# Semi-Automated BIM-LCA Integration for Early-Stage Embodied Carbon Assessment: A Case Study of a Five-Story Office Building

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**Abstract:** The integration of Building Information Modelling (BIM) and Life Cycle Assessment (LCA) for early-stage building design is often limited by inconsistent material naming, manual classification, and time-consuming carbon calculations. Existing BIM-LCA approaches typically focus on structural components such as concrete and steel, while non-structural elements including partitions, finishes, and insulation remain underexplored despite their potential contribution to total embodied carbon. This study presents a semi-automated BIM-LCA workflow for whole-building embodied carbon assessment during cradle-to-gate (A1–A3) stages, developed in accordance with EN 15978:2011 and ISO 14040:2006. The workflow integrates automated material name cleaning, keyword-based classification with priority logic, and embedded density and emission factor assignment within a unified Excel-based framework using Visual Basic for Applications (VBA). A five-story office building modelled in Autodesk Revit at Level of Development (LOD) 300 serves as the case study, with material quantities extracted from the BIM model and processed through the VBA-based classification system; density values were obtained from the Engineering ToolBox and emission factors from the ICE Database Version 3.0. The workflow reduces manual processing time from 74.8 minutes to 4.5 minutes (94% reduction) through rule-based material classification and automated emission factor assignment. Results indicate that metal-related materials contribute 82% of total embodied carbon, with metal stud framing alone accounting for 81.6% due to its extensive use in partition walls across all five floors. Pareto analysis further confirms this concentration, with the top five materials responsible for over 94% of total embodied carbon, demonstrating that a small number of materials can dominate a building's embodied carbon profile. These findings highlight the importance of accounting for non-structural elements, frequently overlooked in conventional BIM-LCA assessments. The proposed method enables early-stage low-carbon design decisions without requiring specialized LCA expertise, offering a transparent, non-proprietary alternative to commercial BIM-LCA tools adaptable to different building typologies through modification of the keyword-based classification system.

**Keywords:** Building Information Modelling (BIM); Early-Stage Design; Embodied Carbon; Life Cycle Assessment (LCA); Level of Development (LOD) 300; Pareto Analysis

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## 1 Introduction

The building sector accounts for nearly 40% of global $CO_2$ emissions [1]. While operational carbon has traditionally been the primary focus of building energy regulations, embodied carbon emissions arising from material extraction, manufacturing, transportation, construction, maintenance, and end-of-life processes represent a significant and

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growing share of whole-life emissions [2]. As buildings become increasingly energy efficient, embodied carbon can exceed 50% of total emissions in low-energy and net-zero buildings [3]. Consequently, reducing embodied carbon during early design stages is critical for achieving global climate targets. Early-stage design decisions exert the greatest influence on a building's environmental performance, as material selection, structural systems, and spatial configurations are defined when changes are still economically feasible. However, conventional Life Cycle Assessment (LCA) methods are often time-consuming, data-intensive, and require specialized expertise, limiting their routine application in design practice [4, 5].

Building Information Modelling (BIM) offers strong potential to automate embodied carbon assessment because it contains structured material and quantity information [28]. Several BIM–LCA integration approaches have been proposed, ranging from manual spreadsheets to plugin-based and API-driven systems [6, 7], along with broader reviews of BIM–LCA developments [27, 29, 32]. Despite this progress, the effective use of BIM for early-stage embodied carbon assessment remains limited due to persistent data and workflow inefficiencies.

A major challenge lies in inconsistent material naming in BIM exports, where typographical variations, duplicates, and special characters require extensive manual preprocessing before analysis [8, 9]. In addition, automated mapping between BIM materials and LCA datasets remains underdeveloped, with most studies relying on manual classification procedures [10], although automated tools for building material selection have begun to emerge [36]. Furthermore, density and emission factor assignment is typically fragmented: volume-to-mass conversion requires external density databases, while emission factors are independently retrieved from sources such as the ICE database [11]. This fragmented workflow increases the risk of inconsistencies, unit conversion errors, and mapping inaccuracies [12].

Beyond data handling issues, most existing BIM–LCA studies focus primarily on structural components such as concrete and steel, while overlooking non-structural elements including partitions, finishes, insulation, and openings [13], and this gap extends to building services, which can also substantially influence whole-building LCA outcomes when properly incorporated [37]. However, these components can significantly contribute to total embodied carbon, particularly in office and multi-story buildings. In addition, relatively few studies explicitly address Level of Development (LOD) considerations, despite LOD 300 being widely recognized as suitable for early design assessment due to its balance between geometric reliability and design flexibility [14]. Moreover, the lack of embedded decision-support tools, such as hotspot identification, limits the practical usefulness of BIM–LCA outputs for designers [9]. Existing BIM–LCA integration methods can generally be grouped into four categories: plugin-based systems, visual programming approaches (e.g., Dynamo), openBIM/API-based frameworks using IFC, and rule-based classification systems [15], as confirmed by systematic reviews of BIM–LCA integration [31, 35]. Frameworks using IFC for early-stage embodied carbon benchmarking have also been proposed [26]. While each approach offers advantages, they all face limitations related to interoperability, manual data preparation, or dependence on specific software environments. In particular, rule-based classification methods show promise but remain highly dependent on predefined keyword libraries and require further automation to reduce manual intervention [13].

To address these gaps, this study develops a semi-automated BIM–LCA workflow based on LOD 300 BIM data for whole-building embodied carbon assessment. The proposed approach integrates automated material name cleaning, rule-based classification, and embedded assignment of density and emission factors into a unified Excel-based framework using Visual Basic for Applications (VBA). Unlike existing methods, the system simultaneously handles data cleaning, material classification, and carbon calculation, reducing fragmentation in the assessment process. In addition, the workflow explicitly incorporates non-structural building components and applies EN 15978:2011 [16] cradle-to-gate (A1–A3) boundaries.

Three objectives guide this research: (1) to develop a semi-automated BIM–LCA workflow for LOD 300 models covering both structural and non-structural components; (2) to quantify the reduction in manual processing time compared to conventional spreadsheet-based methods; and (3) to identify embodied carbon hotspots using Pareto analysis to support early-stage low-carbon design decisions. The scope is limited to A1–A3 stages, as these represent upfront material-related emissions that are most relevant during conceptual design, while operational and end-of-life stages are excluded for future work.

The proposed workflow contributes a transparent and non-proprietary alternative to commercial BIM–LCA tools, enabling greater adaptability without requiring specialized software environments. By integrating automated preprocessing, classification, and hotspot analysis within a single framework, the method improves both efficiency and interpretability of embodied carbon assessment in early design stages.

Overall findings of this study show that the developed workflow significantly reduces manual processing effort while enabling reliable whole-building embodied carbon quantification at LOD 300. The case study further demonstrates that non-structural elements can constitute major carbon hotspots, and that Pareto-based analysis effectively identifies a small number of materials responsible for the majority of emissions. These results highlight the importance of integrated, automated BIM–LCA workflows for supporting early-stage sustainable design decisions.

## 2 Materials and Methods

The proposed semi-automated workflow for whole-building embodied carbon assessment integrates BIM-based quantity extraction with LCA calculations for the cradle-to-gate (A1–A3) stages, following the principles described in EN 15978:2011 [16] and the ISO 14040:2006 standard for Life Cycle Assessment [17]. The workflow comprises four sequential phases: (1) BIM quantity extraction and quality control at Level of Development (LOD) 300; (2) VBA-based material cleaning and keyword classification with priority logic; (3) automated density assignment and emission factor matching; and (4) embodied carbon calculation with cumulative percentage and Pareto analysis.

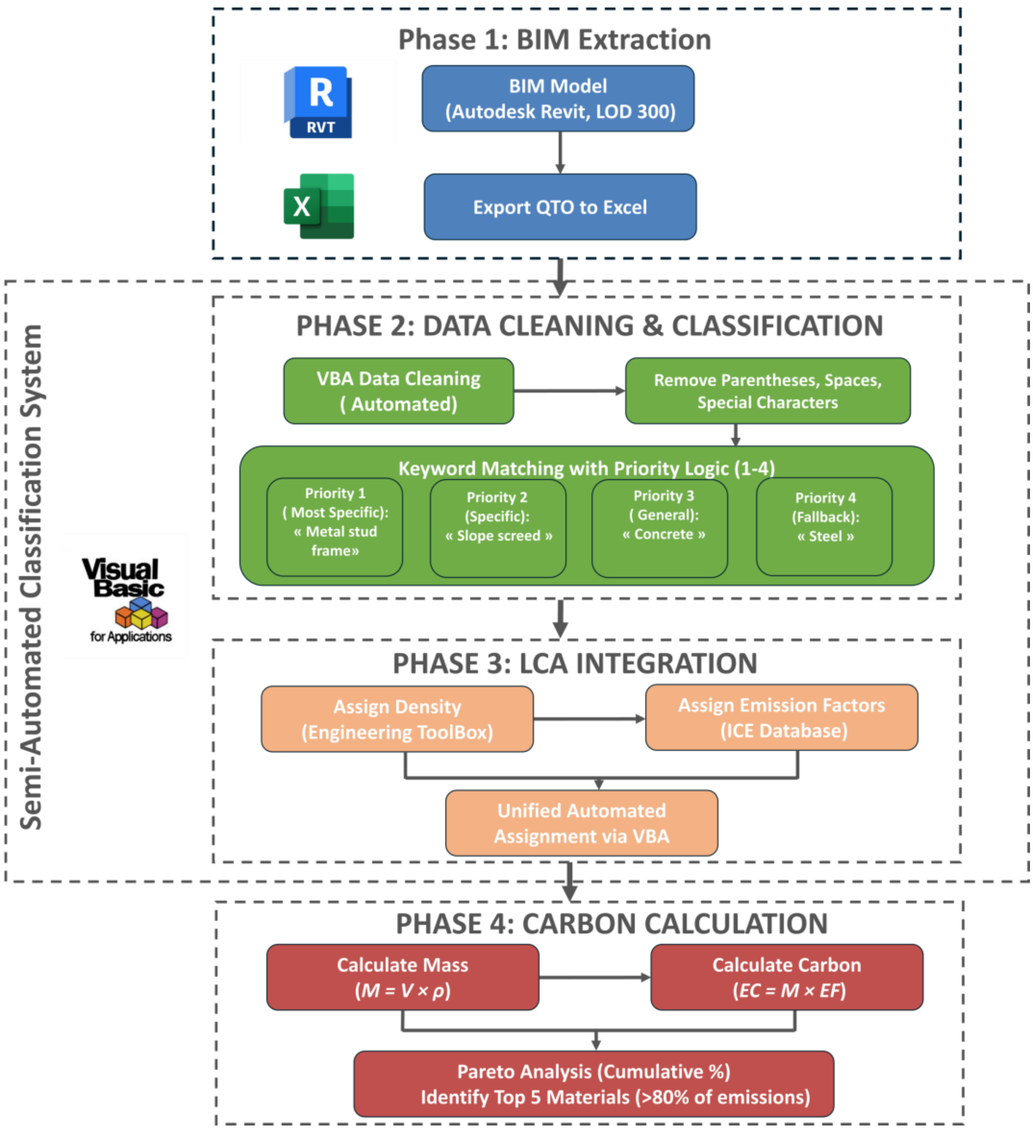



Figure 1 Methodology flowchart of the proposed semi-automated BIM-LCA workflow, showing sequential steps from Revit model extraction to Pareto-based hotspot identification (cradle-to-gate scope A1–A3)

The system boundaries of this study are defined as cradle-to-gate (modules A1–A3 according to EN 15978:2011 [16]): raw material supply (A1), transportation to manufacturing (A2), and manufacturing processes (A3). The functional unit is defined as one five-story office building. Operational carbon (B1–B7), maintenance, replacement, construction (A4–A5), and end-of-life stages (C1–C4) are excluded from the present scope, as the focus is on early-stage embodied carbon assessment where material production emissions dominate design decisions.

## 2.1 BIM Extraction and Quality Control

The BIM model was developed using Autodesk Revit for a five-story office building project, including slabs, columns, beams, foundations, external walls, internal partitions, finishes, and openings. The model was developed to Level of Development (LOD) 300 following the AIA framework. At LOD 300, building elements contain sufficient geometric accuracy and material information for reliable quantity takeoff, including element-specific volume and area parameters, while remaining within the early design phase where modifications remain economically practical. This balance between information accuracy and design flexibility makes LOD 300 particularly suitable for early-stage BIM-LCA integration.

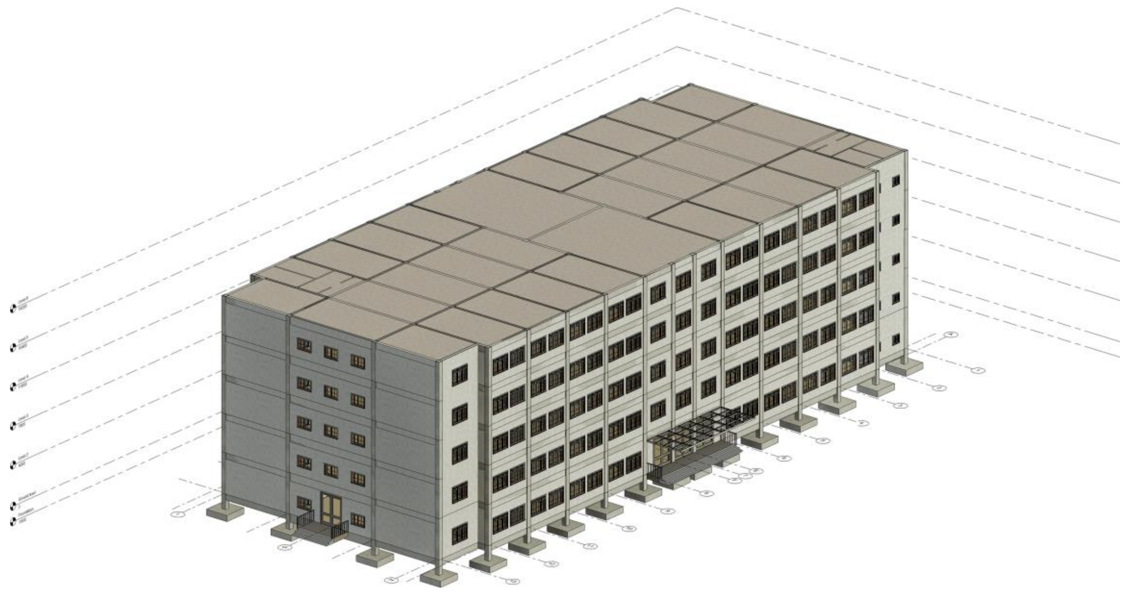


Figure 2 Three-dimensional BIM model visualization at LOD 300 of the case study five-story office building

Quality control procedures were applied to the BIM model before quantity extraction, including geometric consistency checks (verifying element connectivity and absence of unintended overlaps), material verification (confirming that each element had an assigned material with consistent naming), completeness assessment (ensuring all major building systems were modelled), and LOD boundary documentation (recording any simplifications or assumptions).

Table 1 Summary of case study building and BIM model specifications

| Parameter | Value |
| --- | --- |
| Building Type | Five-story office building |
| BIM software | Autodesk Revit |
| Level of Development (LOD) | 300 (AIA framework) |
| Key Structural Components | Slabs, columns, beams, foundations |
| Key Architectural Components | External walls, internal partitions, finishes, and openings |
| Total Material Types Extracted | 25 distinct materials |
| Quality Control Procedures | Geometric consistency, material verification, completeness checks |

*Table 1 summarizes the BIM model specifications.

Material data were extracted through the Multi-Category Material Quantity Takeoff function in Revit, capturing material name, area, and volume for each building element. Following extraction, the raw material dataset was preprocessed to improve consistency. Materials were sorted by name, while minor materials and negligible quantities were excluded to reduce unnecessary complexity. Similar materials were grouped into unified categories. Total area and volume values for each material were aggregated so that each material type was represented in a single row. Area was extracted to act as a quality check: if Area is zero but Volume is positive, this indicates a potential modeling error. The processed dataset was then exported to Microsoft Excel as a raw data file for subsequent classification and carbon calculation.

Table 2 BIM-based Multi-Category Material Takeoff schedule at LOD 300, showing raw material names, area, and volume parameters prior to cleaning and classification

| Material: Name | Material: Area | Material: Volume |
|---|---|---|
| Aluminium | 52 $m^2$ | 0.94 $m^3$ |
| Ceiling | 10426 $m^2$ | 104.26 $m^3$ |
| Cement Plaster (Exterior) | 2946 $m^2$ | 58.64 $m^3$ |
| Cement Screed ( Slab) | 8719 $m^2$ | 348.78 $m^3$ |
| Ceramic Tile ( Floor Finish) | 8672 $m^2$ | 86.72 $m^3$ |
| Clad - White (window frame & trim) | 288 $m^2$ | 2.06 $m^3$ |
| Concrete | 25 $m^2$ | 4.28 $m^3$ |
| Concrete Blocks | 2936 $m^2$ | 581.73 $m^3$ |
| Concrete, Cast-in-Place gray | 9343 $m^2$ | 1035.27 $m^3$ |
| Glass | 1792 $m^2$ | 7.70 $m^3$ |
| Gravel | 48 $m^2$ | 7.15 $m^3$ |
| Gypsum Board (Finishing) | 10053 $m^2$ | 150.80 $m^3$ |
| Internal Gypsum Plaster | 2906 $m^2$ | 86.75 $m^3$ |
| Lightweight Concrete | 48 $m^2$ | 4.77 $m^3$ |
| Metal - Stainless Steel (exterior pull + panic bar) | 6 $m^2$ | 0.04 $m^3$ |
| Metal Stud Frame ( Interior wall) | 5027 $m^2$ | 603.21 $m^3$ |
| Plaster | 50 $m^2$ | 0.76 $m^3$ |
| Reinforced Concrete Slab | 10474 $m^2$ | 1484.31 $m^3$ |
| Slope Screed ( Slab) | 1754 $m^2$ | 105.24 $m^3$ |
| Steel - Paint Finish - Grey (door frame) | 253 $m^2$ | 5.63 $m^3$ |
| Steel- Paint Finish - Grey (office door frame + glass stop) | 221 $m^2$ | 4.19 $m^3$ |
| Stone Grey Stone Finish | 48 $m^2$ | 1.19 $m^3$ |
| Thermal Insulation ( XPS) | 4697 $m^2$ | 286.68 $m^3$ |
| Wood - Birch (door panel) | 594 $m^2$ | 12.53 $m^3$ |
| Wood - Stained | 1835 $m^2$ | 23.51 $m^3$ |

*Table 2 presents the raw Multi-Category Material Takeoff extracted from the BIM model at LOD 300, comprising 25 distinct material types with their corresponding area and volume parameters prior to name cleaning and classification.

## 2.2 Data Cleaning and Classification

The extracted raw dataset was transferred to Excel for cleaning and classification. First, material name standardization was automated using Visual Basic for Applications (VBA), removing parentheses, extra spaces, special characters, typographical inconsistencies, and repeated hyphens. The VBA script used InStr for keyword matching, Replace to remove special characters, Trim to eliminate extra spaces, and LCase for case-insensitive standardization.

Second, material categories were assigned using keyword-based matching. Main categories included: Structural, Metal, Finishing, Opening, Masonry, Glass, Wood, Insulation, and Earthworks. Subcategories were automatically identified using predefined keywords developed from the BIM modelling stage. The keyword library is adaptable to different building types; users can modify the keyword lookup table (categories, subcategories, density values, emission factors) without changing the VBA code structure.

To minimize incorrect or overlapping matches, priority-based logic (levels 1–4) was implemented, where lower numbers indicate higher priority based on specificity, engineering meaning, LCA relevance, and conflict resolution.

```
Attribute VB_Name = "Module1"
Sub Step1_CleanAllMaterialsNames()
    Dim i As Long
    Dim lastRow As Long
    Dim txt As String
    Dim p As Integer

    ' Find last row in column A
    lastRow = Cells(Rows.Count, 1).End(xlUp).Row

    ' Start from row 2 as specified
    For i = 2 To lastRow
        txt = Cells(i, 1).Value

        ' Remove parentheses and everything after
        p = InStr(txt, "(")
        If p > 0 Then txt = Trim(Left(txt, p - 1))

        ' Clean the text
        txt = LCase(txt)
        txt = Replace(txt, "&", "and")
        txt = Replace(txt, "  ", " ")
        txt = Replace(txt, "lighweight", "lightweight")
        txt = Application.Trim(txt)

        ' Write cleaned name to column B (Cleaned Name)
        Cells(i, 2).Value = txt
    Next i

    ' Optional: Add header "Cleaned Name" to cell B1
    Cells(1, 2).Value = "Cleaned Name"

    MsgBox "Cleaning complete! Processed " & (lastRow - 2) & "
materials."
End Sub
Sub Step2_Classification()

    Dim wsData As Worksheet, wsKey As Worksheet
    Dim lastRow As Long, lastKey As Long
    Dim i As Long, j As Long
    Dim material As String
    Dim bestMatchRow As Long
    Dim bestPriority As Integer

    Set wsData = Sheets("BIM-LCA cleaned")
    Set wsKey = Sheets("KEYWORDS")

    lastRow = wsData.Cells(wsData.Rows.Count, 2).End(xlUp).Row
    lastKey = wsKey.Cells(wsKey.Rows.Count, 1).End(xlUp).Row

    For i = 2 To lastRow

        material = LCase(wsData.Cells(i, 2).Value)

        wsData.Cells(i, 3).Value = ""
        wsData.Cells(i, 4).Value = ""

        bestMatchRow = 0
```

a

```
        bestPriority = 9999

        For j = 2 To lastKey

            If InStr(1, material, LCase(wsKey.Cells(j, 1).Value)) > 0
Then

                currentPriority = wsKey.Cells(j, 4).Value

                If currentPriority < bestPriority Then
                    bestPriority = currentPriority
                    bestMatchRow = j
                End If
            End If
        Next j

        If bestMatchRow > 0 Then
            wsData.Cells(i, 3).Value = wsKey.Cells(bestMatchRow, 2).Value
            wsData.Cells(i, 4).Value = wsKey.Cells(bestMatchRow, 3).Value
        End If

    Next i

    MsgBox "Classification complete.", vbInformation

End Sub
```

b

Figure 3 a. Visual Basic for Applications (VBA) module structure showing the material name cleaning routine (Step1_CleanAllMaterialsNames). b. Keyword-based classification routine (Step2_Classification) with priority logic implementation

## 2.3 LCA Integration: Density and Emission Factor Assignment

After automatic assignment of material categories and subcategories using the VBA-based classification system, density values were assigned through the same semi-automated workflow. Density data were obtained from Engineering ToolBox [18] to convert BIM-derived volumes into mass values required for LCA calculations. To improve workflow integration, density values were incorporated directly into the keyword reference sheet. Each keyword entry contained the corresponding material category, subcategory, priority level, and density value. Using VBA-based keyword matching, the system automatically assigned density values according to the classified material type.

Following density assignment, embodied carbon emission factors were integrated using a similar VBA procedure. A dedicated worksheet named "LCA FACTORS" was created to store emission factors derived from the ICE Database Version 3.0 [11], which provides cradle-to-gate emission factors corresponding to modules A1–A3 defined in EN 15978:2011 [16]. The "LCA FACTORS" worksheet linked emission factor values to specific material categories and subcategories, ensuring consistent matching between BIM materials and LCA datasets. All 25 distinct material types extracted from the BIM model were successfully matched with appropriate emission factors. Some materials shared identical emission factors due to similar composition.

## 2.4 Carbon Calculation

After assigning all required material parameters, the mass of each building material was calculated automatically by the VBA script using the relationship between volume and density Eq. (1):

$$M_i = V_i \times \rho_i \tag{1}$$

Where: $M_i$ - mass of material $i$ (kg); $V_i$ - volume of material $i$ extracted from the BIM model ($m^3$); $\rho_i$- density of material $i$ ($kg/m^3$).

To ensure correctness, the VBA script was first tested on a single material row to verify mass and embodied carbon outputs. After confirming accuracy, the script was executed on the full dataset.

Once mass values were obtained, embodied carbon for each material was calculated using Eq. (2):

$$EC_i = M_i \times EF_i \tag{2}$$

Where: $EC_i$- embodied carbon of material $i$ (kg$CO_2$e); $M_i$ - mass of material $i$ (kg); $EF_i$- embodied carbon emission factor of material $i$ (kg$CO_2$e/kg).

After completing all calculations, the dataset was copied and pasted as values into a new file named "LCA Calculation Final" to remove formula dependencies and ensure dataset stability for analysis.

Percentage contribution of each material to total embodied carbon was calculated using Eq. (3):

$$P_i = \frac{EC_i}{EC_{total}} \times 100 \tag{3}$$

Where: $P_i$- percentage contribution of material $i$ to the total embodied carbon (%); $EC_i$- embodied carbon of material $i$; $EC_{total}$- total embodied carbon of the building.

To identify the most important contributors, a cumulative percentage calculation was performed, followed by Pareto analysis. All materials were sorted in descending order of embodied carbon, and the cumulative percentage was calculated using Eq. (4):

$$CP_i = \frac{\sum_{j=1}^{i} EC_j}{EC_{total}} \times 100 \tag{4}$$

Where: $CP_i$- cumulative percentage up to material $i$ (%); $EC_j$- embodied carbon of material ranked $j$; $EC_{total}$- total embodied carbon of all materials.

## 2.5 Comparative Timing Test

To quantify the efficiency improvement of the proposed workflow, a comparative timing test was conducted. The same 25-material dataset was processed using two methods: (1) a fully manual spreadsheet-based method following conventional practice (cleaning, classification, density lookup, emission factor matching, calculations); and (2) the proposed semi-automated VBA method. Both workflows were executed three times, and average processing times were recorded. The percentage reduction was calculated as Eq. (5):

$$\text{Reduction} = \frac{\text{Manual time} - \text{Automated time}}{\text{Manual time}} \times 100 \tag{5}$$

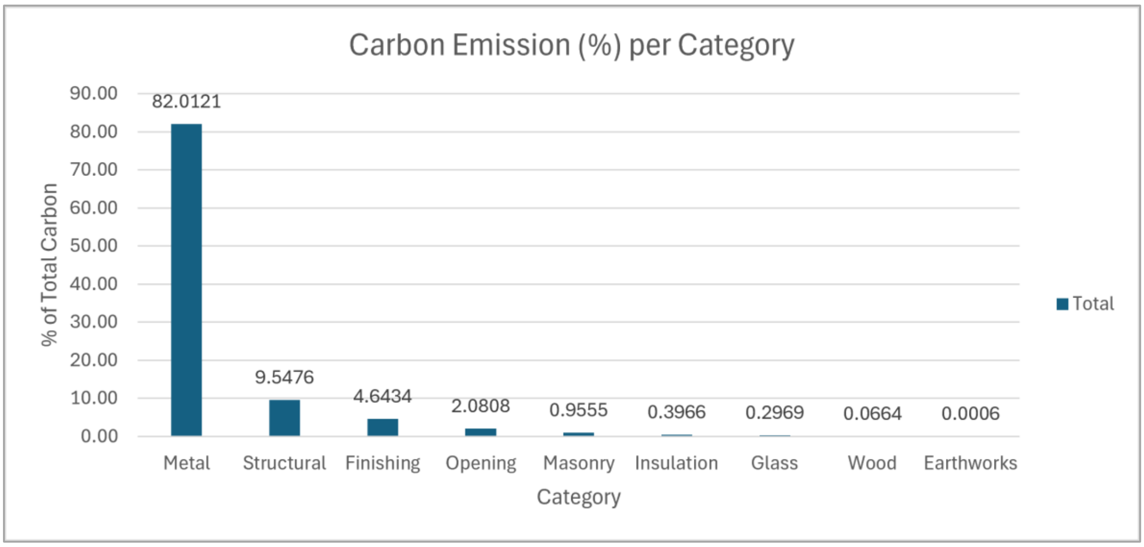
Results are presented in the Results Section.

# 3 Results

The proposed semi-automated BIM-LCA workflow successfully processed all 25 material types extracted from the five-story office building model at LOD 300. The workflow completed material cleaning, classification, density assignment, emission factor matching, mass calculation, embodied carbon calculation, percentage contribution, and cumulative percentage analysis without manual intervention after the initial VBA execution. The total embodied carbon for the building across the cradle-to-gate stages (A1–A3) was calculated to be 9,336,972 $kgCO_2e$.

## 3.1 Embodied Carbon by Material Category

Aggregating results by material category reveals that metal-related materials are the dominant contributors to total embodied carbon. The Metal category accounts for 82.01% of total emissions (7,657,061 $kgCO_2e$), significantly exceeding all other categories. Structural materials are the second-largest contributor at 9.54% (891,413 $kgCO_2e$), followed by Finishing (4.64%, 433,530 $kgCO_2e$), Opening (2.08%, 194,277 $kgCO_2e$), and Masonry (0.95%, 89,214 $kgCO_2e$). Insulation, Glass, Wood, and Earthworks collectively contribute less than 1% each. The total contribution of all categories equals 100%, confirming internal consistency and reliability.

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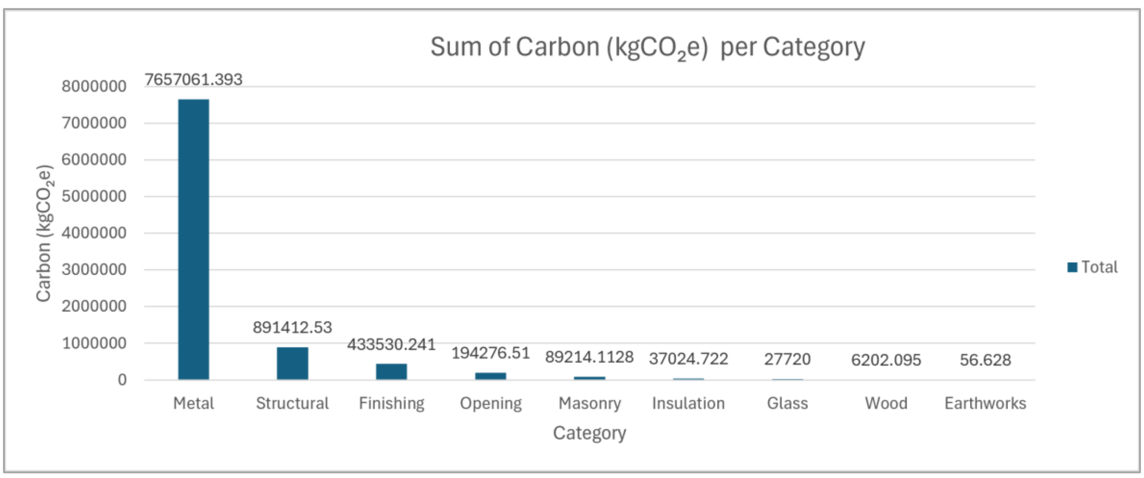


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Figure 4 a. Distribution of cradle-to-gate (A1-A3) percentage of total embodied carbon across material categories. b. Cradle-to-gate (A1–A3) embodied carbon by material category

To simplify interpretation for design practitioners, all material categories contributing less than 1% of total embodied carbon were grouped into a single "Others" category. In this simplified classification, Metal remained the dominant contributor at 81.65%, followed by Structural (9.52%), Finishing (2.93%), Opening (1.18%), and Others (4.70%). The slight differences between detailed and simplified results are attributed to the regrouping of minor subcategories rather than changes in the original data. The simplified analysis confirms that overall findings remain consistent regardless of categorization level.

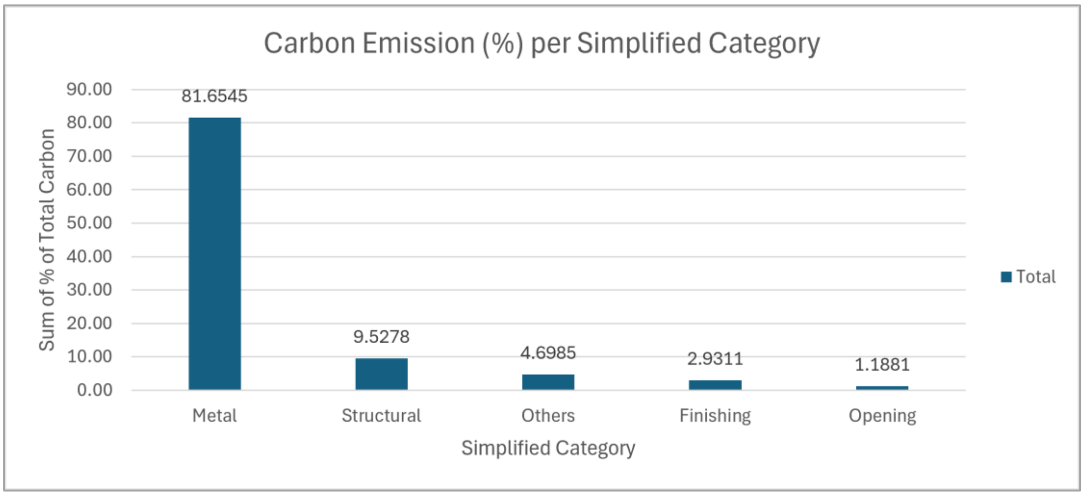


Figure 5 Simplified Distribution of cradle-to-gate (A1-A3) percentage of total embodied carbon across material categories

## 3.2 Embodied Carbon by Individual Material (Hotspot Analysis)

Metal stud framing alone contributes 7,623,670 $kgCO_2e$, representing approximately 81.65% of the total embodied carbon of the building. This exceptionally high contribution is primarily attributed to the extensive use of metal stud framing throughout the building for internal partition wall systems. Unlike localized structural elements, partition walls are distributed across all five floors and interior spaces, resulting in a cumulative volume of 603.21 $m^3$ and a total mass of $4.74 \times 10^6$ kg. Although the emission factor of steel framing (1.61 $kgCO_2e/kg$) is lower than that of materials such as aluminum (13.06 $kgCO_2e/kg$), the very large quantity substantially increases its overall carbon contribution. Thus, the dominance of metal stud framing is driven mainly by material quantity rather than emission factor intensity.

Table 3 Top five embodied carbon hotspots with cumulative percentage contribution

| **Original Name** | **Cleaner Name** | **Category** | **Subcategory** | **Volume ($m^3$)** | **Density ($kg/m^3$)** | **Mass (Kg)** | **Emission Factors ($kgCO_2e/kg$)** | **Carbon ($kgCO_2e$)** | **% Total Carbon** | **Cumulative %** |
|---|---|---|---|---|---|---|---|---|---|---|
| Metal Stud Frame (Interior wall) | metal stud frame | Metal | Steel Framing | 603.21 | 7850 | 4735198.5 | 1.61 | 7623669.59 | 81.6545 | 81.65 |
| Reinforced Concrete Slab | reinforced concrete slab | Structural | Reinforced Concrete | 1484.31 | 2500 | 3710775 | 0.15 | 556616.25 | 5.9617 | 87.62 |
| Concrete, Cast-in-Place gray | concrete, cast-in-place gray | Structural | Cast-in-place Concrete | 1035.27 | 2400 | 2484648 | 0.134 | 332942.832 | 3.5660 | 91.18 |
| Ceramic Tile (Floor Finish) | ceramic tile | Finishing | Ceramic Tile | 86.72 | 2200 | 190784 | 0.758 | 144614.272 | 1.5489 | 92.73 |
| Cement Screed (Slab) | cement screed | Finishing | Floor Screed | 348.78 | 2000 | 697560 | 0.185 | 129048.6 | 1.3822 | 94.11 |

*Table 3 presents the top five embodied carbon hotspots with cumulative percentage contributions. The results show that the first two materials account for more than 87% of total emissions, and the first five materials exceed 94% of total embodied carbon.

Several materials exhibited high embodied carbon intensity per unit mass despite low total quantity. Materials with emission factors exceeding 2 $kgCO_2e/kg$ include aluminum (13.06 $kgCO_2e/kg$), XPS thermal insulation (3.69 $kgCO_2e/kg$), steel paint finish (2.51 $kgCO_2e/kg$), and clad-white cladding panels (2.10 $kgCO_2e/kg$). Although aluminum contributed a relatively small mass (2,557 kg), its high emission factor resulted in 33,392 $kgCO_2e$ of embodied carbon. Despite ranking 12th by total carbon contribution, aluminum's emission intensity is the highest among all materials. This highlights the importance of assessing both total quantity and emission intensity, as materials with low quantities but high emission factors may still have a significant environmental impact and should not be overlooked in design optimization.

## 3.3 Pareto Distribution of Embodied Carbon

The Pareto analysis confirms that embodied carbon is highly concentrated within a limited number of materials. Figure 6 presents the Pareto curve derived from the cumulative percentage analysis. The cumulative line reaches 81.65% after the first material (metal stud framing), 87.61% after the second material (reinforced concrete slab), and 94.11% after the fifth material (cement screed). This concentration pattern validates the application of the Pareto principle to embodied carbon hotspot identification.

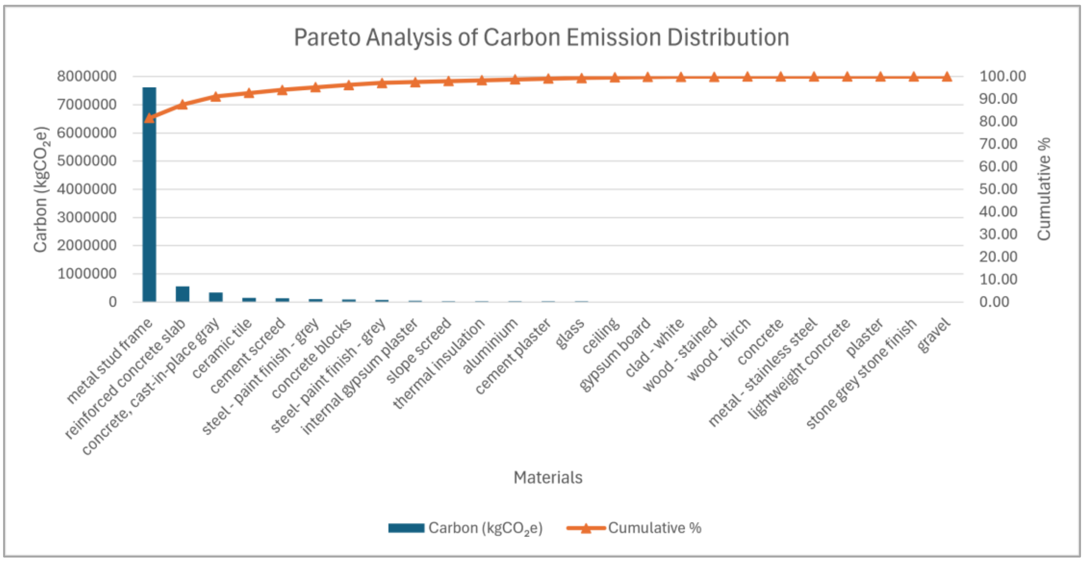


Figure 6 Pareto curve showing cumulative embodied carbon contribution of materials ranked from highest to lowest impact. Blue bars represent individual material contributions; the orange line shows cumulative percentage

## 3.4 Processing Time Comparison

The comparative timing test demonstrated a substantial reduction in manual processing time using the proposed semi-automated workflow. The manual spreadsheet-based method required 74.8 minutes on average to process the 25-material dataset (including cleaning, classification, density lookup, emission factor matching, and calculations). The semi-automated VBA method required 4.49 minutes on average for the same operations.

Percentage reduction was calculated as Eq. (6):

$$Reduction = \frac{(74.8-4.49)}{74.8} \times 100 \tag{6}$$

These results confirm that the proposed semi-automated workflow reduces manual processing time by approximately 94% compared to conventional spreadsheet-based manual methods.

# 4 Discussion

The results of this study demonstrate that a semi-automated BIM–LCA workflow can effectively support whole-building embodied carbon assessment at early design stages using LOD 300 BIM data. The proposed framework significantly reduces manual processing time by 94%, from 74.8 minutes to 4.49 minutes, indicating that embodied carbon evaluation can be integrated into routine design workflows without requiring advanced LCA expertise. This improvement addresses one of the main practical barriers to BIM–LCA adoption, where time-consuming data preparation limits usability in early design practice. Broader adoption is further constrained by stakeholder-related challenges identified in recent studies [25].

The dominance of metal stud framing as the primary embodied carbon hotspot (81.65% of total emissions) contrasts with many previous BIM–LCA studies, where reinforced concrete or structural steel are typically identified as the main contributors [19, 20]. This difference is explained by the specific characteristics of the case study building, which includes extensive internal partition systems distributed across all five floors. Similar patterns have been reported in cases where non-structural elements play a dominant role due to their cumulative material quantities [21]. Unlike structural components, which are concentrated in limited zones, partition systems are spatially distributed, leading to high total material demand. This highlights that excluding non-structural elements can lead to incomplete or biased interpretations of embodied carbon results [13].

The Pareto analysis further confirms a strong concentration effect, with the top five materials accounting for 94.11% of total embodied carbon. This aligns with previous studies showing that a small number of materials typically dominate emissions in office buildings [22, 23]. However, the ranking observed here differs from structural-focused studies where concrete or steel dominate, reinforcing that embodied carbon hotspots are highly dependent on building typology and design configuration. As a result, generalizing hotspot patterns across projects is not reliable, and building-specific assessment is necessary for accurate decision-making.

These findings have direct implications for early-stage low-carbon design. Since metal stud framing alone contributes more than 80% of total emissions, it represents the most influential design lever. Potential reduction strategies include minimizing partition density through spatial optimization, adopting more open-plan layouts where functionally appropriate, or substituting steel studs with lower-carbon alternatives such as timber or recycled systems when feasible. Reinforced concrete and cast-in-place concrete, contributing 9.53% combined, offer secondary reduction opportunities through material optimization, alternative cementitious blends, or structural efficiency improvements such as slab thickness reduction. Finishing materials represent a smaller share (2.93%) and become relevant only after major hotspots are addressed.

The major advantage of the proposed workflow is its ability to support rapid iteration during early design. The 94% reduction in processing time enables designers to test multiple design alternatives and immediately observe embodied carbon implications, shifting assessment from a static evaluation to a more interactive decision-support process. This aligns with recent developments in BIM-based sustainability tools that emphasize feedback-driven design optimization [24], including purpose-driven LCA–BIM integration approaches [30] and automated sustainability assessment frameworks [33].

Several limitations should be considered. The use of static emission factors from the ICE database [11] does not capture regional variations, supply chain differences, or project-specific material properties, meaning results should be interpreted as early-stage approximations rather than precise values. The system boundary is limited to cradle-to-gate stages (A1–A3), excluding transport, construction, operational, and end-of-life impacts, as well as biogenic carbon effects in timber materials. The workflow is also semi-automated, meaning classification accuracy still depends on consistent BIM material naming, which may vary across models and require manual adjustment of the keyword database. Finally, the study is based on a single case study of a five-story office building, which limits the generalizability of numerical results, although the methodological framework remains transferable.

Future work could extend this approach toward more advanced BIM–LCA integration using dynamic emission databases, regionalized material data, and automated material recognition techniques such as machine learning. Further research could also integrate circular economy strategies, including material reuse and recycling scenarios, to expand the analysis beyond cradle-to-gate boundaries and support whole-life carbon assessment. Related work on circular-economy-oriented BIM–LCA integration and end-of-life waste management further supports this direction [34, 38].

## 5 Conclusions

This study presented a semi-automated BIM–LCA workflow for early-stage whole-building embodied carbon assessment within the cradle-to-gate (A1–A3) stages. Using a five-story office building modelled at LOD 300, the proposed framework achieved a 94% reduction in manual processing time compared to conventional spreadsheet-based methods, decreasing from 74.8 minutes to 4.49 minutes. This result demonstrates a substantial improvement in workflow efficiency, indicating that embodied carbon assessment can be integrated into early design practice in a faster and more operationally feasible manner.

The findings show that embodied carbon is highly concentrated in a limited number of material groups. Metal-related components account for 82.01% of total embodied carbon, with metal stud framing alone contributing 81.65% due to its extensive use in partition wall systems across the building. Reinforced concrete and cast-in-place concrete represent the second-largest contributors, accounting for 9.54% combined. The Pareto analysis further confirms this concentration pattern, with the top five materials responsible for 94.11% of total embodied carbon emissions. These results highlight that a small number of materials can dominate the embodied carbon profile of a building, particularly when non-structural elements are included in the assessment.

The study demonstrates the practical relevance of integrating automated BIM–LCA processes into early-stage design workflows. The proposed method enables rapid identification of embodied carbon hotspots at a stage when design modifications remain feasible and cost-effective. By eliminating the need for specialized LCA expertise and operating within a commonly used spreadsheet environment, the workflow lowers the barrier to embodied carbon assessment and supports its wider adoption in design practice. In addition, the approach is adaptable to different building typologies through modification of the keyword-based classification system, enhancing its applicability beyond the presented case study.

Overall, this research confirms that combining automated data cleaning, material classification, and carbon calculation within a unified BIM–LCA framework significantly improves both efficiency and usability of embodied carbon assessment. This contributes to bridging the gap between theoretical LCA methodologies and practical design implementation, supporting more informed and timely low-carbon decision-making in early-stage building design.

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