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Selection of Sustainable Building Material Using Multicriteria Decision-Making Model: A Case Study

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Abstract

In today's world, where the need for construction projects is increasing from time to time, especially in developing countries such as Ethiopia, sustainability issues and principles were not exercised by construction professionals during the material selection process. At the initial stage, the designer considers materials he/she is familiar with. However, their assumption may not work because the structure that is going to be developed may be diferent from the previous one. Thus, the designer shall consider sustainability issues during the design period. This article will guide construction stakeholders in the selection of sustainable building materials, specifically masonry materials in the Ethiopian construction industry. The research was carried out in the Addis Ababa Lideta subcity, to identify sustainable building materials for masonry work. The selection process is not depending on a single factor rather it depends on multifactors. The identification was carried out through exploring factors afecting the selection of sustainable building materials for masonry work. The weights of identified factors were determined by pairwise comparison among the factors under consideration. The research is of the empirical type which uses mathematical formula, matrix concept, and analytical hierarchy process (AHP) as a model. In this method, pairwise comparisons were made among the criteria and subcriteria so that the weights of the criteria or subcriteria/or alternative on the bases of the indicated criteria were computed. Then, prioritization was made on the bases of the weight of the criteria. Finally, an alternative with a high score shall be selected. The article identifies the major factor afecting the selection of sustainable building materials for masonry work as social benefit, performance capability, sustainability of the material to reduce environmental impact, waste minimization, resource efficiency, and life cycle cost of the material. Under each criterion, there are number of subcriteria contributed to them. On the basis of the above criteria, 4 alternatives (stone, brick, CEB, and cement block) were proposed from which compressed Earth block (CEB) was selected.

1. Introduction

Infrastructure development and housing projects generously cover the landscape of modern Ethiopia. Even though there are developments, the awareness of the stakeholders towards the selection of sustainable construction materials is not promoted and more of the consumed material is not environmentally friendly. According to Lomite and Kare, the consumption of unsustainable raw materials by the construction industry is accumulating day by day, resulting in a depletion of natural resources and increasing environmental impacts and CO_2 emissions all over the surroundings [1, 2].

Construction professionals rely on some factors without consideration for other factors during material selection. They focus on only the profit they get without consideration for performance, capability, and the environmental impacts of the constructed facilities. Some of them rely on the cost-minimization approach without considering the project requirements. This mechanism is not a good approach because it

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excludes other criteria to be considered. When a new part is to be developed, the designer more or less consciously considers one material he is familiar with. This approach is based on the assumption that a material which works satisfactorily in one application will do in a similar one. Unfortunately, this is not the case in many situations. The requirements may be diferent and all requirements may not be fully taken into account, frequently giving rise to failures in service. Some requirements may also be over-emphasized; i.e., unnecessarily expensive materials are chosen to satisfy them. Thus, the designer shall consider all factors afecting the selection of environmentally friendly construction materials [3].

Material selection is one mechanism for improving the environmental sustainability and enhancing the quality of life. But, for a long time, the material selection mechanisms were not exercised in the Ethiopian construction industry. The designers recommended the material they were familiar with for new parts going to be constructed. In addition to this, those recommended materials were not tested for sustainability based on multicriteria approaches. These may cause the consumption of materials that are not sustainable [1, 4]. The consumption of unsustainable building materials may cause diferent impacts on the environment and human health. According to the UK Green Building Council, the construction sector uses more than 400 million tons of material a year, and many of these materials have an adverse impact on the environment [5].

To reduce the impacts on the environment and human health due to construction materials, the stakeholders should focus on sustainable construction materials. Understanding the sustainability issues in the selection of construction materials is very crucial. Wikipedia, a free encyclopedia, defines sustainability as the process of change, in which the exploitation of resources, the direction of investments, the orientation of technological development, and institutional change are all in harmony and enhance both current and future potential to meet human needs and aspirations [6]. Therefore, the consumed building materials shall meet sustainability issues and principles and their selection mechanism shall be carried out on the bases of multidimensions by taking into account environmental, economic, and social aspects [6].

The construction of environmentally friendly building materials starts with the selection of the right framework for the selection of materials because every project is unique in its nature and consumes diferent material resources. The modern age of construction focuses on environment's impact on building and building's impact on environment, and so the sustainable building projects have dominant capabilities in framing a valuable and noteworthy role in sustainable development [7]. Other authors proposed that green material selection has a vital role in the construction industry in improving the properties of the materials and promoting sustainable development [8]. The authors further stated that sustainable material selection seeks to guarantee product performance and reduce the entire life cycle impacts to the environment and human health. The selection of sustainable construction materials depends on many factors. The consideration of the life cycle cost of the materials, the performance capability of the materials, the impacts of the materials on the environment, etc., are some of the factors that need to be considered in the selection process [9].

In this paper, research motivation and objectives are addressed. Related literature studies were also searched. Finally, the results of the investigation were written.

Statement of the Problem. In developing countries like Ethiopia, where the need for infrastructure is high, most of the consumed construction materials were not environ- mentally friendly.

The consumption of unsustainable raw materials by the construction industries is accumulating day by day, resulting in a depletion of natural resources, increasing the environmental impacts and CO_2 emissions all over the sur-

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roundings [1]. The use of environmentally friendly construction materials shall cut of the mechanisms. Thus, the designer shall consider multifactors while selecting environmentally friendly construction materials [3].

On the other hand, in Ethiopia, construction professionals do not consider all factors afecting the selection mechanisms. Most of them focus on only the profit they get without consideration for the performance capability and environmental impacts of the constructed facilities. Some of them rely on the cost minimization approach without considering the project requirements. This mechanism is not a good approach because it excludes other criteria to be considered. When a new part is to be developed, the designer more or less consciously considers one material he is familiar with. This approach is based on the assumption that a ma- terial which works satisfactorily in one application will do in a similar one. Unfortunately, this is not the case in many situations. The requirements may be diferent and all re- quirements may not be fully taken into account frequently giving rise to failures in service. Some requirements may also be over-emphasized i.e., unnecessarily expensive materials are chosen to satisfy them.

Research Objectives

General Objectives. The general objective of this research is to select sustainable building materials for masonry work based on the multicriteria decision making model(MCDM).

Specific Objectives. The specific objectives of this research are as follows:

(i) To investigate factors afecting the selection of sustainable materials for masonry work.

(ii) To determine the weights of criteria or factors affecting the selection of sustainable material for masonry work based on experts' opinion.

(iii) To adopt a multicriteria assessment model for aggregating sustainability criteria into a composite index for building material selection.

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2. Literature Review

With rapid development and modernization, cities are growing at a very fast pace and the building is the main components of the city. Hussein and Arif Kamal identified that building construction in the world annually consumes around 25% of the global wood harvest, 40% of stone, sand, and gravel, and 16% of water. It generates 50% of the global output of GHG and agents of acid rains. The manufacturing process of building materials contributes to green house gases such as CO_2 to the atmosphere to a great extent [2]. Ding explained that the construction industry is one of the largest exploiters of both renewable and nonrenewable natural resources. The process and operation of building construction consume a great deal of materials throughout its service life cycle. The author further added the selection and use of sustainable building materials play an important role in the design and construction of green buildings [10].

Construction operations consume both renewable and nonrenewable resources in an unsustainable way during the project life cycle. These cause impacts on natural and built environments in many ways. Govindan et al., suggested that because of depleting resources and environmental concerns, researchers and practitioners have begun to explore sustainable construction strategies. One of the strategies is the selection of sustainable materials. They proposed a model to evaluate the best sustainable construction materials based on sustainable indicators through a hybrid multicriteria decision making (MCDM) methodology with a specific examination of UAE [11]. Other researchers, Hussain et al., examined that rapid urbanization has driven the prosperity of the building industry, which led to the consumption of enormous amounts of energy and resources and the continued deterioration of the environment owing to its unsustainable development. These outcomes impact seriously the ecosystem and the environment [2, 12]. Hussein and Arif Kamal said that due to the continuous exploitation of natural resources, there is an urge to produce environmentally responsive building materials for the construction of new buildings to meet the rapid urban growth. Sustainable buildings are designed, constructed, maintained, rehabilitated, and demolished with an emphasis throughout their life cycle on using natural resources efficiently while also protecting global ecosystems [2].

Kibert suggested that environmental consideration should be an important concern for project stakeholders. This can be carried out by incorporating sustainability issues and principles during the design phases, operations, and demolition of the projects. The author further investigated that depending on owners' interests, the engineers shall undergo preliminary investigation on the project constraints like project cost, time, and quality. These three pillars of the construction project shall be inspected by the assigned supervisor to improve the constraints (especially quality and cost) by a selection of appropriate construction materials during the design phases of the projects [13]. According to Akadiri selection of sustainable building materials has been identified as an important strategy in the design of a building. The author further explained the major barriers

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encountered in the selection of sustainable building materials among building construction professionals in Nigeria [14]. According to Aghazadeh et al., the choice of construction materials for engineering purposes in the construction industry is a time-consuming and costly process [15]. Chen et al. suggested that to alleviate the adverse impacts of the construction on the environment, natural resources, health, and comfort of inhabitants, sustainable principles have been incorporated into the design, construction, decoration, operation, and maintenance of the buildings [16]. The authors developed a novel hybrid multicriteria group decision making model for sustainable building material under uncertainty. According to Zhang, poor choice of materials in construction projects have an impact on the project constraints (especially quality and cost) and it may incur additional costs during the project life cycle [17]. The author further stated that before choosing the material, full assessments of the sustainability of materials are important by using diferent green rating systems. The selection of sustainable materials may depend on many factors. Ogunkah et al. elaborated that economic, life cycle cost, performance capability, social benefits, etc., are some of the factors to be considered. The authors also suggested that multiple factors shall be considered by a designer when evaluating various categories of building materials during the design decision-making process [18]. According to Aghazadeh et al., the selection of sustainable construction materials depends on multifactors like life cycle cost of the material and sustainability. The authors further elaborated that sustainability could be divided into 5 as technical, economic, social, managerial, and environmental categories [15]. Takano et al., demonstrated the influence of building material selection on the environmental and economic parameters of the building in a finish context. They observed the efects of the choice for three building component categories (structural frame, inner components (i.e., insu- lation and sheathing), and surface components (exterior cladding and flooring) in a comparative manner. Their aim was to illustrate the features of the building materials in a relative manner from several aspects in order to use multicriteria decision making for professionals associated with the construction industry [19]. Reddy et al. said that selecting the best material among a pool of alternatives to achieve sustainability is a crucial exercise involving sub- jectivity. The authors further elaborated that choosing an alternative considering multiple conflicting criteria involved with multiple decision makers is a multicriteria decision making (MCDM) problem. Their aim was to integrate the objective and subjective weights of the criteria in choosing the best material alternative and to prioritize using Fuzzy TOPSIS [20].

Uğur et al. declared that material selection is important in many organizations. For the successfulness of an organization, appropriate materials shall be considered in the design and product development for the competitiveness of the manufacturing organization [21]. The selection of sustainable material has many advantages. Damdoo et al., suggested that the selection of environmentally friendly materials has not only an economic benefit but also an

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environmental benefit too, because, the selected materials shall fulfil sustainability issues and principles [7].

Sustainability can be viewed in multi directions; economic, social, and environmental aspects. Sustainability is the process of change, in which the exploitation of resources, the direction of investments, the orientation of technological development, and institutional change are all in harmony and enhance both current and future potential to meet human needs and aspirations [22].

Multicriteria Decision-Making (MCDM). Multicriteria decision-making method is a branch of a general class of operations research models that is suitable for addressing complex problems featuring high uncertainty, conflicting objectives, diferent forms of data and information, multi-interests and perspectives, and the accounting for complex and evolving biophysical and socio-economic sys- tems. This major class of methods is further divided into multiobjective decision-making and multiattribute decision- making. These methodologies share the common character- istics of conflict among criteria, incommensurable units, and difficulties in the design/selection of alternatives [23].

Analytical Hierarchy Process (AHP). The analytic hier- archy process (AHP) is a multicriteria decision-making approach and was introduced by Saaty. The AHP is a de- cision support tool which can be used to solve complex decision problems. It uses a multilevel hierarchical structure of objectives, criteria, subcriteria, and alternatives. The pertinent data are derived by using a set of pairwise com- parisons. These comparisons are used to obtain the weights of importance of the decision criteria, and the relative performance measures of the alternatives in terms of each individual decision criterion [24].

3. Research Methodologies

The research was conducted in Addis Ababa, Lideta subcity, where the rate of construction is high and huge amounts of construction materials were consumed. The research is a questionnaire based where questionnaires were prepared based on factors afecting the selection of sustainable construction materials by considering experts' ideas found in Addis Ababa, Lideta subcity.

In this paper, the respondents were selected purposively on the bases of the following criteria or requirements:

(i) The respondent should have at least a BSc. in construction engineering and related fields from a known institution

(ii) The respondent should have knowledge of construction materials and their properties

(iii) The respondent shall have an experience in con-

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Table 1: The identified respondents.

No.	Respondents	Numbers of respondents
1.	Contractor	23
2.	Consultant	20
3.	Other experts	17
Total number of respondents		60

Questionnaires' Design. Once the criteria were identified from diferent literature studies and experts' views, the questionnaires were prepared by pairwise comparison among the criteria. The comparison was made on the fol- lowing rating scale:

9 � Extreme importance

7 � Very strong or demonstrated importance5 � Strong importance

3 � Moderate importance1 � Equal Importance

In the same way, a comparison was made among the identified alternatives on the bases of indicated criteria.

AHP Model. The collected questionnaires were ana- lyzed using an analytical hierarchy process (AHP) which was developed by Saaty [24]. Analytical hierarchy process (AHP) is selected as a model other struction projects

Accordingly, 60 respondents were identified.

The following Table 1 shows the selected respondents along with their numbers.

than other tools and techniques. Because AHP enables somebody to drive cer- tain figures on the bases of expert judgements. In this research, construction material is going to be selected on the bases of multifactors. The nature of the problem is of hierarchical, and AHP model is the best method in such situations.

Validity Check. The weights of the criteria and sub- criteria were determined by using the matrix concept and certain mathematical computations on the bases of experts' ideas. The criteria and subcriteria were prioritized on the bases of their weights and the consistency ratio were computed.

$$CR = \frac{CI}{RCI}. \quad (1)$$

And, CI is computed as

$$CI = \frac{\lambda \max - n}{n-1}. \quad (2)$$

And, RCI (random consistency index) is the consistency index of a randomly generated pairwise comparison matrix. RCI depends on the number of elements being compared (i.e., size of pairwise comparison matrix) and takes on the following values in Table 2.

Here, CR � consistency ratio, CI � consistency index, λ max � average eigenvalue of the consolidated matrix, n � number of criteria or subcriteria in a consolidated matrix, and RCI �Random consistency index.

The results are consistent if the consistency ratio (CR) is greater than 0.10 [24].

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Table 2: RCI values for diferent values of n [24].

n	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Table 3: Response rate of respondents.

No.	Respondents	Questionnaires		Response rate (%)
		Distributed	Returned	
1	Contractor	23	16	69.57
2	Consultant	20	15	75.00
3	Other experts	17	15	88.24
Total		60	46	76.67

Table 4: The six most important criteria and subcriteria for the selection of sustainable masonry materials.

Criteria	No.	Subcriteria
Life cycle cost (C1)	1	Initial cost (SC1)
	2	Maintenance cost (SC2)
	3	Disposal cost (SC3)
Waste minimization (C2)	4	Environmental sound disposal option (SC4)
	5	Recycling and reuse (SC5)
Performance capability (C3)	6	Fire resistance (SC6)
	7	Resistance to decay (SC7)
	8	Energy saving and thermal insulation (SC8)
	9	Life expectancy (durability) (SC9)
	10	Maintainability (SC10)
Resource efficiency (C4)	11	Method of raw material extraction (SC11)
	12	Amount of wastage in use (SC12)
	13	Embodied energies (SC13)
	14	Environmental impact during harvest (SC14)
Environmental impact (C5)	15	Zero/low toxicity (SC15)
	16	Ozone depletion (SC16)
	17	Minimize pollution (SC17)
	18	Impact on air quality (SC18)
Social benefit (C6)	19	Use of local material (SC19)
	20	Aesthetics (SC20)
	21	Health and safety (SC21)

Finally, the proposed alternative construction materials for masonry work (stone, brick, compressed Earth block, and cement block) were evaluated on the bases of the main criteria. Lastly, the final priority of the proposed alternatives were computed by combining the weights of the criteria and that of alternatives on the bases of indicated criteria. Accordingly, the alternatives with higher final priority were the most sustainable construction material for masonry work it is.

Table 2 shows values of RCI for diferent values of n.

4. Results and Discussion

In this research, 60 questionnaires were distributed to contracting parties(contractors, consultants, and other experts) in the Lideta area from which 46 valid responses were collected from them which comprises a total response rate of 76.67%. Table 3 shows that the response rate of the respondents for distributed questionnaires.

The research identifies 21 subcriteria which were categorized under 6 main criteria [7].

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The criteria were selected after conducting interviews with experts in the construction industry and reading previous related literature studies. The following Table 4 shows the six most important criteria and subcriteria for the selection of sustainablematerial for masonry work.

After a series of mathematical computations, the followingtable shows the weights of the criteria and subcriteria (on bothlocal and global scales). Table 5 shows that the summary of themain and subcriteria on the bases of local and global priority.From Table 5, someone can observe that while selecting sustainable construction material for masonry work, priorityshould be given to the health and safety (13.11%) of thematerials. Recycling and reuse (10.18%), use of local ma-terials (6.67%), fire resistance capability (5.86%), and lowtoxicity (5.12%) of the material are the top 5 prioritizedcriteria for the selection of sustainable material for masonry work.

In the same way to that of criteria and subcriteria, the proposed alternatives were evaluated on the base of the indicated criteria (main criteria). Table 6 illustrates the

Table 5: Summary of main criteria along with their subcriteria (local and global priority).

No.	Main criteria	Weight of main criteria (%)		Subcriteria	Local priority (%)	Global priority (%)	Rank based on GP
			1	Initial cost	62.89	4.71	8
1	Life cycle cost	7.49	2	Maintenance cost	23.09	1.73	20
			3	Disposal cost	14.02	1.05	21
2	Waste minimization	15.06	4	Environmental sound disposal option	32.42	4.88	7
			5	Recycling and reuse	67.58	10.18	2
			6	Fire resistance	28.62	5.86	4
3	Performance capability	20.47	7	Resistance to decay	19.28	3.95	15
			8	Energy saving and thermal insulation	21.93	4.49	10
			9	Life expectancy (durability)	17.71	3.62	16
			10	Maintainability	12.47	2.55	18
4	Resource efficiency	13.71	11	Method of raw material extraction	25.45	3.49	17
			12	Amount of wastage in use	15.25	2.09	19
			13	Embodied energies	30.18	4.14	13
			14	Environmental impact during harvest	29.12	3.99	14
5	Environmental impact	19.11	15	Low toxicity	26.79	5.12	5
			16	Ozone depletion	26.56	5.08	6
			17	Minimize pollution	24.18	4.62	9
			18	Impact on air quality	22.46	4.29	12
6	Social benefit	24.16	19	Use of local material	27.61	6.67	3
			20	Aesthetics	18.12	4.38	11
			21	Health and safety	54.27	13.11	1
Total		100.00				100.00	

Table 6: Comparison of alternatives on the bases of life cycle cost.

	A1	A2	A3	A4				
A1	1	1/2	1/3	3/4				
A2	2	1	3/8	1 1/5				
A3	3 1/4	2 3/4	1	4 1/4				
A4	1 1/3	5/6	1/4	1				
Sum	7 3/5	5	2	7 1/5				
	A1	A2	A3	A4	W	Ws	Eigen value (λ) = Ws.1/{W}	Rank
A1	0.131	0.099	0.161	0.102	12.33 (%)	0.497	4.029	4
A2	0.262	0.197	0.192	0.166	20.44 (%)	0.822	4.023	2
A3	0.428	0.539	0.524	0.592	52.09 (%)	2.126	4.082	1
A4	0.179	0.165	0.123	0.139	15.14 (%)	0.612	4.044	3
Sum	1.000	1.000	1.000	1.000	1.000			
λmax = Average λ value	4.045							
N	4.000							
CI	0.015							
RCI	0.900							
CR	0.017							

Table 7: Proposed alternatives along with criteria, final priority, and their ranks.

Criteria Cr. weights		C1 7.49%	C2 15.06%	C3 20.47%	C4 13.71%	C5 19.11%	C6 24.16%	Final priority (Wfi)	Rank
Alternatives	A1	12.33%	28.14%	53.57%	29.18%	18.09%	25.96%	29.86%	2
	A2	20.44%	37.86%	24.62%	21.25%	12.49%	20.99%	22.64%	3
	A3	52.09%	19.50%	7.26%	33.82%	57.05%	38.48%	33.16%	1
	A4	15.14%	14.50%	14.55%	15.75%	12.38%	14.57%	14.34%	4

comparison of alternative construction material for masonry work on the bases of the life cycle cost of the material.

Here, the evaluation is consistent because the consistency ratio (CR) < 0.10.

Table 6 shows that the 3rd alternative (compressed Earth block) is selected on the bases of the life cycle cost of the material.

The final priority of the proposed alternatives is determined by aggregating the weights of the main criteria and the weights of the proposed alternatives on the basis of the selected criteria. In determining the final priority (A^{i}_{AHP}) of the proposed alternatives, the following equation is used. Table 7 shows the proposed alternative material for masonry work along with criteria, final priority, and their final ranks.

$$A^{i}_{AHP} = \sum_{j=1}^{N} aij * wj(\text{for } i = 1, 2, 3, \ldots, m), \qquad (3)$$

where a_{ij}-weight of the alternative i with respect to criterium j, w_j-weight of criterium j.

From Table 7, it is observed that compressed Earth block (CEB) (A3) is the most sustainable construction material for masonry work.

5. Conclusions

The paper identifies some of the factors, afecting the selection of sustainable building materials for masonry work. The life cycle cost of the materials, waste minimization capability of the material, resource efficiency, environmental impacts of the materials, performance capability of the materials, and the social benefit related to the materials are some of the main criteria or/factors afecting the selection of sustainable materials for masonry work. Each criterion has subcriteria attributed to it.

Pairwise comparison was taking place between each pair of main criteria/subcriteria (within the same group) to derive the weights of the criteria or/subcriteria using the AHP model and diferent mathematical computations. Criteria or/subcriteria were prioritized based on their weights. The evaluation result shows that upon selection of sustainable material for masonry work, priority shall be given, respectively, for the social benefit of the material (24.16%) performance capability of the material (20.47%), sustainability of the material to reduce environmental impact (19.11%), waste minimization capability during construction (15.06%), resource efficiency (13.71%), and life cycle cost of the material (7.49%).

The final priority of the alternatives was computed by combining all criteria and subcriteria into a single composite index using multicriteria decision-making model, MCDM. The alternative with higher priority is the most sustainable masonry material it is. From the proposed alternative building materials, the compressed Earth block (CEB) (33.16%) is a highly prioritized material for the construction of masonry work followed by, respectively, stone (29.86%), brick (22.64%), and cement block (14.34%), and the consistency ratio in all calculations was less than 0.10 and thus the judgement of the respondents was consistent.

Data Availability

The data supporting the results of the study are found from diferent sources: published journals, books, ande websites such as Google scholars are some of the sources for the study. While taking the data, credit is given for the author of the data and the source is cited in the manuscript.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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