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Evaluation of the Energy-Positive Aspects for Optimal Construction Efficiency through Material Realism

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Abstract
Developing upon the tenets of SDG 7 and SDG 11, this paper studies the relationship between materials used in 21st century construction and their characteristic scope for energy-positive application in the housing segment of India against the levels and criterias of 'Optimal Construction Efficiency through Material Realism' (OCEMR). On account of climate change being grossly influenced by the construction sector today due to the choice of materials, processes and construction technologies, it has caused an increase in the Net Carbon Emissions. Hence, the hypothesis of the research is that 'climate considerate architecture' can become 'climate-positive architecture' upon application of optimization techniques to improve the construction efficiency by understanding a material and its construction processes and their many aspects to lower corresponding Global Warming Potential (GWP). In this paper, the concept of an OCEMR is analysed and later formulated based on variables like material choice, regionality of materials, mode of application of materials, available range of alternative material and technology, lifecycle studies of materials, the materials' timeline of carbon emissions, et cetera. Certain factors deduced through a base case using One-click LCA suggest relationships between the aforementioned variables which can be used to measure material-oriented choices in construction against a framework to optimise sustainability, affordability of construction efficiency.

Abbreviations
SDG - Sustainable Development Goals
LCA - Life Cycle Assessment
GWP - Global Warming Potential
BM - Base Model
AM - Alternative Model
OCEMR - Optimal Construction Efficiency through Material Realism

1. Introduction
The construction sector is currently a leading contributor to energy consumption and the materials used in the advanced technology also grossly contributes to greenhouse gas emissions. According to a report by the United Nations Environment Programme the building sector contributes to 30% of global greenhouse gas emissions and consumes approximately 40% of global energy (UNEP, 2019 Amen, 2021; Aziz Amen, 2022). The consequential concerns of the same being irreversible damage to the climate is closely linked with the world's growing population, especially in the developing nations (Liu et al., 2020; Amen et al., 2023; Amen & Nia, 2020). As the demand for housing and infrastructure increases, there is a disproportionately greater increment in the demand for energy requirements, material resources and quicker modes of construction. All of which adds up to the definition of unsustainable construction practices (Kibert, 2008; Huovila & Saari, 2017). This paper aims to evaluate the energy positive aspects of construction materials and techniques to aid in achieving optimal efficiency in the different stages of building construction.

1.1 Premise of the Research
The phrase "energy-positive" suggests that the focus is on using materials and construction techniques that are a part of or can be a part of a larger system of generative architecture, in particular, housing. The implication being that the materials are chosen keeping in mind their life cycles, regionality and timelines of carbon emissions. These would then reduce the energy consumption on various levels of household, local and global when paired with solar panels, passive heating and cooling systems and other means of energy generation (Brown & Gass, 2017).
The phrase "optimal construction efficiency" refers to a standard that will be specific to the correlation between a particular location, climate and properties of the materials to design a framework for energy sustainability and financial sustainability.

The phrase "material realism" refers to a new outlook on understanding the materials used in construction. This approach takes into account the physical properties and limitations of the materials in order to design more sustainable and efficient buildings (Pacheco-Torgal et al., 2019). This involves consideration of factors like embodied energy of the materials (i.e; the energy required to extract, manufacture or transport them for the specific location), their life cycles and operational costs in addition to thermal mass, durability, potential for reuse and recycle, etc. for a more holistic outlook (Adamo, 2017).

Consequently, the authors have delineated the premise of the paper by the three tenets in order to suggest a way for achieving optimal construction efficiency using material realism for energy positive and sustainable material technology that reduce the impact of the construction sector on the climate- the carbon footprint, especially for the demanding housing segment India.

1.2. Objectives and Scope of the Paper

The primary objective of the paper is to evaluate the energy positive aspects of construction materials and techniques in order to achieve optimal efficiency in construction and building design. This will involve exploring the factors that contribute to 'optimal construction efficiency through material realism' (OCEMR) for 21st century construction materials based on factors defining material realism. The paper will use a base case study of a live construction project in Pune, India to explore the various factors that contribute to net carbon emissions and GWP and the correlation between optimised energy and construction. The authors have created a groundwork using variables for developing the concept of OCEMR, which could range from an algorithmic, software or interface form of communication of data. To begin understanding the gaps and to achieve the objectives, the following are the research questions that will be addressed:

- What are the energy positive aspects of building materials and construction techniques?
- What is the impact of the construction sector on climate change, and how can the use of sustainable construction materials and techniques help reduce the carbon footprint and energy consumption, increase energy generation and consequently impact sustainability of the housing sector?
- What factors contribute to OCEMR, and how can they be evaluated and optimised for energy efficiency specific to multi storied housing projects?
- How can a tool be created to represent the OCEMR of construction materials and techniques, and how can it be used to evaluate and optimise energy efficiency?
- What are the limitations and extensions of such a tool that could possibly guide the framework for improved and sustainable construction practices in the housing sector for greater sensitivity to the climate?

1.3. Significance and Contributions

The use of energy-efficient materials, passive heating and cooling systems, and renewable energy sources are just a few of the sustainable building practices that researchers have looked into over the years. These studies' objectives are to encourage the use of sustainable building techniques and the decrease of energy usage in the construction industry. The evaluation of various building materials' energy efficiency has been the subject of certain earlier publications.

For instance, a study conducted in 2016 assessed the thermal performance of several materials, such as concrete, wood, and steel, that are frequently used in building construction. According to the study, concrete and wood have the best thermal properties and can have a considerable impact on a building's energy efficiency (Kicinger et al., 2016).

The energy needed to extract, produce, and transport building materials is known as embodied energy, and it has been the subject of several research. An analysis of the embodied energy of various building materials used in the construction of a single-family home, for instance, was also conducted in 2016. According to the study, buildings' overall energy consumption is strongly influenced by the embodied energy of their building materials, and by lowering this energy, buildings' energy efficiency could be increased significantly (Kim & Lim, 2016).

By introducing the OCEMR, this work hopes to aid in the creation of such a framework. The OCEMR method takes into account a number of variables that affect how energy-efficient the building materials and their corresponding construction technologies and processes are. The unique contribution of this tool is to communicate the analysis and point out the GWP hotspots in the project at different stages. By comparing and contrasting various materials according to their OCEMR values, this visualisation tool makes it possible to spot places where a material's efficiency could be improved. The authors are aware of the limitations of the tool and the potential need for manual analysis at the present stage. Infact, the current variables included in the OCEMR as outlined ahead are derived from the analysis of One-click LCA and will require additional variables as well.

In conclusion, the current work significantly advances the framework for assessing the energy-efficient properties of building materials and encouraging environmentally friendly construction methods in the housing industry. By helping architects, engineers, and builders make more informed decisions regarding material selection and building design, the OCEMR approach and the tool used in this work have the potential to produce structures, specifically multi storied housing typology, that are more energy-efficient, sustainable, and affordable.

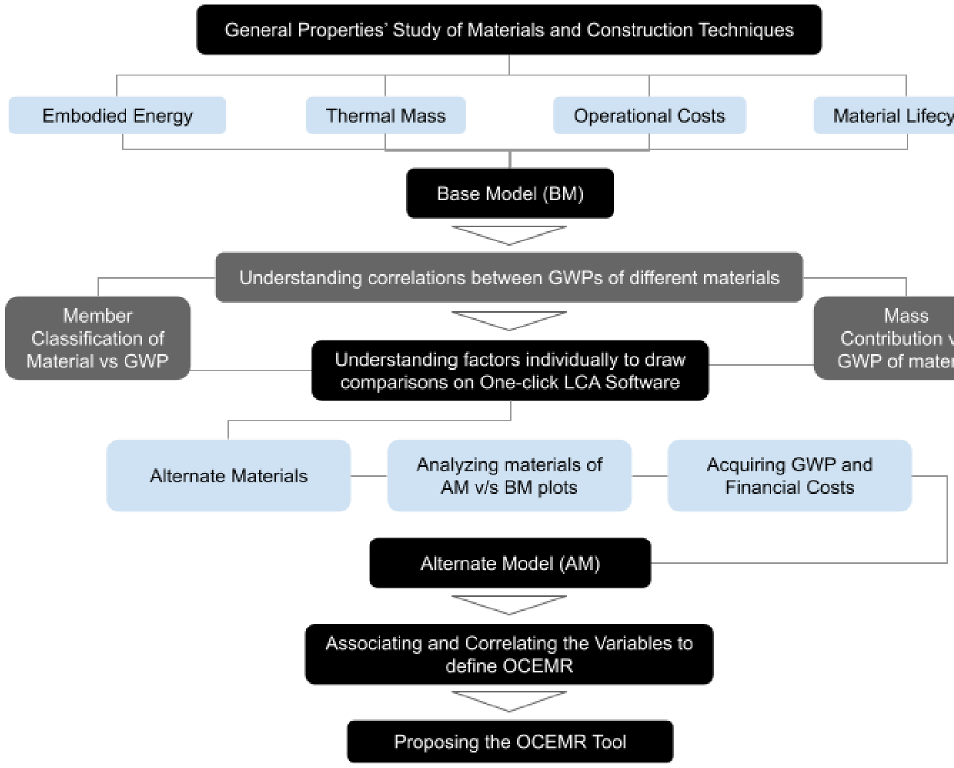


Figure 1. Structure of the Study (Developed by Author)

2. Background Research

The Sustainable Development Goal 7 (SDG 7) aims to ensure access to affordable, sustainable and modern energy for all. Achieving SDG7 requires careful consideration of the tenets of Net Zero Carbon and additionally, GWP, especially in the construction industry due to its significant contribution to the greenhouse gas emissions. According to the Global Alliance for Buildings and Construction, the construction industry and its operations account for around 40% of the global energy related CO2 emissions (UNEP, 2022). Infact, the affordability factor within SDG 7 (United Nations, 2015) and GWP reduction standards are not mutually exclusive and are necessary in the context of construction industry emissions. One important tactic for lowering GWP and achieving net zero emissions is the shift to sustainable and low-carbon technologies. In order to accomplish these goals, energy-efficient building techniques, alternative material choices which are more sustainable and efficient, improved construction processes and technologies, and the usage of renewable energy sources are crucial.

The International Energy Agency (IEA) estimates that by keeping up with the advancing technologies and adoption of affordable, energy efficient measures and sustainable alternatives can contribute up to a 44% reduction in the energy related CO2 emissions by 2050 in the building and construction sector (IEA, 2018). The emission reductions can be significantly increased by focusing on operation and embodied emissions.

SDG 7's affordability component is essential for encouraging the building sector to adopt sustainable practices on a large scale. The affordability aspect of SDG 7 is crucial in driving the widespread adoption of sustainable practices within the construction industry. While the upfront costs of implementing energy-efficient technologies and alternative materials may seem high, they offer long-term benefits by reducing operational costs through lower energy consumption while leading to economic savings and improved well-being by enhancing occupant comfort and productivity (UNEP, 2022). In order to adopt these, an improved understanding of the materials, their alternatives, impacts and corresponding technologies are needed to substantiate the impact and equally importantly, supporting policies.

Various financial methods and encouraging policies are required to obtain inexpensive and sustainable energy solutions. Incentives, grants, subsidies, and advantageous financing choices are some examples of these. Governments and stakeholders should work together to establish a supportive climate that promotes investment in renewable energy sources and energy-efficient technology, making them more affordable and widely available to the construction sector.

2.1. India's Long-Term Low-Carbon Development Strategy

In order to create sustainable built environments and lower greenhouse gas emissions in the construction industry, policies are essential. Energy efficiency and environmentally friendly materials can be promoted through the use of carbon fees and green building techniques. The Sustainable Development Goals (SDGs) give the construction sector a framework to respond to global needs and wants through commercial solutions. (United Nations, 2015). Research efforts have focused on sustainable construction project financing. A peer-reviewed article claims that the adoption of regulations like carbon fees can successfully lower greenhouse gas emissions in the building sector by 12.72%. (Du et al., 2022). Reports also highlight the incentive based programmes developed by the Indian government for pursuing green building certification and opting for construction processes that reduce GWP (MoHUA, 2016).

Specifically for India, the Model Building Codes of 2016 mandates sustainable and green buildings and many states in India offer incentives for green building certification (MoHUA, 2016). The Ministry of Environment, Forest and Climate Change (MoEFCC) offers fast track environmental clearance for green building projects (MoEFCC, 2011). A new code is being established to set standards for energy efficiency, conservation, and the use of renewable energy in green building requirements. In fact, government involvement in promoting green building projects is increasing. This has been realised in 'India's Long-Term Low-Carbon Development Strategy' as outlined below (MoEFCC, 2022).

- India's per capita annual emissions are about a third of the global average, and its historical contribution to cumulative global GHG emissions is minuscule despite having a share of ~17% of the world's population. Additionally, India's current annual per capita emissions will increase to meet its developmental needs and aspirations while responsibly staying within its fair share of the global carbon budget.
- Of all the factors contributing to India's GHG emissions, coal is India's main fossil fuel resource, which suggests that the combustion of coal is a significant contributor to India's carbon emissions. India has significant energy needs for its development and construction requirements, which also contribute to its carbon emissions.
- India updated its Nationally Determined Contributions (NDCs) in August 2022, which along with other targets, highlights that India aims to achieve net-zero emissions by 2070.
- The key policies are (A) Expansion of renewable energy, (B) Energy efficiency, (C) Electric mobility, (D) Sustainable urbanisation, and (E) Afforestation and forest conservation.
- The key policy of Sustainable Urbanization is an initiative adopted by the Indian government to reduce carbon emissions is to promote climate-responsive and resilient building design, construction, and operation in existing and future buildings.
- The primary challenges faced in the application of these policies as per the report are (A) Financing, (B) Technological barriers, and (C) Institutional capacity.
- To expand upon the Sustainable Urbanization Policy, India has implemented several policies to promote sustainable urbanisation, such as the Smart Cities Mission and the Atal Mission for Rejuvenation and Urban Transformation (AMRUT). Specifically in terms of construction, green building rating systems, management of construction waste, circular economy approaches and energy efficiency guidelines are the primary proposals.
- To align with SDG 7 and SDG 11 goals, the report also outlines potential future developments in the Development Strategy. Some of them are, (A) Renewable Energy Development, (B) Green Steel, (C) Alternative Sustainability, and (D) Hydrogen Economy.

2.2. Architectural Materials and the Need for Sustainable Alternatives

The use of ready mixed concrete (RMC) in construction projects has significant environmental impacts, like several other construction materials we use today. The production of cement, the main component of RMC, contributes to 8% of overall global emissions (Global CO2 Initiative, 2021) and 19-20% C02 emissions in India. In a study evaluating the environmental impacts of RMC products, it was found that on-site emissions were dominated by CO2, accounting for 99.38% of total emissions from RMC equipment in India (Xu et al., 2018).

Several sustainable alternatives to RMC have emerged that offer reduced GWP and improved environmental performance. One such alternative is the use of recycled materials and waste additives, such as recycled aggregates and supplementary cementitious materials (SMCs). In order to significantly reduce the environmental impact of manufacturing these materials by diverting waste from landfills, recycled aggregates derived from crushed concrete or demolition waste. SMCs, like fly ash and GGBS, can partially replace cement in concrete production (Dubey et al., 2019). These greener options are becoming more well-known on a global scale and have been effectively incorporated into numerous construction projects. For instance, 'Green Concrete'- a sustainable concrete alternative that incorporates recycled aggregates and SMCs was used in the Netherlands to build the N470 highway, yielding a 60% reduction in CO2 emissions compared to conventional concrete (Van den Heede et al., 2012).

It is important to note that in addition to concrete, sustainable solutions are needed for other architectural materials as well that are commonly used today. For instance, bamboo or engineered wood, which have lower embodied carbon and support sustainable forestry practices, can substitute hardwood, which is frequently used in building. Similar to this, using eco-friendly insulation materials, like cellulose or recycled fibreglass, can save energy use and enhance building performance.

2.3. Architectural Processes and Technologies

Architectural processes and technologies have always evolved over time, but recent technological advancements have not been fully incorporated into the implementation of modern-day architecture. This has resulted in a gap between the advancements in technology and architectural implementation, leading to an urgent need to explore alternatives in either the improvements of the material itself or the technological methods used for implementation.

One of the ways to reduce GWP in architecture is through the use of novel construction technologies such as 3D printed concrete and modernised vernacular technologies. Such processes enable the creation of complex shapes and forms which were formerly impossible to construct, and can use less material than traditional methods, thus reducing the carbon footprint. In 3D printed concrete technology, there are innovations to use waste materials like ground waste tire rubber to further reduce the GWP by an approximate 15%. Additionally, these technologies have been shown to have significant potential in reducing construction times, hence further reducing GWP (Sambucci et al., 2023; Sidika et al., 2019). Efficient technologies such as building-integrated photovoltaics (BIPVs) and green roofs can also be utilised to reduce GWP as means of active methods. BIPVs involve incorporating solar cells into building facades or roofs, thus reducing energy consumption and generating clean energy (Sailor et al., 2021). Green roofs, on the other hand, involve the installation of vegetation on rooftops, which creates a thermal barrier, reduces energy consumption, and improves air quality.

Using active and passive methods like 3D Printed Concrete and BIPVs, the integration of advanced architectural processes and technologies can help reduce carbon emissions and GWP, highlighting the need for the optimal use of new-age construction technologies and materials to attain efficient energy-positive architecture.

3. Research Approach and Analysis using Open Click LCA process

One-click LCA being a comprehensive life cycle assessment (LCA) software, that enables its users to assess the environmental impact of projects in its various stages efficiently and accurately has been used for this paper.. One-click LCA (according to ISO 14040) assesses several environmental impact categories, including the Global Warming Potential (GWP). The software incorporates a wide range of impact categories which are a result of data inputs of material choices, financial and carbon costs, material depletion, transportation and other operational energy requirements, etc (One-click LCA, 2021).

The primary reason why One-click LCA was used was to utilise its up-to-date and comprehensive global database of materials and processes, enabling the author to perform accurate and reliable assessments. It also excels in communicating the data and results for material research and comparative analysis of several impact categories simultaneously (Rinne et al., 2022).

3.1. One-click LCA

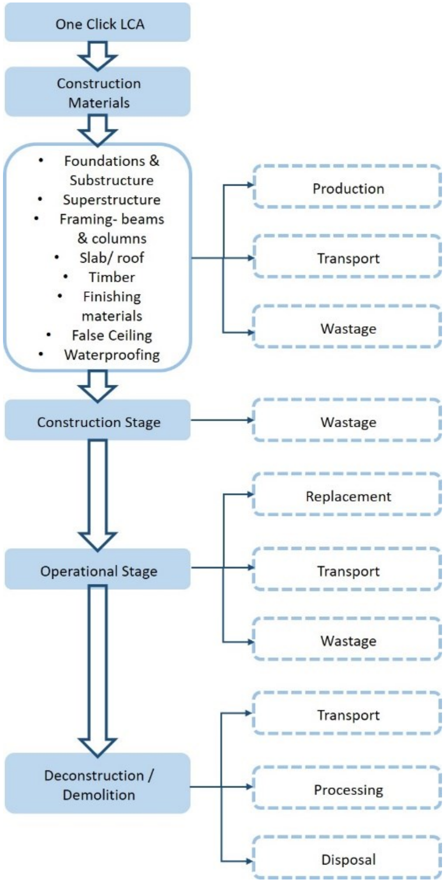


Figure 1. Process followed to using One-click LCA (Developed by Authors)

'Net zero Carbon Tool' offered by Open LCA was used for the impact category study of GWP. Material documentation for 'Navkar Heights'- Pune was provided by the developer Suyog constructions. By taking into account the building's upfront, operating, and end-of-life emissions and deducting any benefits and offsets, the 'Net zero Carbon Tool' calculated the net emissions of the building project.

Step-by-step inputs given:

- Selection of 'Net zero Carbon Tool'
- Calculation period was set to sixty years
- Building area was specified as a minimum gross internal floor area.
- The construction materials and their quantities were added as per the BOQ for respective construction members like 'Columns, External Walls and Other Vertical Members', 'Floor Slabs, Beams', 'Finishes and Coatings', etc. This information was essential to calculate the raw material harvesting, transportation and manufacturing impacts.
- The transportation distances for different materials from their warehouse to the project site and the means of transportation were added.
- Site operations, energy consumption and water demands were set.
- Results were acquired for the LCA, GWP, etc.

Post analysis of the project's graphs for the materials and processes used against carbon benchmarks and for the Net Zero Carbon impact category, the Base Model (BM) was established. For the Alternate Model (AM), the 'most contributing materials' to the GWP were selected and after understanding why their contribution is as high as it is, alternative sustainable materials were selected and the following process was followed:

- Alternative sustainable materials were selected from the existing database of materials in the software by studying its GWP and rating parameters. Material Service Life was assessed before adding or replacing the materials.
- Unit quantity was opted for materials of both BM and AM.
- The transportation distances for different materials from their warehouse to the project site and the means of transportation were added.

- Site operations, energy consumption and water demands were set.
- Financial cost per unit quantity of the materials were added to automatically calculate the Financial + Carbon Cost
- Results were acquired for the LCA, GWP and Affordability of the materials.

The graphs were used to analyse the materials, their comparative GWP contributions and affordability along with thermal efficiency. These graphs were then used to draw conclusions directing the author towards OCEMR.

4. Results and Discussion

One model was simulated on the One-click LCA Software. This Base Model (BM) followed the prototypical 21st century construction practices of Pune in particular, and India at large. This model upon analysis gives an outline of the materials and corresponding technologies used in India that contribute the most to the carbon emissions and subsequently, deviate from SDG 11 goals. The results for simulation of BM based on its material usage and related Net Zero Carbon Building parameters are listed in the graphs below. The analysis is then overlapped with the comparative model which suggests an improved, affordable and climate-positive model using alternative sustainable options for materials and technologies.

4.1 Lifecycle Overview of the Net Carbon

The various stages of a building's life are referred to as its life-cycle. The terms "product," "construction," "use," "end-of-life," and "benefits beyond the system boundary" are used to describe them. Global Warming Potential (GWP) is the most well-known category of environmental impact that LCA evaluates. Assessments that just measure GWP are referred to as carbon footprint.

Net carbon, often referred to as net carbon balance or net carbon emissions, is a crucial metric in assessing the overall carbon footprint of an activity or system. It represents the balance between carbon emissions and carbon removal or sequestration. Positive net carbon indicates that the activity or system is a net emitter of carbon dioxide (CO_2) and other greenhouse gases, contributing to global warming and climate change. Accurate measurement and quantification of net carbon are essential for evaluating the environmental impact of various sectors, such as energy, transportation, and construction, and informing policy decisions for sustainable carbon management (Smith et al., 2019; van Vuuren et al., 2020; IPCC, 2021). Table 1. outlines the final report of Net Carbon Emissions at different Life-cycle Stages for the Navkar Heights project..

Net Carbon Emissions at different stages of building life-cycle		
Sr. No.	**Category**	**Net Carbon Emission in kg CO_2e**
Pre Construction Stage		
1	Upfront carbon (carbon emitted in the production phase)	15852193.05
2	Construction Materials	14944926.58
3	Transport to the building site	173801.26
Construction Stage		
4	Material wastage - Materials (process)	795660.14
5	Material wastage - Transport	7447.52
6	Material wastage - Waste	16764.71
7	Material wastage - Benefit (Reused)	-86407.14
Operational Stage		
8	Operating carrbon	5212109.5
9	Material replacement - Materials (production process)	5199410.59
10	Material replacement - Transport	4615.75
11	Material replacement - Waste	8083.16
Demolition/ Deconstruction Stage		
12	End of life - Materials reused	-1147699.05
13	Waste transport	203602.89
14	Waste processing	460.89
15	Waste disposal	555927.94
16	External impacts	-1907690.77
	Total	**39833207.02**

Table 1. Final Report on Net Carbon Emissions at different Life-cycle Stages for Navkar Heights.

4.1.1 Embodied Carbon in Lifecycle Stages

Based on the kgCO2e simulation data acquired from One-click LCA for BM construction materials as seen in Fig. 2, the materials used in construction itself contribute the most to the GWP. This is followed by the replacement stage of the lifecycle stages. To reduce an approximate 26.17% kg CO2e contribution, there is a need for an optimization between O&M and Replacement of building assets to balance the spending on energy and cost. The materials, however, contribute 75.4% to the GWP across all life-cycle stages. As shown in Table 2., upon corresponding this with the list of materials that contribute the most to the GWP emphasises the importance and priority that must be placed on implementation of alternative materials through sustainable construction technologies.

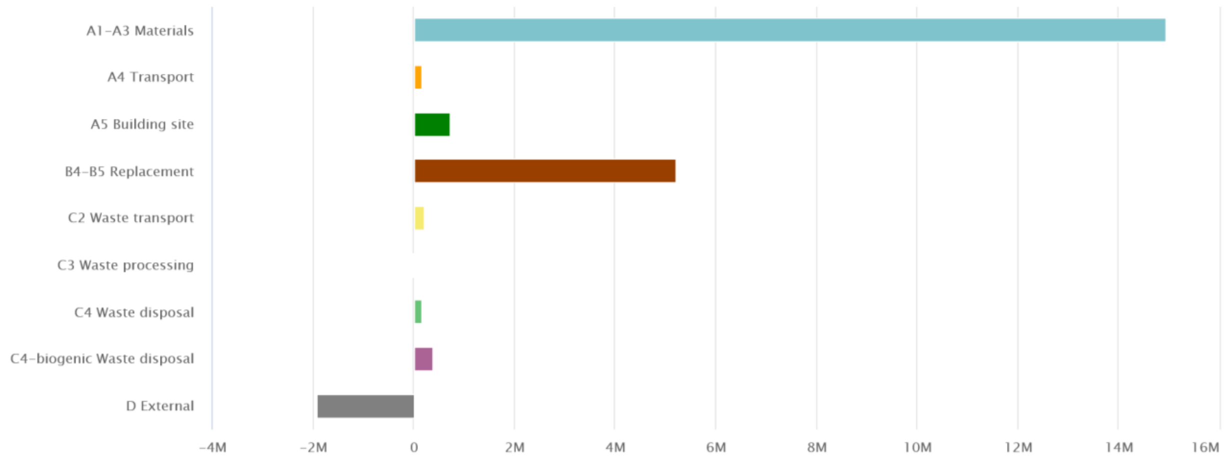
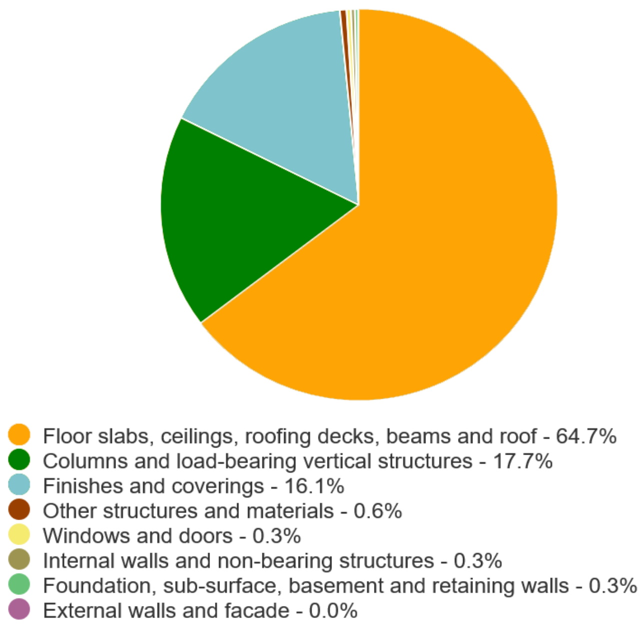


Figure 2. Net Carbon kg CO2e across the Life-cycle Stages.

Net Carbon Emissions by construction materials		
Sr. No.	**Materials**	**Net Carbon tonnes CO2e**
1	Ready-mix concrete, normal strength, generic, C35/45	7485
2	Ready-mix concrete, normal-strength, generic, C40/50	2495
3	Marble products	1960
4	Alkyd emulsion-based paint	744
5	Emulsion paint	698
6	PVC	619
7	Aluminium-plastic window	280
8	Autoclaved aerated concrete (AAC) blocks	194
9	EAF Steel	160
10	Gypsum plaster board	101
11	Dry mortar, adhesive for facades and tiles	91
12	Removable/mobile partitions with aluminum frame	66
13	Stone floor tile	56
14	Water based textured paint	45
15	Ready-mix concrete, normal strength, generic, C25/30	28
16	Sintered fly ash solid bricks	27
17	Autoclaved aerated concrete (AAC) blocks	12
18	Double glazing, toughened glass	19
19	Vitrified ceramic floor tiles	11
20	Cementitious mortar (waterproofing)	0.1
21	Acrylic topcoat paint for exterior	6.8
22	Fiberglass reinforcing mesh	1.4
23	Plywood	-151.36
	Total	**14947.94**

Table 2. Most Contributing Materials

4.1.2. Member Classification for Mass v/s Embodied Carbon



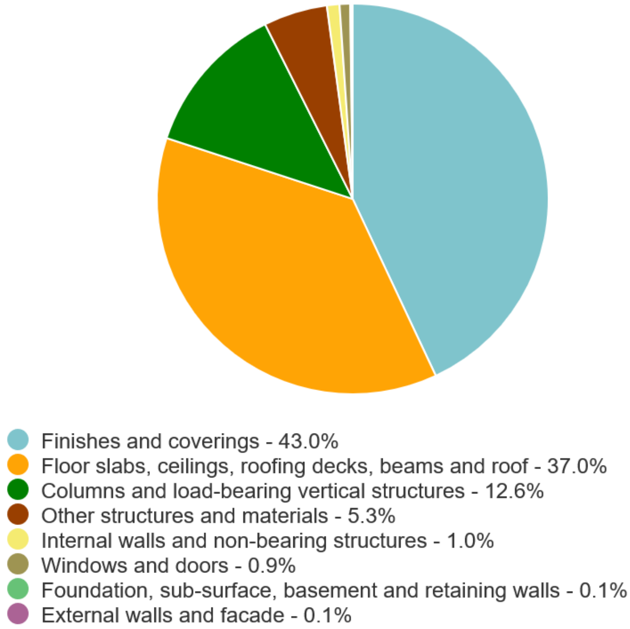


Figure 3. Member Classification based on Mass
Figure 4. Member Classification based on GWP

Fig. 3 shows the GWP in kg CO2e for all the members in the construction (finishes and coverings, RCC structural members, windows and doors, etc.) of BM. Fig 4. shows the classification of the mass of materials used in the building. This variable is relevant in the life cycle stages overview of a building, as it helps to determine the environmental impact of the building over its entire life cycle. The graphs individually imply the GWP and Mass of the construction members at large which consequently suggest the climate positivity of the building as a Net Zero Carbon Building. When the graphs are cross analysed, it suggests the following:

- Floors, Slabs and Beams comprise 64.7% of the construction mass owing to the usage of Ready Mix Concrete and it contributes to 37% of the Equivalent Carbon Emissions or GWP.
- Finishes and Coverings comprise 16.1% of the construction mass owing to the usage of concrete or paint and it contributes to 43% of the Equivalent Carbon Emissions or GWP.
- Columns and Load-bearing Vertical Structures comprise 17.7% of the construction mass owing to the usage of Ready Mix Concrete and it contributes to 12.6% of the Equivalent Carbon Emissions or GWP.

The following Table 3 lists an analysis of the proportions of the two graphs for each majorly contributing member wrt. their Mass and the GWP:

	Mass (%)	GWP (%)	GWP/Mass
Floor Slabs	64.7	37	0.57
Columns	17.7	12.6	0.71
Finishes	16.1	43	2.67

Mass Ratios	
Floor/Column	3.66
Floor/Finish	4.02
Column/Finish	1.10

GWP Ratios	
Floor/Column	2.94
Floor/Finish	0.86
Column/Finish	0.29

Table 3. Mass and GWP of Construction Members with highest corresponding contributions

In the above table, the GWP/Mass ratio's magnitude is directly proportional to the climate impact of that construction member. The Mass Ratios and GWP Ratios are similarly derived in an attempt to comparatively outline the emphasis needed on particular members.

The ratios suggest that Finishes and Coverings contribute relatively the least to the mass of the construction and subsequently should contribute the least to the environmental impact and GWP but it has the greatest magnitude of Embodied Carbon contribution as suggested by the 2.67 ratio for its Mass/GWP, and hence, must be relooked at in terms of material choice and technology used. A similar conclusion can be drawn for the Floor, Slabs and Beams wherein, even though the Mass/GWP ratio is lower, the GWP contribution is high overall. This again emphasises the need to rethink the material choices in the Indian construction practices and the need to suggest and implement more sustainable, climate positive and affordable options. This has to be done especially for the (1) Floor, Slabs and Beams, (2) Finishes and Coverings, and (3) Columns and other Vertical load-bearing Structures.

4.1.3. Life Cycle Impacts of the Construction Materials

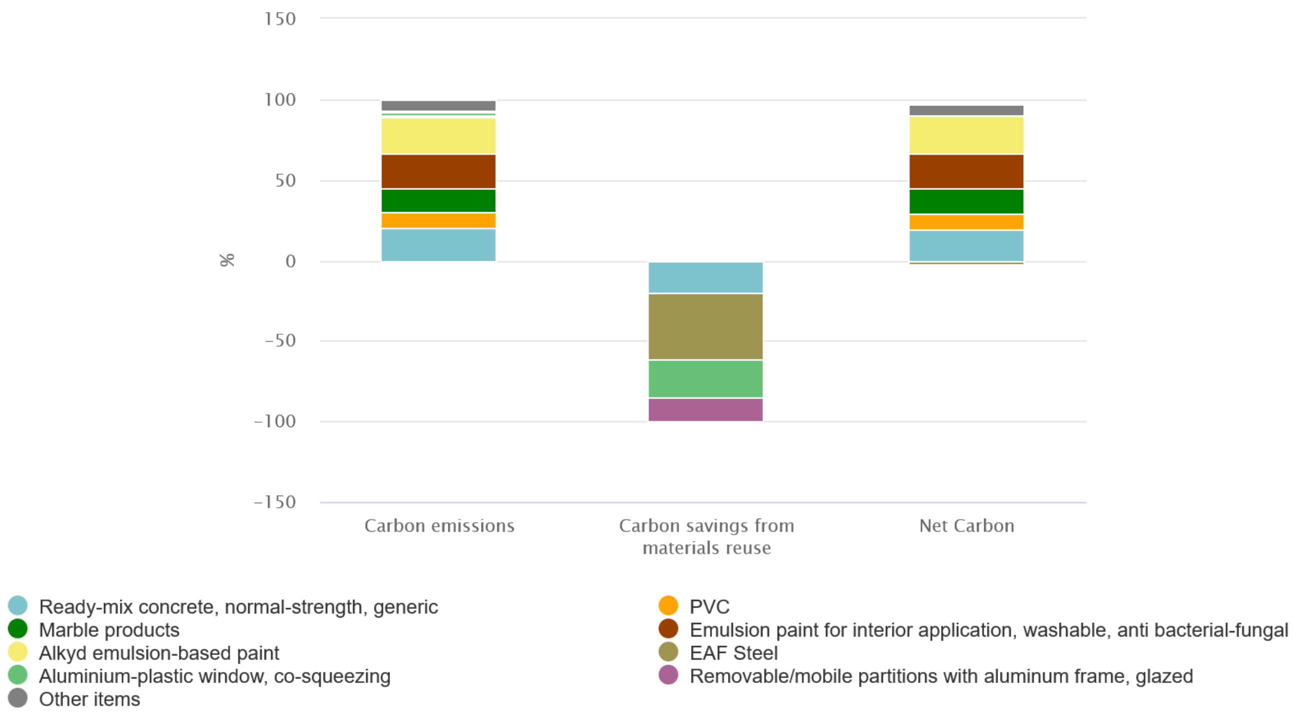


Figure 5. Life Cycle Impacts of Materials Used .

The above graph, Fig. 5, shows the materials used in the construction of the project, irrespective of their use in particular members or mass of the material used, in a stacked column plot to highlight which materials contributed how much to the carbon emissions, carbon savings and overall net carbon values. The net carbon values finally convert to the GWP and environmental impact of the material. Upon analysing the graph, the Paints, Ready Mix Concrete, Marble Products and PVC comprise of the greatest Carbon Emissions, i.e.; 20.3%, 43.93%, 15.21% and 9.52% respectively. The Carbon Savings, however, are based primarily only on EAF Steel (24.4%) and Aluminum Building Assets (14.27%). Contrarily, both EAF Steel and Aluminum Assets have 2.0% and 0.5% contribution to the Carbon Emissions. Without any active techniques applied for carbon savings, the net carbon goes down by 4.03% due to the carbon saving from material reuse of 2-3 materials itself. This again layers on the emphasis that materials like Ready Mix Concrete, Concrete, Paints and Plastic aggregates need to be relooked at to provide more sustainable options.

4.1.4. Net Carbon Classifications based on Life Cycle Stages, Member Classification and Resource Type

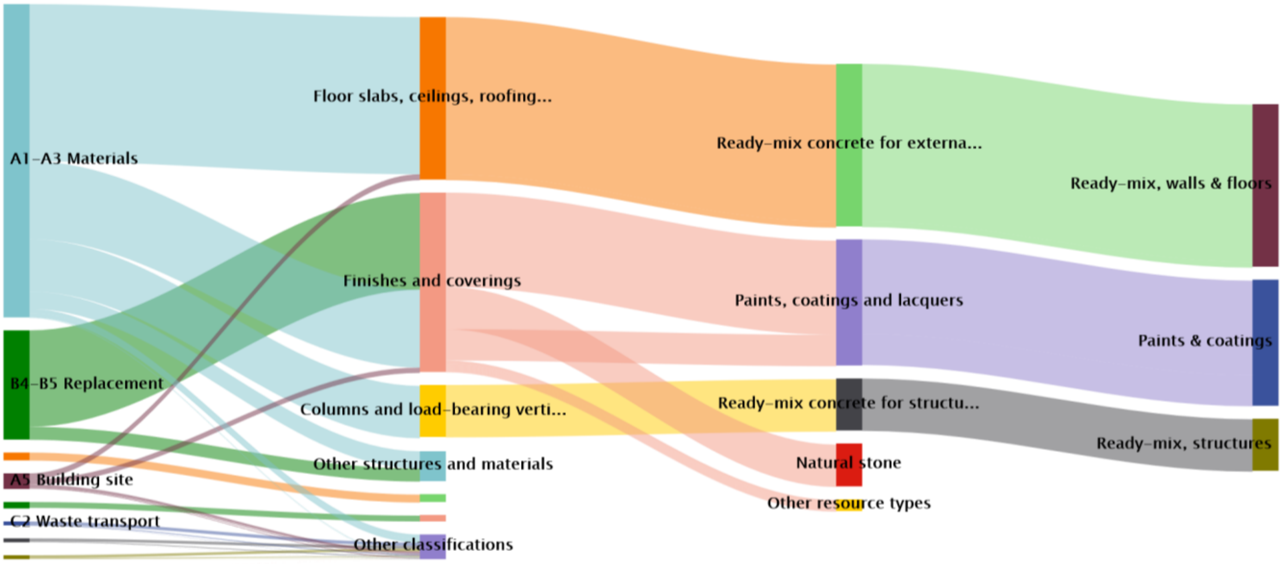


Figure 6. Net Carbon Emissions (GWP) across Project Classifications.

Sankey diagrams are a visualisation tool with nodes along the vertical components with heights conveying an empirical value or 'count' with links between nodes consisting of curves with thicknesses representing the transfer or flow of state from one to another over a set period. The width of the node corresponds to the 'degree centrality'. Fig. 6 shows the width of the 'stripe' across the diagram and corresponds to the 'between centrality' parameter (Oguntona et al., 2021). Fig. 6 gives the values of the carbon emissions across each stage as it begins from the first column of life-cycle stage of Materials, Replacement, Transport, etc., and gets divided to the second column of Construction Member Classifications of Slabs, External Walls, Windows, etc. The classification finally moves onto the third and fourth columns of resource/material types and subtypes respectively. The graph highlights our previous findings of Materials being the highest contributor to the GWP in the Life-cycle Stages. This is architecturally realised through the RMC, Concrete used primarily in the Structural Members like slabs, columns, beams, etc., and in the external walls through AAC Blocks including the finishes and Coverings. A quantified analysis through Sankey Diagrams are outlined below for the aforementioned material types and subtypes for specific member classifications:

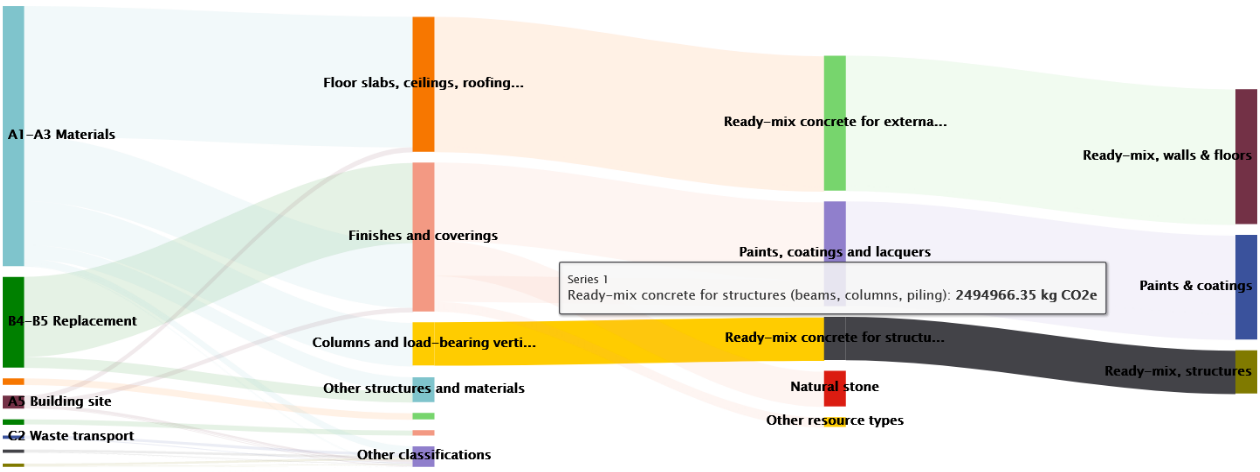


Figure 7. GWP in kg CO2e for Structures using RMC.

Fig.7 shows that the Ready-mix Concrete used for the structural frame and the foundation of the building comprises 11.28% of the GWP which is 16.69% of the Material Life Stage itself. This suggests the need for an alternative that reduces overall and individual GWP through active or passive construction methods and reduces operational costs through decrements in need for repair by improving thermal efficiency and hydraulic stability of the alternative.

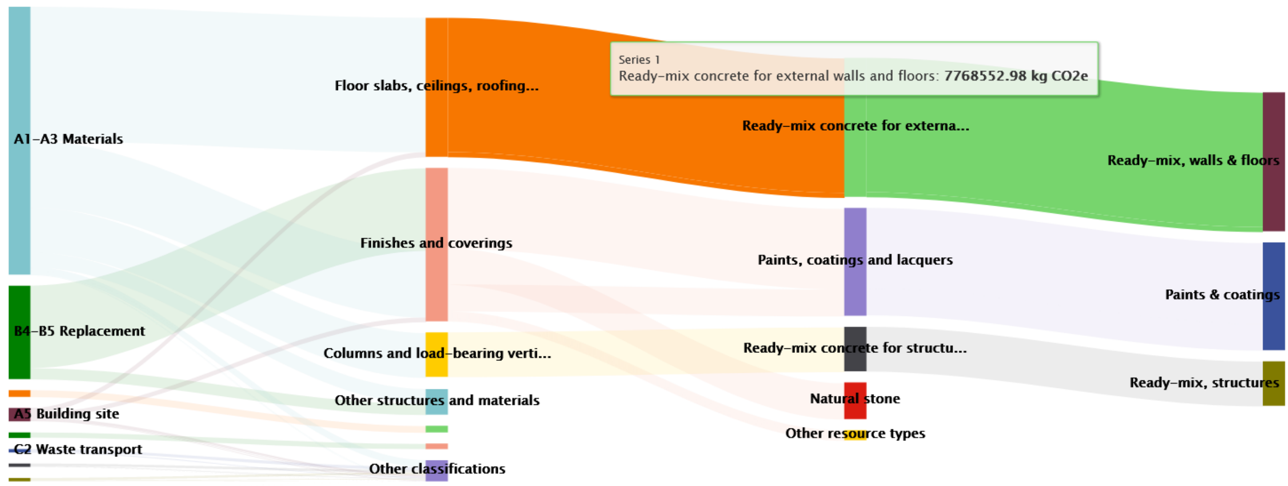


Figure 8. GWP in kg CO2e for Walls and Slabs using RMC

Fig. 8 shows that the Ready-mix concrete used in the Floors and the AAC Blocks used in the Walls contribute to approximately 35.14% of the GWP which is 51.98% of the Material Life Stage. Similarly to the RMC used in Structures, alternatives for the RMC used in slabs should reduce the GWP, improve thermal efficiency and generally reduce the operational costs. The materials used for the external walls, i.e.; the building envelope also needs to be relooked at to improve the thermal efficiency and subsequently reduce the GWP.

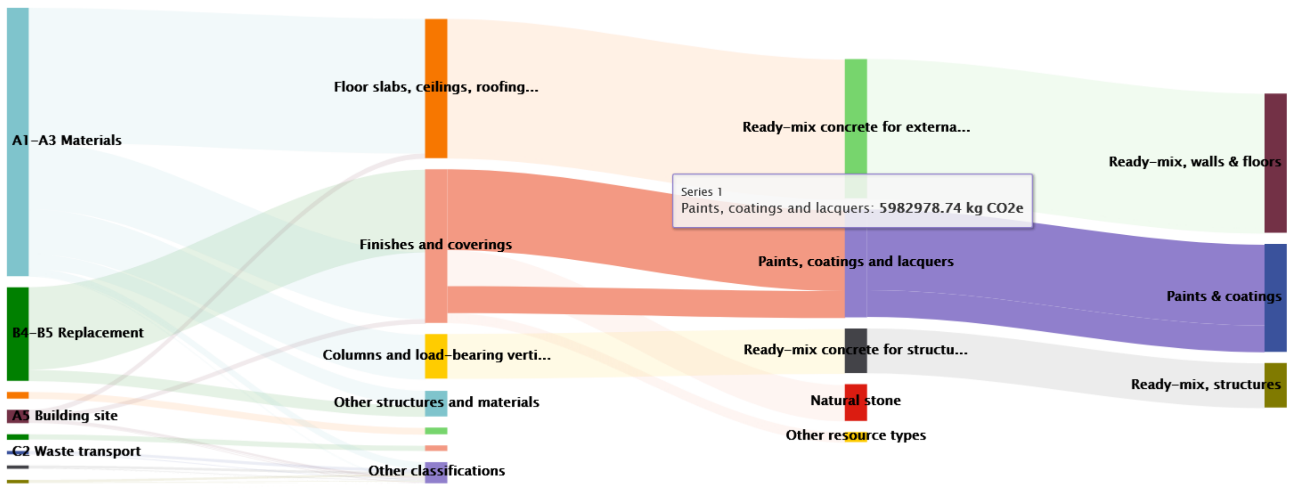


Figure 9. GWP in kg CO2e for Finishes using Paints and Plaster Coatings

Fig. 9 shows that the Paints and Plaster Coatings used in the Finishes and Coverings of the buildings, particularly the building envelope contributes 27.07% to the GWP. The alternatives to be implemented must again reduce the GWP by increasing the thermal efficiency and carbon emissions by keeping the operational costs in control.

4.2. Material Alternatives and Improvement Models against BM

With the conclusions derived regarding the Materials being the greatest contributors to the GWP across the Life Cycle Stages and Concrete, its derivatives used and the Finishes used comprising the greater pool of Equivalent Carbon Emissions, we have the parameters to be prioritised when selecting alternatives. This will then be used to formulate the Alternative Model (AM) to compare its GWP reductions and thermal efficiency improvements against the Base Model (BM).

4.2.1. Alternatives to RMC in Structures and Slabs

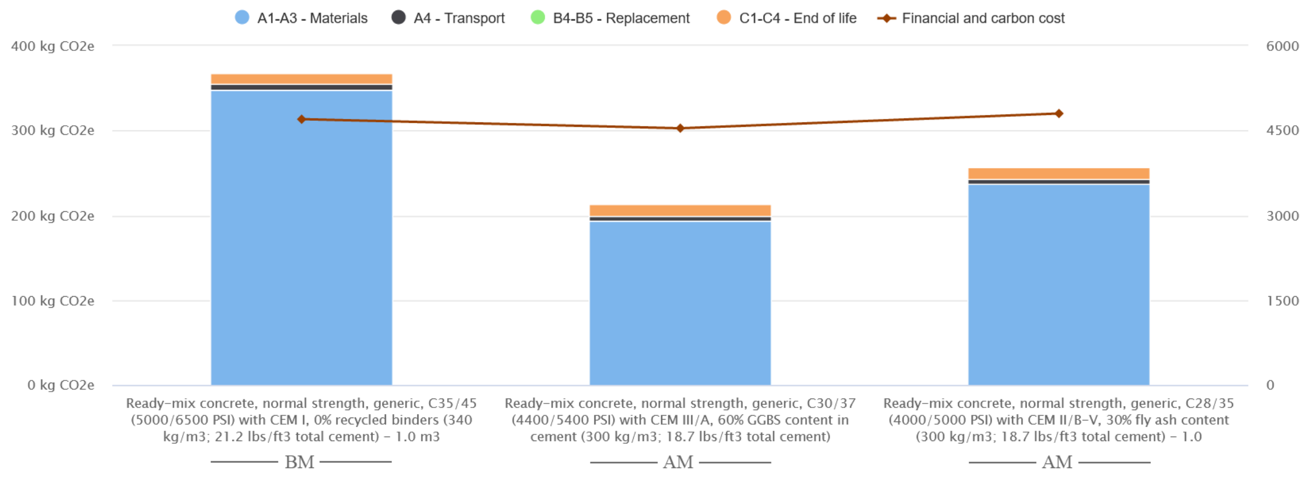


Figure 10. Life Cycle Impact of RMC and Additive Alternatives based on GWP and Carbon Cost

Fig. 10 shows the BM's Material Life cycle Stage contributing 348.43 kg CO2e to the GWP through the RMC used. In both the AMs, the RMC GWP contribution is 193.41 kg CO2e and 237.22 kg CO2e for using GGBS and Fly Ash content respectively. With comparable strengths and densities, the options with least GWP emerge as the Ready-mix Concrete with GGBS content with a 44.49% decrement and then the Ready-mix Concrete with Fly Ash Content with a 31.9% decrement. When considering the financial aspect of the material choices in both the AMs, we can observe that the RMC with GGBC content allows a 3.5% cost reduction per kg from BM whereas the RMC with Fly Ash Content increases the cost by 2.12%. Both the BM material and AM materials already being present in the Indian Market, the clear indication is the need to pivot onto the more sustainable options which reduce the GWP, and provide thermal efficiency with a possible added benefit of cost reduction..

4.2.2. Alternatives to AAC Blocks in Building Envelope

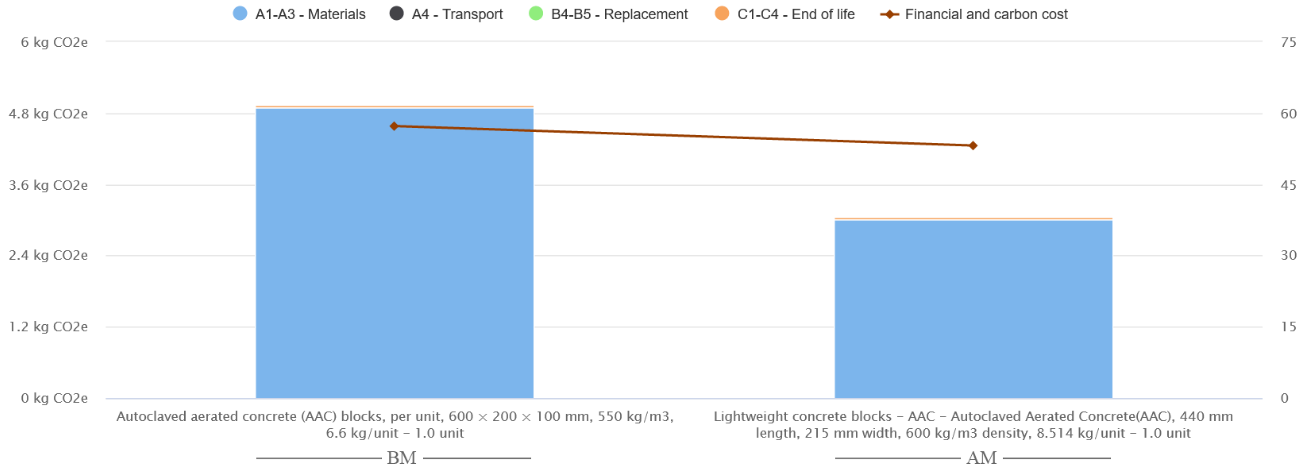


Figure 11. Life Cycle Impact of AAC and Masonry Units based on GWP and Carbon Cost

Fig. 11 indicates similar inferences as Fig. 10. BM and AM are similar material options with similar dimensions of AAC block. However, the differences start from the density of the block being more in AM, which could potentially allow greater thermal mass of the building due to the building envelope. Additionally, a 37.85% reduction in GWP is seen in AM and a 7.14% cost reduction including carbon cost reduction. This again highlights that the building envelope's material alternatives can reduce the GWP of the overall construction, reduce costs and increase thermal efficiency to improve climatic comfort.

4.2.3. Alternatives to Finishes and Coatings in Building Envelope

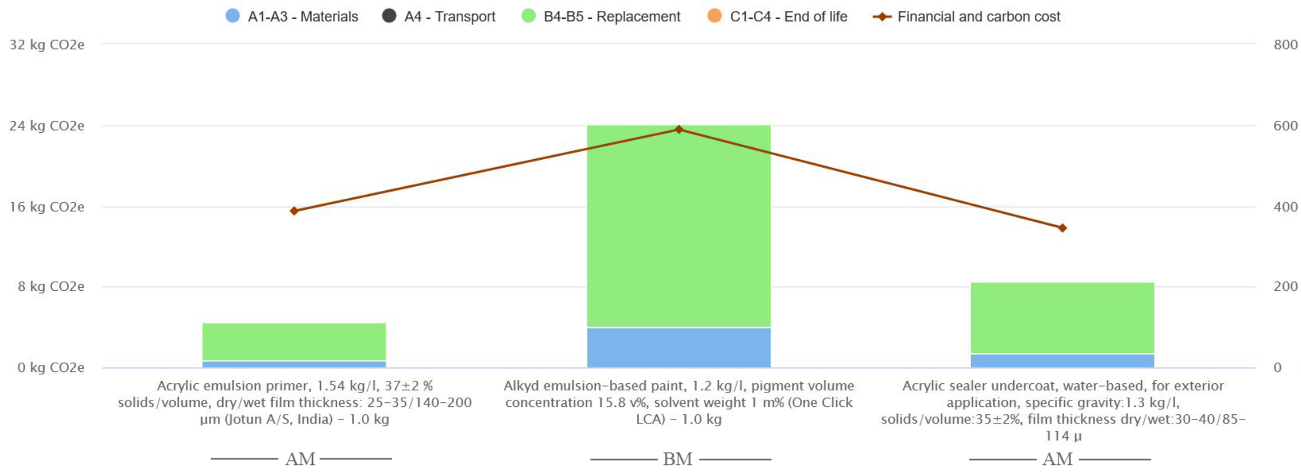


Figure 12. Life Cycle Impact of Paints and Finishes based on GWP and Carbon Cost

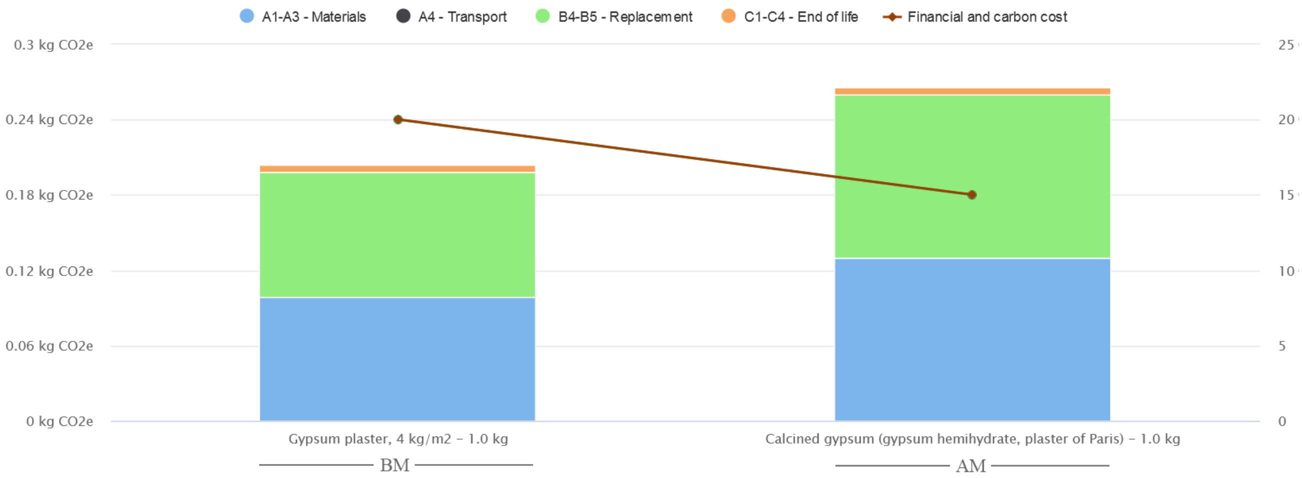


Figure 13. Life Cycle Impact of Plaster and Coatings based on GWP and Carbon Cost

Fig. 12 indicates that GWP can be reduced by over 64.67% and costs by 34.23% from 24.12 kg CO2e of BM by changing the chemical treatments and composition of coatings used with the Alkyd paints as suggested in the AMs. Fig. 13 shows that the BM's Material contribution to the GWP is 23.08% lesser than the 0.13 kg CO2e / sq.ft / kg of unit Gypsum Plaster used. On the contrary, the AM allows 25% cost reduction from BM. Both the finishes and coatings of the building envelope and walls suggest that the more sustainable option which can reduce the GWP and improve thermal efficiency cannot also provide cost reduction.

4.2.4. Alternatives to Materials Contributing Most to the GWP

In order to draw attention to the large variety of materials that have been used which are ranked higher in the list of materials contributing most to the GWP, their alternatives with similar parameters for reducing GWP, and increasing thermal efficiency have been plotted in the following graphs in Fig. 14:

Figure 14. Life Cycle Impact of all the Materials used in the construction based on GWP and Carbon Cost

The above plots in Fig. 14 when looked at individually suggest the best possible alternatives that reduce the kg CO2e and the GWP while also improving thermal efficiencies. But, when the plots in Fig. 10, Fig. 11, Fig. 12, Fig. 13 and Fig. 14 are looked at together as a larger palette of materials used and the alternatives that can be used instead, it becomes clear that while some materials offer improved sustainability like Ready-mix Concrete with Fly Ash Content or Plaster Coatings in Gypsum or type of masonry units used for External Walls, they might be the more expensive options. On the other hand, there are alternative materials like RMC with GGBS and Paints with alternative finishes and Glass with greater u-values and more recyclability can provide cheaper options and also drastically reduce the GWP.

4.3.Optimal Construction Efficiency through Material Realism (OCEMR)

Taking into consideration the analysis of the findings from One-click LCA about the life-cycle stages of GWP, the net carbon classifications, and material alternatives, we can understand that each material has a very different impact on the project's energy positivity. This variation in the impact of the material and their corresponding technologies is a consequence of their differences in mass contributions, global warming potential or net carbon emissions, life-cycle contributions through material procurement and use, transportation, etc. Additionally, each material has a variety of alternatives which provide an array of increments and decrements in the financial cost, carbon cost, GWP, Life-cycle contributions, etc.

With the materials used today in the 21st century in the Indian market and abroad with the latest technology, climate positive designs are an achievable goal. The concern however, is almost always the financial cost of such materials and technology that can provide improved sustainability. But when attempting to achieve affordability, the agenda of including energy positive design aspects takes a back-seat. This implies that to achieve climate positive designs that are thermally efficient and affordable, there is a need for optimization. This process of optimization of a construction project can be outlined using the variables found:

- GWP
- Mass Contribution
- Financial + Carbon Cost
- Material Life-cycle Contribution
- Thermal Efficiency

This directs us towards a tool that can possibly help us better visualise the optimised scenarios for a project. To improve the energy-positivity of a project, the tool is primarily a cumulative of the variables mentioned above in order to visualise the Optimal Construction Efficiency through Material Realism (OCEMR).

OCEMR can provide either an individual or comparative analysis of the project at different stages of the design and construction. OCEMR is not decidedly a software. It is a tool that can aid in understanding the materials used, the materials that can be used and the improvement in certain variables through slight variations in the material palette and construction technologies used. It could be an algorithm that provides empirical values to guide the design onto later stages which are comparatively more energy positive and sustainable while taking into account cost. It could be an interface to highlight the alternative materials to build a comparative AM against the BM being developed and worked on. The way forward with the accumulated data could be to build the idea of OCEMR. However, the current model for OCEMR involves a groundwork consisting of variables that are primarily derived from One-click LCA itself which does not suggest optimal construction efficiency as per the newly-coined term of 'material realism'. The need for additional variables like thermal efficiency and Mass contributions as per Member classifications of the different materials is pertinent. It will also have to include the process and technologies used in the project that can help in reducing GWP of certain materials. It will also have to include the construction time of up-and-coming materials and technologies like 3D Printed Concrete and modern-day modifications to vernacular construction techniques which are potentially faster than conventional modern day construction even. These could possibly be influenced by building typology, policies and regionality of material.

5. Conclusions

In conclusion, this paper has explored the correlation between the various aspects of material choices and technologies used in today's 21st century Indian construction which indicates that instead of prioritising, there is a need for optimising the sustainability, energy efficiency and affordability aspects of design.

The paper findings suggested that the materials and technology used in the 21st century in the Indian construction and architectural fraternity do not provide a palette that can help the project align with SDG 11 goals of sustainability and affordability. The paper also outlines how alternative materials not yet commonly used in the housing or other sectors in India can potentially reduce the GWP and improve the energy positivity of the building. The paper also highlighted how not every alternative can provide everything and hence, there is a need to balance and optimise. Key findings from the paper are:

- The GWP of different materials is directly correlated with their life-cycle stages and can be further associated with the cost aspect for a holistic understanding of all variables.
- Mass Contribution of the Material and Construction Member Classification can be an overriding factor when deciding materials for a project to control the GWP.
- GWP, Affordability and Thermal Efficiency are three key aspects that need to be optimised as co-dependent variables when comparing materials and their alternatives.

These findings suggested the need to include a gradation system called OCEMR which cumulatively includes all the variables discussed in the paper. This gradation is not decidedly a software or an algorithm or an interface. It is a tool that can be used to visualise the project's energy positivity on stand-alone and comparative levels. This tool can be imaged as the way forward which has endless possibilities for visual representation. The primary intent of this tool would be to invoke the realisation of the lack of an optimised design in terms of its energy positivity and affordability amongst architects and designers through a visual medium.

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Conflict of Interests

The authors declare no conflict of interest.

References

Amen, M. A. (2021). The Assessment of Cities Physical Complexity through Urban Energy Consumption. Civil Engineering and Architecture, 9(7), 2517–2527. https://doi.org/10.13189/cea.2021.090735

Aziz Amen, M. (2022). The effects of buildings' physical characteristics on urban network centrality. Ain Shams Engineering Journal, 13(6), 101765. https://doi.org/10.1016/j.asej.2022.101765

Amen, M. A., Afara, A., & Nia, H. A. (2023). Exploring the Link between Street Layout Centrality and Walkability for Sustainable Tourism in Historical Urban Areas. Urban Science, 7(2), 67. https://doi.org/10.3390/urbansci7020067

Amen, M. A., & Nia, H. A. (2020). The Effect of Centrality Values in Urban Gentrification Development: A Case Study of Erbil City. Civil Engineering and Architecture, 8(5), 916–928. https://doi.org/10.13189/cea.2020.080519

(Amen, 2021; Aziz Amen, 2022; Amen et al., 2023; Amen & Nia, 2020)

United Nations Environment Programme (UNEP). (2022). Global status report for buildings and construction 2022. UNEP. https://www.unep.org/resources/publication/2022-global-status-report-buildings-and-construction

Liu, Y., Yang, Y., Wang, S., & Zhao, Y. (2020). Exploring sustainable building certification systems: A review of research progress. Journal of Cleaner Production, 255, 120244. https://doi.org/10.1016/j.jclepro.2019.120244

Kibert, C. J. (2008). Sustainable construction: green building design and delivery (pp. 20-22). John Wiley & Sons.

Huovila, P., & Saari, A. (2017). Environmental and economic sustainability of urban densification: A life cycle assessment approach. Journal of Cleaner Production, 168, 916-925. https://doi.org/10.1016/j.jclepro.2017.09.062

Brown, R. B., & Gass, S. (2017). Toward net zero: Energy and water efficiency strategies for affordable housing. Island Press. 115-116. https://doi.org/10.5822/978-1-61091-880-9

Pacheco-Torgal, F., Jalali, S., & Fucic, A. (2019). Handbook of eco-friendly buildings and infrastructure: Materials, energy systems and environmental impacts (pp. 3-15). Woodhead Publishing. https://doi.org/10.1016/C2016-0-02414-3

Adamo, N. (2017). Material Realism in Architecture: Understanding the Role of Building Materials in Energy Efficiency. Journal of Sustainable Development, 10(2), 59-72. https://doi.org/10.5539/jsd.v10n2p59

Kicinger, R., Wawrzeńczyk, J., & Szymańska, K. (2016). Comparative analysis of the thermal performance of selected building materials used in energy-efficient construction. Energy and Buildings, 128, 862-869. https://doi.org/10.1016/j.enbuild.2016.07.048

Kim, J. S., & Lim, J. Y. (2016). Assessment of embodied energy and CO2 emission for building construction using LCA: A case study of an apartment building in Korea. Sustainability, 8(7), 630. https://doi.org/10.3390/su8070630

United Nations. (2015). Sustainable Development Goal 7: Ensure access to affordable, reliable, sustainable, and modern energy for all. Retrieved from https://sdgs.un.org/goals/goal7

IEA. (2018). The Future of Cooling in Buildings. International Energy Agency. Retrieved from https://www.iea.org/reports/the-future-of-cooling

Du, Q., Dong, Y., Li, J., Zhao, Y., & Bai, L. (2022). Assessing the Impacts of Carbon Tax and Improved Energy Efficiency on the Construction Industry: Based on CGE Model. Buildings, 12(12), 2252. MDPI AG. Retrieved from http://dx.doi.org/10.3390/buildings12122252

Town and Country Planning Organization, Ministry of Urban Development (2016). Model Building Bye Laws. Retrieved from https://mohua.gov.in

Ministry of Environment, Forest and Climate Change (MoEFCC) (2011). Memorandum. Retrieved from https://moef.gov.in/hi/

Government of India. (2015). India's long-term low carbon development strategy. Ministry of Environment, Forest and Climate Change (MoEFCC). https://www.moef.gov.in/wp-content/uploads/2018/04/India_Low_Carbon_Development_Strategy.pdf https://moef.gov.in/hi/

Global CO2 Initiative. (2021). Cement and CO2. https://www.globalco2initiative.org/cement-and-co2/

Xu, Y., Wang, X., Li, R., Zhu, J., Wang, L., & Zhang, X. (2018). Assessment of environmental impacts of ready mixed concrete production in China. Journal of Cleaner Production, 184, 790-799. https://doi.org/10.1016/j.jclepro.2018.02.082

Dubey, S., Singh, A., & Kushwah, S. S. (2019). Utilization of iron and steel slag in building construction. AIP Conference Proceedings, 2158(1), 020032. https://doi.org/10.1063/1.5127156.

Van den Heede, P., De Belie, N., & Van Driessche, I. (2012). Environmental impact and life cycle assessment (LCA) of traditional and 'green' concrete: Literature review and theoretical calculations. Construction and Building Materials, 26(1), 416-425. https://doi.org/10.1016/j.cemconcomp.2012.01.004

Sambucci, M., Biblioteca, I., & Valente, M. (2023). Life Cycle Assessment (LCA) of 3D Concrete Printing and Casting Processes for Cementitious Materials Incorporating Ground Waste Tire Rubber. Recycling, 8(1), 15. MDPI AG. http://dx.doi.org/10.3390/recycling8010015

Siddika, A., Al Mamun, M. A., Alyousef, R., Amran, Y. H. M., Aslani, F., & Alabduljabbar, H. (2019). Properties and utilizations of waste tire rubber in concrete: A review. Construction and Building Materials, 224, 711-731. ISSN 0950-0618. https://doi.org/10.1016/j.conbuildmat.2019.07.108

Sailor, D. J., Anand, J., & King, R. R. (2021). Photovoltaics in the built environment: A critical review. Energy and Buildings, 253, 111479. ISSN 0378-7788. https://doi.org/10.1016/j.enbuild.2021.111479.

One Click LCA (2021). Life Cycle Assessment for Buildings: Why it Matters and How to Use it? (pp. 5-18, 22-27). One Click LCA Ltd. https://www.oneclicklca.com/building-life-cycle-assessment-ebook/

Rinne, R., Ilgın, H. E., & Karjalainen, M. (2022). Comparative Study on Life-Cycle Assessment and Carbon Footprint of Hybrid, Concrete and Timber Apartment Buildings in Finland. International Journal of Environmental Research and Public Health, 19(2), 774. MDPI AG. Retrieved from http://dx.doi.org/10.3390/ijerph19020774

Smith, P., et al. (2019). IPCC Special Report on Climate Change and Land. Cambridge University Press. https://www.ipcc.ch/report/srccl/

van Vuuren, D. P., et al. (2020). IPCC Special Report on Global Warming of 1.5°C. Cambridge University Press. https://www.ipcc.ch/sr15/

IPCC. (2021). Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., et al. (eds.)]. Cambridge University Press. https://www.ipcc.ch/report/ar6/wg1/

O.A. Oguntona, C.O. Aigbavboa, & W.D. Thwala (2021) A Scientometric Analysis and Visualization of Green Building Research in Africa. Journal of Green Building 1 March 2021; 16 (2): 83–86. doi: https://doi.org/10.3992/jgb.16.2.83