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Strategies to Minimize the Embodied Carbon Emissions in Building Construction Project

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Abstract

It is imperative that sustainability in construction be addressed immediately because the building industry contributes significantly to global energy consumption and carbon emissions. In 2019, the Construction sector accounted for 36% of total energy consumption and 38% of total carbon emissions, making it one of the three major sectors in terms of energy consumption and a significant area of responsibility for direct and indirect carbon emissions. To address this issue, this paper proposes an embodied carbon emission reduction methodology for construction projects. The methodology involves identifying and implementing effective strategies to reduce embodied carbon emissions using sustainable building materials and a multi-criteria decision-making (MCDM) tool. The necessary information was gathered, examined, and verified using a real-world building case using the MCDM tool. The findings suggest that the structured and objective approach of MCDM can be highly effective in identifying the most sustainable building material. The results demonstrate that the use of sustainable building materials can significantly reduce embodied carbon emissions and achieve cost savings compared to conventional R.C.C buildings. The proposed methodology can provide decision-makers with valuable insights into reducing embodied carbon emissions and improving sustainability in construction projects.

Keywords- Carbon Emissions, Carbon neutrality, Low carbon construction, Embodied emissions, multi-criteria decision making, MCDM, ELECTRE, Sustainable materials

INTRODUCTION

The global population is increasing at an alarming rate, necessitating an alarming amount of new construction worldwide. India is one of the top three emitters in the world, and its energy demand is increasing with the country's rapid economic and population growth. Over the next 20 years, buildings are anticipated to contribute half of India's CO2 emissions. In 2019, the building sector in India accounted for 24% of total CO2 emissions, with indirect emissions nearly tripling between 2000 and 2017. India's urbanization goal is to reach 40% in the next decade, which will significantly boost ECCE in the building sector. (Sun et al., 2022). [1]

The carbon footprint of buildings refers to the total amount of greenhouse gases (GHGs) emitted directly and indirectly as a result of the construction, operation, and decommissioning of a building. These emissions can come from a variety of sources, including energy consumption, building materials, and waste. (Sun et al., 2022). [1]

Developed countries and major economies have set their own goals for reducing greenhouse gas emissions and are doing their part. For example, China, a major greenhouse gas emitter, has

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pledged to peak its carbon emissions by 2030 and achieve carbon neutrality by 2060. In comparison to 2005 levels, the United States aims to reduce carbon dioxide emissions by 17% by 2020 and 83% by 2050. The United Kingdom has set a goal of reducing greenhouse gas emissions by at least 20% by 2050 compared to 1990 levels(Sun et al., 2022). [1] [48] At the CoP26 meeting, India, a signatory to the Paris Agreement, which aims to limit global warming to 1.5 degrees Celsius above pre-industrial levels, made an ambitious pledge to achieve net-zero carbon emissions by 2070. Getting to net zero will necessitate massive efforts across multiple sectors and levels.

Construction activity returned to pre-pandemic levels in 2021, accompanied by more energy-intensive building use. As a result, the energy demand for buildings increased by around 4% beginning in 2020, the largest increase in the last ten years. CO2 emissions from buildings have reached an all-time high of around 10 GtCO2, representing a 5% increase from 2020. The Global Buildings Climate Tracker 2022 update confirms this observation, revealing a growing gap between the sector's actual climate performance and the necessary decarbonization pathway.

By 2060, there will be 2.5 trillion square feet more buildings worldwide, which is equivalent to the current building stock. This is the same as adding a new "New York" City to the earth every 34 days for the next 40 years. While increasing the capacity to generate renewable energy and improving building energy efficiency have both been beneficial, they have not been nearly enough to offset the rise in emissions from new construction.

The Intergovernmental Panel on Climate Change states that in order to maintain 1.5 degrees Celsius, building carbon emissions must be lowered by 80% to 90% by the middle of the century, and all new construction must use nearly zero energy and no fossil fuels.(Voss & Musall, 2011). [2] Because the building industry uses a lot of energy and produces a lot of carbon emissions, there is a lot of room for improvement.

Low-carbon building promotion can not only reduce carbon emissions continuously but also lower the concentration of air pollutants, improving air quality. In general, reducing carbon emissions does not rely solely on one path, rather it necessitates the synergistic effect of multiple carbon-reduction strategies(Wu et al., 2022a).[3] In fields like construction, more quantitative research should be conducted on the capability and potential for low-carbon construction, to enhance reference significance for future research.(Wu et al., 2022a). [3]

To highlight the need of study. A significant portion of carbon emissions are generated during the construction stage. At the moment, most studies on building emissions focus solely on CO2 emissions during building operation, with few focusing on the construction stage due to a lack of actual engineering cases of carbon emission management during the construction stage. (Xu et al., 2021). [4]

With the increased demand for low-carbon buildings, decision-makers must now identify specific actions to take that will have a high positive impact on sustainability. This is because designing these buildings is a complex task that necessitates continuous decision-making on technical, energy, exergy, economic, and environmental trade-offs(New Building Institute, 2021). [5]

While research into low carbon and carbon neutrality in building projects is gaining traction, the literature lacks objective decision support tools and frameworks for continuously identifying decarbonization opportunities through different stages of project. There exist disparities amongst definitions concerning the range of emissions sources covered, the goals for reducing emissions, and the caliber of offsets employed.

Although there are approaches like Green Building rating systems like- LEED, GRIHA, IGBC, etc. that talks about sustainable initiatives in a building and claim to reduce energy and carbon emissions, but various types of research show these claims are conflicting and are not much promising.

Since the UNDP report, predicted that the global raw material consumption will nearly double by 2060. The International Resource Panel has emphasized the massive potential reduction in greenhouse gas emissions from material efficiency strategies implemented across the building stock.

Despite its significant contribution to global greenhouse gas emissions, embodied carbon has previously been overlooked in building emission reduction strategies. Industry leaders are increasingly using a whole life cycle analysis approach to guide strategies that address both embodied and operational carbon.

There is rising interest in lowering the carbon footprint of building materials as sustainability gains importance in the construction sector. The following research questions were formulated: What are the primary sources of embodied carbon emissions in building materials, and how significant are they? How can alternative building materials be proposed and evaluated for their potential to reduce embodied carbon emissions? What process can be developed to select building materials that reflect a reduction in embodied carbon, and how can it be validated? How effective are the proposed alternative building materials in reducing embodied carbon emissions, and how do they compare to conventional building materials? Finally, what are the economic and environmental implications of using alternative building materials to reduce embodied carbon emissions, and how can they be evaluated? This study intends to lessen the construction industry's carbon footprint and advance sustainable building practices by providing answers to these research questions.

RESEARCH METHODOLOGY

The research followed a four-step approach. Firstly, the study conducted an extensive literature review to gain a deeper understanding of carbon emissions and identify their sources. Various resources such as research papers, guidelines, handbooks, textbooks, national and international codes were consulted. Secondly, the research explored different methods of reducing carbon emissions in buildings. A mixed approach involving literature reviews, primary and secondary case studies, and expert opinions was used to identify the effective ways of achieving this. The third step of the research involved creating various scenarios through expert opinions and a multi-criteria decision-making approach using ELCTRE analysis. Finally, the research demonstrated the potential impact of different scenarios by implementing them in case studies and performing calculations. The different scenarios were also compared to determine the amount of savings in carbon emissions as well as the costs associated with each.

CARBON EMISSIONS AND RELATED CONCEPTS

Carbon Footprint or Carbon Emissions**:** The total quantity of greenhouse gases (GHGs) released during a building's construction, use, and eventual decommissioning is referred to as its "carbon footprint." These emissions can originate from waste, building materials, and energy use, among other things (Figure 1).

Carbon Neutrality: Carbon neutrality refers to offsetting the production of carbon dioxide (CO2) over a specific period through carbon capture, storage, and conversion to achieve "zero emission" of greenhouse gases. This concept originated in 1997 on Samsoe Island, Denmark, and has since been adopted by people all over the world and implemented in a variety of industries (Wu et al., 2022b). [6] Projects should always seek to reduce emissions first, thereby minimizing the emissions that need to be offset.

The total amount of CO2 released during the building process is known as embodied carbon. This covers the production and extraction of materials needed for building as well as their transportation from production facilities to the construction site. Additionally, the carbon emitted by equipment and plants during construction as well as during renovations, demolition, and retrofitting.

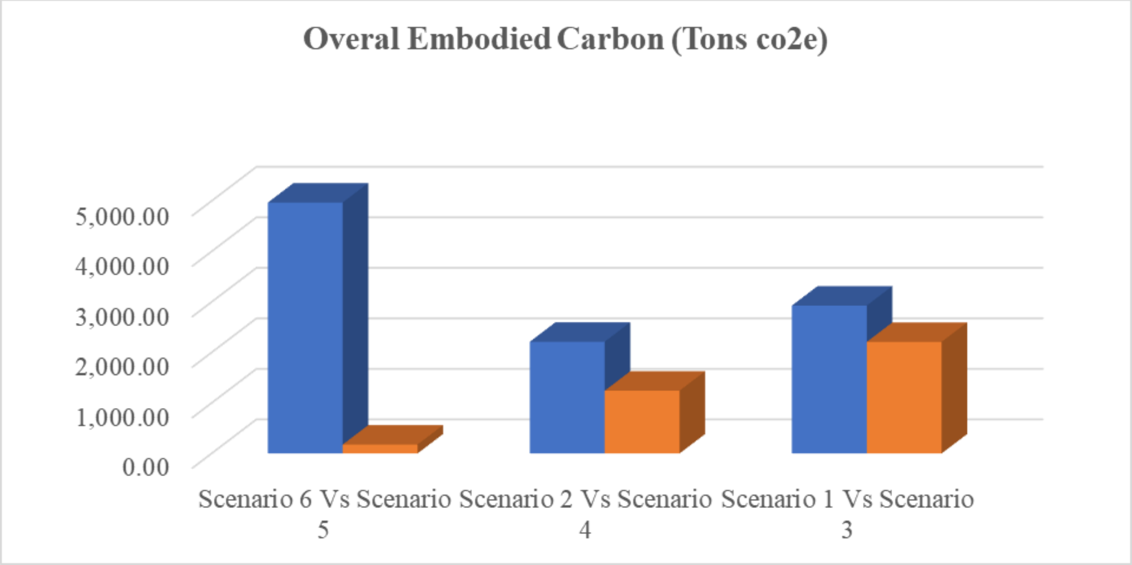

Figure 1. Embodied carbon emissions comparison between scenarios.

Although the emissions produced prior to the building's use are sometimes referred to as "upfront carbon," we will stick with the majority and call it embodied carbon for simplicity's sake.

The potential cost of embodied carbon in the construction sector is enormous, and it is only expected to rise. Although it currently contributes 11% of greenhouse gas emissions, it is anticipated that by 2050, operational and embodied carbon emissions will be equal due to the anticipated growth in construction projects over the next several decades. (Figure 2)

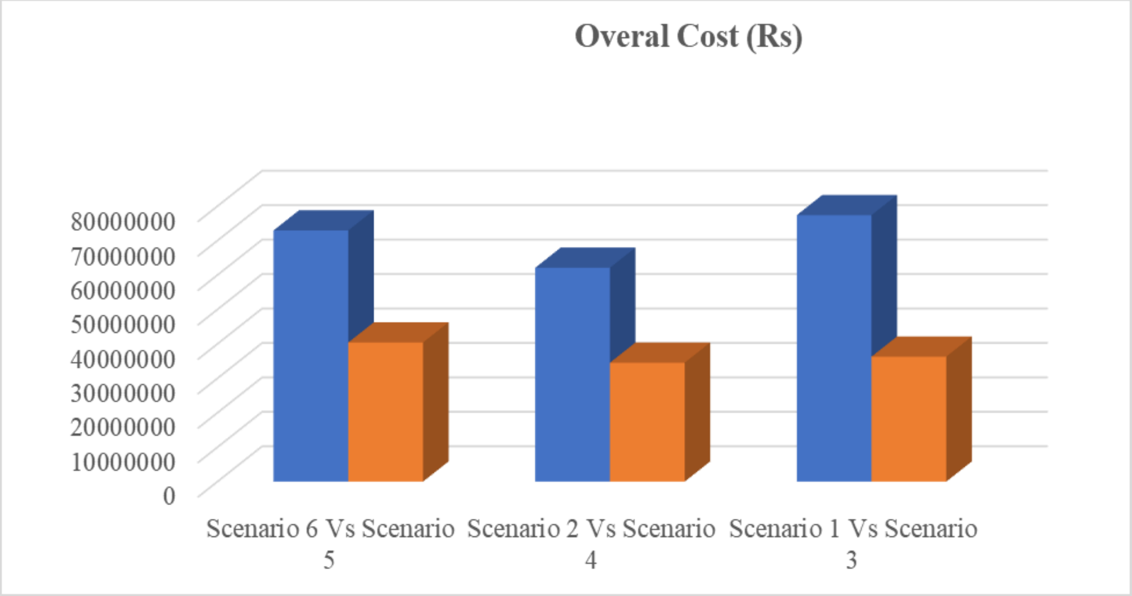

Figure 2. Cost comparison between scenarios.

Planning and creating more environmentally friendly building alternatives require an understanding of the distinction between embodied and operational carbon. The two can be considered in much the same way as capital expenditure and operational expenditure in finance.

The total amount of CO2 released during the building process is known as embodied carbon. Similar to CAPEX, embodied carbon comes from discrete carbon-producing processes as opposed to continuous ones. This covers the carbon emitted by plants and machinery during the building process as well as the extraction, production, and transportation of the materials used in construction. Demolition raises a site's embodied carbon in rebuild situations.

Similar to OPEX, operational carbon is the carbon emitted during continuous building operations. Energy sources will include air conditioning, heating, ventilation, lighting, power, and other infrastructure like automatic doors and lifts.

Embodied carbon can be reduced during the initial design and planning stages but cannot be removed from an existing building. Reducing embodied carbon is only achieved by thoughtful initial design and specifying construction products and materials that are more locally available, extracted, manufactured, and delivered via low-carbon means. This should include minimizing energy use and reducing waste through recycling wherever possible. Using materials and products with longer lifespans and more resilience to change will reduce future carbon impact.

Carbon Emissions from a Buildings

To determine the difference between net-zero energy and net-zero carbon, a life cycle assessment (LCA) of a net-zero energy building (NZEB) in Ahmedabad, Gujarat, India, was carried out. Annual net-zero energy building evaluations do not account for greenhouse gas (GHG) emissions released before the building operation phases. It also does not account for GHG emissions during end-of-life processes. As a result, an NZEB may not be a net-zero emission building throughout its life. (Jain & Rawal, 2022)[7]

The results demonstrate that despite a building's annual net-zero operation status, it has a negative impact of 866 tCO2e during a predicted lifespan of 60 years. To reach net-zero carbon status, the building's emissions must be offset by 866 tCO2e. Emissions from manufacturing, construction, consumption, end-of-life activities, and recycling are all included. The case study illustrates the analysis's sensitivity to the system boundaries, data quality criteria, and acceptable levels of uncertainty. (Jain & Rawal, 2022) [7]

Another study conducted an LCA for a residential building in India, which resulted in carbon emissions of 2.30 tCO2e/m2, and the construction of two four-story blocks of flats emitted 148,180 kg CO2 eq/year and 312,596.55 kg CO2 eq/year, respectively Dabaieh, M., Heinonen, J., El-Mahdy, D., & Hassan, D. M. (2020) [8]

70% to 90% of the carbon emissions from making concrete come from the very carbon-intensive ingredient cement. Different types of cement require diverse production techniques, therefore their impact on the carbon emissions of concrete might vary. OPC uses a lot of energy to calcine limestone and burn cement, which results in a high carbon emission factor (1.005 kg CO2-e/kg). Although structural components account for 48% of emissions during the embodied phase, their contribution declines to 2% during use (B1–B6). HVAC, on the other hand, emits 1% of emissions during the embodied phase but 78% of emissions during the use period. The (Table 1) below show the embodied carbon emissions percentage share form different components of building.

Table 1. Percentage distribution of Embodied carbon emissions in a building.

Building Component	Approximate Embodied Carbon Emissions (kgCO2e/m2)	Percentage Share	Sources
Structural Components (including roof)	300-1200	30-50%	(Zhang & Wang, 2016)
Walls	170-500	18-25%	(Shafiq et al., 2015)
Windows and Doors	20-150	2-5%	(Simonen et al., 2017)

Services (mechanical, electrical, plumbing)	50-200	5-10%	(Pomponi et al., 2018)
Finishes (flooring, ceilings, paint, plaster, etc.)	40-300	5-15%	(Kuittinen & Häkkinen, 2020)
Landscaping	20-100	2-5%	(Akbarnezhad & Xiao, 2017)
Other (e.g., lifts, escalators)	20-100	2-5%	(Akbarnezhad & Xiao, 2017)

Reducing Carbon Emissions

It has been reported that the application of alternative additives/materials or techniques/systems can reduce more than 90% of CO2 emissions at different stages in construction and building operations. (Sizirici et al., 2021). [14] It is safe to replace 30% of the clinker content (by weight of the total binder) without sacrificing strength or performance. Lightweight concretes (LWCs) with high additive volumes, such as fly ash or silica fume, lower overall structural volume to sustain load, reduce CO2 emissions by 30-50% when compared to conventional concrete, and increase the mechanical qualities of LWC (Sizirici et al., 2021).[14]

A fractional substitution of cement in concrete with fly-ash, along with the use of ground granulated blast furnace slag and the replacement of natural aggregates with recycled crushed aggregate, can cut CO2 emissions by up to 3.8% (10.5 kg CO2-e) throughout the life of the structure. Dakwale, V. (2019). [9]

Bulldozers and backhoes have equipment productivity that ranges from 80% to 85%. However, considering that a major portion of their time is spent cycling idling, primarily loading and unloading cargo, off-road trucks have equipment productivity of 41%. Off-road vehicle average operational efficiency may rise from 40% to 50% by cutting idle time by just 6 minutes per hour, which would result in a 10% decrease in fuel consumption and CO2 emissions per hour. (Sizirici et al., 2021) [14]

Reusing water is thought to save roughly 75% of the potable water inside a typical office building. With the use of water efficiency technologies, the average water savings of a green building was predicted to reach 37.6%. Water conservation will increase, which will cut down on energy use and CO2 emissions. When it rains, the passive irrigation system collects water, and when there is a drought, it supplies water. (Sizirici et al., 2021) [14]

Using a rainwater recycling system, a 250-room hotel in Birmingham, United Kingdom, was able to conserve up to 780 m3 of potable water annually. Up to 8.5% of GHG was saved by a high-rise building in Mexico using a gravity-fed rainwater harvesting system. (Sizirici et al., 2021) [14]

For a building located in Vancouver the study suggests the use of wood as much as feasible since it offsets carbon dioxide and replacing the concrete core with an all-steel core that could potentially contain a lower embodied carbon are the two key methods connected to the building structure that was identified to help achieve carbon neutrality. (Sizirici et al., 2021) [14]

As per literature different strategies can be clubbed into basically four components, such as- Low-Carbon Building Materials, Material Reuse and Recycling, (Table 2) Material Minimization, Construction Optimization. Their average potential to reduce down the embodied emissions are also listed below and was validated through an expert survey.

Table 2. Approximate Carbon emissions reduction potential through different strategies

S.N.	**Strategy**	**Average Embodied Carbon Emissions Reduction Potential**

1	Low-Carbon Building Materials	30-97%
2	Material Reuse and Recycling	
3	Material Minimization	15-30%
4	Construction Optimization	10-20%

1. *Low carbon materials:* Low carbon construction materials are those that have a reduced carbon footprint compared to traditional construction materials. These materials are designed to minimize the amount of carbon dioxide emitted during their production, transportation, and use. Because more people understand how crucial it is to cut greenhouse gas emissions in order to combat climate change, low carbon building materials are becoming more and more common.
2. *Material Reuse and Recycling*: Construction material reuse and recycling are two additional strategies for reducing the environmental impact of construction activities. Reusing and recycling materials can help to minimize waste and reduce the need for virgin materials, which often require significant amounts of energy to produce.
3. *Material minimization:* It is the practice of reducing the number of materials used in construction projects while still maintaining their functionality and structural integrity. By minimizing the number of materials used, it is possible to reduce the embodied emissions of buildings.
4. *Construction Optimization*: Optimizing construction equipment, on-site site layout, on-site transportation, and passive plumbing systems can all help to reduce the embodied emissions of buildings. This can be achieved by using fuel-efficient or electrically powered equipment, locating building materials close to the construction site, optimizing delivery routes and using fuel-efficient vehicles, reducing water use through low-flow fixtures and water-efficient appliances, and utilizing water reuse systems. It is also possible to optimize passive plumbing systems to minimize water consumption and related emissions. Daneshvar Rouyendegh, B., & Erol, S. (2012). [10]

Based on the literature, it was found that the use of low-carbon building materials has the highest potential to significantly reduce embodied carbon emissions. Also, from the literature it was found that majority of carbon emissions in a building are from Civil works components. Hence, alternative buildings materials and different strategies in details are listed in the (Table 3) below.

Table 3. Strategies for reducing the embodied emissions

S.N.	**Category**	**Conventional Material/Method**	**Strategy**	**Details**
1	*Low - Carbon Material + Material Reuse and Recycling*	Cement /Binder	Alternative Material	Novacem cement
2				Geopolymer cement
3				Calera cement
4				Limestone calcined clay cements
5				Portland Slag Cement
6				Composite Cement
7		Concrete (Structural and Nonstructural)	Alternative Material	Light Weight Concrete
8				TImbercrete
				Ferrock
9				Ashcrete
10				Hempcrete
16		Reinforcement	Alternative Material	Recycled content steel bars
17				Basalt Bars
18				Fiberglass Reinforced Polymer (FRP)
19				Bamboo Reinforcement

20				Timber Reinforcement
21				Natural Fiber Reinforced Composites
22				Geopolymer Concrete Reinforcement
23		Wall	Alternative Material`	Recycled C&D waste blocks
24				Compressed Stabilized Earth Blocks
25				Ferrock
26				Rammed Earth Walls
27				Timber Frame Walls
28				Unfired Clay Bricks
29				Aerated Autoclaved Concrete blocks
30				Fly Ash Bricks
31				Mycelium Wall
32				Straw Bales Clay Wall
33		Plaster	Alternative Material	Lime plaster
34				Earthen plaster
35				Gypsum Plaster
36				Clay plaster
37				Hemp Plaster
38				Straw bale plaster
39				Venetian plaster
40				Lime pozzolana plaster
41		Sand	Recycled Material	Recycled sand
42		Aggregates		Recycled aggregates
42	*Material Minimization*	Structural System		Structural System Optimization
43		Design		Avoiding overdesign
44		Principles		Lean Construction Practices
45	*Construction Optimization*	Equipment		Reduce the idle time of equipment
46		Equipment		Selection of optimal equipment
47		Transportation		Minimizing the on-site transport
48		Layout		Optimizing the layout of construction facilities
49		Pumping System		Water flow in the system under natural under gravity or capillarization method.

SCENARIOS FOR A BUILDING CONSTRUCTION PROJECT

The next step of the research was to finalize building materials of different components for a construction project. For this different scenario were generated. Fatriady, M. R., Aprianti, E., & Pamungkas, B. D. (2021). [11] To generate various case scenarios for the selection of sustainable building materials, three approaches were employed. Firstly, expert opinions were taken to comprehend their preferences for selecting building materials for a green project. Two cases were generated with the assistance of two expert opinions. The subsequent phase of the study involved utilizing the ELECTRE analysis tool for the selection of sustainable building materials. Figueira, J., Mousseau, V., & Roy, B [12] Two scenarios were employed to execute the ELECTRE analysis.

Firstly, when all building materials were taken into account, and subsequently, the materials were finalized after the analysis. Secondly, the responses obtained from expert opinions were employed as input data for the ELECTRE analysis tool to select the material. In addition, a conventional building materials case was also used to facilitate a comparative analysis of the outcomes. (Table 4)

Table 4. Summary of Scenarios and their descriptions.

S.N.	**Scenario**	**Description**
1	Scenario 1 & 2	Expert opinions were conducted to gain insight into the preferences and decision-making processes of professionals in the field of sustainable building materials. The selection of materials is typically based on the knowledge and judgment of these experts, as well as considerations such as material availability and Cost. Two cases were generated with the assistance of two expert opinions.
2	Scenario 3 & 4	The second approach involves utilizing the MCDM analysis method to evaluate building materials based on the considerations and preferences identified through the Expert opinions.
3	Scenario 5	Using MCDM analysis to evaluate all sustainable building materials identified through literature. (Ideal Case)
4	Scenario 6	Constructing the building by using Conventional building materials.

Multi criteria decision making – AHP and ELECTRE

For the research initially AHP- MCDM method of analysis was adopted, and a pilot data collection was done to check out the feasibility of AHP tool for this study. But the evaluation of different materials based on multiple criteria can be a complex task, and it becomes even more challenging when subjective parameters are involved. Since the perception of these parameters can vary from person to person, relying solely on subjective judgments to evaluate the materials may not be suitable. This could lead to skewed or inconsistent assessments, which would ultimately compromise the validity and accuracy of the study's conclusions. Furthermore, with the emergence of many new and innovative materials, it is not uncommon for some of them to be relatively unknown to researchers or evaluators. This can pose a challenge when making judgments about their scores and performance among the given parameters. Hence, it was found crucial to use objective and standardized methods of evaluation that can account for both subjective and objective parameters and ensure the accuracy and validity of the research outcomes. Garg, N., & Shrivastava, S. (2019). [13]

The next tool selected for the analysis was ELECTRE analysis. A multi-criteria decision-making technique called the "Electre" method is used to assess and prioritise options according to a set of criteria. "Elimination et choix traduisant la réalité" is the full French term for "Elimination and Choice Expressing Reality" that describes the Electre method. It is a multi-criteria decision-making method developed in the late 1960s by a French research group led by Bernard Roy. The Electre method is widely used in decision-making contexts where multiple criteria need to be considered and weighed to make a final decision. One of the key features of the Electre method is that it allows decision-makers to consider multiple criteria simultaneously, which is important when making decisions.(Figueira et al., n.d.) [12]

Electre is a suitable choice for this problem as it can handle multiple criteria without conflicting preferences(Figueira et al., n.d.; [15] Gökhan Yücel & Görener, 2016) [16] as it would have been in the case of AHP where the alternatives are compared pairwise and scored are allocated on perspectives of different peoples where it would have been subjective.

In the case of this research, selecting a sustainable material the decision criteria identified were cost, embodied energy, and embodied carbon and technical factor values. It is a well-known fact that the cost of materials rises as a result of numerous processes used throughout a product's life cycle, beginning with the energy used to extract raw materials, transport them to the factory, process them for manufacturing, pack them, and finally transport them to the construction site.

Each alternative material has different values for these criteria, and the decision maker needs to evaluate the alternatives among these non-subjective criteria to select the most suitable material. Since, all values are numerical and scientific values.(Daneshvar Rouyendegh & Erol, 2012; [17] Gökhan Yücel & Görener, 2016). [16]

With the help of literature evaluation criteria and its weightages were derived and are mentioned in the (Table 5)

Table 5. ELECTRE analysis criteria and weightages.

S.N.	**Criteria**	**Weightages**	**Source**
1	Cost	.2	(Alwafi, 2022)[18]
2	Embodied energy	0.25	
3	Embodied Carbon	0.25	
4	Technical factor	.3	

The technical values related to cost, embodied energy, Embodied carbon and technical factors are referred through published literatures and current market rates. The table for the same is mentioned in the (Table 6) below.

Table 6. Technical Values for different building materials.

		Cement/Binder						
S.N.	***Materials***	***Cost in INR / Unit***	***Unit***	***EE (MJ/kg)***	***EC (kgCO2)***	***Unit***	***Compressive Strength (MPa)***	***Source of Data***
1	Novacem cement	7.6	Kg	6	0.05	kg CO2e/kg	65	(Bravo et al., 2021)[19]
2	Geopolymer cement	8.892	Kg	4.4	0.1	kg CO2e/kg	35	(Nath & Sarker, 2017) (Thaarrini et al., 2016)[20] [21]
3	Calera cement	8	Kg	2	0.01	kg CO2e/kg	30	(Thaarrini et al., 2016)[21]
4	Limestone calcined clay cements	5.84	kg	3.3	0.4	kg CO2e/kg	40	(Joseph et al., 2016) (Martirena et al., 2018)[22] [23]
5	Portland Slag Cement	6.5	kg	4.1	0.76	kg CO2e/kg	45	(Joseph et al., 2016), (Zemri & Bachir Bouiadjra, 2020) [22], [24]
6	Composite Cement	7.8	kg	3.6	0.75	kg CO2e/kg	35	(Fatriady et al., 2021), (Korolev & Vatin, 2021) [25], [26]
7	OPC Cement	6.5	Kg	6.4	1.48	kg CO2e/kg	30	(Jain & Rawal, 2022), (Haecker et al., 2005), (Sounthararajan & Sivakumar, 2012), (International Finance Corporation, 2017) [7], [27], [28], [29]

		Concrete (Non-Structural)						
		Material cost in INR / Unit	***Unit***	***EE (MJ/kg)***	***EC (kgCO2)***	***Unit***	***Average Compressive Strength (MPa)***	***Source of Data***
1	Light Weight Concrete (Structural and Non-Structural)	3500	m3	300	75	kgCO2e/m3	29.31	(Kh Mohammad Ali, 2018), (Bremner, 2008) [30], [31]
2	TImbercrete (Non-Structural)	5000	m3	55	125	kgCO2e/m3	5.69	(Ugwa Okoroafor et al., 2017) [32]
3	Ferrock (Structural and Non-Structural)	4400	m3	65	30	kgCO2e/m3	58.61	(Shivani A.B.1, Nihana N.2, Gowri A.S.3 Hasna Jalal 4, Arjun R.5, 2022), (Shewalul, 2021) [33], [34]
4	Ashcrete (Structural and Non-Structural)	3903	m3	70	175	kgCO2e/m3	31.03	(Sakthivel et al., 2019), (Singh, 2017) [35], [36]
5	Hempcrete (Non-Structural)	6000	m3	55	85	kgCO2e/m3	3.6	(Rhydwen, 2010) [37]
6	Conventional Concrete (Non-Structural)	5800	m3	450	347	kgCO2e/m3	25.86	(Sizirici et al., 2021),(Persson, 2001) [14],[38]
		Reinforcement						
		Material cost in INR / Unit	***Unit***	***EE (MJ/kg)***	***EC (kgCO2)***	***Unit***	***Average Tensile Strength (MPa)***	***Source of Data***
1	Recycled content steel bars	68	kg	2.2	0.48	kg CO2e/kg	500	(Sudarsan et al., 2022) [39]
2	Basalt Bars	150	kg	1.5	0.12	kg CO2e/kg	1000	(Pavlović et al., 2022) [40]
3	Fiberglass Reinforced Polymer (FRP)	85	kg	22.5	0.45	kg CO2e/kg	450	(Garg & Shrivastava, 2019) [41]
4	Bamboo Reinforcement	5	kg	3.21	0.25	kg CO2e/kg	600	(Archila et al., 2018) [42]
5	Timber Reinforcement	20	kg	4.6	0.23	kg CO2e/kg	70	(Oh et al., 2023) [43]
6	Natural Fiber Reinforced Composites	34	kg	9.55	0.68	kg CO2e/kg	110	(Khalid et al., 2021) [44]
7	Fe Bars (No recycled content)	85	kg	22	1.25	kg CO2e/kg	500	(International Finance Corporation, 2017) [29]
		Internal Wall						
		Material cost in INR / Unit	***Unit***	***EE (MJ/kg)***	***EC (kgCO2)***	***Unit***	***Thermal Conductivity(W/mK)***	***Source of Data***
1	Recycled C&D waste blocks	7500	m3	1.4	0.15	kg	.78	(International Finance Corporation, 2017) [29]
2	Compressed Stablized Earth Blocks	6160	m3	0.55	0.073	kg	.85	(International Finance Corporation, 2017)

								[29]
3	Ferrock	7450	m3	0.557	0.1	kg	.625	(Nadir et al., 2022),(Niveditha et al., 2020) [45],[46]
4	Rammed Earth Walls	8250	m3	2	0.0084	kg	.7	(Kamaladasa & Jayasinghe, 2005),(Gupta et al., 2020) [47],[48]
5	Timber Frame Walls	N/a	m3	N/a	N/a	kg	-	-
6	Unfired Clay Bricks	1800	m3	1.4	0.11	kg	.7	(Dabaieh et al., 2020) [49]
7	Aerated Autoclaved Concrete blocks	3500	m3	3.7	0.5	kg	.16	(Dakwale, 2019), (International Finance Corporation, 2017) [50], [29]
8	Fly Ash Bricks	2000	m3	0.83	0.2	kg		(Dakwale, 2019),(Nadir et al., 2022), (International Finance Corporation, 2017)
9	Mycelium Wall	-	-	-	-	-	-	Eliminated due to lack of Information
10	Straw Bales Clay Wall	-	-	-	-	-	-	Eliminated due to lack of Information
11	Burnt Clay Bricks	2500	m3	6122.5	642.9	m3	1.05	(Dakwale, 2019) [50]
		Internal Plaster						
		Material cost in INR / Unit	***Unit***	***EE (MJ/kg)***	***EC (kgCO2)***	***Unit***	***Average Density (kg/m³)***	***Source of Data***
1	Lime plaster	530	Sq.m	1.31	0.14	Kg	1700	(International Finance Corporation, 2017) [29]
2	Earthen plaster	640	Sq.m	0.21	0.03	Kg	1500	(Miljan & Miljan, 2015) [51]
3	Gypsum Plaster	430	Sq.m	0.75	0.08	Kg	950	(Ranesi et al., 2022) [52]
4	Hemp Plaster	750	Sq.m	0.15	0.03	Kg	750	(Rhydwen, 2010) [37]
5	Straw bale plaster	670	Sq.m	0.09	0.02	Kg	180	(Sodagar et al., 2011) [53]
6	Venetian plaster	2100	Sq.m	0.53	0.06	Kg	1600	(Chen et al., 2018) [54]
7	Lime pozzolana plaster	530	Sq.m	1.31	0.14	Kg	1700	(Kupwade-Patil et al., 2018) [55]
8	Cement Mortar Plaster	400	Sq.m	1.5	0.16	Kg	2100	(Brás, 2017) [56]

The next step to generate material selection preferences using ELECTRE analysis. The (table 7) below includes a mention of the final scenarios.

Table 7. Different material combinations scenario summary.

Scenario Summary					
	Binder / Cement	*Reinforcement*	*Internal Wall material*	*Non-Structural*	*Internal*

				Concrete	*Plaster*
Scenario-6	OPC Cement	Fe Bars (No recycled content)	Burnt Clay Bricks	Conventional Concrete	Cement Plaster
Scenario-5	Calera Cement	Bamboo Reinforcement	Unfired clay bricks	Ferrock	Earthen Plaster
Scenario-4	Limestone calcined clay cement	Bamboo Reinforcement	Unfired clay bricks	Ashcrete	Earthen Plaster
Scenario-3	Portland slag cement	Bamboo Reinforcement	Unfired clay bricks	Ashcrete	Earthen Plaster
Scenario-2	Portland Slag Cement	Recycled content steel bars	Rammed Earth Walls	Ashcrete	N/A
Scenario-1	Composite cement	Fiberglass Reinforced Polymer (FRP)	Aerated Autoclaved Concrete blocks	Conventional Concrete	Lime plaster

Embodied Carbon Emissions for a Building

To showcase the impact of selecting various building materials in different scenarios, a commercial building was chosen. Relevant items of work were identified form BOQ, and calculations were done by replacing traditional building materials with sustainable alternatives. The (Table 8) below represents the summary of total embodied carbon emissions in different scenarios.

Table 8. Calculated Embodied Carbon emission summary.

	Binder / Cement	**Reinforcement**	**Internal Wall material**	**Non-Structural Concrete**	**Internal Plaster**	**Overall Embodied Carbon (Tons co2e)**	**Overall Cost (Rs)**
Scenario-6	OPC Cement	Fe Bars (No recycled content)	Burnt Clay Bricks	Conventional Concrete	Cement Plaster	4,966.88	72,946,592.31
Scenario-5	Calera Cement	Bamboo Reinforcement	Unfired clay bricks	Ferrock	Earthen Plaster	175.41	40,397,490.90
Scenario-4	Limestone calcined clay cement	Bamboo Reinforcement	Unfired clay bricks	Ashcrete	Earthen Plaster	1,241.98	34,524,001.13
Scenario-3	Portland slag cement	Bamboo Reinforcement	Unfired clay bricks	Ashcrete	Earthen Plaster	2,208.72	36,296,354.97
Scenario-2	Portland Slag Cement	Recycled content steel bars	Rammed Earth Walls	Ashcrete	N/A	2,211.54	62,090,445.81
Scenario-1	Composite cement	Fiberglass Reinforced Polymer (FRP)	Aerated Autoclaved Concrete blocks	Conventional Concrete	Lime plaster	2,927.14	77,383,625.64

Comparison between Scenarios

The analysis showed that using sustainable building materials can significantly reduce embodied carbon emissions and achieve cost savings in conventional R.C.C buildings. (Table 9) Specifically, the use of MCDM-Electre analysis led to a 24% to 96% reduction in embodied carbon compared to the alternative method. In addition to the environmental benefits, MCDM-Electre analysis revealed potential cost savings of 44% to 53%.

Table 9. Summary of comparisons between different scenarios

	Cost (Rs) / Embodied Carbon emissions (T co2)	**Scenario-6/2/1**	**Scenario-5/4/3**	**% Difference**
Scenario 6 Vs Scenario 5	Cost	72,946,592.31	40,397,490.90	44.62
	Embodied Carbon emissions	4,966.88	175.41	96.47
Scenario 2 Vs	Cost	62,090,445.81	34,524,001.13	44.40

Scenario 4	Embodied Carbon emissions	2,211.54	1,241.98	43.84
Scenario 1 Vs Scenario 3	Cost	77,383,625.64	36,296,354.97	53.10
	Embodied Carbon emissions	2,927.14	2,208.72	24.54

The analysis showed that using sustainable building materials can significantly reduce embodied carbon emissions and achieve cost savings in conventional R.C.C buildings. Specifically, the use of MCDM-Electre analysis led to a 24% to 96% reduction in embodied carbon compared to the alternative method. In addition to the environmental benefits, MCDM-Electre analysis revealed potential cost savings of 44% to 53%.

CONCLUSION

The building sector is a major contributor to the emissions of pollutant gasses, which are responsible for the health-damaging effects of climate change. To address this challenge, the use of sustainable building materials has emerged as a promising solution, offering a range of benefits that go beyond simply reducing carbon emissions. The study results indicate a significant difference in the embodied carbon savings between the two methods of decision-making. Specifically, the use of the MCDM-Electre analysis tool led to a 96.47%, 43.84%, 24.54% reduction of embodied carbon in different scenarios. In addition to the environmental benefits, the MCDM-Electre analysis also revealed a cost savings potential of 53.10%, 44.62%, 44.40% in different scenarios. Selecting the most suitable sustainable building materials for a project can be challenging due to the wide range of options available. The findings suggests that the structured and objective approach of MCDM-Electre can be highly effective in identifying the most sustainable building material. This means that the sustainable materials selected through the MCDM-Electre approach not only reduce the project's carbon footprint but also lead to cost savings. These findings highlight the potential of MCDM-Electre as a comprehensive decision-making tool that can balance environmental, technical and economic considerations. Sustainable building materials and tools like ELECTRE can help the construction industry achieve its sustainability goals while also contributing to a better future for both people and the planet.

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