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Assessment of Building Envelope Materials for Sustainable Private House Reconstruction (A Multi-Criteria Decision Analysis for case of Dhoksan)

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Abstract

Massive earthquake damaged many private houses in Nepal and made many victims deprived of shelter which is the one of the basic need of human being. Currently, Private house reconstruction process is continuous at different affected areas. The focus of private house reconstruction is mostly on disaster resiliency, and sustainability aspect of reconstruction has been quite underestimated. Thus this paper discusses about sustainability of private house through building envelope. Building envelope covers all those elements that separate indoor environment from outdoor like roof, walls, doors, windows, floors. But this paper here focuses only upon wall and roof materials. Multi-criteria assessments of five wall and five roof materials were done by developing a sustainability indexes for a case of Dhoksan. Sustainability Index covers four pillars of sustainability, socio-cultural, economic and environmental sustainability. Those five wall and roof materials were chosen from "Design Catalogue for Earthquake Resilient houses, Vol-I and Vol-II". Brick, Stone, Hollow Cement Concrete block (HCCB), Compressed Stabilized Earth Block (CSEB), EPS sandwich panel were selected for assessment of wall materials. For assessment of roof materials, clay tiles, slates, Reinforced Cement Concrete (RCC) slab, CSEB roof, Corrugated Galvanized Iron (CGI) sheets were selected. The sustainability assessment using Analytic Hierarchy Process gave the result that stone is the most sustainable wall material and CGI sheets are the most sustainable roof materials for Dhoksan. The overall relative sustainability score of stone is 0.278 while that of CGI sheet is 0.244. However, the socio-cultural sustainability of brick is highest (0.230) and stone has highest environmental(0.333) and economic score(0.293) among wall materials. In case of roof materials,CGI sheet, CSEB roof and Clay tile have highest socio-cultural sustainability score(0.412), environmental score(0.331) and economic score(0.270) respectively.

Keywords

Sustainable, Building Envelope, Multi-criteria Decision Analysis

1. Introduction

Nepal faced an earthquake of 7.8 Richter scale magnitude on 25th April 2015. The earthquake destroyed 498,852 and damaged 256,697 number of houses [1]. Private house or shelter is a place that can protect human being from elements, keeps warm and safe and gives the encouragement to satisfy out other needs. According to Post Disaster Need Assessment there will be the requirement of 609,938 number of new houses [1]. National Recovery Framework recommends to reconstruct the private houses following both "sustainability" and "disaster resiliency". Disaster resilient house ensure the safety during another earthquake while sustainable house ensures that a house fulfills the socio-cultural needs without excessive exploitation of environmental and economic resources. This paper here focuses upon sustainable private house reconstruction through sustainable building envelope materials for the case of "Dhoksan". Dhoksan is a village of Tamang, at the hill top of Sankarapur municipality. It is surrounded by three districts Sindupalchowk, Kavre and Bhaktapur. The total no of houses is 145 among which 90% was damaged by earthquake[2].

This paper discusses about one of the key element of a building i.e. envelope. Building envelope covers all those elements that separate indoor environment from outdoor like roof, walls, doors, windows, floors. But this paper focuses only upon wall and roof materials. Dhoksan has wide options for wall and roof materials however Nepal Reconstruction Authority, has narrowed down the options to 14 wall and 5 roof materials in Design Catalog for Earthquake resistant houses, vol-I and Vol-II. Among those five wall materials, brick, stone, hollow cement concrete block (HCCB), compressed stabilized earth block (CSEB)and EPS core sandwich panels (as a representative of prefabricated panels) and five roof materials, clay tiles, Slate, Reinforced Cement Concrete (RCC) slab, CSEB roof and Corrugated Galvanized Iron (CGI) sheets were selected for sustainability assessment.

2. Objective

- General Objective:
  - To find out the most sustainable building envelope materials for private house reconstruction of Dhoksan.
- Specific Objective:
  - To develop a sustainability index for wall and roof material for sustainability assessment,
  - To study technical aspects, socio-cultural aspects, environmental aspects and economic aspects of selected materials with reference to Dhoksan.

3. Literature Review

After the oil embargo in the fall 1973, people started to pay more attention on the energy and fuel consumption. Different energy saving techniques, energy efficient alternatives were searched on[3]. As a result, energy codes were adopted as mandatory for energy efficient new home construction. Super-insulated house were developed in order to minimize energy for space conditioning without considering their embodied energy . Later in 1998, Patrick Pierquet, Jim L. Bowyer, Pat Huelman compared the predicted thermal performance and embodied energy for a number of different wall systems used in cold climate regions of the United States. Eleven different wall systems were modeled and compared against a reference standard (wood 2 by 4 construction). The wall systems studied included several variations of standard wood stud construction, EPS structural insulated panels, steel stud construction, two "historic vernacular" building systems (plastered strawbale, cordwood masonry), and two non-conventional systems (autoclaved cellular concrete, EPS insulating concrete forms). The result showed that the wall systems of conventional materials had the best long-term energy savings. Wall systems made from non-renewable materials such as concrete, steel, synthetic foams showed generally poorer long-term energy performance. One of the vernacular systems (plastered strawbale constructions) appeared promising in terms of long-term energy savings. Along with energy aspects, research on building envelope started including other performances as well. In 2003, International Energy Agency developed comprehensive performance assessment methodology leading to rational strategies for the evaluation and optimization of envelopes with respect to physical, environmental and energy-related qualities. Different parameters were considered in the design requirements like use: suitability and adaptability; occupant comfort: hygrothermal, air quality, visual, acoustical, hygiene, water/ air-tightness; safety: fire and operational; identity; cost and environmental: energy, raw & building materials, air, water, land in terms of impacts and tool output[4].

Goal	To Select Sustainable Building Wall Materials for Private House Reconstruction for Dhoksan					
General Criteria	Socio-cultural Sustainability		Environmental Sustainability		Economic Sustainability	
Secondary Criteria	Preference	Safety	Energy	CO_2 emission	Life Cycle Cost	Cost for space conditioning
Tertiary Criteria	Awareness	Compressive strength	Life cycle energy	Life cycle CO_2 emission		
	Cultural Linkage	Density	Energy for space conditioning	CO_2 Emission due to space conditioning		
	Accessible distance					
	Useful life					
Wall Alternative	Common Burnt Brick	Stone	Hollow Cement concrete Block	Compressed Stabilized Earth Block	EPS sandwich panel	

Figure 1: Sustainability Index for wall materials of Dhoksan

Sustainability aspects was later added to building envelope assessment by Iwaro, Mwasha, Williams. They prepared the sustainability indicative parameters of building envelope of residences and tried to find out the ranks of those parameters in terms of sustainability. The ranking of the criteria was computed on the basis of the relative important index for each factor after questionnaire survey. Ten indicators were used in criteria appraisal namely, aesthetics, energy efficiency, environmental impact, social benefits, material efficiency, envelope life span, recycling/refurbishment potential, affordability, maintenance/durability and functional efficiency. Among all Energy efficiency came first in ranking order, followed by affordability[5]. Later again, Iwaro, Mwasha, Williams,& Zico presented a complete sustainable matrix with 6 general criteria: Material efficiency, Environmental Impact, Regulation Efficiency, Energy Efficiency, External Benefit and Economic Efficiency and other 55 sub–criteria. This methodology was applied to test three alternatives i.e. alternative A: red clay roof tiles with PV component on the roof, 100 mm thick Hollow Cement Concrete Block with 0.5" reinforcement; alternative B: Corrugated aluminum roof with PV component and 100 mm thick hollow clay block with 0.5" reinforcement and alternative C: 26 gauge Aluzinc roofing sheet with PV cells and 150 mm thick Hollow Cement Concrete Block with 0.5" reinforcement. The result showed that Alternative A was the most sustainable solution[6].

4. Methodology

Post-positivist paradigm was followed during this research. The research seeks an objective truth to find the most sustainable wall and roof material among five. Etic approach was applied as researcher's personal opinion was not included in data collection instead all extrinsic data were collected from various sources. After the selection of materials, sustainability index were prepared for roof and wall materials for sustainability assessment. Each index consists of general criteria, secondary criteria and tertiary criteria as shown in figure1 & figure2. Four pillars of sustainability, socio-cultural, economic and environmental were assigned as general criteria. Likewise those criteria which influence general criteria are placed as secondary criteria and criteria which influence secondary criteria are placed as tertiary

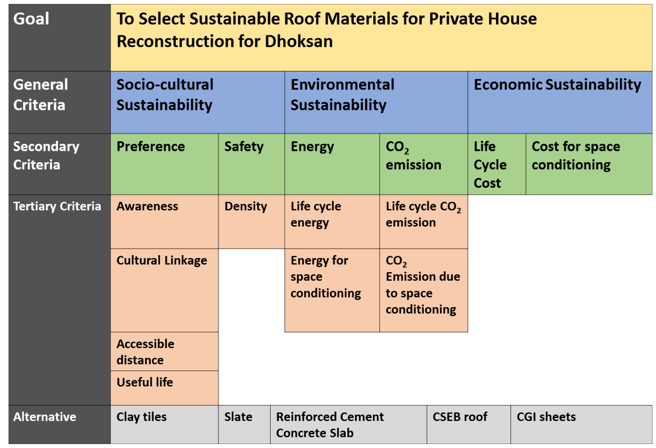

Figure 2: Sustainability Index for roof materials of Dhoksan

criteria in hierarchy of sustainability index. That material or alternative which can score highest in this index is the most sustainable one. This assessment is called multi-criteria decision analysis (MCDA) as it has multiple criteria to decide the most sustainable one. MCDA was applied using analytical hierarchy process (AHP) method. AHP requires pairwise comparison of different component of same hierarchy. For e.g.: a pairwise comparison of one general criteria with another, a pairwise comparison of one alternative with another. At first, questionnaire survey of 8 experts was done to find out the priority of criteria. Experts were from different background like architects, engineers, academicians, material supplier etc. Each expert was asked to make pairwise comparison of criteria and assign the relative priority of criteria in the scale of 1 to 5. 1 being equally important than other, 3 being moderately important than other, 5 being strongly important than other and 2 and 4 being inbetween 1 & 3 and 3 & 5 respectively. Then, pairwise comparison of alternatives was done with respect to all the criteria of respective sustainability index. For that performance values of all materials in each criteria of sustainability index were collected from both primary and secondary sources. Socio-cultural data like preference of materials as per lifespan, awareness, accessible distance, culturally linkage etc. were collected from the questionnaire survey and key resource informant interview from Dhoksan field visit. Economic data like material procurement cost, labor cost and transportation cost and cost of fuel for space conditioning were collected from key-informant interviews. Embedded energy and CO_2 emission, energy and CO_2 emission due to transportation materials were collected from literature. For energy and emission due to space conditioning of materials, thermal conductivity and outdoor temperature data were collected from literature and Department of Hydrology and Meteorology, Kathmandu respectively.

The pairwise comparison form of 8 experts form expert's questionnaire survey was analyzed in AHP based online tool i.e. bpmsg.com to find the average priorities of each criteria. The consensus obtained from expert's questionnaire survey is 70.2% which is moderate value. All raw data of materials from different sources were analyzed to find out their performance value of materials under each criteria. Then socio-cultural data from questionnaire survey of Dhoksan were first analyzed in SPSS tool. Similarly, economic data like procurement cost, labor cost and transportation cost were used to calculate the cost of 1 m^2 of roof and wall materials with the help of Microsoft Excel. In case of environmental analysis, energy required to cover the heat lost/heat gained through 1 m^2 of wall or roof was found out with the help of Heating Degree Days (HDD) and Cooling Degree Days (CDD) of Dhoksan using Meteorological Office equations. At last, two models for roof and wall sustainability indexes were developed in Expert's choice software 2000 and all alternatives were assessed.

4.1 Sample size calculation

The sample size for questionnaire survey at Dhoksan was calculated using given equation1[7]:

$$S = \frac{X^2NP(1-P)}{d^2(N-1)+x^2P(1-P)} \tag{1}$$

where, S: Required sample size; X^2: Table value of chi-square for 1 degree of freedom at the desired confidence level (here: 3.841); N: Population size (here: 131 no of houses); P: Population proportion (assumed to be 0.50 since this would provide the maximum sample size); d: Degree of accuracy expressed as a proportion (here: 0.15)

The equation gave the sample size of 33 no of houses.

4.2 Energy consumption for Space Conditioning

Energy for space conditioning started with analysis of temperature data of Nagarkot which is nearest weather station from Dhoksan. Daily maximum temperature and minimum temperature of Nagarkot were used to calculate the HDD and CDD. HDD and CDD was calculated at base temperature of 13°C for HDD and 28°C for CDD [8] respectively following "The Meteorological Office equations" manually. However instead of calculating HDD for every single day, monthly average HDD and CDD were calculated as done in [9]. Obtained HDD and CDD were used to calculate required heat energy gained or lost through 1 m^2 of different envelope materials, using equation2. The equation 2 also requires U-value of envelope thus was calculated with the help of thermal conductivity of material without mortar or any finishing, outside air resistance and inside air resistance[10].

$$E = \frac{24*U*DD*A*N}{n} \tag{2}$$

where, U: Thermal transmittance (Unit: W/m^2-K); DD: Degree Days in a year (Unit:K-day); A: Area of wall/roof (here, 1 m^2); N: Lifespan (here, 50 yrs); n: Heating efficiency of heating or cooling machine,(here: 77% [11])

5. Results

This section consists of result of priority of criteria of sustainability index, result of sustainability assessment of wall materials and result of sustainability assessment of roof materials.

5.1 Priority of criteria

The result of criteria of sustainability index (figure3) shows that lifecycle cost possesses the highest priority followed by cost for space conditioning i.e. 32% and 15% respectively. Energy for space conditioning, Lifecycle energy, density, compressive strength possess priority >5% to =10% while Lifecycle CO_2 emission, CO_2 due to space conditioning , useful life, accessible distance, cultural linkage and awareness possess priority less than 5%.

It was found out that economic sustainability possesses

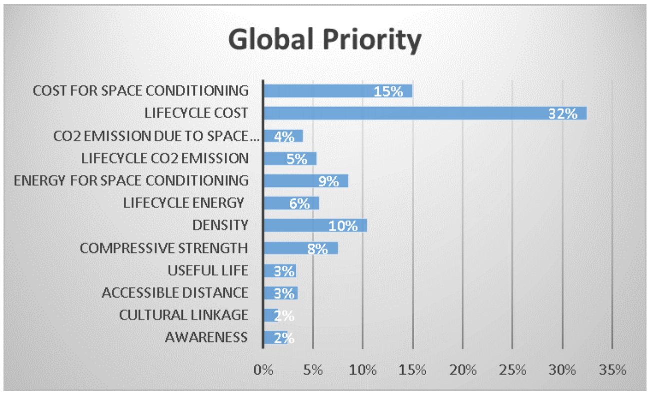

Figure 3: Global priority of all end note criteria

the highest priority among general criteria i.e. 47.5% followed by socio-cultural sustainability and environmental sustainability i.e. 28.8% and 23.7%. which means economic sustainability is far more important than socio-cultural and environmental for selecting envelope material for private house reconstruction.

5.2 Result of sustainability assessment of wall materials

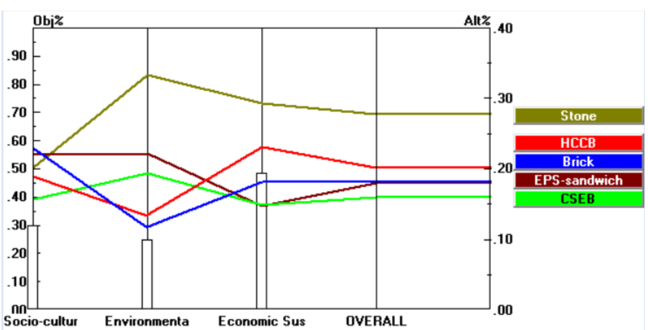

Figure 4: Performance of wall materials in different criteria

Figure 1 and 2 shows the MCDA result of wall and roof materials. At the bottom those figures, there are general criteria of sustainability index. The rectangular bar just above them shows the priority of those criteria. The graduated scale at the left hand side is the scale of priority of general criteria. And the colored lines shows the performance value of five alternatives. The priority of alternatives can be obtained from graduated scale at right hand side. The graduated scale starts with zero and ends at one.

When all five materials are assessed through the sustainability index (refer to figure 1) it was found out that brick is most socio-cultural sustainable wall material (0.23). The highest score in compressive strength contributed highest score in socio-cultural sustainability as compressive strength of brick and priority of compressive strength is high. Likewise stone is most environmentally sustainable material because stone at Dhoksan are used without any dressing, thus they neither require any energy during processing nor emits CO_2. Stone is also the most economically sustainable wall material because stone is locally available at Dhoksan and the procurement cost is zero. Overall stone is the most sustainable wall material as shown in figure4 as stone tops two out of three general criteria by far.

5.3 Result of sustainability assessment of roof materials

Among all five roof materials, overall CGI sheets is the most sustainable roof material for Dhoksan as shown in figure3. But when looked in detail, CGI sheets is the most socio-culturally sustainable (score: 0.412) materials especially because of its lightness. Light roof on one hand reduces the load in walls and foundation and on the other hand increases the safety during earthquake. In case of environmental sustainability, CSEB roof scores the highest i.e.0.33 because it consumes less energy and emits less CO_2. CSEB roof are often produced by human labor intensive machine thus the embodied energy is low. Also CO_2 emission of CSEB is low because main constituent of CSEB is soil which doesn't emit any kind of CO_2. Likewise in case economic sustainability, clay tiles scores the highest i.e. 0.270 because the construction cost of clay tiles is lowest among all.

6. Discussion

The results are based upon the arrangement of criteria in sustainability index, their priority and performance of material. The "arrangement of criteria" factor has influenced significantly in the analysis of socio-cultural sustainability. Socio-cultural sustainability are dependent on many subjective and objective factors. But only few are included in this sustainability index for assessment. Some key influencing factors like local participation%, health etc. were not integrated which

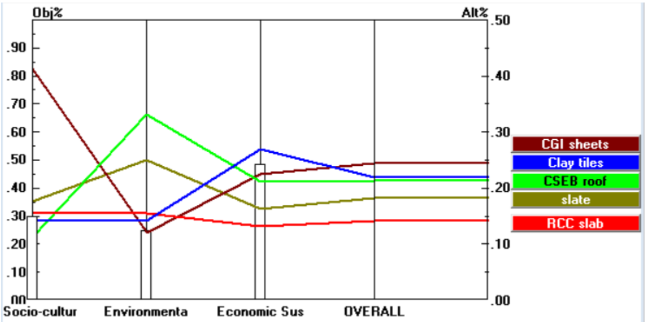

Figure 5: Performance of roof materials in different criteria

could have given different result. Also, the result is based upon performance of material at present. This factor has heavily influenced in the analysis of CSEB roof. CSEB is an alternate roof material which was originally developed to manufacture locally in community effort but at Dhoksan, CSEB blocks are purchased from the 12 km away market center. This increased the price of CSEB and decreased its overall sustainability score. The results support the concept of local material is the most sustainable material in case of wall materials as stone is the local indigenous wall material of Dhoksan. Whereas the result opposes the same concept in case of roof material as the results show CGI sheet as the most sustainable roof material. The result could have been different if "Khar" roof was added for the sustainability assessment as Khar is local indigenous roofing material, but "Khar" roof is not suggested by government for private house reconstruction.

7. Limitation

This paper is based on an exploratory research thus sustainability assessment was done with limited criteria and limited alternative due to time, data and resource limitation.

8. Conclusion

This paper is based upon quantitative research, thus it gives the succinct and precise result. The multi-criteria decision analysis for selection of sustainable wall and roof materials through AHP shows that stone is the most sustainable wall material(0.278) and CGI sheet is most sustainable roof material(0.244)for Dhoksan. However, the socio-cultural sustainability of brick is highest (0.230) and stone has highest environmental(0.333) and economic score(0.293) among all wall materials. In case of roof materials,CGI sheet has highest socio-cultural sustainability score(0.412), CSEB roof has highest environmental score(0.331) and Clay tile has highest economic score(0.270) among all. Thus if only one pillar of sustainability is considered then selection should be different than overall sustainability .

9. Recommendation

Local stone (sandstone) of Dhoksan has low compressive strength and high density, hence requires an improvement while constructing the wall. A layer of insulation is required to decrease thermal transmittance, cost, energy and emission due to space conditioning. Before selecting the Stone and CGI sheets for sustainable reconstruction, detail assessment is strongly recommended including other important criteria such as local participation, health, reused% etc.

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