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DEVELOPING A FRAMEWORK FOR SELECTION OF SUSTAINABLE MATERIALS BASED ON THE EMBEDDED ENERGY FOR BUILDING CONSTRUCTION

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ABSTRACT

Material selection in conventional construction projects concentrate on various criteria. However, sustainable construction must take into account of embodied energy of materials during material selection which is rarely addressed by construction professionals. Analysis of embodied energy of construction materials is important as increase in energy consumption will indirectly trigger a series of collisions leading to instability of the environment. Therefore, this research study aims at developing a framework for selection of materials based on embodied energy and other identified main parameters. The study was carried out based on figures retrieved from literature survey as well as on the perceptions of professionals involved in construction through questionnaire survey. The study categorized the identified significant materials based on five major elements (foundation, wall, roof, floor finishes and doors &windows) with two materials per each and evaluated their performance based on the parameters of embodied energy, price, durability and maintainability. According to empirical findings, most of the selected materials of the same element have performed in similar manner on the selected parameter. However, in some selected materials the results for embodied energy has a significant difference with their counterparts which had an impact on the overall score of those materials. Further, even though embodied energy parameter ranked last in the importance weightings, the parameter is of acceptable significance which can have a huge impact on material selection. Ultimately, framework for material selection was developed with the aid of research findings which comprises of four combinations of each of the selected materials with each other in terms of their performance on each individual parameter and on overall performance.

Keywords: *Embodied Energy; Material Selection; Sustainable Construction.*

1. INTRODUCTION

The increased number of construction activities worldwide has effected severely on the stability of the environment. This has led to the enhanced concern of the protection of environment in which construction activities takes place where sustainable construction has been hailed as a way forward to eradicate adverse impacts on environment (Hussein, 2009). Though there is no agreement as to what is meant by sustainability it has been interpreted as ensuring adoption and maintenance of communities and local organizations to cope with future challenges while achieving set objectives (Bracht *et al*., 1994). Abenayake (2010) describes sustainable buildings as energy and environmentally efficient buildings, providing economic, environmental and social benefits over the whole building environment, while protecting and improving the needs of future generation.

Sustainability in built environment has been the choice of most architects, developers as well as authorities all across the world in order to tackle the environmental impact (Mastor, 2008). According to Grace (2006), there are so many environment assessment methods available to evaluate the environment sustainability of the project. In context of the alarming rate of energy consumed in

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various sectors, building designs apart from their structural and functional requirements also need to be planned and designed for energy conservation (Krishnakedar, 2006).

2. LITERATURE REVIEW

2.2. EFFECT OF BUILDINGS IN ENVIRONMENTAL SUSTAINABILITY

Construction projects usually consume large amounts of materials, produce tons of waste and can involve the weighing of the preservation of historically significant structures against the strong desire for new and modern designs (Kheel, 1992). Therefore, according to Roper and Beard (2006) buildings and civil infrastructure are considered to be presenting a difficult challenge in the field of sustainability due to their profound impact upon the environment.

According to Carswell and Smith (2009), Schendler *et al*. (2008) and US Department of Energy (2007), the built environment accounts for nearly two-thirds of electricity consumption, over one-third of primary energy use and close to one-half of greenhouse gas emissions within the United States. Furthermore, Walker *et al*. (2007) has stated that the construction activity worldwide consumes 3 billion tons of raw materials annually. Buildings also consume a quarter of all the wood harvested as stated by Roper (2003 cited Roper and Beard, 2006) and are responsible for producing 50 percent of chlorofluorocarbons and indirectly 33 percent of CO_2 and 40 percent of the landfill waste (Walker *et al*., 2007).

Therefore, whether it is construction or operation, built environment has become a broader global concern, as buildings are major contributors to global environmental issues with consequent impacts on the natural environment. As discussed by Wyatt *et al*. (2000) and Newell (2008), organizations and specifically built environment professionals, themselves clearly have a role to play in the development of technology and innovations, if they are to sustain their business operation for the long-term. The greatest opportunity for an organisation to review the environmental performance of its built assets is at the initial design and procurement stages (Walker *et al*., 2007).

Thus, Walker *et al*. (2007) also suggests that more appropriate sustainable design solutions need to be developed, which reduce the use of raw materials and addresses the issues of future maintenance and replacement cycles, through to eventual decommissioning and disposal. Therefore better attention must be given as sustainable development is unattainable without sustainable buildings (Lai and Yik, 2006). Subsequently, a sustainable building or green building design focuses on increasing the efficiency of resource use while reducing building impacts on human health and the environment during the building's lifecycle through better design, construction, operation, maintenance, and removal (Wikipedia, 2009).

Typically, buildings are designed to meet building code requirements, whereas green building design challenges designers to go beyond the codes to improve overall building performance, and minimize life-cycle environmental impact and cost (Gowri, 2004). This has lead to the continuous assessment and monitoring from the planning/design stage up to the completion of construction, for declaring a building as a “green building” (Malarthamil, 2009). As a result several green building rating systems have been developed to objectively evaluate energy and environmental performance of built environments (Jayasinghe, 2010).

2.2. EMBODIED ENERGY

Sustainable development is a pattern of resource use that aims to meet human needs while preserving the environment (Wikipedia, 2009). Since construction materials use resources of a country, a proper selection of materials is thus important for sustainable development. Therefore assessment of environmental burdens associated with different construction materials used for buildings is necessary in order for decision-makers to select environmentally benign materials (Abeysundara *et al*., 2008).

Integration of several factors such as environmental, economic and social provides an overall picture of a material and thus, helps in selecting suitable materials for buildings through a multi-criteria decision-making approach (Abeysundara *et al*., 2007). Embodied energy is one such measure of the environmental impact related to construction materials (Commonwealth Scientific and Industrial Research Organization, 2008). According to Miller (2001), the term "embodied energy" is subject to various interpretations rendered by different authors and its published measurements are found to be quite unclear as all these definitions represent differences of opinion about the system boundaries to be included in embodied energy analysis. There are two ways in which embodied energy can be analysed: embodied energy of materials and embodied energy of building. This research focuses on embodied energy of materials only. Basically, the energy consumed in production (raw material extraction, transport, manufacture, installation) is called the "embodied energy" of the material and is the concern of energy consumption and carbon emissions (Dixit *et al*., 2010).

The Figure 1 represents the proportion of energy used by different industries where construction industry consumes high energy. Therefore, it is an important parameter for comparing materials or products in environmental terms (Menzies and Muneer, 2000). Proper accountability of embodied energy will contribute to data and information needed to create an energy economy that accounts for indirect and direct contributions (Dixit *et al*., 2010).

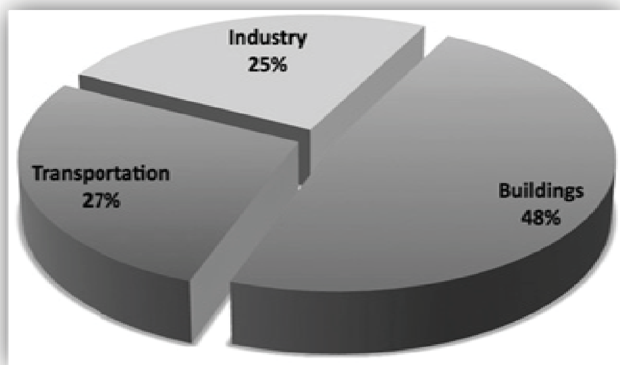

Figure 1: US Building Energy Use Comparison (Source: Cole and Kernan, 1996)

2.3. SIGNIFICANCE OF EMBODIED ENERGY

According to Crowther (1999) and Pullen *et al*. (2006), major endeavors for energy conservation assumed the operating energy of a building to be much higher than the embodied energy of a building. However, current research has disproven this assumption and found that embodied energy accounts for a significant proportion of total life cycle energy.

Embodied energy is expended once in the initial construction stage of a building, while operational energy accrues over the effective life of the building. Operational energy conservation could be accomplished more optimally with energy efficient appliances and advanced insulating materials, which are available more readily (Sartori and Hestnes, 2007). But embodied energy can only be reduced by preferring low energy intensive materials. Commonwealth Scientific and Industrial Research Organization (2008), has demonstrated that in developed countries, the embodied energy contained in a building is 20–50 times the annual operational energy needed for the building.

The building material production industry is responsible for 20 percent of the world's fuel consumption. Therefore, embodied energy results are critical for national and global strategic plans for energy (Tiwari, 2001). Consequently, a modest knowledge and awareness of the embodied energy contents of building materials could encourage the use of not only production and development of low embodied energy materials, but also their preference among construction design and industry to curb energy use and carbon dioxide discharge (Ding, 2004).

Due to the significance of embedded energy of materials, several green rating systems have also identified embedded energy as an important criterion in green certification.

2.4. *EMBEDDED ENERGY IN GREEN BUILDING RATING SYSTEMS*

As discussed earlier, green buildings have become a flagship of sustainable development, several green building rating systems have been developed to objectively evaluate energy and environmental performance of the so-called green built environments. Since these rating systems are employed for construction works throughout the world for evaluation of sustainability, it would be beneficial to identify the recognition given to embodied energy in them. Therefore, the embodied energy significance in green building rating systems of developed countries, namely LEED and BREEAM and Sri Lankan GREEN^{SL} are discussed here.

LEADERSHIP IN ENERGY AND ENVIRONMENTAL DESIGN – NEW CONSTRUCTIONS (LEED-NC) – UNITED STATES

The LEED rating system attempts to balance the need to reduce both embodied energy and operating energy of buildings. Whether a new or renovated building, LEED encourages reduction in embodied energy through;

- Use of salvaged and recycled content
- Re-use of materials
- Construction waste management
- Reduce transport impact by use of regional and rapidly renewable materials
- Providing points for designing building durability

(Carpenter, 2010)

BUILDING RESEARCH ESTABLISHMENT ENVIRONMENTAL ASSESSMENT METHOD (BREEAM) – UNITED KINGDOM

According to Building Research Establishment (2009), BREEAM identifies that it is important not only to consider the raw materials used but also the embodied energy used to create each element in a building.

BREEAM does this by rewarding:

- Materials with a low embodied energy i.e. 'A' rated in the Green Guide to Specification
- Buildings where part or all of an existing building is being re-used (i.e. refurbishment projects)
- Responsibly resourced materials
- Use of recycled materials

(Building Research Establishment, 2009)

GREEN^{SL}RATING SYSTEM FOR BUILT ENVIRONMENT

The GREEN^{SL} rating system also attempts to reduce both embodied energy and operating energy of buildings through;

- Use of salvaged and recycled content
- Re-use of materials
- Construction waste management
- Reduce transport impact by use of regional and rapidly renewable materials
- Buildings where part or all of an existing building is being re-used
- Designing energy efficient buildings

(Green Building Council of Sri Lanka, 2011)

2.5. Significance of Embodied Energy for Material Selection in Sri Lanka

Sustainable development should be the theme for all development projects as per Rio Declaration in 1992 of which Sri Lanka is a signatory country. Further, Sri Lanka has committed itself to the control of substances that deplete the ozone layer according to the Montreal Protocol of 1985 and the emissions of green house gases according to the Kyoto Protocol in 1997. In this context, assessment of environmental burdens associated with different construction materials used for buildings is compulsory for Sri Lanka (Abeysundara, 2008). But for the time being, above assessments are yet to be accounted in a proper manner.

Embodied energy is one way to measure the environmental impacts of construction. Since embodied energy concerns about the energy input for construction, it would be beneficial to identify the sources and types of energy used for various activities to study the impact and significance of energy in the Sri Lanka context.

The domestic sector and manufacturing industries in Sri Lanka mostly use electrical energy supplied by the national power supply which has a mix of electricity; mainly thermal (generated by burning oil) and hydro (Ceylon Electricity Board, 2008). For transport also, the major energy source is fossil fuel (i.e., gasoline or diesel). Therefore, it can be identified that, energy for manufacture of materials and building construction is mainly from fossil fuels.

According to United Nations Environment Program (2001), it is well known that with burning of fossil fuels, emissions are released to the environment and this may have a great potential for increasing global warming, acidification, nutrient enrichment, photochemical smog formation, etc. Out of the above, significant environmental impacts affecting the Sri Lanka are nutrient enrichment and acidification. Global warming may also have an effect, as Sri Lanka is an island in the Indian Ocean.

Based on the above discussions, increase in energy use of construction will indirectly trigger a series of collisions leading to instability of the environment in the island nation. Therefore by identifying and reducing the embodied energy for construction and materials, the impact of energy use on the environment can be reduced extensively.

Even though a specific guideline has been developed to cater the needs of the Sri Lankan construction industry, yet it has not been well established. Building professionals are also in confusion in terms of embodied energy. Therefore, a proper and well guided evaluation criterion is needed to be established for material selection if sustainable construction is to bloom more effectively within the local construction industry. Hence, this research aims at developing a framework for sustainable material selection based on embodied energy of materials.

3. Methodology

Construction of a building requires vast numbers of different types of resources in different quantities. Out of this vast number of resources, construction materials plays a vital role as they directly contributes to the physical existence of the structure. Therefore, it would be less feasible to identify and evaluate the embodied energy factor of each and every materials used for construction projects. To facilitate this research, it is necessary to identify the significant materials used in the construction industry today. In order to achieve this task, several similar construction projects were selected where, these projects will act as a sample to represent the total commercial construction projects in the Colombo district.

The basis for identifying the significant materials was by using input percentages identified for the calculation of price fluctuations. These input percentages are calculated for the project by considering the cost contribution of individual input to the construction project. Therefore these percentages can be identified as a rational and appropriate method for identifying the significant materials for construction.

The following table (Table 1) shows the major input percentages obtained from six construction projects. For the ease of clarification, the materials are sorted based on the descending average value of their input percentages to the project

Table 1 - Categorization of Significant Materials Based on Input Percentages

Material	**Project 1**	**Project 2**	**Project 3**	**Project 4**	**Project 5**	**Project 6**	***Average***
RF Steel	22.33	17.21	14.26	7.00	12.03	16.43	***14.88***
Cement	10.56	8.60	7.66	10.00	7.67	9.32	***8.97***
Aluminium Doors & Windows	5.17	6.32	5.27	0.50	18.72	9.73	***7.62***
Steel Work	1.07	3.03	5.72	18.00	0.10	6.39	***5.72***
Form work Planks	4.24	3.56	1.80	4.10	1.47	2.45	***2.94***
Sand	3.06	1.23	3.06	2.00	0.43	2.22	***2.00***
Floor tiles (Ceramic/Porcelain)	1.74	5.65	0.30	3.00	2.23	2.67	***2.60***
Clay roof tiles	2.26						***2.26***
Metal	3.41		2.48	3.00	0.03	2.04	***2.19***
Brick	3.14	1.72	1.52	6.00	0.59	0.03	***2.17***
Asbestos sheet roof		1.52		2.75			***2.14***
Timber Doors & Windows	3.61		1.95	0.90	0.01		***1.62***
Glass	0.00	1.11	0.14		5.51	0.19	***1.39***

Since identification of the embodied energy distribution deemed to be beneficial, consideration of embodied energy of materials based on major elements of the building structure will be more conversant. As a result, the significant materials identified earlier will be categorized based on several key elements of the buildings.

The categorization will consist of key material for the element along with alternatives for comparison. For this study to be feasible, the number of materials selected for further energy analysis as shown in Table 2, needed to be limited and certain elements will consist of material not based on the significance list but as commonly used materials for commercial construction in Sri Lanka. Table 3.2 also shows the comparison of embodied energy per Kg which were available through previous research articles.

Energy was credited during the calculations of embodied energy of material for timber as 60% firewood at the end of life. The energy of vinyl tiles was calculated by including offshore energies as Vinyl tiles have to be imported from India. Wire cut brick and hollow concrete blocks were considered for walls.

As this research aims at developing a framework for selection of sustainable material based on embodied energy views of various professional involved in the construction projects in Sri Lanka need to be evaluated. To aid that purpose, quantitative approach has been identified as the most suitable research approach. Quantitative approach tends to relate to positivism and seek to gather factual data. It studies relationships between facts and how such facts and relationships accord with theories and the findings of any research executed previously (Fellows and Lui, 2003).

Table 2 - Categorization of Significant Material Based on Building Elements Embodied Energy Comparisons

	MJ/Kg	MJ/m3 / MJ/m2
Foundation		
Rubble	0.37	712.00 MJ/m3
Concrete	0.95	1000.00 MJ/m3
Wall		
Brick	1.32	343.12 MJ/m2
Block	0.81	187.50 MJ/m2
Finishes (floor)		
Ceramic/Porcelain tile	9.00	11.83 MJ/m2
Vinyl Tile	79.09	97.99 MJ/m2
Doors and Windows		
Timber	1.80	360.00 MJ/m2
Aluminium	236.80	5470.00 MJ/m2
Roof		
Asbestos sheet	2.85	219.67 MJ/m2
Clay tile	27.76	91.87 MJ/m2

(Source: Abeysundara, 2008)

Data required for the research were collected using a "Questionnaire Survey". Evaluation of environmental sustainability will not be the only criterion in building up framework for materials material selection for the modern day buildings. Therefore, in addition to the embodied energy parameter, several other parameters had to be included to the evaluation process to make the outcome of this research both environmentally and economically sustainable considering the total life line of the construction project. Consequently, four parameters were selected to evaluate the performance of the materials which include;

- Embodied energy
- Price
- Durability
- Maintainability

Durability is the ability of materials to endure, while maintainability is the ease with which a material can be maintained. The questionnaire survey facilitated the respondents to perform pair wise comparisons on the selected parameters and to provide their judgment with regard to each selected materials performance considering each parameter. Analytical Hierarchical Process (AHP) Prioritization tool scoring methods was used for the pair wise evaluation of parameters while the respondents were required to give the credits as appropriate on a scale of 1 to 10 for the evaluation of material performance with regard to parameters.

The questionnaire considered the views of professionals, thus making the individual professional the subject or unit for analysis. The population for the study consisted of individuals pertaining to different professions relating to the field of construction. The questionnaire was distributed to thirty numbers of professionals, personally as well as via electronic mail out of which only twenty five responded.

Data collected through the questionnaire survey were analyzed in several stages. Firstly, AHP tools were used to analyze the data for prioritizing the parameters of material evaluation. Parallel to prioritization of parameters, the scores given to each material with regard to these parameters was evaluated by taking the mean values. Thereafter, the derived mean values were normalized to reduce redundancy and statistical errors.

Normalization of mean values was done by considering the performance of each parameter with regard to the element. Therefore, anomalies will be decomposed by considering the value of a certain materials performance with the regard to the performance of the same parameter on the alternative material of the same element in accordance with equation Eq: 01.

$$x = \frac{Xa}{Xa + Xb} \times 10$$

(Eq: 01)

x	-	Normalized mean value
Xa	-	Mean value of material
Xb	-	Mean value of alternative material

When it came to normalization of values for embodied energy, a slightly different equation had to be used as materials with high embodied energy required to be given a lower score. Therefore, equation Eq: 02 was used for this purpose.

$$x = 10 - \frac{Xa}{Xa+Xb} \times 10$$ (Eq: 02)

Evaluation of overall performance through linear equation

Finally, the materials will be evaluated as a whole by developing a linear equation (Eq: 03) which uses the weightings derived from the AHP tools and normalized mean scores of each material. The equation is as follows.

$$y = m_e x_e + m_p x_p + m_d x_d + m_m x_m$$ (Eq: 03)

y	-	Overall score of the material
m_e	-	Weighted factor for embodied energy
x_e	-	Mean score of the material on embodied energy
m_p	-	Weighted factor for price
x_p	-	Mean score of the material on price
m_d	-	Weighted factor for durability
x_d	-	Mean score of the material on durability
m_m	-	Weighted factor for maintainability
x_m	-	Mean score of the material on maintainability

The following AHP approach was deliberated in order to prioritize the lists of the parameters.

1. Carrying out Pair wise comparisons among the parameters of
    - Embodied energy
    - Prices of Materials
    - Durability of Materials
    - Maintainability of Materials
2. Development of Pair wise comparison matrices
3. Development of Normalised weight matrices
4. Working out of Consistency calculations

4. DATA ANALYSIS AND FINDINGS

4.1. EVALUATION OF IMPORTANCE INDICES

4.1.1. DEVELOPMENT OF PAIR WISE COMPARISONS MATRIX

Different respondents had provided their judgments as pair wise comparisons in the questionnaires and a "Resultant" set of judgments attributable to judgment of all respondents had to be developed to make them usable in pair wise comparison matrices. In order to develop such a resultant set of judgments, it was required to calculate the "Arithmetic Mean" of similar comparison pairs in all the Questionnaires.

Calculation of arithmetic mean had to be carried out in a logical manner since there were some anomalies among the judgments provided by respondents. Without considering this anomaly of importance within same comparison pair, if the arithmetic mean is calculated for the corresponding levels of importance, the result might not be adequately accurate. In order to prevent such erroneous results, the following procedure was adopted.

It has been considered that a factor A to be more important over the factor B in any comparison pair as a convention. And whenever a respondent has judged the reverse, the "Reciprocal" value of the corresponding level of importance has been considered for mean calculation. Such an arithmetic mean of judgments of a comparison pair will be identified as the "Rating" of the comparison pair.

The completed comparison matrix is shown in Table 3 Main parameters have been arranged in same order as "Row headings" and "Column headings" in the matrix. Rating of each comparison pair has been entered into the matrix. In the next instance, the sum of each column was calculated.

Table 3: Pair Wise Comparison Matrix of Main Parameters

Criteria	Embodied Energy	Prices	Durability	Maintainability
Embodied Energy	1.0000	1.0213	0.8248	0.6914
Prices	0.9791	1.0000	1.5562	1.9874
Durability	1.2124	0.6426	1.0000	1.0267
Maintainability	1.4463	0.5032	0.9740	1.0000
Column Total	**4.6379**	**3.1671**	**4.3550**	**4.7055**

4.1.2. DEVELOPMENT OF NORMALIZED COMPARISON MATRIX

Subsequently, by dividing each entry of a particular column of the matrix by the sum of the respective column, the "Normalised comparison matrix" has been developed. Getting normalisation completed, arithmetic means (Averages) of figures in each row were calculated consequently obtaining the "Principle Eigen vector" of the matrix. Hence the averages became "Eigen values" of the matrix. Eigen values considered as "Importance Indices" of respective parameters, based on which the prioritisation of them has been carried out. The completed normalised comparison matrix is shown in Table 4.

Table 4: Normalized Comparison Matrix

Criteria	Embodied Energy	Price	Durability	Maintainability	Importance Indices
Embodied Energy	0.2156	0.3225	0.1894	0.1469	**0.2186**
Price	0.2111	0.3158	0.3573	0.4224	**0.3266**
Durability	0.2614	0.2029	0.2296	0.2182	**0.2280**
Maintainability	0.3119	0.1589	0.2236	0.2125	**0.2267**
		Sum of relative weights			**1.0000**

4.1.3. CONSISTENCY CALCULATIONS FOR MATRICES

The consistency calculations have to be done to measure the consistency of judgments made by respondents with regard to main parameters. As described in the research methodology a questionnaire having a CR value more than 0.1 will hinder the expert evaluation as random, causing the questionnaire to be rejected. According to the Consistency calculations, the derived CR value was 0.40 which depicts that the expert survey can be accepted.

4.1.4. IMPORTANCE INDICES OF MAIN PARAMETERS

Based on the results of the analysis using AHP tools, following importance indices shown in Table 5 were derived for each parameter of this study. These weightings will be used for developing the framework at later stages of the analysis.

Table 5: Importance Indices of Main Parameters

Criteria	Importance Indices	Rank
Embodied Energy	**0.2186**	**4**
Price	**0.3266**	**1**
Durability	**0.2280**	**2**
Maintainability	**0.2267**	**3**

According to above table, price is the most important parameter among the identified parameters followed by durability and maintainability. Embodied energy is considered as the least important parameter. But the difference between the indices among the factors of Embodied energy, Durability and maintainability is marginal. In the other hand, parameter of price has achieved the top position by a greater margin.

4.2. MATERIAL PERFORMANCE ON MAIN PARAMETERS

Figure 1 represents the normalized values derived from the scores of the questionnaire survey. Normalization was done as described in research methodology chapter using equation Eq: 01 and equation Eq: 02.

One of key points of this analysis is that, the research doesn't try to find the best material among the above list of materials. Rather, it prefers to identify the best material for each element among the above list. Based on the data from the above table, each material has performed differently on each parameter. Therefore, it would be beneficial to identify the performance of materials on each parameter individually before combining the results.

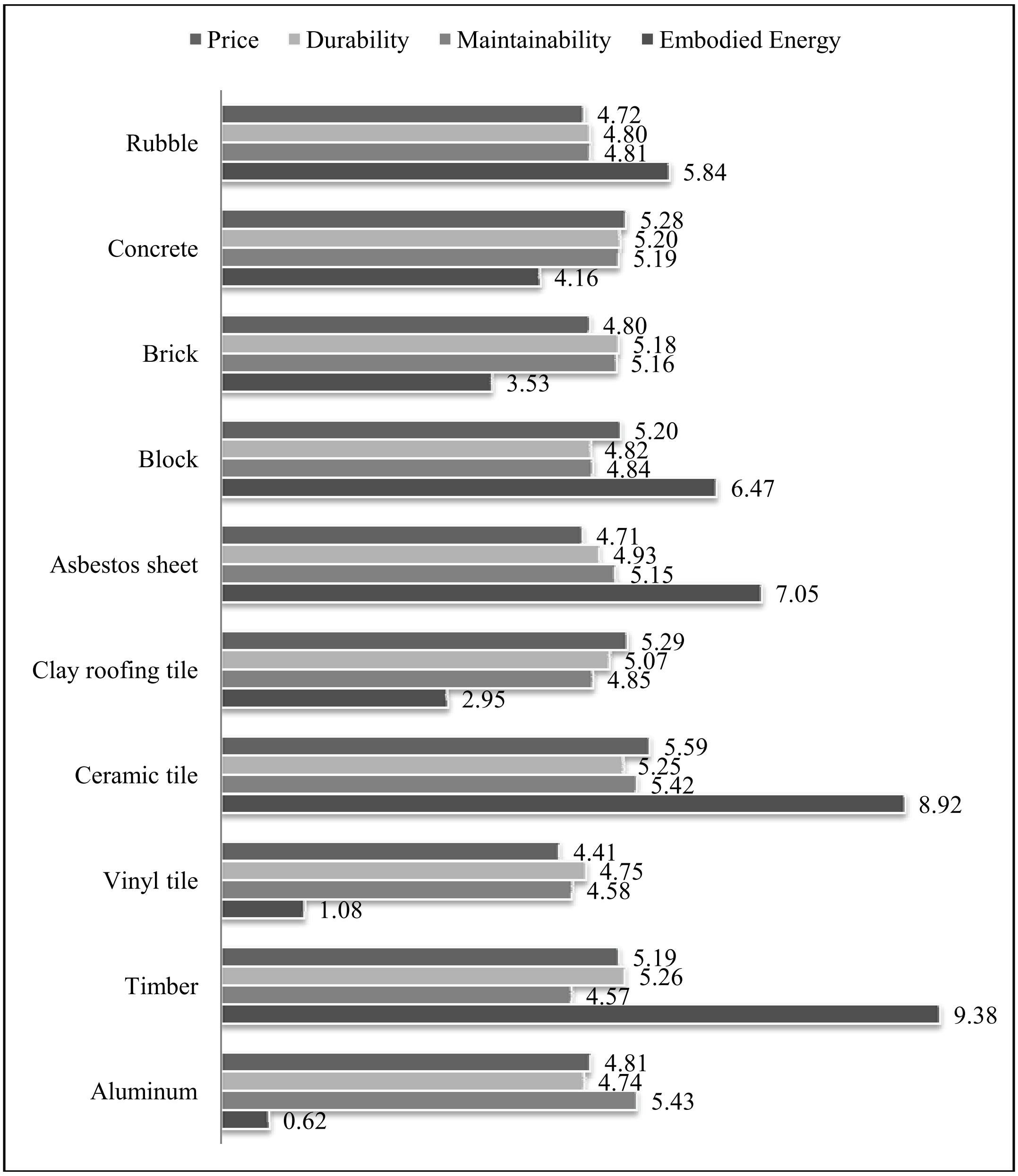

Figure 1: Normalized Mean Values of Material Performance on Main Parameters

4.2.1. EVALUATION ON INDIVIDUAL PARAMETERS

Figure 2 shows the performance of each material with regard to the parameter of embodied energy. Based on these results, the key point to be indentified is how certain materials of the same element have performed in diverse manner. These results are based on the findings from the literature review and not from the expert survey.

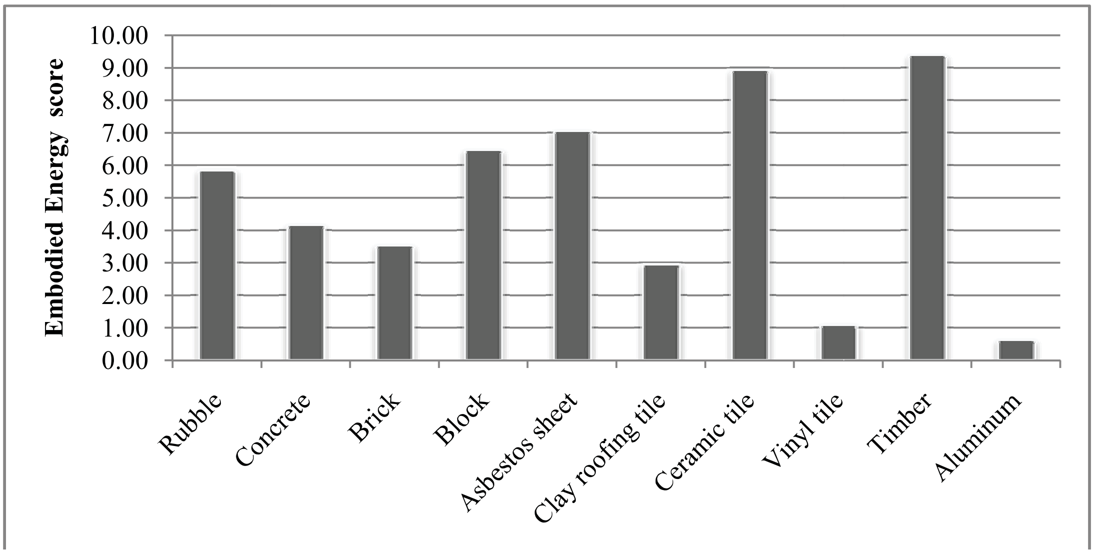

Figure 2: Performance of Materials Based on Embodied Energy

Vinyl tiles require large amount of energy for transportation while aluminium requires energy for extraction and preparation which increase the embodied energy of these materials compared to other material for the same element. These in terms have given them low score for the parameter of embodied energy. Timber has performed well in this regard as it has a very low embodied energy figure due to its ability to be dispose as firewood releasing energy. This has lead to timber achieving the highest score in this parameter.

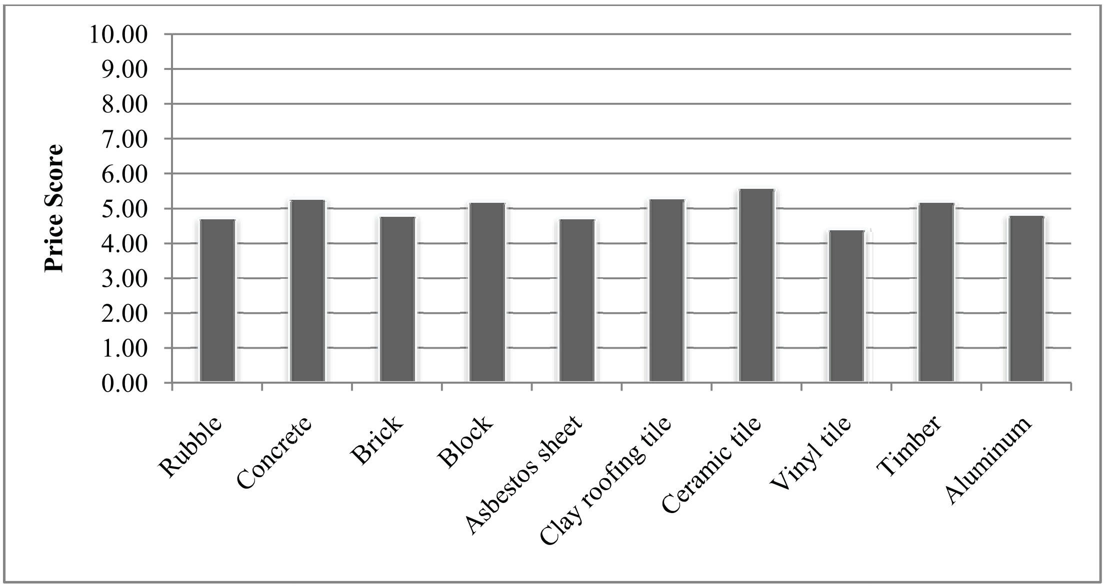

Figure 3: Performance of Materials Based on Price

According to Figure 3, all material has performed reasonably in the parameter of price compared to the alternative material of the element. Same can be said for durability and maintainability parameters by referring to Figure 4 and Figure 5.

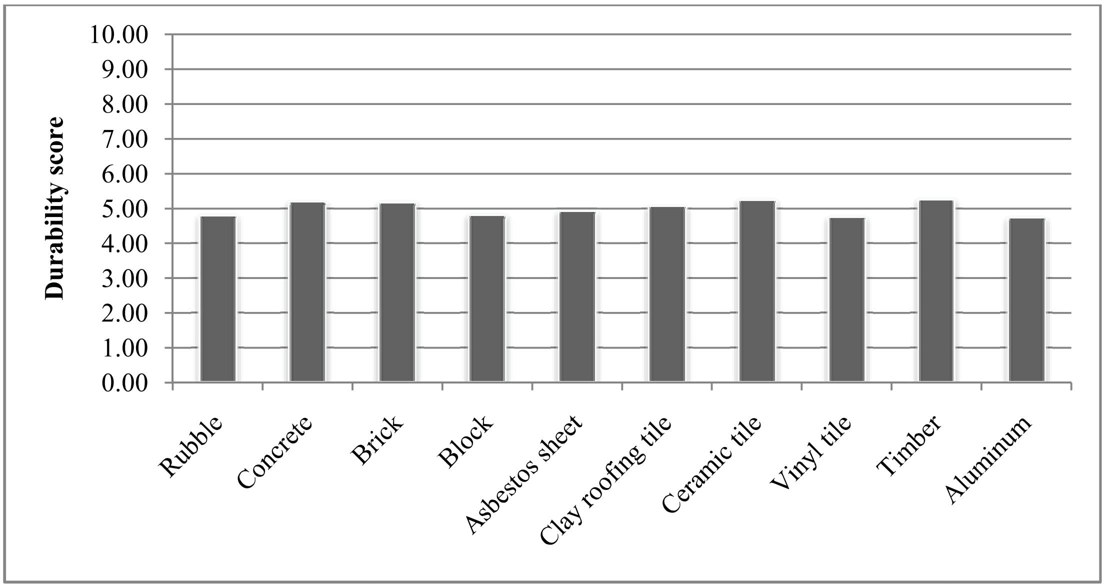

Figure 4: Performance of Materials Based on Durability

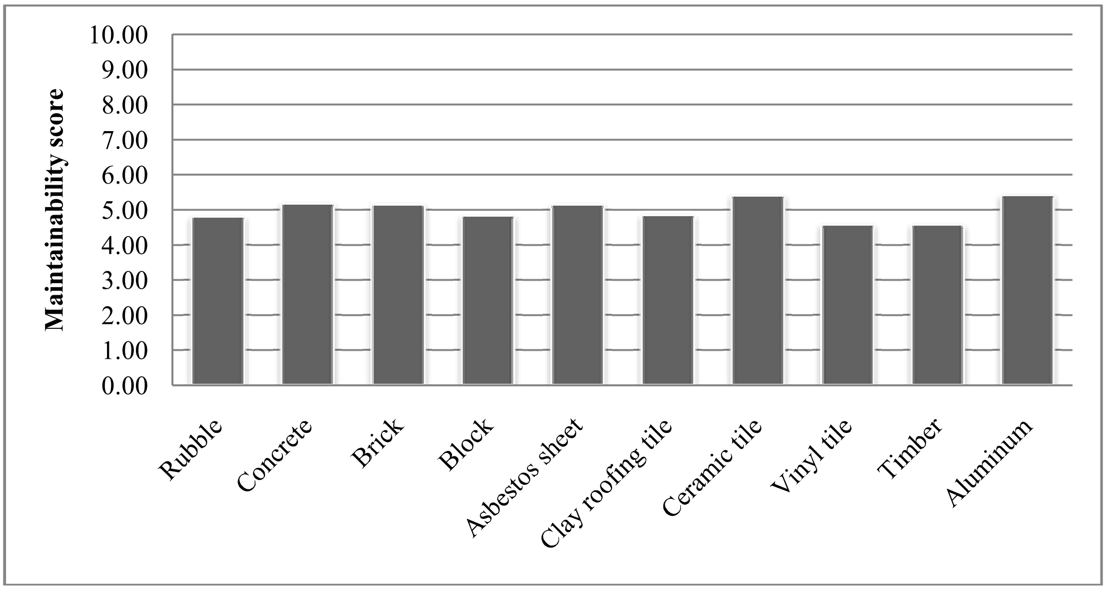

Figure 5: Performance of Materials Based on Maintainability

4.2.2. EMBODIED ENERGY VS. OTHER PARAMETERS

Ignoring the importance indices derived from the AHP analysis tools; this research mainly focuses on the embodied energy parameter of materials. Therefore, it would be ideal to analyze how each material had performed on other parameters alongside embodied energy parameter.

In order to facilitate this, a scatter diagram was employed. Embodied energy of materials was considered in 'x' axis and other corresponding parameter in 'y' axis. Thereafter, the materials were placed in the diagram. The materials which perform best on both parameters can be found in the top right corner, while the materials underperforming were found in the bottom left corner of the diagram. This simplified the process of identifying the materials performance with regard to multiple parameters.

Based on the comparison among Embodied energy and price given in Figure 6, ceramic tile is the material which has performed best on both aspects compared to its counterpart. Even though aluminium for doors and windows has performed weakest in embodied energy, it has a reasonable score in the parameter of price. Vinyl tile has performed the weakest in price parameter and is among the worst performed materials in embodied energy parameter. Therefore, Vinyl tile can be identified as the least performed material considering both the parameters.

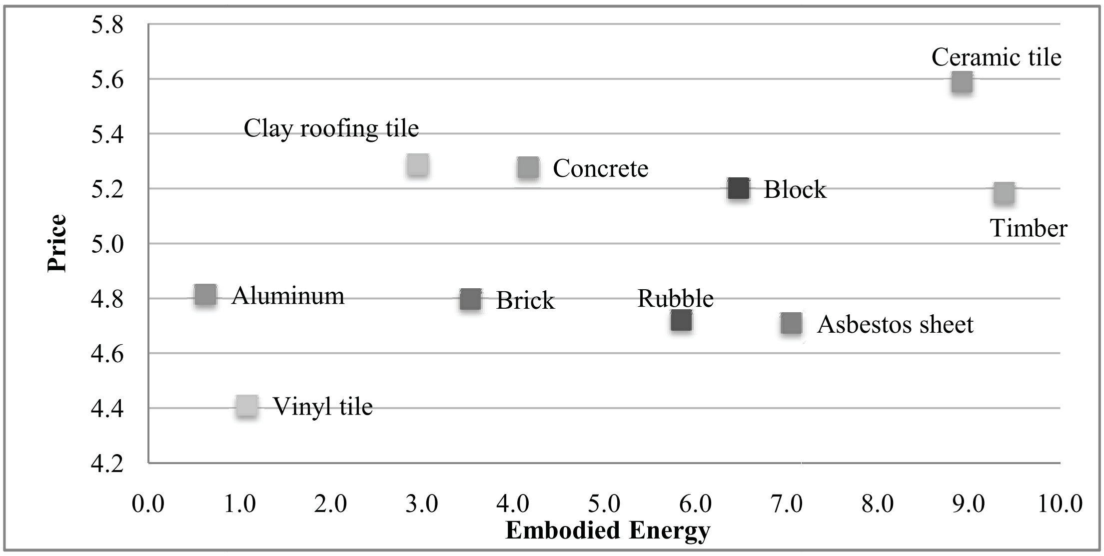

Figure 6: Material Performance Considering Embodied Energy vs. Price

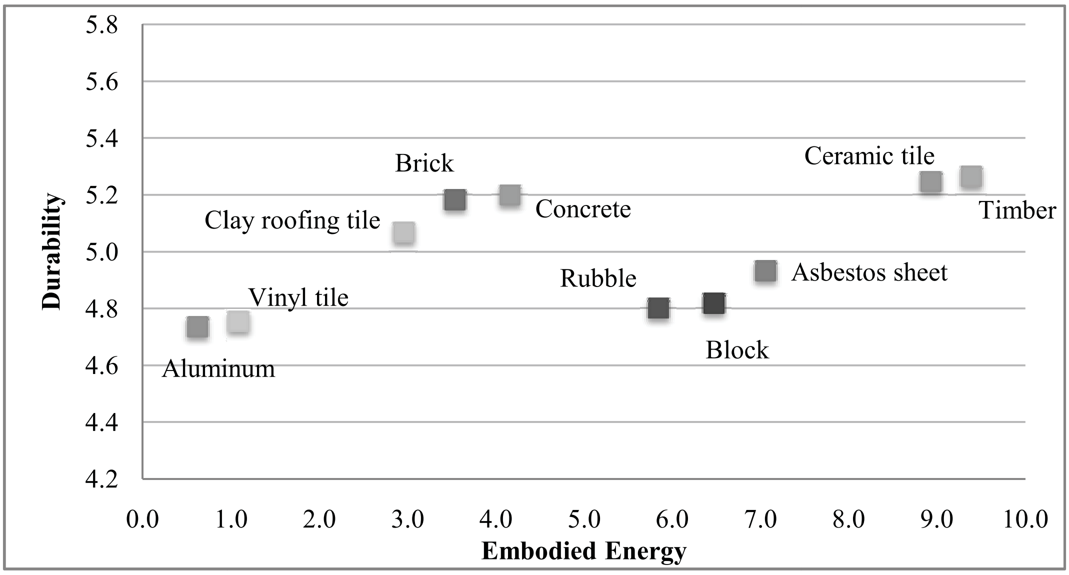

Figure 7: Material Performance Considering Embodied Energy vs. Durability

Figure 7 considers the parameters of embodied energy alongside durability. According the placement of materials in the diagram, Ceramic tile and timber doors and windows can be considered as the best performance while their counterparts are the materials which have the weakest performance. All other materials have scattered in between these elements.

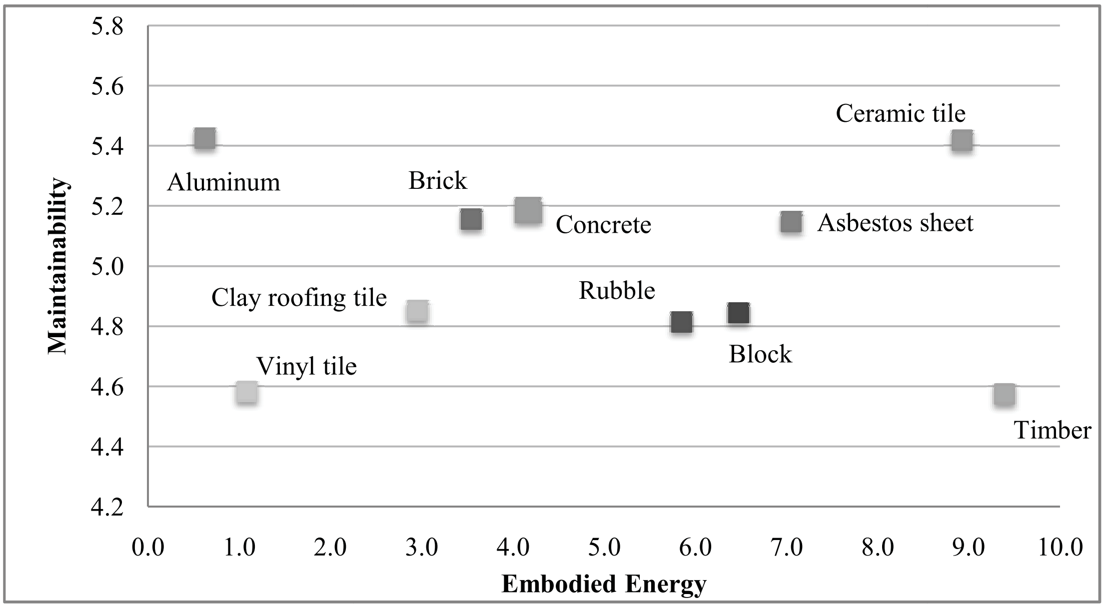

Figure 8: Material Performance Considering Embodied Energy vs. Maintainability

Ceramic tiles again have outperformed its counterpart vinyl tile by a huge margin when embodied energy figures were compared along with the figures of maintainability as shown in Figure 8. All other material combinations are reasonably spread in the diagram.

4.2.3. EVALUATION OF OVERALL PERFORMANCE OF MATERIAL

As discussed in the research methodology, a linear equation (Eq. 03) was developed in order to evaluate each material with all the parameters considered. All the necessary inputs of importance weightings and normalized mean scores have been calculated and based on those calculated figures, Figure 9 is a graphical representation of the results derived for each material.

Figure 10 shows the overall score received by each material alongside the scores received for main parameters. This information helps to identify how the each parameter performances have affected the overall score. It is graphical representation of the effect of importance weightings derived from AHP tools.

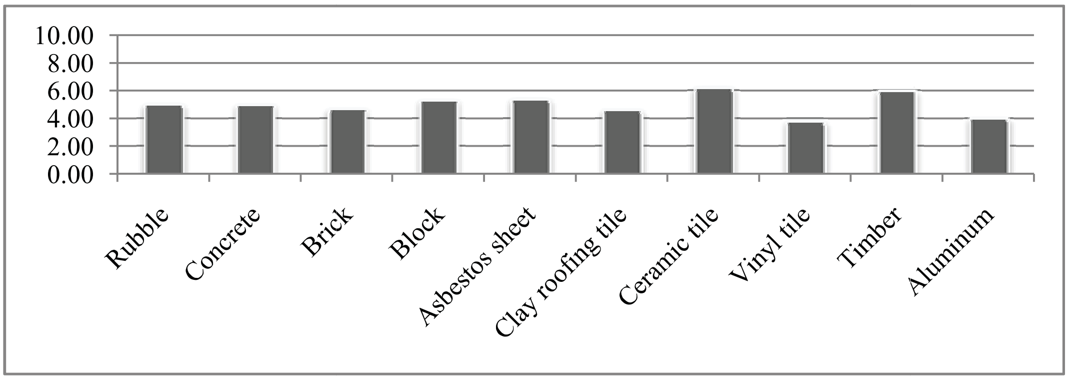

Figure 9: Overall Performance of Materials

For most of the materials, the overall score has vastly deviated from the embodied energy parameter score. This is due to embodied energy having the lowest of importance from the AHP weightings. Other considerable fact is the minimal deviation between the price parameter and overall score. This can be clarified as due to the high value weightings received by price parameter in the AHP weightings.

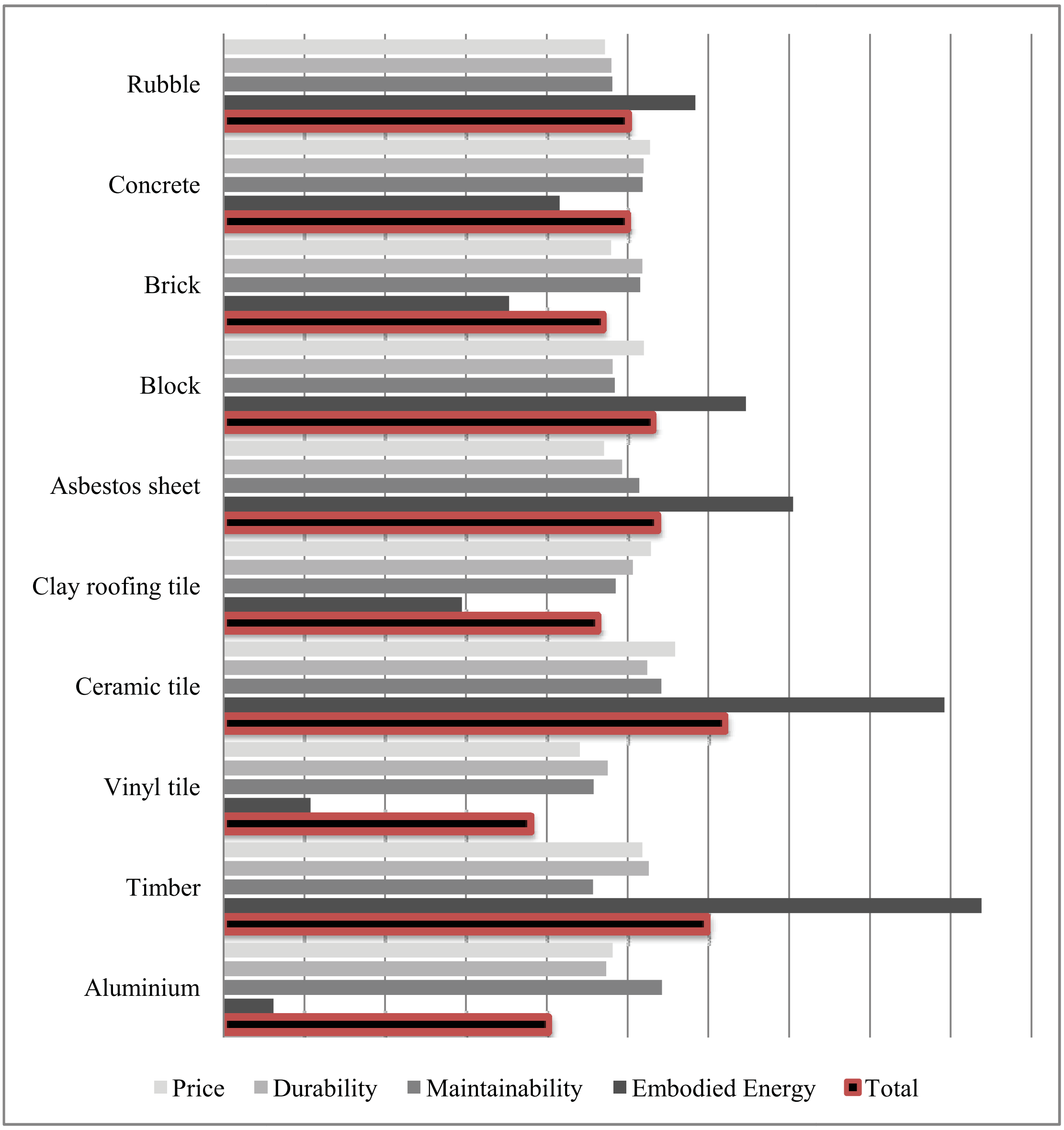

Figure 10: Comparison of Overall Performance with Parameter Performance of Materials

4.3. *DEVELOPMENT OF FRAMEWORK FOR SELECTION OF MATERIAL*

In order to achieve the aim, different combinations of the selected materials for each building element had to be drawn up. Therefore, four combinations of each of these materials were analyzed with each other in terms of their performance in each individual parameter and on overall performance. Thus, results from previous sections are used in this evaluation process.

Based on the materials' overall performance, two combinations of material types were selected. Type 1 combination consists of the materials which had the highest overall score for each element while Type 2 combinations is the opposite of Type 1 and consists of materials with the lowest overall score for their respective element. Type 3 combination consists of a random selection of materials for each element whereas Type 4 combination consists of the counterparts of the Type 3 materials. Materials applicable for each type of combinations are listed in Table 6.

Each combination was evaluated for performance on the main parameters with the use of the normalized mean scores derived from the questionnaire survey. Thereafter, overall performances of the combinations were calculated using the importance weightings calculated using AHP tools.

Table 6 - Material Combinations for the Framework

	Type 1	Type 2	Type 3	Type 4
Foundation	Rubble	Concrete	Rubble	Concrete
Wall	Block	Brick	Brick	Block
Roof	Asbestos sheet	Clay roofing tile	Clay tile	Asbestos sheet
Floor finishes	Ceramic tile	Vinyl tile	Ceramic tile	Vinyl tile
Doors & windows	Timber	Aluminium	Timber	Aluminium

Figure 10 is the graphical representation of performance of each configuration of materials whereas of same data.

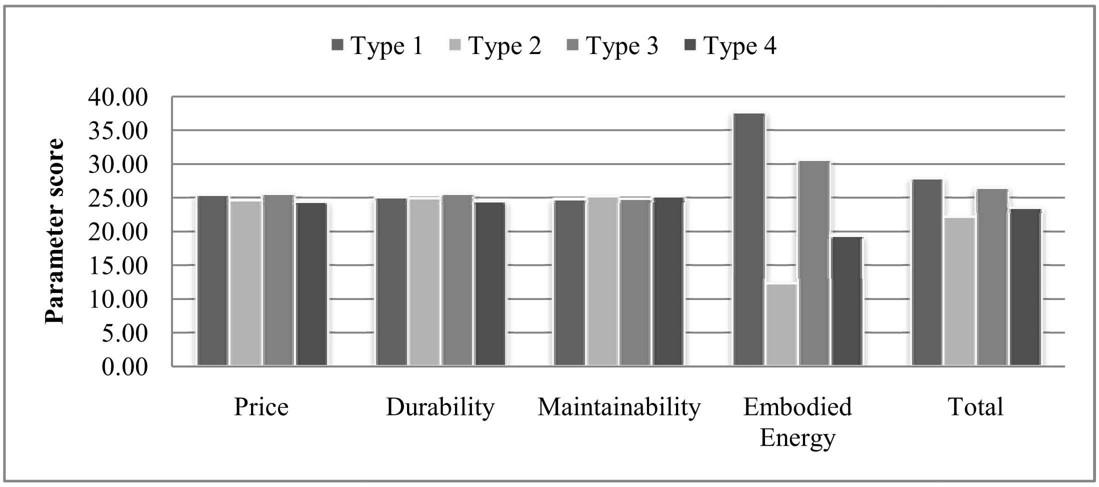

Figure 10: Performance of Material Combinations

Based on the facts it can be understood that performance of all combinations are somewhat similar on parameters of price, durability and maintainability. But in the case of embodied energy, Type 1 has achieved a very high score, whereas type 2 has performed very weak. This was an expected result as Type 1 and type 2 combinations are the highest performed and lowest performed combinations of materials. But the scale at which they have differed is hefty.

When considering the overall score of each combination, the results are obvious about how each combination have performed given that in all other parameters except embodied energy, all the combinations have performed at the same level with minor variations. Therefore, it can be determined that results of the embodied energy have twisted the results to a certain extent. But it has required embodied energy to deviate by a large amount in order to diverge the overall results by a reasonable amount. The low importance weighting received for embodied energy parameter can be identified as the effect for this phenomenon.

Table 7 shows the rankings of each combination on overall performance and individual parameters parameter performance.

Table 7 - Ranking of Material Combinations Based on Performance

	Price	Durability	Maintainability	Embodied Energy	Total
Type 1	2	2	4	1	**1**
Type 2	3	3	1	4	**4**
Type 3	1	1	3	2	**2**
Type 4	4	4	2	3	**3**

Rankings in parameters of price, durability and maintainability are different from the overall ranking of material combinations while embodied energy ranking is the same. Therefore it can be identified that even though embodied energy score in importance weightings is low, it still has the some momentum to change the overall rankings of the framework.

It should be predicted at the beginning that Type 1 material combination will supersede all other combinations while Type 2 will become last in the ranking. All other possible combinations of material will eventually have their overall score value between the values derived by Type 1 and Type 2. This is due to the selection of all highest overall scoring materials for Type 1 combination and lowest scoring materials for Type 2 combination.

Above mentioned incident can also be observed by referring to Figure 11. The radar diagram shows how each selected materials configuration has performed in terms of selected parameters. Therefore, all possible combination of materials for the elements will eventually be place between the Type 1 and Type 2 values.

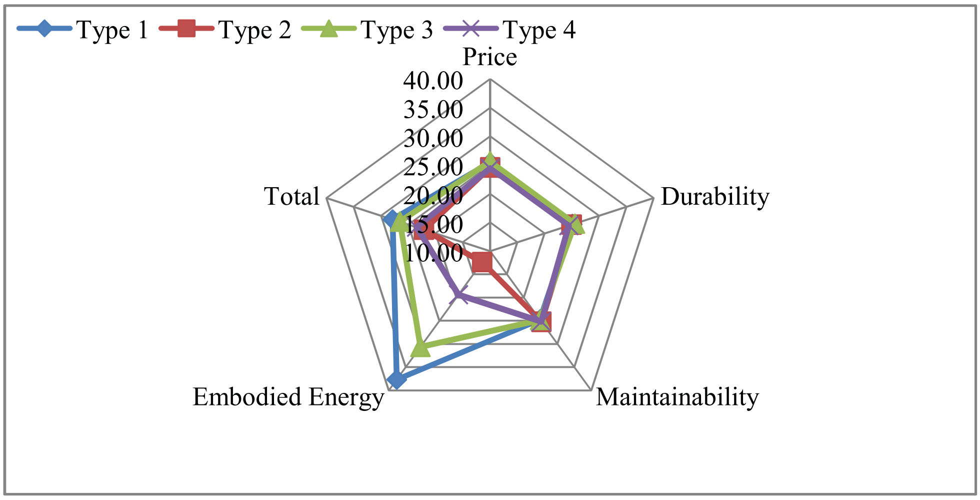

Figure 11: Radar Diagram for Performance of Material Combinations

5. SUMMARY

Many developed countries have made substantial progress in the green building movement establishing standards and benchmarking green building practices. All green rating systems evaluate a wide range of factors to ensure that a selected construction can be accredited as environmentally sustainable. Out of the several factors considered, materials selection can be considered as a high priority aspect as construction materials uses resources of the country. Almost all resources available to mankind are scarce by default and needs to conserve for future generations. Therefore assessment of environmental burdens associated with different construction materials used for buildings is necessary in order for decision-makers to select environmentally benign materials. Hence, this research focused on identifying the cost significant and mostly used building materials for construction in Sri Lanka and to develop a framework for selection of materials based on embodied energy and other identified main parameters.

The study was carried out based on figures retrieved from literature survey as well as on the perceptions of professionals involved in construction through questionnaire survey. The study categorized the identified significant materials based on five major elements with two materials per each and evaluated their performance based on the parameters of embodied energy, price, durability and maintainability. During the questionnaire survey it was identified that most of the professionals were not aware of the concept of embodied energy. But when clued-up, they have considered it to be a relatively important factor for materials selection.

According to the view of professionals, most of the selected materials of the same element have performed in similar manner on the selected parameter. But in the case of vinyl tile for floors and aluminium for doors and windows the results for embodied energy has a significant difference with their counterparts. This has lead to the reduction in the overall score of these materials. Materials were also evaluated based on their performance in multiple parameters where price, durability and maintainability were compared with the main parameter of embodied energy. In all these evaluations, Aluminium doors and windows along with vinyl floor tiles have performed weak compared to their counterparts. Ceramic tiles and timber doors and windows have outperformed all other materials in every multiple comparisons of parameters.

Based on those findings, the development of framework was done by identifying four combinations of the selected materials for analysis. One of these combinations consisted of materials with the highest overall score for each element while another with the lowest. The analysis showed that even though the performance of each combination varied according to the parameters, the overall score of each combination varied in between the scores of highest scored material combination (Type 1) and lowest scored material combination (Type 2).

During this development process, it was also identified that, even though embodied energy parameter ranked last in the importance weightings, the parameter is of acceptable significance. This is clearly depicted when analysing the scores derived for each material configuration (Table 4.6) in framework development process. In Table 4.7, Embodied energy is the only parameter which has ranked the combinations similar to that of the overall rankings. All other parameters, including the top ranked price parameter also had ranked materials differently to that of the overall ranking. Thus, it can be concluded that embodied energy has a very high implication to the overall material selection process and should be given serious consideration.

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