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EMBODIED CARBON VARIABILITY IN INDIAN HIGH-RISE RESIDENTIAL BUILDINGS: A CASE-BASED ASSESSMENT

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ABSTRACT

The results of studies on embodied carbon in high-rise residential buildings are frequently given as a single-point estimate without considering the variability in results due to input parameter variability. This study examines the variability in embodied carbon of a 30-storey high-rise residential shear wall building with four datasets of embodied carbon factors that help to set up a baseline. The building embodied carbon was found to range from 373 $kgCO_2eq/m^2$ (IFC Indian database) to 530 $kgCO_2eq/m^2$ (EPiC database), with a mean of 454 $kgCO_2eq/m^2$ and a standard deviation of 65.3 $kgCO_2/m^2$. Concrete and reinforcement steel are major influencers that contribute 80% of the embodied carbon of the high-rise residential building. The minimum and the maximum embodied carbon of concrete are 157 $kgCO_2eq/m^2$ and 247 $kgCO_2eq/m^2$, respectively. The embodied carbon of reinforcement steel varies from 141 $kgCO_2eq/m^2$ to 207 $kgCO_2eq/m^2$. The analysis highlights the importance of understanding the variability in embodied carbon for establishing a reliable baseline, primarily for high-consumption materials.

Keywords*: Embodied Carbon Assessment; High-rise Residential Building; Sensitivity Analysis.*

1. INTRODUCTION

The building sector accounts for around 37% of the global greenhouse gas (GHG) emissions and more than 35% of global energy consumption, making it one of the most significant contributors to environmental impacts (United Nations Environment Programme [UNEP], 2023). In 2023, the worldwide greenhouse gas emissions touched a record 57.1 $GtCO_2eq$, representing a 1.3% increase from 2022. India's total greenhouse gas emissions in 2023 were 4140 $MtCO_2eq$, accounting for 8% of global emissions, a 6% rise over 2022. With per capita GHG emissions of 2.9 tCO_2eq, India stays below the world average, but has substantial problems regulating growing emissions (UNEP, 2024). In India, compared to 2011, 0.6 billion people, or 40% of the population, will be living in metropolitan areas by 2036 (Kouamé, 2024), fostering a massive demand for residential housing, particularly high-rise residential buildings in urban cities like Delhi, Mumbai,

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Chennai, and Bengaluru. High-rise buildings have significant material intensity, which makes addressing the embodied carbon a critical priority in the built environment.

The entire life cycle of a building includes four phases: production, construction, operation, and demolition. The total life cycle carbon of a building consists of embodied carbon and operational carbon (Royal Institution of Chartered Surveyors [RICS], 2023). The building embodied carbon refers to the emissions from the mining of raw materials (A1), transport of raw material to the factory (A2), manufacturing of building material (A3), transport of material to the project location (A4), and onsite construction works (A5). Adding to this are the emissions from energy used for maintenance, repair, and renovation at regular intervals during the building's service life (B2, B3, B4, and B5). The operational carbon is from the energy consumed for lighting, heating, cooling, ventilation, appliances, and equipment. According to Ramesh et al. (2010), buildings typically account for 80–90% of their total energy consumption through operational energy and 10–20% through embodied energy. However, embodied carbon alone makes up 27–58% of the building's total lifecycle carbon emissions, depending on the future energy mix (Robati et al., 2021).

Whole-life embodied carbon (WLCA) yields a benchmark of 1,300kgCO_2eq/m² for A-C stages, aligning with data from RIBA, GLA, and LETI (World Green Building Council [WGBC], 2022), making it a helpful baseline for future comparisons. In a high-rise residential building, 85% of the carbon emissions are related to the production phase (A1-A3) (Zhang et al., 2023). The embodied carbon intensity for the production phase varies from 210.4 kgCO_2eq/m^2 to 769.4 kgCO_2eq/m^2; mean and median values are 379 kgCO_2eq/m^2 and 370.8 kgCO_2eq/m_2, respectively. The embodied carbon intensities attributed to the material production and transportation phases are evaluated as 379 kgCO_2eq/m^2 (89.9%) and transportation to the location, 45.1 kgCO_2eq/m^2 (10.1%) on average, respectively. The variations in the embodied carbon are higher due to the uncertainty in the data quality of the emission factors, due to the use of material energy, manufacturing process, and lifespan of products, primary energy sources, chemical processes, transport fuel type, and the extent of waste or recycling (Ibn-Mohammed et al., 2013), additional variations also from inaccurate quantity measurements and the methodologies adopted for calculations.

This paper presents a case study to demonstrate the variability in embodied carbon of high-rise residential buildings using four different datasets, focusing on the contributions of material-specific embodied carbon to the overall building emissions. The scope of the study is limited to the production phase (A1-A3), and the materials commonly used in high-rise residential buildings, such as civil and finishing. The embodied carbon factors are considered for virgin materials without any replacement or waste material content included. The goal is to establish a more reliable baseline for future embodied carbon calculations.

2. METHODOLOGY

Figure 1 shows the method for assessing the embodied carbon emission with the different data sources and the sensitivity analysis at the building level. The input parameters for the embodied carbon calculation are the quantity of materials and the embodied carbon factors. The scope of the study is limited to the product stage. The data related to the embodied carbon factors are taken from peer-reviewed literature and technical reports.

The material quantities are taken from the bill of quantities (BOQ) and the related building drawings. The life cycle inventory data for the material are taken from the technical reports of ICE UK BATH, EPiC of Australia, IFC Indian data set, and the In-house tool. These datasets have been selected because they are publicly available and account for global geographical conditions to understand the variability.

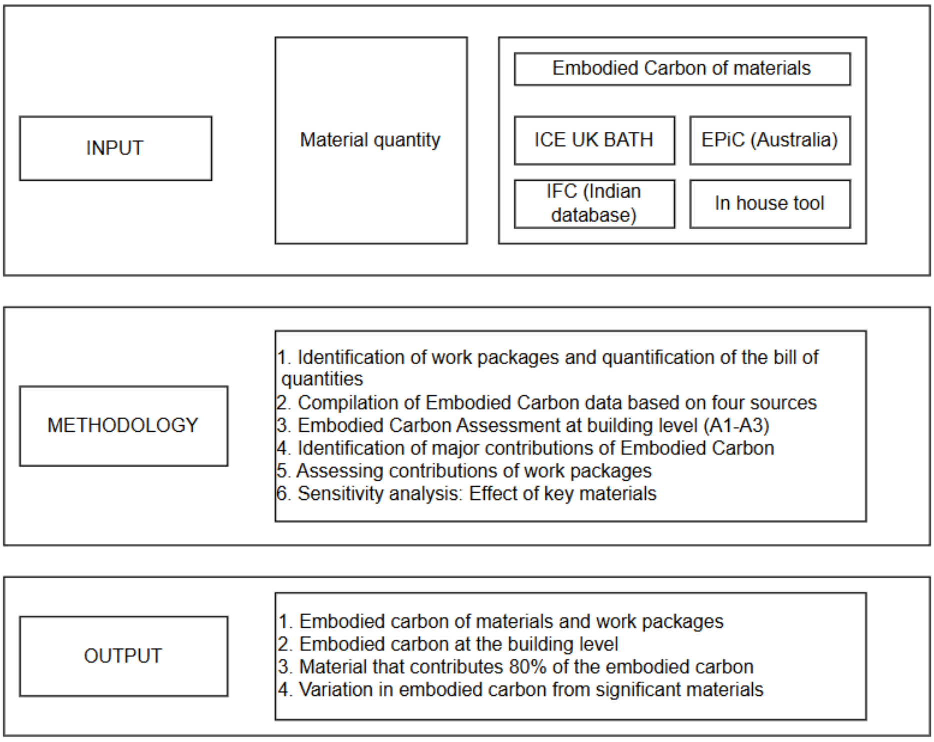

Figure 1: Methodology considered for the embodied carbon assessment

3. CASE STUDY

A high-rise residential building project is considered for the embodied carbon assessment and to understand the variations in the embodied carbon factor's effect on the building-level carbon emission. The project details are mentioned in Table 1. The work packages and the bill of quantities considered for the embodied carbon assessment are shown in Figure 2 and Table 2.

Table 1: Description of the building

Specification	Building
Number of floors	2B+G+30 floor
Number of dwellings	420
Floor height	3m
Total building height	92.625m
External wall	Concrete shear wall 160mm
Total area of the project	4.1 Acres
Super built-up area	6,98,321 sqft
Total built-up area	8,97,710 sqft
Type of dwellings	4BHK, 3BHK, 2BHK and 1BHK

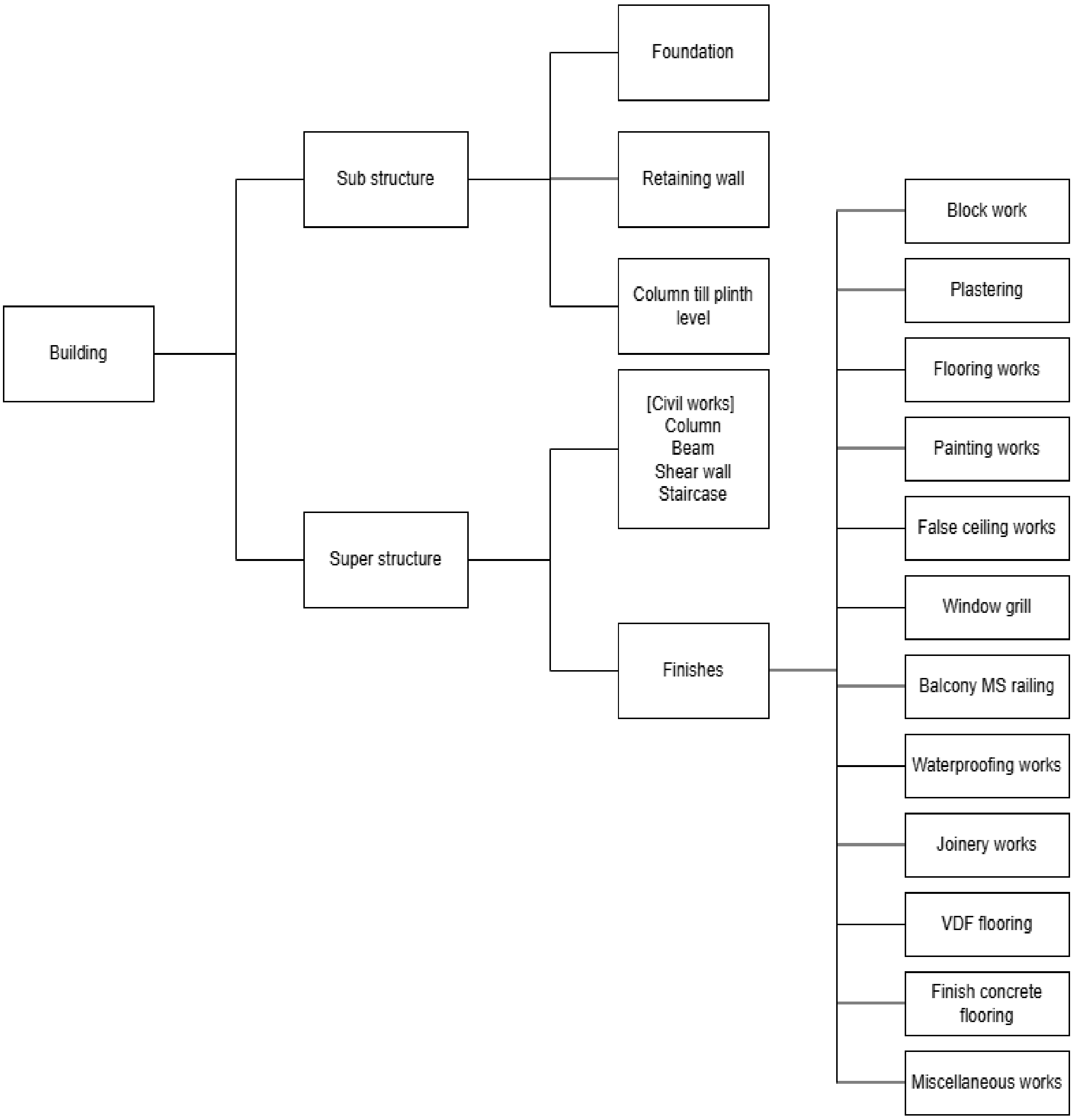

Figure 2: Work breakdown structure

4. EMBODIED CARBON ASSESSMENT

Life cycle assessment is a process that quantifies and evaluates the material and energy flows of a system to understand its environmental impact. The embodied carbon of the material from cradle to factory is considered for the assessment because the impact is highest in the construction phase (Zhang et al., 2024). The material quantities were converted to the required unit, and the embodied carbon factor was multiplied to get the embodied carbon contribution under each material. Consistent material quantities were considered to manage variability across the database, while only the emission factors varied. The effect of variability in the embodied carbon coefficients of construction materials on the embodied carbon of the residential building is evaluated. The embodied carbon factor variation for each material for four different databases is presented in Figures 3 and 4. Calculation is done for all four cases. The embodied carbon calculated at the material level is represented in $kgCO_2eq$, and at the building level in $kgCO_2eq/m^2$.

Table 2: Bill of quantities

Building components	Building materials	Quantity	UoM
Foundation	PCC	1459	m^3
	Concrete	10817	m^3
	Reinforcement	1350	MT
Column, beam, and shear wall	Concrete	16550	m^3
	Reinforcement	3150	MT
Block work	Solid blocks	5265	m^2
Plastering	Cement	270300	kgs
	M sand	1126.62	m^3
Flooring	Vitrified tile	76750	m^3
	Cement tile	3432	m^2
	Granite	2295.3	m^2
	Cement	1398911	kgs
	M sand	5701.24	m^3
Painting	Gypsum plaster	8000	m^2
	Texture	56149	m^2
	Putty	409048	m^2
	Primer	262536	m^2
	Paint	153568	m^2
	Enamel painting	11416	m^2
Doors	Wooden frame	2712	No's
	Wooden shutters	2712	No's
	Fire-rated GI door	1254	m^2
Window	UPVC	445.71	m^2
	Glass	9164.29	m^2
Waterproofing	HDPE membrane	12605	m^2
	Polymer cementitious	29887	m^2
	Cement	104672	kgs
	Sand	291	m^3
False ceiling	Gypsum boards	9221.15	m^2
	Calcium silicate boards	4365	m^2
Railing, Window grills	MS	141.4	MT
Miscellaneous works	RCC precast slab	40	m^2
	Aggregate	60	m^2
	Concrete	5003.37	m^3
	Steel	100	kgs

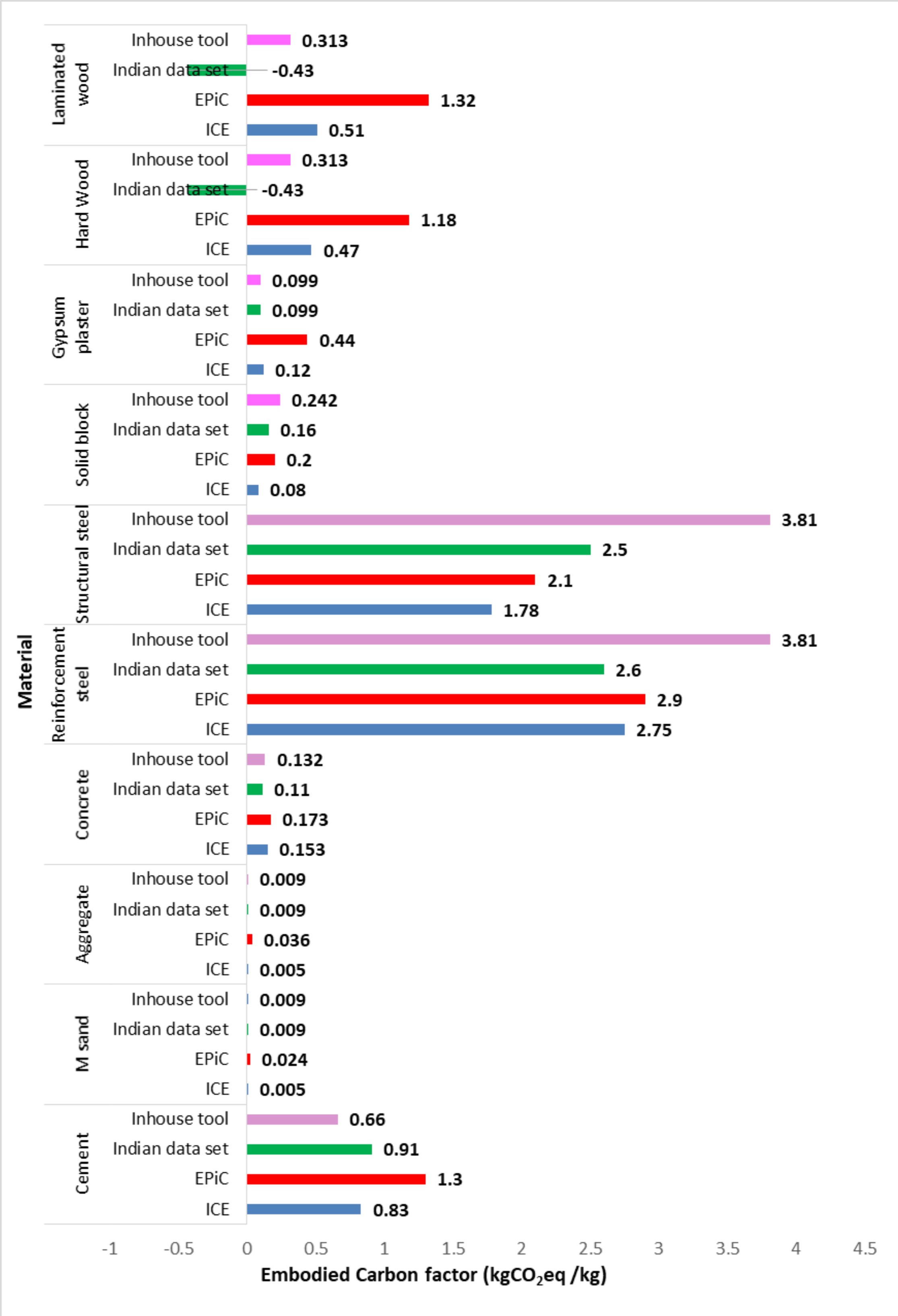

Figure 3: Material embodied carbon factors for the four databases

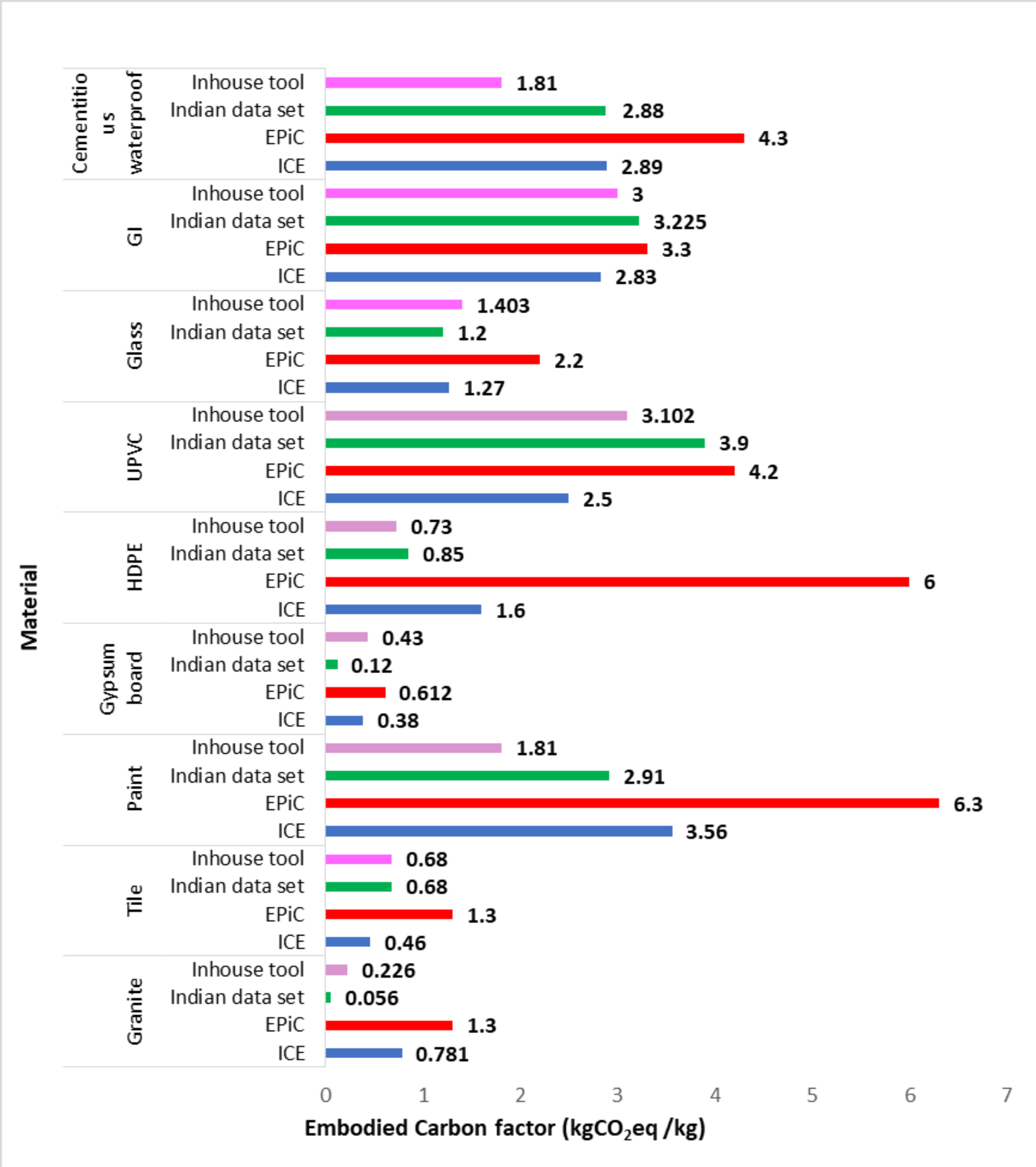

Figure 4: Material embodied carbon factors for the four databases

5. RESULTS AND DISCUSSION

The embodied carbon of the building, from the sources considered, has the lowest value of 373 kgCO_2eq/m2 (IFC) and the highest of 530 kgCO_2eq/m2 (EPiC). This is due to the variation of embodied carbon factors. The average value is 454 kgCO_2eq/m^2, the standard deviation is 65.3 kgCO_2eq/m^2, and the Coefficient of variation (CV) is 14.40%. The embodied carbon emission from the material for all the cases at the building level is represented in Figures 5 and 6.

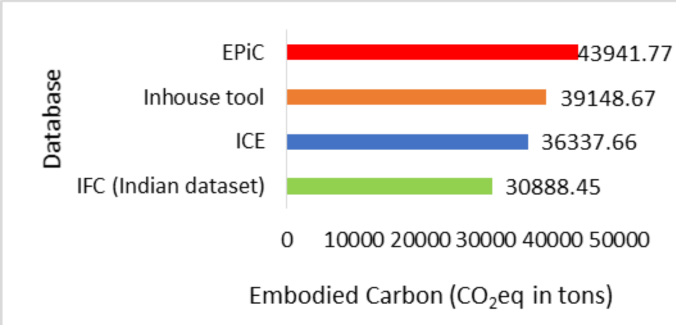

Figure 5: Embodied carbon emission (TonsCO_2eq)

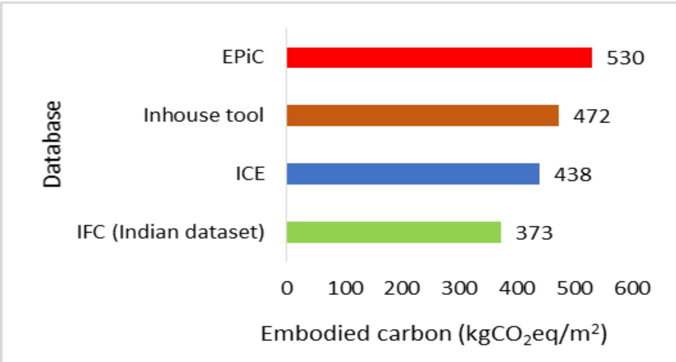

Figure 6: Embodied carbon emission (kgCO_2eq/m^2)

The concrete works and reinforcement steel contribute 80% of the embodied carbon for the overall embodied carbon emission, as shown in the Pareto chart in Figure 7. This is due to the shear wall construction and more RCC quantity. The variations in the embodied carbon of high-rise residential buildings are due to the variability in the embodied carbon factors of materials. The variability is mainly due to inaccurate and insufficient information for the quantification, diverse methodologies for assessing, improperly defined system boundaries, data quality, and a lack of data on all the construction material processes (RICS, 2023). The system boundaries set for the LCA also play a significant role in embodied carbon emissions at the building level.

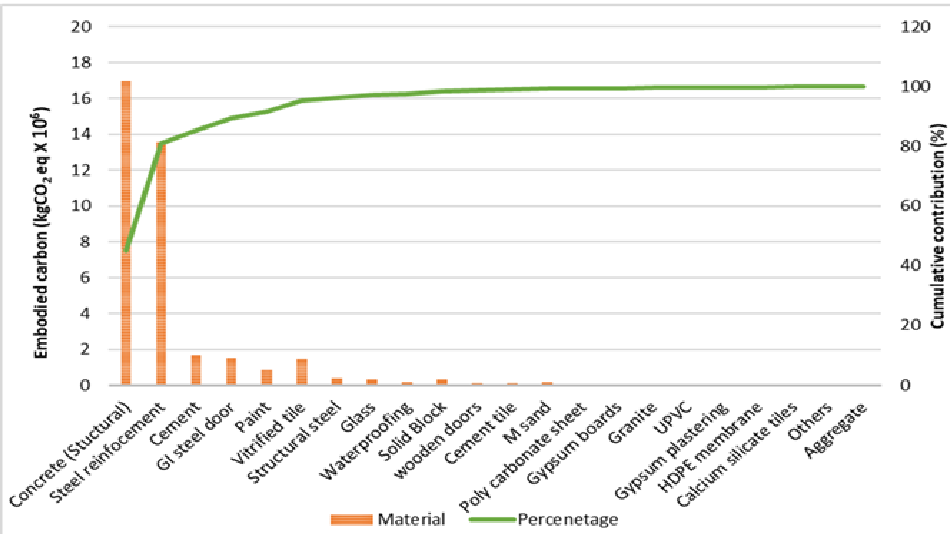

Figure 7: Pareto chart on material embodied carbon contribution

Considering the work package level, substructure and superstructure contribute the most, followed by finishing, joineries, and site work, as shown in Figure 8. Even though the embodied carbon value of the finishing materials is higher in most cases, due to the quantity of usage being less than that of RCC, the overall contribution is significantly less. So, optimization in the quantity of materials used in the structural part helps significantly reduce the carbon emissions at the building level.

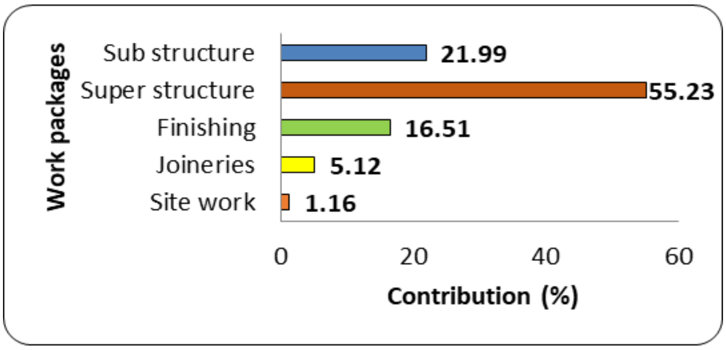

Figure 8: Work packages contributions to the overall carbon emissions (Mean value)

The top materials contributing 95% of the embodied carbon are concrete, reinforcement steel, cement, GI door, Tile, and paint. The quantity of materials and the embodied carbon values also play an important role. Even though the concrete embodied carbon value is less than the reinforcement steel's, 50% of the embodied carbon emission comes from concrete due to the large quantities. Figure 9 shows that the embodied carbon of concrete varies from 156.85 $kgCO_2eq/m^2$ to 246.68 $kgCO_2eq/m^2$ at the building level. The embodied carbon of reinforcement steel varies from 141.3 $kgCO_2eq/m^2$ to 206.81 $kgCO_2eq/m^2$ in the overall building. When the quantity is higher, variability plays a crucial role in the LCA calculation of the embodied carbon. Setting up a baseline for embodied carbon calculation is very important. The highest and lowest values are 89.63 $kgCO_2eq/m^2$ for concrete and 65.51 $kgCO_2eq/m^2$ for reinforcement steel. So, the variation in the dataset needs to be addressed by collecting more samples from the manufacturers in Indian conditions and setting a baseline for the embodied carbon factors, especially cement and steel, where the consumption is highest for the construction works in India. Since concrete and steel are the highest contributors of shear wall-based high-rise residential buildings, wastes like GGBS and fly ash can be used partially instead of cement, which has the highest embodied carbon in the concrete component. For the same grade of concrete, 42% of embodied carbon emission can be reduced using geopolymer concrete (Kiruthika et al., 2024), where the main components are GGBS and Fly ash. For the reinforcement, we can use the recycled steel, where embodied carbon is 0.42 $kgCO_2eq/kg$ (ICE data), compared to 2.68 $kgCO_2eq/kg$, resulting in up to 80% carbon reduction.

Table 3 shows a comparative analysis of embodied carbon values across the global case studies. This reveals the significant regional variation based on construction practices, building typologies, and life cycle scope definitions. The embodied carbon of the high-rise residential building assessed in this study ranged from 373 to 530 $kgCO_2eq/m^2$ (A1–A3), depending on the emission factor dataset. This variation aligns well with the international benchmarks reported for similar building types. For instance, embodied carbon values for high-rise buildings in Chicago (338.22 $kgCO_2eq/m^2$, A1–A3) and Hong Kong (465 $kgCO_2eq/m^2$, A1–A3) fall within or near this range (Ma et al., 2024; Zhang et al., 2024). The lower bound of the present study is also close to the German DGNB benchmark (365 $kgCO_2eq/m^2$, A1–A3), whereas the upper bound slightly exceeds it. In contrast, the IGBC Net Zero Carbon rating suggests a much higher indicative value of 700 $kgCO_2eq/m^2$ (A1–A4) for Indian contexts.

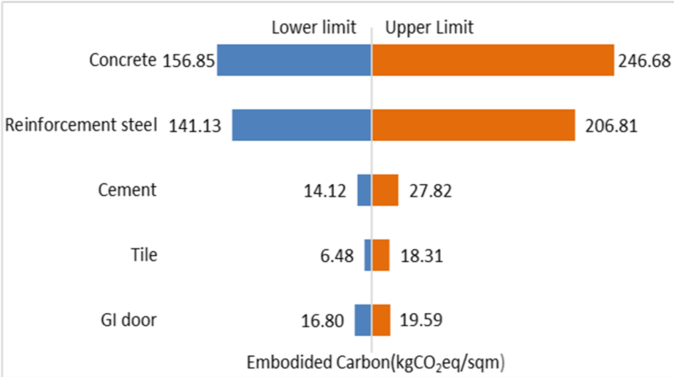

Figure 9: Variation in embodied carbon ($kgCO_2eq/m^2$)

Table 3: Comparison of embodied carbon

Country	Building type	Life-cycle stages	Embodied carbon ($kgCO_2eq/m^2$)	Reference
China	Residential	A1-A3	210.4–769.4	Zhang et al., 2023
Chicago	High-rise Office & Retail	A1-A3	338.22	Ma et al., 2024
Hong Kong	High rise Office & Retail	A1-A5	524.63	Yan et al., 2010
UK	2-storey residential	A1-A5	521.78	Keyhani et al., 2024
Hong Kong	High-rise Residential	A1-A3	465	Zhang et al., 2024
India	-	A1-A4	700	IGBC Net Zero carbon rating
Germany	-	A1-A3	365	DGNB
Denmark	More than 1000 m^2 building	A1-A3,B4,B6,C3-C4	600	Denmark county policy, WGBC, 2022

6. CONCLUSION AND FUTURE SCOPE

The variability in the embodied carbon of materials across different databases may be attributed to differences in the mining methods, quality of raw materials, materials processing, production technology, transport methods, electricity mix, packaging, and supply chain processes. Understanding the variability in embodied carbon of building materials from different sources plays a vital role in assessing the embodied carbon of high-rise residential buildings. This paper presents a case study on variation in embodied carbon of high-rise residential buildings in India. The high-rise residential building is based on RC monolithic concrete construction. The significant findings are listed below:

- The total embodied carbon (A1-A3) of the building (Built up area: 82,902 m2) varies from 373 $kgCO_2eq/m^2$ (IFC Indian dataset) to 530 $kgCO_2eq/m^2$ (EPiC) based on four embodied carbon datasets. The mean value of embodied carbon of the high-rise residential building is 454 $kgCO_2eq/m^2$. The standard deviation associated with the building embodied carbon is 65.3 $kgCO_2eq/m^2$. Considering India's urban development and high-rise residential building construction, the variability would be significant at the aggregate level.
- Concrete and steel emerge as the most significant contributors to embodied carbon, accounting for approximately 80% of total embodied carbon. Specifically, concrete contributes to about 45%, while reinforcement steel accounts for 36%. The total embodied carbon of concrete ranges from 157 $kgCO_2eq/m^2$ (based on the Indian dataset) to a maximum of 247 $kgCO_2eq/m^2$ (as per the EPiC dataset), with a mean value of 277$kgCO_2eq/m^2$. For reinforcement steel alone, the embodied carbon varies from 141 $kgCO_2eq/m^2$ (Indian dataset), 207 $kgCO_2eq/m^2$ (In-house tool), with a mean of 164$kgCO_2eq/m^2$.
- Even though the embodied carbon intensity of finishing materials is higher, their contribution is not prominent due to the lower usage in the building. We can observe that the substructure and superstructure represent 80% of the total embodied carbon. In particular, replacing cement with waste fine materials with the lowest embodied carbon is much appreciated in reducing carbon emissions.
- The variability in embodied carbon has critical implications for designers and builders, directly affecting material selection, design optimization, and compliance with carbon benchmarks. This study helps to set a benchmark for carbon emissions in the Indian context and the importance of having a standard dataset.

Suggestions for future research work are:

- Multiple case studies of high-rise residential buildings are needed to validate the findings that help set benchmarks in India.
- The scope can be extended to on-site construction (A4-A5) and the recurring embodied carbon due to periodical maintenance and repair work.
- Data collection to determine the embodied carbon of MEP components.

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