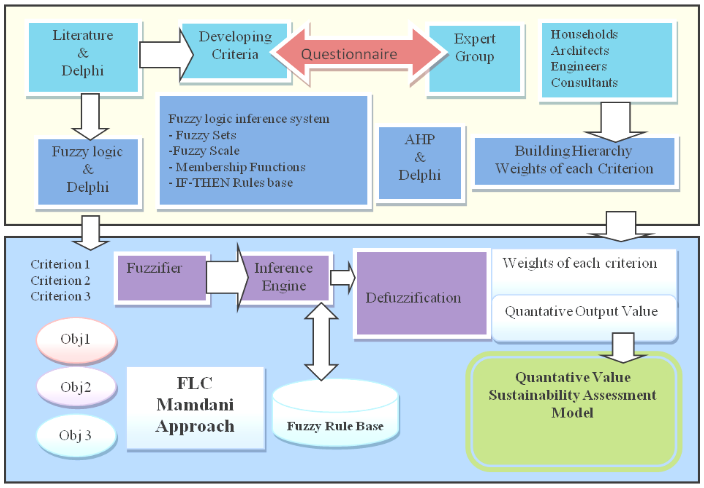

Figure 2: Framework of the Sustainability Assessment Model

Calculation of Sustainability Model Value:

The main five criteria functions are first defined as $\boldsymbol{y_1}$ represents energy efficiency and thermal performance, and $\boldsymbol{f(y_1)}$ represents the fuzzy quantified output value of energy efficiency and thermal performance; $\boldsymbol{y_2}$ represents environmental aspects, and $\boldsymbol{f(y_2\ )}$ represents the fuzzy quantitified output value of environmental aspects; $\boldsymbol{y_3}$ represents socio-cultural acceptance, and $\boldsymbol{f(y_3)}$ represents the fuzzy quantitified output value of socio-cultural acceptance; $\boldsymbol{y_4}$ represents economical aspects, and $\boldsymbol{f(y_4)}$ represents the fuzzy quantified output value of economical aspects, and $\boldsymbol{y_5}$ represents service quality aspects, and $\boldsymbol{f(y_5)}$ represents the fuzzy quantified output value of service quality aspects etc.

Once these definitions are completed, global weights of the criteria derived from AHP and the Fuzzy quantified output values derived from fuzzy FLC systems $\boldsymbol{(y_i)}$, could be used to calculate the quantified assessment magnitude value to assess the level of sustainability compliance of traditional built forms, which equals $\boldsymbol{\Sigma f(y_i) \times (w_i)}$. Since the model shows the potential importance of each criterion the decision-making is made efficient.*

Case Studies

I. Case Study from West Bengal: As a part of this research, a case study of Swapan Adhikari House, a naturally ventilated building in the Khataranga village, Pachim Medinipur, South West Bengal, India, Laitude-22^0 , 30' N and 87^0 , 20' E is carried out on June, 21st, and 22nd of 2013. The house is a two storey, built form standing for the last 37 years. It is surrounded by verandah, reception hall and rooms (Fig.3a). The building material used for wall is mud and ground floor roof is made of flat mud slab-supported by pine wood purlins and planks on wall plates. The hipped roof is roofed in thatch and Asbestos Cement sheets. Similar types, of other nine built forms are also studied, supported with interview based questionnaire survey (Fig.3b). The survey attempted to gather user-perceptions of thermal comfort and overall performance of their houses in *Sonamukhi* village, where predominantly, modern building came up with walls in 230 mm brick work with both side plastering , 150 mm hollow concrete blocks walls plastered both sides, and 200 mm fly ash block both side plastered walls. Roofs are made of Asbestos Cement sheets, Clay tiles or 100 mm thick RCC slab.

(3a)

(3b) *Source:* Author

Figure 3a and 3b: The photographs showing vernacular traditional houses in Khataranga and Sonamukhi village, West Bengal, India

II. Case Study from Western Maharashtra: As a part of this research, another one case study of Raghoba Salunkhe Wada, House No.38, a naturally ventilated building in the village Basarapur, Taluka: Bhor, District: Pune, Western Maharashtra, India, and Latitude: 18.17^0 N and 73.85^0 E was studied on December, 21st and 22nd of 2013, and March, 21st and 22nd of 2014, which was under investigation. This *Wada* is a single storied, built about 109 years ago. The *wada* is surrounded by verandah, courtyard, reception hall, and other rooms (Fig.4a).Its walling is of basalt stone and sedimentary rock with lime mortar. The hall, kitchen and other rooms are roofed with clay tiles with false ceiling in wood. Bed room and entrance passage have flat mud roof supported on wooden joists and purlins. Similar kinds, of other two built forms are studied from same village (Fig. 4b). In addition to this, other eleven wadas constructed with stone masonry or composite material stones and bricks with mud/lime mortar built more than 100 years ago, are also surveyed at Pune.

(4a)

(4b) *Source: Author*

Figure 4a and 4b: The photographs showing vernacular traditional Houses in Basarapur village, Taluka: Bhor, Dist: Pune, Maharashtra, India

Results and Discussions

Social and Cultural Acceptance of Vernacular House Forms

Demographic and General Information:

Houses studied were so chosen to ensure that they represent traditional residential built forms. Occupants of the houses surveyed in the South, West Bengal said that they have been living there for more than 30 years and the other two houses are 37 years old. Moreover, all the houses under investigation were at least 30 years old.

House and its Usability

Information on using pattern of the houses on a diurnal and seasonal basis; time spent by the occupants inside the houses were needed to relate their perception of thermal comfort conditions inside the houses with the outside temperature.

On an average, the occupants surveyed in all cases remained in their respective houses for more than twelve hours a day, which substantiated their responses.

Indoor Thermal Comfort

Perceived thermal comfort conditions of occupants, from South West Bengal showed that 93% of the households felt more comfortable on all daytime indoor during summer because it was relatively cooler. More than 90% users said spring to be best season outside the house; occupants of three houses uses rarely ceiling fans to circulate air for comfortable indoor while the occupants of rest of the houses depends on natural ventilation.

Similarly, 98% occupants, from Western Maharashtra felt comfortable all the day inside their houses during summer. The occupants of five houses uses rarely a ceiling fan to circulate air in summers to make comfortable and rest of the houses depends on air movement for comfort. Most of them opined that mud walls and thick stone walls with mud or lime mortar, flat-mud roof, and attic spaces makes comfortable indoors.

Outdoor Discomfort

This section of the survey gathered information regarding discomfort levels as perceived by the occupants of the houses surveyed with an intention to compare occupant responses. The research was carried out for a limited time; however, this response helps to understand their year-round perceptions. Ninety seven percent of occupants in both the places opined that outdoor temperature is most uncomfortable in summer. They felt higher RH and lack of ventilation as the causes for discomfort. Occupants of these houses expressed that the rainy season is the most unfavorable season, since they could not perform their day-to-day activities due to heavy rain.

Adaptability

This section of the survey collected users' responses concerning changes in climatic conditions and their perception of thermal comfort indoor over the years, as well as assessed the changes, if any, had been made to the house forms from their respective original conditions. All the occupants surveyed said that the climate had changed over the years, becoming hotter and all the houses are in their original state and only repair works are done to keep the houses in good condition. The occupants added that, except for adding ceiling fans in the house, no other measures were taken to create comfortable conditions inside the house over the years. Changes in lifestyle have also brought in change in living patterns of the people. Bathrooms and toilets have been incrementally added into the dwellings, mostly within courtyards and backyards. Small openings and *jaalis* create an interior that is darker. Present day activities in most cases, therefore, require artificial lighting.

Indoor Environments

This part of the survey sought additional environmental factors that contribute to comfortable conditions inside traditional houses. The survey questionnaire and rating system developed by Rohles (1989) was used. This section covered acoustics, light, air quality, thermal environment, and pest control. The thermal environment inside the houses was highly rated. The occupants said that indoor thermal levels are more comfortable than outside and they are highly satisfied by their houses performance. Occupants of all these houses rated the acoustical quality of their house highly on loudness, pitch, and audibility of distracting sounds. Occupants of the houses surveyed rated the air quality high, with fewer amounts of odor, dust, and smoke inside indoors. Occupants rated the light quality inside the houses satisfactory. Occupants rated the indoor environment quality poor for pests. Overall, occupants of these houses are highly satisfied with the overall performance of their houses.

Energy Efficiency

The last section of the survey is conducted based on energy consumption and monthly electricity bills. The most of energy consumed is for lighting, TV, and other electrical/electronic appliances/gadgets, and occasionally, for ceiling fans. The occupants said that 25-30 units are their monthly energy consumption costing ₹135-150 per month for 100 square meter carpet area house. Users' perception shows that mud walls and composite stone masonry walls with mud mortar or lime mortar, and flat mud slabs or thatch or clay tiled roofs effectively reduced the dependence of artificial means for comfort indoors.

Thermal Performance

The mass effect provided by a heavy construction is beneficial in many situations, even without any special devices. In warm-humid climate it is still possible to keep stable comfort temperature by passive means for continuous occupancy. Thick and massive walls of thermally resistive materials like mud and stone give longer time-lag and the stored heat would be dissipated during cooler night hours.

It is observed that thermal conductivity of mud wall is about 20-25% less than contemporary building wall materials (Alapure et al., 2014). Moreover, the *wadas* save energy in terms of comfort conditions due to the time-lag offered by stone walls. *Night ventilation* if, provided, modifies the mass effect, where the day's average temperature is higher than the comfort limit, by increased heat dissipation and cooler wind flow.

This may be achieved by natural ventilation through windows and other openings, supplemented with an exhaust fan having required air delivery and noise rating.

Ecological Factors

The relationship between man and nature is reflected in a number of geographic factors which determine the availability of local materials, orientation of buildings, among various other aspects and are design determinants for development of settlements and house forms. Locally available building material in a way to provide shelter from the climatic elements so as to give shape and organization of built forms in a region. A hot-dry climate requires massive walls incorporating elements such as verandahs and balconies which provide shade, and also provide protection against rain in monsoon, depicts architecture suitable for a given climatic condition. The focus of ecological sustainability is to create a balance between humans and their environment including both natural and manmade, is designed keeping in mind the elements of climate such as solar radiation, wind, precipitation, and humidity.

Physical and Cultural

Physical sustainability is that quality of a building which enables it to adapt to the changing needs. Figure 3a, 3b and 4a, 4b shows that the building uses materials like mud, stone and timber which are of low embodied energy and have the potential to be recycled and reused. Almost in all local cultures, the landscapes with their natural forms have symbolic and spiritual meanings, design logic of their practices, cultural embodiments and spatial patterns and routes that allow their daily choreography. These patterns of cultural, environmental, economy and social status of the society are inextricably linked to sustainability of a living environment (Alnaser et al., 2008).

Socio-Economic factors

The planning of the house is in accordance to principles of *Vasstu Shastra*. It is square in plan based on the *Vaastupurush Mandala*, using the template of concentric squares. Figure 3a, 3b and 4a, 4b shows that the traditional houses are planned around a courtyard which is a private zone, with the kitchen and living areas built around it. In vernacular environment, streets and junctions are the main spaces for social interaction. The otta, chowk, verandah acts as a semi-public zone, where people generally interact with their societal members.

Social and religious patterns also play an important part in the design of neighborhood or *mohallas*. Materials used in mud houses and wadas shows that vernacular traditional houses are built and constructed by local craftsmen using cheap, locally available materials which are cost effective, durable, versatile and adaptive.

Spatial planning

It is observed that generally, vernacular-traditional houses are aligned with the topography of site and deep in plan with narrow street frontage.

They are densely clustered around narrow streets which ensure that the built form cast shadow on each other at the overheated hours of the day and keeps the streets cool and livable.

*(*Note: The survey results and analysis for developing*

sustainable assessment model is out of the scope of this research paper)

Conclusion

The most prevalent design elements of vernacular built forms are passive in nature and their comfort strategies are evolved over generations. Rituals such as sprinkling of water in courtyard integrate the cultural and belief systems in establishing comfort. Significant difference in temperature between indoor and outdoor of traditional buildings in summer is due to the evaporative cooling that takes place in mud mortar. The South West Bengal climatic conditions are such that high thermal mass in buildings helps to create more stable indoor conditions, and evens out the diurnal variations in temperature. The case study of Maharashtra, validate the use of high thermal mass as a passive cooling strategy in these climatic conditions and create comfort conditions in winter by absorbing the radiant heat during the daytime and re-radiating it during the cool night hours. The study therefore, recommends the use of mass resistance for walls in combination with internal courts and attic spaces that are appropriately ventilated. Attic space helps to reduce the temperature of the ceiling of the living zone in summer; however, this can act as a constraint in winter, when the heat from the sun is desirable to heat the ceiling which requires judicious mix of the three elements of building.

Light quality in the interior rooms and kitchen are poor and necessitates artificial lighting for most of the day hours. The study demonstrates the relevance of traditional wisdom for creating indoor comfort conditions of *Wadas;* however, have a basic courtyard planning with verandah combined with the use of high thermal mass-walls, minimal openings on the external walls which create lower diurnal variations and comfort conditions indoors. It is inferred that these house forms have been effective in use and are relevant in contemporary times too.

Local and regional based sustainability assessment model derived values can be used to assess contemporary built forms in that region. The research establishes the role and relevance of traditional built forms in the development of sustainable built forms without any prejudice to the location.

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