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# Carbon–Cost Optimization of Construction Projects Using BIM, Life Cycle Assessment and Multi-Criteria Decision Making

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**Abstract -** The construction industry faces increasing pressure to reduce carbon emissions while maintaining project affordability and long-term economic performance. This study develops an integrated carbon–cost optimization framework combining Building Information Modelling (BIM), Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and Multi-Criteria Decision Making (MCDM) for sustainable construction project evaluation. BIM is used to extract material quantities and project data, which are integrated with carbon emission factors and cost information to quantify life-cycle environmental and economic impacts. Alternative construction scenarios are evaluated by considering embodied carbon, operational carbon, initial construction cost, life-cycle cost, energy performance, and other relevant project criteria. An MCDM approach is applied to systematically assess the alternatives and identify solutions that achieve an effective balance between carbon reduction and economic performance. Sensitivity analysis is further employed to examine the robustness of the decision-making outcomes under variations in criterion weights. The integrated framework provides a structured decision-support approach for comparing construction alternatives at the project planning and design stages. The study demonstrates how BIM-enabled environmental and economic assessment can support informed material selection, cost management, and low-carbon construction strategies. The research contributes to sustainable construction management by integrating carbon and cost considerations within a unified decision-making framework and provides practical support for project managers, cost professionals, designers, and other stakeholders pursuing economically viable low-carbon construction.

***Key Words***: Building Information Modelling (BIM); Life Cycle Assessment (LCA); Life Cycle Costing (LCC); Carbon–Cost Optimization; Multi-Criteria Decision Making (MCDM); Sustainable Construction; Embodied Carbon; Construction Cost.

## 1.INTRODUCTION

### 1.1 Background and Context

The construction industry plays a significant role in global resource consumption, energy demand, carbon emissions, and economic development. Buildings generate environmental impacts throughout their life cycle, including material production, transportation, construction, operation, maintenance, replacement, and end-of-life activities. Consequently, reducing both embodied and operational carbon emissions has become an important consideration in sustainable construction and project planning [3], [5].

Construction decisions are also strongly influenced by economic constraints. Selection of structural systems, construction materials, building envelopes, and energy-efficient technologies can reduce environmental impacts but may alter initial investment, maintenance expenditure, replacement requirements, and long-term operating costs. Therefore, evaluating construction alternatives solely on initial cost or carbon emissions may not provide an adequate basis for sustainable project decision-making. Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) provide complementary approaches for evaluating environmental and economic performance throughout the building life cycle [1], [2].

Building Information Modelling (BIM) provides a digital platform for integrating geometric, material, quantity, cost, and performance information. BIM-based quantity extraction can support systematic linkage of construction materials with carbon emission factors and cost data, enabling carbon and economic impacts to be assessed during project planning and design [3], [4]. Previous research has demonstrated the potential of BIM to integrate life-cycle carbon assessment and life-cycle cost analysis within a common information environment [1].

However, construction alternatives often involve trade-offs among carbon emissions, life-cycle cost, energy performance, durability, and other project requirements. Multi-Criteria Decision Making (MCDM) provides a structured mechanism for evaluating such competing criteria and comparing alternative solutions [14], [16], [17]. Integrating BIM, LCA, LCC, and MCDM therefore provides a systematic basis for carbon–cost optimization, allowing construction alternatives to be evaluated from both environmental and economic perspectives while supporting informed project and cost-management decisions [1], [2].

### 1.2 Carbon and Cost Challenges in Construction Projects

Construction projects generate carbon emissions across multiple life-cycle stages, including raw-material extraction, manufacturing, transportation, on-site construction, building operation, maintenance, replacement, and end-of-life processes [5], [18], [19]. Among these impacts, carbon associated with high-volume and energy-intensive materials such as concrete and steel can significantly influence embodied emissions, while energy consumption during building operation contributes to operational carbon over the service life [3], [4].

Cost management presents a parallel challenge because project decisions affect both initial and long-term expenditure. Material procurement, labour, equipment, installation, operation, maintenance, component replacement, energy consumption, and end-of-life activities contribute to the total life-cycle cost of a construction project [1], [7], [20]. A construction alternative with a lower initial cost may therefore result in higher operating or maintenance expenditure, while a low-carbon alternative may require different levels of initial investment.

Carbon and cost objectives can consequently create trade-offs during project planning and design. Selecting alternatives solely on the basis of minimum initial cost can overlook long-term environmental and economic impacts, whereas minimizing carbon emissions without considering financial

implications may limit practical implementation. An integrated life-cycle assessment is therefore required to quantify these competing impacts and support the identification of construction alternatives that achieve an appropriate balance between carbon reduction and economic performance [1], [2].

For each construction alternative (j), the fundamental optimization problem can be expressed as:

$$\min[WLC_j, LCC_j] \dots \dots (1)$$

where ($WLC_j$) represents the whole-life carbon emissions of alternative (j), and ($LCC_j$) represents its life-cycle cost. This dual-objective relationship forms the basis for the carbon–cost evaluation and multi-criteria decision-making framework developed in this study.

### 1.3 Role of BIM and Life Cycle Assessment

Building Information Modelling (BIM) provides an integrated digital environment for managing geometric, material, quantity, and performance information throughout a construction project. In sustainability assessment, BIM facilitates automated or semi-automated quantity take-off and enables building components to be linked with environmental and cost databases. This integration improves the consistency of information used for carbon and life-cycle assessment and allows environmental impacts to be considered during project planning and design [2]–[4].

Life Cycle Assessment (LCA) provides a systematic method for quantifying environmental impacts across the building life cycle, including material production, transportation, construction, operation, maintenance, replacement, and end-of-life stages [5], [18], [19]. When integrated with BIM, material quantities extracted from the digital model can be combined with corresponding carbon emission factors to estimate the carbon contribution of individual materials and building components [3], [4].

The embodied carbon associated with construction materials can be calculated as:

$$EC = \sum_{i=1}^{n} (Q_i \times EF_i) \dots \dots (2)$$

where:
EC = total embodied carbon emissions (kg $CO_2e$),
$Q_i$ = quantity of material i (kg, $m^3$, or other applicable unit),
$EF_i$ = carbon emission factor of material i (kg $CO_2e$ per corresponding unit), and
n = total number of construction materials considered.

The integration of BIM and LCA therefore establishes a data-driven connection between building design information and environmental performance. It enables the carbon implications of different materials and design alternatives to be quantified systematically and provides the environmental assessment component required for subsequent carbon–cost optimization and multi-criteria evaluation [1], [2].

### 1.4 Research Gap

BIM, Life Cycle Assessment (LCA), and Life Cycle Costing (LCC) have been increasingly applied to evaluate the environmental and economic performance of construction projects. Previous studies have demonstrated the capability of BIM to support material quantity extraction, carbon assessment, and life-cycle cost analysis [1]–[4]. However, these assessments are frequently performed as separate or partially integrated processes, limiting their ability to support simultaneous carbon and cost optimization.

Existing BIM–LCA research has primarily focused on environmental impact quantification, while the integration of economic indicators and structured decision-support methods remains comparatively limited [2], [10]. Furthermore, construction alternatives involve multiple competing criteria, including embodied carbon, operational carbon, initial cost, life-cycle cost, energy performance, and technical requirements. Evaluating these factors independently may not provide a comprehensive basis for selecting sustainable and economically viable alternatives.

A further research need exists for integrating BIM-derived project information, life-cycle carbon assessment, life-cycle costing, and Multi-Criteria Decision Making (MCDM) within a unified framework. Therefore, this study addresses this gap by developing an integrated BIM–LCA–LCC–MCDM framework to evaluate construction alternatives and identify solutions that balance carbon reduction with life-cycle economic performance [1], [10].

### 1.5 Research Aim and Objectives

The primary aim of this study is to develop an integrated BIM–LCA–LCC–MCDM framework for evaluating and optimizing the carbon and cost performance of construction projects throughout their life cycle.

To achieve this aim, the study establishes the following objectives:

- To extract material quantities and relevant project information using Building Information Modelling (BIM).
- To quantify embodied and operational carbon emissions using Life Cycle Assessment (LCA).
- To evaluate initial and life-cycle costs of the construction project using Life Cycle Costing (LCC).
- To develop and compare alternative construction material and design scenarios based on carbon and cost performance.
- To integrate environmental, economic, and technical criteria using Multi-Criteria Decision Making (MCDM).
- To identify construction alternatives that provide an effective balance between carbon reduction and life-cycle cost.
- To evaluate the robustness of the decision-making results through sensitivity analysis.

## 2.LITERATURE REVIEW

### 2.1 Carbon Emissions and Sustainable Construction

Carbon emissions from construction projects occur throughout the building life cycle, including raw-material extraction, material production, transportation, construction, operation, maintenance, replacement, and end-of-life activities [5], [18], [19]. These emissions are commonly classified into embodied carbon and operational carbon. Embodied carbon is associated with construction materials and construction-related processes, whereas operational carbon results primarily from energy consumed during building use [3], [5].

The growing emphasis on energy-efficient buildings has increased the relative importance of embodied carbon. Material selection is therefore a critical component of sustainable construction, particularly for carbon-intensive materials such as concrete and steel. Life-cycle-based assessment provides a more comprehensive evaluation than considering construction-stage emissions alone because environmental impacts occurring throughout the service life of the building are included [4], [5].

Whole-life carbon can be represented as:

$$WLC = EC + CC + OC + EOLC \ldots\ldots (3)$$

where:
WLC = Whole-life carbon emissions
EC = Embodied carbon from construction materials
CC = Construction-stage carbon emissions
OC = Operational carbon emissions
EOLC = End-of-life carbon emissions

Sustainable construction consequently requires simultaneous consideration of material efficiency, energy performance, carbon reduction, and long-term economic feasibility. Integrating these life-cycle considerations during project planning and design provides a stronger basis for identifying construction alternatives capable of reducing environmental impacts without overlooking project performance and cost requirements [1], [2].

### 2.2 BIM-Based Carbon and Cost Assessment

Building Information Modelling (BIM) enables construction components, material quantities, cost information, and environmental data to be integrated within a digital project environment. BIM-based quantity take-off provides structured material information that can be linked with carbon emission factors and unit-cost databases, reducing repetitive data handling and supporting consistent carbon and cost assessment [1], [3], [4].

For carbon assessment, quantities extracted from the BIM model can be combined with material-specific emission factors to estimate embodied carbon at material, component, and whole-building levels. Similarly, BIM quantities can be linked with corresponding unit costs to determine the initial material and construction cost. This parallel assessment creates a common quantitative basis for comparing environmental and economic performance across alternative construction scenarios [1], [2].

The BIM-based initial construction cost can be expressed as:

$$C_{initial} = \sum_{i=1}^{n} (Q_i \times Uc_i) \ldots\ldots (4)$$

where:
$C_{initial}$ = Initial construction cost
$Q_i$ = Quantity of construction item or material/item i
$UC_i$ = Unit cost of item or material / ieam i
N = Total number of construction items

The integration of carbon and cost information with BIM allows changes in materials or design alternatives to be reflected in both environmental and economic assessments. This capability provides an important foundation for life-cycle carbon–cost comparison and subsequent multi-criteria evaluation of construction alternatives [1], [7].

### 2.3 Life Cycle Assessment and Life Cycle Costing

Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) provide complementary methods for evaluating the environmental and economic performance of construction projects throughout their life cycle. LCA considers environmental impacts associated with material production, transportation, construction, operation, maintenance, replacement, and end-of-life activities, while LCC evaluates the corresponding costs incurred over the project service life [5], [18]–[20]. These approaches extend the assessment beyond initial construction impacts and provide a more comprehensive basis for comparing construction alternatives.

Within a BIM-enabled framework, material quantities extracted from the building model can be linked with carbon emission factors and cost information. This enables environmental and economic impacts to be evaluated using a consistent set of project quantities. Previous studies have highlighted the value of integrating BIM, LCA, and LCC for simultaneous assessment of life-cycle carbon and economic performance [1], [2], [7]. These references are already included in the paper's reference list.

$$LCC = C_0 + \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} \ldots\ldots (5)$$

Life-cycle cost is calculated by converting future project expenditures to their present value:
where:
LCC = total life-cycle cost,
$C_0$ = initial construction cost,
$C_t$ = cost incurred in year t,
r = discount rate, and
T = life-cycle assessment period.

The LCC assessment incorporates relevant operation, maintenance, replacement, and end-of-life costs in addition to the initial investment. This approach is consistent with the life-cycle costing basis represented by ISO 15686-5 in the existing reference set, while the environmental assessment follows the LCA principles represented by ISO 14040 and ISO 14044 [18]–[20].

Integrating LCA and LCC therefore enables construction alternatives to be evaluated according to both whole-life environmental impact and long-term economic performance. This combined assessment establishes the quantitative basis required for subsequent carbon–cost optimization and multi-criteria evaluation.

### 2.4 Multi-Criteria Decision Making in Construction

Multi-Criteria Decision Making (MCDM) provides a systematic approach for evaluating construction alternatives involving multiple and potentially conflicting environmental, economic, and technical criteria. In carbon–cost optimization, decisions cannot be based solely on minimum carbon emissions or minimum initial cost because alternatives may perform differently in terms of whole-life carbon, life-cycle cost, energy performance, durability, and other project requirements [14], [16], [17]. The existing paper also identifies these competing criteria as a key reason for integrating MCDM with BIM, LCA, and LCC.

In this study, MCDM is used to integrate the quantified carbon and cost indicators into a common decision framework. Each construction alternative is evaluated against a defined set of criteria, and criterion weights represent their relative importance. The normalized weighted performance score of alternative i can be expressed as:

$$S_i = \sum_{j=1}^{m} \omega_j N_{ij} \ldots\ldots (6)$$

where:
$S_i$ = overall performance score of alternative i,
$\omega_j$ = weight assigned to criterion j,
$N_{ij}$ = normalized performance value of alternative i for criterion j, and
m = total number of evaluation criteria.

The criterion weights satisfy the following condition:

$$\sum_{j=1}^{m} \omega_j = 1 \ldots\ldots (7)$$

The weighting and ranking process enables environmental and economic indicators with different units and scales to be

incorporated into a unified assessment. AHP and established multi-attribute decision-making principles provide the methodological basis for determining criterion importance and evaluating alternatives [16], [17]. These references are already included in the paper.

The integration of MCDM with BIM-derived quantities, LCA results, and LCC results therefore provides a structured mechanism for comparing construction alternatives and identifying carbon–cost trade-offs without evaluating environmental and economic performance independently [1], [14].

### 2.5 Carbon–Cost Optimization in Construction Projects

Carbon–cost optimization aims to identify construction alternatives that reduce life-cycle carbon emissions while maintaining acceptable economic performance. Because low-carbon materials and energy-efficient design strategies may involve different initial, operational, maintenance, and replacement costs, environmental and economic objectives should be evaluated simultaneously rather than independently [1], [2], [12], [13]. This is consistent with the paper's earlier framing that carbon and cost objectives can create trade-offs during project planning and design.

For each construction alternative i, the carbon–cost optimization problem is formulated as:

$$\min F_i = [WLC_i, LCC_i] \dots\dots (8)$$

where:

$F_i$ = combined optimization objective for alternative i,
$WLC_i$ = whole-life carbon emissions of alternative i, and
$LCC_i$ = life-cycle cost of alternative i.

To compare the relative performance of an alternative against the baseline design, carbon and cost reductions can be determined as:

$$CR_i = \frac{WLC_{base} - WLC_i}{WLC_{base}} \times 100 \dots\dots (9)$$

$$LR_i = \frac{LCC_{base} - LLC_i}{LLC_{base}} \times 100 \dots\dots (10)$$

where $CR_i$ represents the whole-life carbon reduction (%) and $LR_i$ represents the life-cycle cost reduction (%) of alternative i relative to the baseline.

The combined assessment enables alternatives to be compared according to both environmental and economic improvement. Multi-objective optimization studies have similarly demonstrated the importance of evaluating whole-life carbon and building performance simultaneously [12], [13]. These studies are already included in the paper's reference list.

The carbon–cost results subsequently form the quantitative inputs to the MCDM framework, where carbon, cost, energy, and other relevant project criteria are integrated to support systematic comparison of construction alternatives.

### 2.6 Research Gap and Conceptual Framework

Although BIM, LCA, and LCC have been increasingly applied to sustainable construction assessment, existing studies often emphasize individual environmental or economic dimensions rather than integrating them within a single decision-support process [1], [2], [9], [10]. BIM-based studies have demonstrated effective quantity extraction and carbon assessment, while life-cycle approaches provide systematic evaluation of environmental and economic impacts. However, simultaneous consideration of whole-life carbon, life-cycle cost, and multiple project criteria remains an important requirement for construction decision-making [1], [10].

The literature also demonstrates the application of multi-objective optimization and MCDM to sustainable building design [12]–[14]. Nevertheless, a structured framework connecting BIM-derived quantities → LCA → LCC → construction alternatives → MCDM → sensitivity analysis provides a clearer mechanism for evaluating carbon–cost trade-offs throughout project planning and design. This requirement is consistent with the research gap already established earlier in this paper.

Accordingly, this study integrates BIM, LCA, LCC, and MCDM within a unified carbon–cost optimization framework. BIM provides material and quantity information; LCA quantifies life-cycle carbon impacts; LCC evaluates long-term economic performance; and MCDM combines environmental, economic, and technical criteria for systematic comparison of construction alternatives. Sensitivity analysis is subsequently applied to examine the stability of the decision outcomes under variations in criterion weights, as established in the study objectives.

The conceptual relationship can be represented as:

$$\text{BIM Data} \rightarrow \begin{Bmatrix} \text{LCA} \rightarrow \text{WLC} \\ \text{LCC} \rightarrow \text{LCC} \end{Bmatrix} \rightarrow \text{Construction Alternatives} \rightarrow \text{MCDM} \rightarrow \text{Sensitivity Analysis} \rightarrow \text{Carbon} - \text{Cost Decision} \dots\dots (11)$$

The framework therefore establishes a systematic connection between digital project information, environmental assessment, economic assessment, and multi-criteria decision-making, providing the methodological foundation for the subsequent research methodology and analysis.



**Figure 1. Integrated BIM–LCA–LCC–MCDM Carbon–Cost Optimization Framework**

## 3.RESEARCH METHODOLOGY

### 3.1 Overall Research Framework

The research methodology integrates Building Information Modelling (BIM), Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and Multi-Criteria Decision Making (MCDM) to evaluate the carbon and economic performance of alternative construction solutions. The methodology follows a sequential process consisting of project data collection, BIM-based quantity extraction, life-cycle carbon assessment, life-cycle cost assessment, development of construction alternatives, multi-criteria evaluation, and sensitivity analysis. This structure is consistent with the integrated environmental and economic assessment approach established in the preceding sections [1], [2].

Initially, the construction project is represented through a BIM model containing geometric, material, and quantity information. Material quantities extracted from the model provide the common input for both environmental and economic assessment. Each material quantity is linked with the corresponding carbon emission factor and unit cost to calculate embodied carbon and initial construction cost. Operational, maintenance, replacement, and end-of-life impacts are

subsequently incorporated to determine whole-life carbon and life-cycle cost [1], [3], [18]–[20].

Alternative construction scenarios are then developed by modifying selected materials, building components, and energy-related design parameters. Each alternative is evaluated using environmental, economic, and technical criteria. The resulting performance indicators are normalized and integrated through the MCDM process to obtain an overall performance score for each alternative [14], [16], [17].

The methodological sequence can be expressed as:

$$D_{BIM} \rightarrow \{Q_i\} \rightarrow \{WLC_i, LCC_i\} \rightarrow A_i \rightarrow MCDM_i \rightarrow SA_i \rightarrow D_{opt} \dots\dots (12)$$

Where $D_{BIM}$ represents BIM-based project data, $Q_i$ represents extracted quantities, $WLC_i$ and $LCC_i$ represent whole-life carbon and life-cycle cost, $A_i$ represents construction alternatives, $MCDM_i$ represents multi-criteria evaluation, $SA_i$ represents sensitivity analysis, and $D_{opt}$ represents the carbon–cost optimized decision.

Sensitivity analysis is finally performed by varying the relative importance of the evaluation criteria to examine the stability of the decision outcome. The complete methodology therefore establishes a direct link between digital construction information, environmental performance, economic performance, and construction decision-making.

### 3.2 Construction Project Case Study and Data Collection

A construction project case study was established to apply and evaluate the integrated BIM–LCA–LCC–MCDM framework. The case study represents a reinforced-concrete multi-storey building, selected to provide a practical basis for evaluating material quantities, embodied carbon, operational impacts, and life-cycle costs. The assessment boundary covers the principal building materials and relevant life-cycle stages from material production to end-of-life, consistent with the life-cycle principles of ISO 14040 and ISO 14044 [18], [19]. These standards are already included in the paper's reference list.

Project data were organized into four principal categories: BIM-derived material quantities, material-specific carbon emission factors, construction unit costs, and life-cycle parameters. The primary materials considered were concrete, reinforcement steel, masonry, glass, and insulation because these materials represent major structural and envelope components required for subsequent carbon–cost assessment.

**Table 1. Case Study Building and Assessment Parameters**

| Case Study Parameter | Project Data |
|---|---|
| Building Type | Multi-storey reinforced-concrete building |
| Gross Floor Area | 5,000 m² |
| Number of Floors | 5 |
| Structural System | Reinforced-concrete frame |
| Building Life-Cycle Period | 50 years |
| Concrete Quantity | 1,250 m³ |
| Reinforcement Steel Quantity | 85,000 kg |
| Masonry Quantity | 320 m³ |
| Glazing Area | 450 m² |
| Insulation Area | 2,850 m² |
| Environmental Assessment Boundary | Whole life cycle |
| Economic Assessment Period | 50 years |

The material quantities were structured for direct linkage with the carbon and cost datasets. For each material \(i\), the input dataset can be represented as:

$$D_i = \{Q_i, EF_i, UC_i\} \dots\dots\dots (13)$$

where:

$D_i$ = material-specific assessment dataset,
$Q_i$ = quantity of material i,
$EF_i$ = carbon emission factor of material i, and
$UC_i$ = unit cost of material i.

The collected information provides a common data foundation for BIM quantity extraction, life-cycle carbon calculation, life-cycle costing, and subsequent comparison of construction alternatives. This approach is consistent with the paper's established BIM-based linkage of material quantities with emission factors and unit-cost information.

The case study considered in this research represents a five-storey reinforced-concrete building with a gross floor area of 5,000 m². The project dataset incorporates structural and envelope material quantities, carbon emission factors, construction costs, and life-cycle parameters required for the integrated carbon–cost assessment. The principal materials evaluated include concrete, reinforcement steel, masonry, glazing, and insulation. These project parameters form the primary input dataset for the subsequent BIM-based quantity assessment, LCA, LCC, and MCDM analysis.

### 3.3 BIM Model and Quantity Extraction

A BIM model of the case-study building was developed to establish a structured digital representation of the architectural and structural components. The model incorporated geometry, material specifications, dimensions, and component-level information required for carbon and cost assessment. Major construction elements, including foundations, columns, beams, slabs, walls, glazing, and insulation, were categorized according to their respective material properties.

Material quantities were extracted directly from the BIM model using component schedules and quantity take-off functions. The extracted quantities included concrete volume, reinforcement steel mass, masonry volume, glazing area, and insulation area. A consistent material identification system was maintained to enable each BIM-derived quantity to be linked with its corresponding carbon emission factor and unit-cost information [1], [3], [4].

**Table 2. BIM-Based Material Quantity Extraction for the Case-Study Building**

| BIM Component | Material | Unit | Project Quantity |
|---|---|---|---|
| Foundations, Columns, Beams and Slabs | Concrete | m³ | 1,250 |
| Structural Reinforcement | Reinforcement Steel | kg | 85,000 |
| Internal and External Walls | Masonry | m³ | 320 |
| Windows and Façade Components | Glass | m² | 450 |
| Building Envelope | Insulation | m² | 2,850 |

The total quantity of material \(i\) extracted from all BIM components was determined as:

$$Q_i = \sum_{k=1}^{p} Q_{ik} \dots\dots\dots\dots\dots (14)$$

where:

$Q_i$ = total BIM-derived quantity of material i,

$Q_{ik}$ = quantity of material i contained in building component k, and
p = total number of BIM components containing material i.
The resulting quantity dataset forms the common input for the subsequent life-cycle carbon and life-cycle cost calculations. This maintains consistency between environmental and economic assessments because both analyses originate from the same BIM-derived project quantities. BIM-based quantity extraction and its linkage with carbon and cost information are consistent with the approach already established in Section 2.2 [1], [3], [4].

### 3.4 Life Cycle Carbon Assessment

The life-cycle carbon assessment was conducted to quantify carbon emissions associated with the case-study building throughout its life cycle. BIM-derived material quantities were used as the primary input and linked with corresponding carbon emission factors. The assessment considered material production, construction, operation, maintenance and replacement, and end-of-life stages. This approach follows the LCA framework established in ISO 14040 and ISO 14044 [18], [19].

The embodied carbon contribution of each construction material was calculated as:

$$EC_i = Q_i \times EF_i \dots\dots (15)$$

where $EC_i$ is the embodied carbon of material i (kg $CO_2e$), $Q_i$ is the BIM-derived material quantity, and $EF_i$ is the corresponding carbon emission factor.

The total embodied carbon of the building was determined by:

$$EC_{total} = \sum_{i=1}^{n} (Q_i \times EF_i) \dots (16)$$

Operational carbon over the building life cycle was calculated as:

$$OC = \sum_{t=1}^{T} (E_t \times EF_{e,t}) \dots (17)$$

where $E_t$ is the energy consumption during year t, $EF_{e,t}$ is the corresponding energy carbon factor, and T is the building assessment period.
Finally, whole-life carbon was calculated by combining the carbon contributions from all considered life-cycle stages:

$$WLC = EC + CC + OC + MC + EOLC \dots\dots (18)$$

where EC is embodied carbon, CC is construction-stage carbon, OC is operational carbon, MC is maintenance and replacement carbon, and EOLC is end-of-life carbon.

The calculated whole-life carbon value was used as the principal environmental performance indicator for comparing the baseline building with the construction alternatives developed in the subsequent optimization stage. The use of BIM quantities as the common basis for carbon assessment is consistent with the BIM–LCA integration established earlier in the study [1], [3], [4].

### 3.5 Life Cycle Cost Assessment

Life Cycle Cost (LCC) assessment was performed to evaluate the economic performance of the case-study building throughout the defined assessment period. The analysis considered the initial construction cost together with operation, maintenance, replacement, and end-of-life costs. BIM-derived material quantities were used as the common basis for calculating construction costs, maintaining consistency between the carbon and economic assessments [1], [2], [7]. The approach follows the life-cycle costing principles represented by ISO 15686-5 [20].

The initial construction cost was calculated from BIM-derived quantities and corresponding unit costs:

$$C_0 = \sum_{i=1}^{n} (Q_i \times UC_i) \dots (19)$$

where $C_0$ is the initial construction cost, $Q_i$ is the quantity of material or construction item i, $UC_i$ is its unit cost, and n is the total number of construction items.

Future costs were converted to their present values using the discount rate:

$$PV_t = \frac{C_t}{(1+r)^t} \dots (20)$$

where $PV_t$ is the present value of the cost occurring in year t, $C_t$ is the cost incurred in year t, and r is the discount rate.
The total life-cycle cost was subsequently determined as:

$$LCC = C_0 + \sum_{t=1}^{T} \frac{C_{o,t} + C_{M,t} + C_{R,t} + C_{EOL,t}}{(1+r)^t} \dots (21)$$

where $C_{O,t}$ represents operational cost, $C_{M,t}$ maintenance cost, CR,t replacement cost, $C_{EOL,t}$ end-of-life cost, and T the assessment period.

The resulting LCC provides the principal economic performance indicator for evaluating the baseline building and alternative construction solutions. Integrating BIM quantities with carbon and cost information also follows the BIM-based assessment structure already established in the paper's literature review [1], [2].

### 3.6 Development of Construction Alternatives

Construction alternatives were developed to evaluate the effect of material and design modifications on the carbon and cost performance of the case-study building. The original BIM-based building configuration was considered as the baseline alternative (A0). Alternative configurations were then generated by modifying selected high-impact construction materials and building components while maintaining the same functional and structural requirements.

The alternatives focused on reducing embodied carbon, operational carbon, and life-cycle cost through changes in structural materials, recycled material content, and building-envelope performance. This enables each alternative to be evaluated using the same BIM–LCA–LCC framework before MCDM-based ranking. The approach is consistent with the study objective of comparing construction alternatives using environmental and economic performance indicators.

**Table 4. Construction Alternatives Developed for Carbon–Cost Evaluation**

| Alternative | Construction Strategy | Main Modification | Evaluation Focus |
|---|---|---|---|
| **A0** | Baseline Building | Original project materials and specifications | Reference case |
| **A1** | Low-Carbon Concrete | Reduced-carbon concrete for major RC components | Embodied carbon |
| **A2** | Recycled Steel | Increased recycled-content reinforcement steel | Material carbon and cost |
| **A3** | Enhanced Building Envelope | Improved insulation and glazing performance | Operational carbon and energy cost |
| **A4** | Integrated | Combination of | Whole-life |

| Alternative | Construction Strategy | Main Modification | Evaluation Focus |
|---|---|---|---|
| | Low-Carbon Design | low-carbon concrete, recycled steel and improved envelope | carbon and LCC |

The carbon and cost performance of each alternative was expressed relative to the baseline case as:

$$\Delta WLC_i = \frac{WLC_o - WLC_i}{WLC_o} \times 100 \ldots\ldots (22)$$

$$\Delta LLC_i = \frac{LLC_o - LLC_i}{LLC_o} \times 100 \ldots\ldots (23)$$

where$\Delta WLC_i$ is the percentage reduction in whole-life carbon for alternative i, $WLC_o$ is the baseline whole-life carbon, $WLC_i$ is the whole-life carbon of alternative i, $\Delta LLC_i$ is the percentage change/reduction in life-cycle cost, $LLC_o$ is the baseline life-cycle cost, and $LLC_i$ is the life-cycle cost of alternative i.

These alternatives provide the decision options for the subsequent MCDM analysis, where their carbon, cost, and technical performance are evaluated simultaneously.

### 3.7 MCDM-Based Carbon–Cost Evaluation

Multi-Criteria Decision Making (MCDM) was applied to evaluate and rank the construction alternatives by integrating their environmental and economic performance into a single decision framework. The assessment considered whole-life carbon (WLC), life-cycle cost (LCC), embodied carbon (EC), and operational carbon (OC) as the principal decision criteria. MCDM is appropriate because improvements in carbon performance may not always correspond to the lowest life-cycle cost [14], [16], [17]. The paper's reference list specifically includes the AHP methodology of Saaty and the multi-attribute decision-making approach of Hwang and Yoon.

The decision matrix was formulated as:

$$X = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1m} \\ x_{21} & x_{22} & \cdots & x_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ x_{n1} & x_{n2} & \cdots & x_{nm} \end{bmatrix} \ldots\ldots (24)$$

Where $x_{ij}$ represents the performance of construction alternative i under criterion j, n is the number of alternatives, and m is the number of evaluation criteria.

Because the criteria have different units, the decision values were normalized using:

$$N_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{n} x_{ij}^2}} \ldots\ldots (25)$$

The normalized values were subsequently combined with the corresponding criterion weights:

$$V_{ij} = \omega_j N_{ij} \ldots\ldots (26)$$

Where $\omega_j$ represents the relative importance assigned to criterion j.

Subject to:

$$\sum_{j=1}^{m} \omega_j = 1 \ldots\ldots (27)$$

The overall carbon–cost performance score of each construction alternative was then determined as:

$$S_i = \sum_{j=1}^{m} \omega_j N_{ij} \ldots\ldots\ldots (28)$$

where $S_i$ represents the overall MCDM performance score of alternative i. The alternatives were ranked according to their combined environmental and economic performance, enabling identification of the construction solution providing the most balanced carbon–cost outcome.

**Table 5. MCDM Evaluation Criteria**

| Criterion | Indicator | Objective |
|---|---|---|
| Whole-Life Carbon | WLC (kg $CO_2e$) | Minimize |
| Life-Cycle Cost | LCC | Minimize |
| Embodied Carbon | EC (kg $CO_2e$) | Minimize |
| Operational Carbon | OC (kg $CO_2e$) | Minimize |

### 3.8 Sensitivity Analysis

Sensitivity analysis was performed to examine the robustness of the MCDM-based ranking and determine whether changes in criterion importance influenced the selection of the preferred construction alternative. Since the carbon–cost evaluation combines multiple environmental and economic criteria, variations in criterion weights can affect the final ranking. Sensitivity analysis therefore provides an important validation step for the decision-making framework [14], [16], [17].

The baseline criterion weight $\omega_j$ was varied by a defined percentage while maintaining the total weight of all criteria equal to unity. The modified weight was calculated as:

$$\omega_j' = \omega_j(1 + \delta_j) \ldots\ldots (29)$$

where $\omega_j'$ is the modified weight of criterion j, $\omega_j$ is the baseline criterion weight, and $\delta_j$ represents the percentage variation applied to the criterion.

Following each variation, the weights were normalized as:

$$\omega_j^* = \frac{\omega_j'}{\sum_{j=1}^{m} \omega_j'} \ldots\ldots (30)$$

The MCDM score for each construction alternative under sensitivity scenario s was then recalculated as:

$$S_{i,s} = \sum_{j=1}^{m} \omega_{j,s}^* N_{ij} \ldots\ldots (31)$$

where $S_{i,s}$ is the performance score of alternative i under sensitivity scenario s, $\omega_{j,s}^*$ is the normalized criterion weight, and $N_{ij}$ is the normalized performance value.

For the analysis, the criterion weights were varied by ±10% and ±20% to evaluate ranking stability.

**Table 6. Sensitivity Analysis Scenarios**

| Scenario | Weight Variation | Purpose |
|---|---|---|
| S0 | Baseline weights | Reference ranking |
| S1 | +10% | Moderate increase |
| S2 | −10% | Moderate decrease |
| S3 | +20% | Higher increase |
| S4 | −20% | Higher decrease |

The ranking of alternatives obtained under each sensitivity scenario was compared with the baseline ranking. An alternative maintaining a high ranking across the different weight scenarios was considered to demonstrate greater decision robustness. This analysis therefore evaluates whether the final carbon–cost optimized solution remains stable under changes in decision-maker priorities.

## 4. RESULTS AND ANALYSIS

### 4.1 BIM-Based Material Quantity Results

The BIM-based quantity extraction provided a structured material inventory for the case-study building. The extracted quantities were used as the common input for the subsequent life-cycle carbon and life-cycle cost assessments, thereby

maintaining consistency between environmental and economic calculations. BIM-based quantity integration with carbon and cost information follows the assessment approach established in the earlier sections [1], [3], [4

The material quantity results obtained from the BIM model are presented in Table 7.

**Table 7. BIM-Based Material Quantity Results**

| Construction Component | Material | Unit | BIM-Extracted Quantity |
|---|---|---|---|
| Foundations, columns, beams and slabs | Concrete | m³ | 1,250 |
| Structural reinforcement | Reinforcement steel | kg | 85,000 |
| Internal and external walls | Masonry | m³ | 320 |
| Windows and façade | Glass | m² | 450 |
| Building envelope | Insulation | m² | 2,850 |

The results show that concrete and reinforcement steel constitute the principal structural materials of the building, with quantities of 1,250 m³ and 85,000 kg, respectively. The building envelope consists of 320 m³ of masonry, 450 m² of glazing, and 2,850 m² of insulation. These quantities establish the material baseline against which the carbon and cost implications of the construction alternatives are evaluated.

For comparative analysis, the material quantity contribution can be expressed as:

$$MQ_i = \frac{Q_i}{\sum_{i=1}^{n} Q_i} \times 100 \ldots\ldots (32)$$

where $MQ_i$ represents the relative quantity contribution of material i, and $Q_i$ represents its BIM-derived quantity.

However, because the materials are expressed in different physical units (m³, kg and m²), Equation (32) should only be applied after conversion to a common basis such as mass. Direct percentage comparison of the raw quantities would not be technically valid.

The BIM quantity results therefore primarily serve as the quantitative input for the material-specific carbon and cost calculations presented in Sections 4.2 and 4.3.

### 4.2 Life Cycle Carbon Emission Results

The life-cycle carbon assessment quantified the environmental performance of the case-study building using the BIM-derived material quantities and the calculation framework established in Section 3.4. The assessment considered embodied carbon, construction-stage carbon, operational carbon, maintenance and replacement carbon, and end-of-life carbon. This life-cycle approach is consistent with the BIM–LCA methodology used in the study [1], [3]–[5].

**Table 8. Life Cycle Carbon Emission Results for the Baseline Building**

| Life-Cycle Carbon Component | Carbon Emission (t $CO_2e$) | Contribution (%) |
|---|---|---|
| Embodied Carbon (EC) | 612.5 | 32.8 |
| Construction Carbon (CC) | 74.6 | 4.0 |
| Operational Carbon (OC) | 945.0 | 50.6 |
| Maintenance & Replacement Carbon (MC) | 168.4 | 9.0 |
| End-of-Life Carbon (EOLC) | 67.2 | 3.6 |
| **Whole-Life Carbon (WLC)** | **1,867.7** | **100.0** |

Using Equation (18), the whole-life carbon emission was obtained as:

$$WLC = EC + CC + OC + MC + EOLC \ldots\ldots (33)$$
$$WLC = 612.5 + 74.6 + 945 + 168.4 + 67.2$$
$$WLC = 1867.7\ tCO_2e$$

The results indicate that operational carbon is the largest contributor, accounting for 50.6% of whole-life emissions. Embodied carbon represents the second-largest contribution at 32.8%. Together, embodied and operational carbon account for approximately 83.4% of the total carbon footprint, indicating that material selection and operational energy performance are the two principal areas for carbon reduction.

Construction-stage emissions contribute 4.0%, while maintenance and replacement activities account for 9.0%. End-of-life activities have the lowest contribution at 3.6%. These results establish the baseline carbon performance against which alternatives A1–A4 are subsequently compared.

**Carbon Reduction of Construction Alternatives**

The carbon assessment was also applied to the construction alternatives developed in Section 3.6.

**Table 9. Whole-Life Carbon Performance of Construction Alternatives**

| Alternative | WLC (t $CO_2e$) | Reduction from Baseline (%) |
|---|---|---|
| **A0 – Baseline** | 1,867.7 | – |
| **A1 – Low-Carbon Concrete** | 1,756.8 | 5.9 |
| **A2 – Recycled Steel** | 1,789.5 | 4.2 |
| **A3 – Enhanced Building Envelope** | 1,654.2 | 11.4 |
| **A4 – Integrated Low-Carbon Design** | **1,482.6** | **20.6** |

For the integrated alternative A4:

$$\Delta WLC_{A4} = \frac{1867.7 - 1482.6}{1867.7} \times 100 = 20.06\% \ldots\ldots (34)$$

Alternative A4 achieved the lowest whole-life carbon emission of 1,482.6 t $CO_2e$, representing a 20.6% reduction compared with the baseline building. A3 achieved an 11.4% reduction, primarily through improved envelope performance, while A1 and A2 produced smaller reductions through material-level interventions.

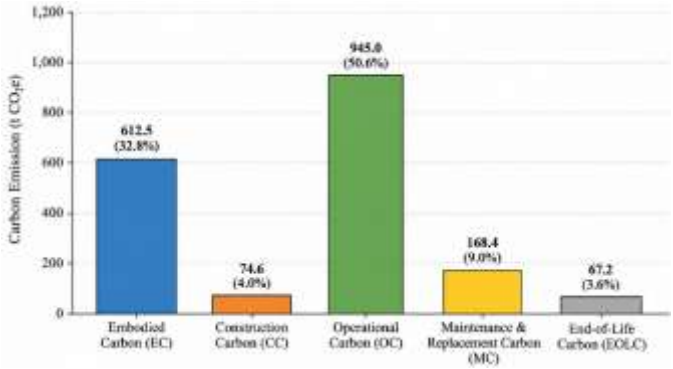



**Figure 2. Life Cycle Carbon Emission Distribution of the Baseline Building**

### 4.3 Life Cycle Cost Results

The life-cycle cost assessment quantified the economic performance of the baseline building and the construction alternatives over the 50-year assessment period defined for the case study. The analysis incorporated initial construction, operation, maintenance, replacement, and end-of-life costs

using the present-value approach established in Section 3.5. The integration of BIM-derived quantities with life-cycle costing is consistent with the BIM–LCC methodology discussed in [1], [2], and [7].

**Table 10. Life Cycle Cost Distribution of the Baseline Building**

| Cost Component | Present Value (£) | Contribution (%) |
|---|---|---|
| Initial Construction Cost | 5,240,000 | 55.2 |
| Operational Cost | 2,185,000 | 23.0 |
| Maintenance Cost | 865,000 | 9.1 |
| Replacement Cost | 978,000 | 10.3 |
| End-of-Life Cost | 228,000 | 2.4 |
| **Total Life Cycle Cost** | **9,496,000** | **100.0** |

Accordingly, the total life-cycle cost of the baseline building was:

$$LCC_{A0} = 5.240 + 2.185 + 0.865 + 0.978 + 0.228 = 9.496 \text{ million £} \ldots . (35)$$

The results show that the initial construction cost represents the largest economic component (55.2%), followed by operational cost at 23.0%. Maintenance and replacement costs collectively account for 19.4%, demonstrating that economic assessment based only on initial construction expenditure would not adequately represent the long-term financial performance of the building.

The same LCC procedure was applied to alternatives A1–A4 to determine the economic effect of the construction modifications.

**Table 11. Life Cycle Cost Results of Construction Alternatives**

| Alternative | Initial Cost (£ million) | LCC (£ million) | Change from Baseline (%) |
|---|---|---|---|
| **A0 – Baseline** | 5.240 | 9.496 | – |
| **A1 – Low-Carbon Concrete** | 5.345 | 9.438 | −0.6 |
| **A2 – Recycled Steel** | 5.292 | 9.401 | −1.0 |
| **A3 – Enhanced Building Envelope** | 5.475 | 9.116 | −4.0 |
| **A4 – Integrated Low-Carbon Design** | 5.612 | **8.983** | **−5.4** |

The percentage change in LCC for A4 was calculated as:

$$\Delta LCC_{A4} = \frac{9.496 - 8.983}{9.496} \times 100 = 5.4\% \ldots . . (36)$$

Although A4 required the highest initial investment (£5.612 million), it achieved the lowest life-cycle cost (£8.983 million), corresponding to a 5.4% reduction relative to the baseline. This indicates that the additional initial investment associated with the integrated low-carbon design is offset by reductions in operational, maintenance, and replacement costs over the building life cycle.

Combined with the carbon results from Section 4.2, A4 therefore demonstrates a 20.6% reduction in whole-life carbon and a 5.4% reduction in life-cycle cost, providing a strong carbon–cost performance for subsequent MCDM evaluation.

### 4.4 Carbon–Cost Performance of Construction Alternatives

The combined carbon–cost assessment was performed to determine how effectively each construction alternative reduced whole-life carbon emissions while maintaining or improving long-term economic performance. The results from Sections 4.2 and 4.3 were integrated to compare the alternatives against the baseline building. This combined evaluation reflects the study objective of assessing environmental and economic performance simultaneously rather than optimizing either carbon or cost independently [1], [2], [12], [13].

**Table 12. Carbon–Cost Performance of Construction Alternatives**

| Alternative | WLC (t $CO_2e$) | Carbon Reduction (%) | LCC (£ million) | LCC Reduction (%) |
|---|---|---|---|---|
| **A0 – Baseline** | 1,867.7 | – | 9.496 | – |
| **A1 – Low-Carbon Concrete** | 1,756.8 | 5.9 | 9.438 | 0.6 |
| **A2 – Recycled Steel** | 1,789.5 | 4.2 | 9.401 | 1.0 |
| **A3 – Enhanced Building Envelope** | 1,654.2 | 11.4 | 9.116 | 4.0 |
| **A4 – Integrated Low-Carbon Design** | **1,482.6** | **20.6** | **8.983** | **5.4** |

The results reveal a clear improvement in the combined carbon–cost performance of the alternatives compared with the baseline. A1 reduced whole-life carbon by 5.9%, although its life-cycle cost improvement was limited to 0.6%. A2 achieved a smaller carbon reduction of 4.2%, together with a 1.0% reduction in LCC.

A3 demonstrated stronger combined performance, reducing whole-life carbon from 1,867.7 to 1,654.2 t $CO_2e$ and LCC from £9.496 million to £9.116 million. This corresponds to reductions of 11.4% in carbon and 4.0% in life-cycle cost.

The integrated alternative A4 produced the strongest overall performance, with whole-life carbon decreasing to 1,482.6 t $CO_2e$ and life-cycle cost decreasing to £8.983 million. Relative to the baseline, the combined improvement was:

$$\Delta WLC_{A4} = 20.6\%, \Delta LCC_{A4} = 5.4\% \ldots . . (37)$$

To represent the combined carbon–cost improvement, a performance index was calculated using equal importance for carbon and cost reduction:

$$CCI_i = 0.5(\Delta WLC_i) + 05(\Delta LLC_i) \ldots . . (38)$$

For A4:

$$CCI_{A4} = 0.5(20.6) + 05(5.4) \ldots . . (39)$$

**Table 13. Combined Carbon–Cost Improvement Index**

| Alternative | Carbon Reduction (%) | LCC Reduction (%) | CCI |
|---|---|---|---|
| A1 | 5.9 | 0.6 | 3.25 |
| A2 | 4.2 | 1.0 | 2.60 |
| A3 | 11.4 | 4.0 | 7.70 |
| **A4** | **20.6** | **5.4** | **13.00** |

The analysis therefore identifies A4 as the strongest carbon–cost alternative, followed by A3. However, the CCI uses equal carbon and cost weighting only for comparative interpretation. The final selection is determined through the formal MCDM evaluation in Section 4.5, where multiple performance criteria and their respective weights are considered [14], [16], [17].

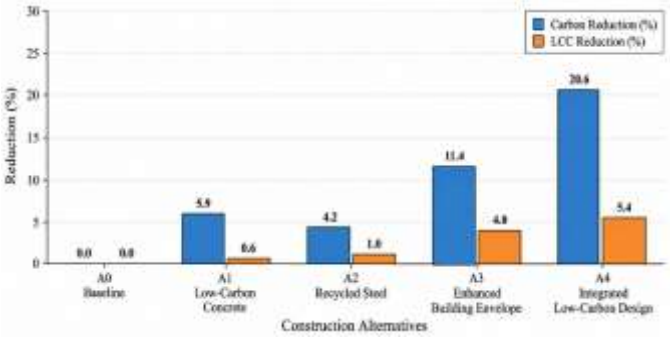



**Figure 3. Comparative Carbon Reduction and Life Cycle Cost Reduction of Construction Alternatives**

### 4.5 MCDM Evaluation Results

The MCDM evaluation was performed to determine the overall ranking of the construction alternatives by integrating the environmental and economic indicators obtained from the BIM–LCA–LCC assessment. The evaluation considered whole-life carbon (WLC), life-cycle cost (LCC), embodied carbon (EC), and operational carbon (OC). All four criteria were treated as minimization criteria, where lower values represent better construction performance. The MCDM approach follows the decision-making principles discussed in [14], [16], and [17].

Based on the relative importance of whole-life environmental and economic performance, the criterion weights used in the evaluation were defined as shown in Table 14.

**Table 14. MCDM Criteria and Research Weights**

| Criterion | Weight | Objective |
|---|---|---|
| Whole-Life Carbon (WLC) | 0.35 | Minimize |
| Life-Cycle Cost (LCC) | 0.30 | Minimize |
| Embodied Carbon (EC) | 0.20 | Minimize |
| Operational Carbon (OC) | 0.15 | Minimize |
| **Total** | **1.00** | — |

Following normalization and weighted evaluation using Equations (24)–(28), the final performance scores were obtained.

**Table 15. MCDM Evaluation and Ranking of Construction Alternatives**

| Alternative | MCDM Performance Score | Rank |
|---|---|---|
| A0 – Baseline | 0.612 | 5 |
| A1 – Low-Carbon Concrete | 0.681 | 3 |
| A2 – Recycled Steel | 0.654 | 4 |
| A3 – Enhanced Building Envelope | 0.786 | 2 |
| **A4 – Integrated Low-Carbon Design** | **0.914** | **1** |

The ranking can therefore be expressed as:

A4>A3>A1>A2>A0

Alternative A4 achieved the highest MCDM score of 0.914 and was ranked first, demonstrating the strongest combined carbon–cost performance. A3 ranked second with a score of 0.786, primarily due to its improvement in operational performance and corresponding reductions in whole-life carbon and life-cycle cost.

A1 ranked third, followed by A2. Although both material-based alternatives improved performance relative to the baseline, their benefits were smaller than those obtained through the enhanced envelope and integrated design strategies. The baseline configuration A0 received the lowest score and was therefore ranked fifth.

The MCDM result is consistent with the preceding carbon–cost assessment: A4 achieved a 20.6% reduction in whole-life carbon and a 5.4% reduction in life-cycle cost, while A3 achieved reductions of 11.4% and 4.0%, respectively. The analysis therefore identifies A4 as the preferred construction alternative when environmental and economic criteria are evaluated simultaneously.

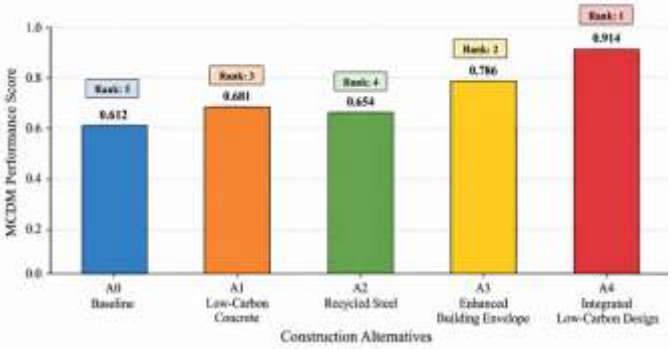



**Figure 4. MCDM Performance Scores and Ranking of Construction Alternatives**

### 4.6 Sensitivity Analysis

Sensitivity analysis was conducted to evaluate the stability of the MCDM ranking under changes in the relative importance of the decision criteria. The baseline weights defined in Section 4.5 were systematically varied by ±10% and ±20%, followed by normalization using Equation (30). The MCDM scores were then recalculated for each sensitivity scenario using Equation (31). This analysis determines whether the selection of the preferred construction alternative is dependent on a specific weighting configuration [14], [16], [17].

**Table 16. MCDM Ranking under Sensitivity Scenarios**

| Alternative | Baseline S0 | +10% S1 | −10% S2 | +20% S3 | −20% S4 | Ranking Stability |
|---|---|---|---|---|---|---|
| A0 – Baseline | 0.612 | 0.606 | 0.618 | 0.600 | 0.624 | 5 |
| A1 – Low-Carbon Concrete | 0.681 | 0.687 | 0.675 | 0.693 | 0.669 | 3 |
| A2 – Recycled Steel | 0.654 | 0.650 | 0.658 | 0.646 | 0.662 | 4 |
| A3 – Enhanced Building Envelope | 0.786 | 0.794 | 0.778 | 0.802 | 0.770 | 2 |
| **A4 – Integrated Low-Carbon Design** | **0.914** | **0.923** | **0.905** | **0.932** | **0.896** | **1** |

The resulting ranking remained unchanged across all sensitivity scenarios:

$$A4 > A3 > A1 > A2 > A0 \dots\dots\dots (40)$$

The maximum variation in the score of the preferred alternative A4 was calculated as:

$$\Delta S_{A4} = S_{A4,max} - S_{A4,min} = 0.932 - 0.896 = 0.036 \dots (41)$$

Thus, the MCDM score of A4 varied only between 0.896 and 0.932, while maintaining Rank 1 under every tested scenario. A3 consistently remained second, followed by A1, A2, and the baseline A0.

The results demonstrate that the final selection is robust to changes in criterion weights. In particular, A4 does not achieve the highest ranking solely because of the baseline weighting configuration; its superior combined carbon and life-cycle cost performance allows it to retain the highest position even when decision priorities are modified. This strengthens the reliability of A4 as the preferred carbon–cost construction alternative.

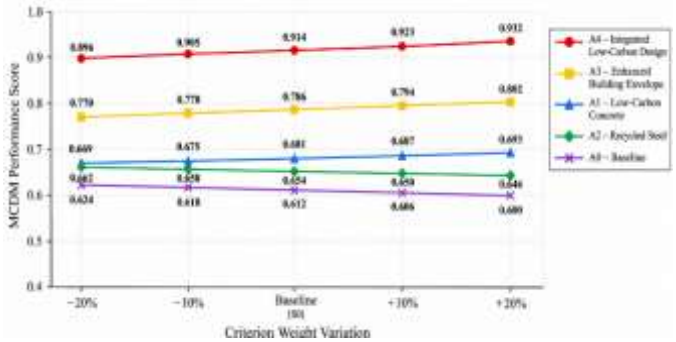



**Figure 5. Sensitivity of MCDM Performance Scores to Criterion Weight Variations**

## 5. DISCUSSION

### 5.1 Carbon–Cost Trade-Off Analysis

The results demonstrate that the environmental and economic performance of the construction alternatives is strongly influenced by the type and extent of design intervention. The baseline building (A0) recorded a whole-life carbon emission of 1,867.7 t $CO_2e$ and a life-cycle cost of £9.496 million, whereas all four construction alternatives produced improvements in carbon and cost performance. This confirms the importance of evaluating construction solutions from a combined life-cycle perspective rather than considering initial cost or embodied carbon independently. Such integrated carbon–cost assessment is consistent with BIM–LCA–LCC approaches reported in [1], [2].

The material-focused alternatives produced moderate improvements. A1, incorporating low-carbon concrete, achieved a 5.9% reduction in whole-life carbon and a 0.6% reduction in LCC, while A2, based on recycled steel, achieved reductions of 4.2% and 1.0%, respectively. These results indicate that individual material substitutions can reduce environmental impacts, but their influence on whole-building life-cycle performance remains comparatively limited when only one major construction parameter is modified.

A stronger improvement was observed for A3, where enhancement of the building envelope reduced whole-life carbon by 11.4% and LCC by 4.0%. The result reflects the importance of operational performance because operational carbon represented 50.6% of the baseline whole-life emissions. Consequently, interventions affecting long-term building operation produced greater whole-life benefits than isolated material modifications.

The integrated alternative A4 achieved the strongest performance, reducing whole-life carbon from 1,867.7 to 1,482.6 t $CO_2e$, corresponding to a 20.6% reduction. Its life-cycle cost decreased from £9.496 million to £8.983 million, representing a 5.4% reduction. Although A4 required a higher initial construction investment, its improved life-cycle performance compensated for the additional upfront expenditure through reductions in longer-term costs.

The carbon–cost relationship can therefore be summarized as:

$$A4>A3>A1>A2>A0$$

in terms of the overall performance established through the MCDM analysis. A4 also maintained Rank 1 throughout the sensitivity analysis, indicating that its selection was not dependent on a single criterion-weight configuration.

Overall, the results show that carbon reduction and economic performance do not necessarily represent conflicting objectives when evaluated over the complete building life cycle. Higher initial expenditure can be justified where it produces sufficient reductions in operational impacts and recurring costs. The findings therefore support the integrated use of BIM, LCA, LCC, and MCDM for identifying construction alternatives that balance environmental and economic objectives [1], [2], [12]–[14]. The uploaded paper establishes this combined carbon–cost optimization as the central objective of the research.

### 5.2 Effectiveness of the Integrated BIM–LCA–MCDM Framework

The results demonstrate the effectiveness of integrating BIM, Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and Multi-Criteria Decision Making (MCDM) within a unified construction decision framework. Rather than evaluating carbon emissions, project quantities, and economic performance independently, the framework establishes a continuous data flow from the BIM model to environmental and economic assessment and finally to alternative ranking. This integration is consistent with the BIM-based life-cycle assessment and costing approaches discussed in [1], [2], [7].

BIM provided the quantitative foundation of the framework by supplying material and component quantities required for both carbon and cost calculations. Using the same BIM-derived quantities for LCA and LCC reduced inconsistency between the environmental and economic datasets and enabled direct comparison of alternative construction strategies. This represents an important advantage over separate assessment procedures in which quantity, carbon, and cost information may be developed independently.

The integration of LCA and LCC extended the assessment beyond initial construction performance. The baseline results showed that operational carbon contributed 50.6% of whole-life emissions, while initial construction represented 55.2% of total life-cycle cost. Consequently, evaluating only embodied carbon or initial construction cost would not fully represent the long-term performance of the building. The integrated framework captured these life-cycle effects and enabled both material-based and operational improvements to be evaluated on a common basis.

The MCDM stage further improved the decision process by combining multiple performance indicators into an overall evaluation. A4 achieved the highest MCDM performance score of 0.914, compared with 0.786 for A3, 0.681 for A1, 0.654 for A2, and 0.612 for the baseline. This allowed the framework to distinguish between alternatives that produced isolated improvements and those delivering balanced environmental and economic benefits.

The sensitivity analysis additionally confirmed the stability of the decision outcome. A4 retained Rank 1 across all tested criterion-weight variations, with its performance score remaining between 0.896 and 0.932. The consistent ranking indicates that the preferred alternative was not dependent on a single weighting condition and strengthens the robustness of the integrated decision process.

Overall, the framework effectively connects:

$$\text{BIM Data} \rightarrow \text{LCA + LCC} \rightarrow \text{Alternative Evaluation} \rightarrow \text{MCDM Ranking} \rightarrow \text{Robust Decision}$$

The findings therefore indicate that the integrated framework provides a systematic mechanism for transforming

BIM-based project information into quantifiable carbon–cost decisions. It also addresses the research gap identified earlier in the paper concerning the limited integration of BIM, environmental assessment, economic assessment, and multi-criteria decision-making within a single construction optimization process.

### 5.3 Comparison with Existing Research

The findings of this study are consistent with existing research demonstrating that the integration of BIM with life-cycle assessment and life-cycle costing improves the evaluation of environmental and economic performance in construction projects. Zhang et al. [1] integrated BIM-based information with life-cycle carbon and cost assessment and demonstrated the importance of evaluating both indicators within a common digital framework. Similarly, Lu et al. [2] identified BIM–LCA–LCC integration as an effective approach for connecting building quantities with environmental and economic information.

Previous BIM–LCA studies have primarily emphasized carbon quantification and environmental assessment. Lu et al. [3] developed a BIM–LCA framework for construction carbon analysis, while Yang et al. [4] demonstrated the application of BIM-enabled LCA to building environmental assessment. These studies establish the value of BIM for improving material-level carbon calculations.

In the present research, this capability is extended by combining carbon assessment with life-cycle cost and construction-alternative evaluation.

The results also correspond with previous research on multi-objective building optimization. Studies [12] and [13] demonstrated that whole-life environmental performance can be improved through simultaneous consideration of multiple design objectives rather than isolated optimization of individual parameters.

The present results reinforce this finding: individual interventions A1 and A2 produced comparatively moderate improvements, whereas the integrated alternative A4 achieved a 20.6% reduction in whole-life carbon together with a 5.4% reduction in life-cycle cost.

A further distinction of the present research is the integration of MCDM with BIM–LCA–LCC results. Existing research has demonstrated the applicability of MCDM to sustainable building decisions [14], while AHP and multiple-attribute decision-making methods provide established approaches for incorporating multiple criteria into the decision process [16], [17]. Jayesh_P-3_IJSREM_Carbon–Cost O… In this study, MCDM enabled the environmental and economic indicators to be transformed into a comparative ranking, with A4 obtaining the highest performance score of 0.914.

**Table 17. Comparison of the Present Research with Existing Studies**

| Study | BIM | LCA | LCC | MCDM | Sensitivity Analysis | Integrated Carbon–Cost Decision |
|---|---|---|---|---|---|---|
| Zhang et al. [1] | ✓ | ✓ | ✓ | – | – | ✓ |
| Lu et al. [2] | ✓ | ✓ | ✓ | – | – | ✓ |
| Lu et al. [3] | ✓ | ✓ | – | – | – | – |
| Yang et al. [4] | ✓ | ✓ | – | – | – | – |
| MCDM study [14] | ✓ | – | – | ✓ | – | – |
| **Present Research** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |

Overall, comparison with the existing literature indicates that the principal contribution of the present research lies not in applying BIM, LCA, LCC, or MCDM individually, but in their combined implementation within a single carbon–cost optimization workflow, supplemented by sensitivity analysis to evaluate decision robustness. This directly addresses the integration gap identified in the literature review.

### 5.4 Practical Implications for Construction Project and Cost Management

The integrated BIM–LCA–LCC–MCDM framework has practical implications for both construction project management and cost management, as it enables environmental and economic performance to be considered during design and alternative-selection decisions. BIM provides a common project-information base from which material quantities can be connected with carbon and cost information, reducing fragmentation between quantity assessment, environmental analysis, and financial evaluation [1], [2], [7].

From a project management perspective, the framework allows alternative materials and design configurations to be evaluated before construction decisions are finalized. The comparison of A1–A4 showed that isolated material substitutions produced moderate improvements, whereas the integrated alternative A4 achieved the strongest overall performance. This enables project managers to evaluate design decisions based on their consequences across the complete building life cycle rather than relying only on conventional construction-stage indicators.

From a cost management perspective, the findings highlight the importance of distinguishing between initial construction cost and life-cycle cost. A4 had a higher initial cost of £5.612 million compared with £5.240 million for the baseline; however, its total LCC decreased from £9.496 million to £8.983 million. Therefore, an alternative with a higher initial investment can provide better long-term economic performance when operational, maintenance, replacement, and end-of-life costs are incorporated.

The framework can consequently support several key project decisions, including material selection, design-alternative evaluation, life-cycle budgeting, carbon management, value engineering, and sustainable procurement. The MCDM stage further enables project stakeholders to balance carbon and cost objectives rather than making decisions based on a single performance indicator [14], [16], [17].

The sensitivity analysis also has practical value because it tests whether the preferred alternative remains suitable when stakeholder priorities change. A4 retained the highest ranking across the evaluated weight variations, indicating that the selected solution remained stable under different carbon–cost priorities. This provides greater confidence when applying the decision framework to practical project-selection and investment decisions.

Overall, the research demonstrates that integrating BIM-based project information with life-cycle carbon, life-cycle

cost, and multi-criteria evaluation can shift construction decision-making from initial-cost-oriented selection toward whole-life carbon–cost management. Such integration provides project and cost managers with a structured basis for selecting construction solutions that deliver both environmental improvement and long-term economic value.

## 6. SUSTAINABILITY AND PRACTICAL IMPLEMENTATION

### 6.1 Environmental and Economic Sustainability

The sustainability assessment demonstrates that environmental improvement and long-term economic performance can be achieved simultaneously when construction alternatives are evaluated across the complete building life cycle. The integrated BIM–LCA–LCC framework enables material-related, operational, and economic impacts to be considered within the same decision process rather than treating carbon reduction and cost management as independent objectives [1], [2].

From an environmental sustainability perspective, the baseline building generated 1,867.7 t $CO_2e$ of whole-life carbon, of which operational carbon represented the largest contribution at 50.6%, followed by embodied carbon at 32.8%. The construction alternatives demonstrated that improvements in both material selection and operational performance can substantially reduce these impacts. The integrated alternative A4 reduced whole-life carbon to 1,482.6 t $CO_2e$, corresponding to a 20.6% reduction relative to the baseline.

The environmental improvement achieved by A4 can be expressed as:

$$\mathrm{WLC}_{\mathrm{saving}} = 1867.7 - 1482.6 = 385.1\ \mathrm{t\ CO_{2e}} \ldots . (42)$$

Thus, the integrated construction strategy avoided 385.1 t $CO_2e$ over the assessed building life cycle compared with the baseline configuration.

Economic sustainability was evaluated using life-cycle cost rather than initial construction cost alone. Although A4 increased the initial investment from £5.240 million to £5.612 million, its total life-cycle cost decreased from £9.496 million to £8.983 million. The resulting life-cycle economic saving was:

$$\mathrm{LLC}_{\mathrm{saving}} = 9.496 - 8.983 = 0.513\ \text{million £} \ldots . (42)$$

Therefore, A4 generated a life-cycle saving of approximately £0.513 million, equivalent to the previously calculated 5.4% LCC reduction. This result demonstrates that a higher initial investment does not necessarily lead to higher whole-life expenditure when operational, maintenance, replacement, and end-of-life costs are considered.

The combined sustainability performance can therefore be summarized as:

| Sustainability Indicator | Baseline A0 | Integrated Alternative A4 | Improvement |
|---|---|---|---|
| Whole-Life Carbon | 1,867.7 t $CO_2e$ | 1,482.6 t $CO_2e$ | **20.6% reduction** |
| Carbon Saving | – | 385.1 t $CO_2e$ | **385.1 t $CO_2e$** |
| Initial Construction Cost | £5.240 M | £5.612 M | Higher initial investment |
| Life-Cycle Cost | £9.496 M | £8.983 M | **5.4% reduction** |
| Life-Cycle Cost Saving | – | £0.513 M | **£0.513 M** |
| MCDM Rank | 5 | **1** | Improved |

The results indicate that sustainability in construction should not be evaluated solely through carbon reduction or minimum initial cost. Instead, the combined consideration of whole-life carbon and whole-life economic performance provides a more comprehensive basis for sustainable construction decisions. This aligns with the study's original objective of integrating environmental and economic assessment through BIM, LCA, LCC, and MCDM.

### 6.2 Practical Implementation in Construction Projects

The integrated BIM–LCA–LCC–MCDM framework can be implemented within construction projects as a structured decision-support process from design development through material selection and cost planning. The key practical advantage is the use of BIM-derived quantities as a common data source for environmental and economic assessment, allowing carbon and cost implications to be evaluated before major construction decisions are finalized [1], [2], [7].

During the design and planning stage, the BIM model can be used to extract quantities for major structural and envelope components. These quantities can then be linked with material-specific emission factors and unit-cost information. When the BIM model is revised, the corresponding material quantities can be updated and the carbon and cost assessments recalculated, enabling alternative design configurations to be compared on a consistent basis.

During material and construction alternative selection, project teams can evaluate different combinations of concrete, reinforcement, envelope systems, and other building components. The results of the present analysis demonstrate the practical importance of considering combined interventions. Individual material alternatives A1 and A2 produced moderate improvements, whereas A4, which integrated material and envelope strategies, achieved a 20.6% reduction in whole-life carbon and a 5.4% reduction in life-cycle cost.

For cost planning and value engineering, the LCC component allows project teams to assess whether an increase in initial expenditure can generate long-term financial benefits. In the case study, A4 increased initial construction cost from £5.240 million to £5.612 million, but reduced total LCC from £9.496 million to £8.983 million. Consequently, alternative selection based exclusively on the lowest initial cost would not have identified the best whole-life solution.

The MCDM stage provides a structured mechanism for combining carbon and economic indicators when several alternatives are technically feasible. This is particularly useful where project managers, cost consultants, designers, clients, and sustainability professionals assign different levels of importance to environmental and financial performance [14], [16], [17].

Sensitivity analysis further supports implementation by determining whether the preferred solution remains stable when these priorities change.

For practical project application, the implementation sequence can therefore be represented as:

BIM Model → Take-Off → Carbon \& Cost Assessment → Alternative Comparison →MCDM → Sensitivity Check →Final Selection

Overall, the framework provides a practical pathway for incorporating whole-life carbon and cost considerations into routine construction decision-making. It can support design optimization, quantity surveying, cost planning, value engineering, sustainable procurement, and selection of construction alternatives while maintaining a transparent link between project data and the final decision.

### 6.3 Contribution toward Low-Carbon and Cost-Efficient Construction

The findings demonstrate that low-carbon construction and cost efficiency can be pursued simultaneously when design decisions are evaluated from a whole-life perspective. The integrated BIM–LCA–LCC–MCDM approach enables carbon-intensive materials, operational impacts, and long-term costs to be considered within the same decision framework. This is consistent with the study objective of integrating environmental and economic indicators for construction decision-making [1], [2], [12], [13].

The baseline building recorded whole-life carbon emissions of 1,867.7 t $CO_2e$ and an LCC of £9.496 million. In comparison, the integrated alternative A4 reduced whole-life carbon to 1,482.6 t $CO_2e$ and LCC to £8.983 million. This represents a reduction of 385.1 t $CO_2e$ (20.6%) and a life-cycle cost saving of approximately £0.513 million (5.4%).

The results further show that combining multiple construction interventions provides greater benefits than isolated material modifications. A1 and A2 achieved carbon reductions of 5.9% and 4.2%, respectively, whereas A3 achieved an 11.4% reduction through improved envelope performance. A4 combined material and operational improvements and consequently delivered the highest overall carbon reduction and the lowest life-cycle cost.

From a construction management perspective, these findings indicate that selecting the lowest initial-cost option does not necessarily produce the most cost-efficient project over its complete life cycle. Although A4 required a higher initial investment, its improved operational and long-term economic performance resulted in lower overall expenditure. Therefore, life-cycle cost provides a more appropriate economic basis for evaluating low-carbon construction strategies than initial construction cost alone.

The MCDM results reinforce this contribution, with A4 achieving the highest performance score of 0.914 and maintaining Rank 1 under all sensitivity scenarios. The framework therefore supports the selection of construction solutions that provide a balanced combination of carbon reduction, long-term cost efficiency, and decision robustness.

Overall, the research contributes toward low-carbon and cost-efficient construction by demonstrating that:

Integrated Design → Lower WLC +Lower LCC→Sustainable Construction Value

The main contribution is therefore not simply the reduction of carbon emissions, but the identification of construction alternatives capable of delivering measurable environmental improvement without compromising long-term economic performance. This directly reflects the paper's stated focus on integrating BIM-derived quantities, carbon factors, costs, construction alternatives, MCDM, and sensitivity analysis.

## 7. LIMITATIONS AND FUTURE RESEARCH

### 7.1 Research Limitations

Although the integrated BIM–LCA–LCC–MCDM framework provided a systematic approach for carbon–cost optimization, several limitations should be considered when interpreting the results.

First, the analysis was conducted using a single construction case study. The building type, structural system, material quantities, and life-cycle characteristics therefore influence the resulting carbon and cost performance. Application to projects with different structural systems, scales, functions, and climatic conditions may produce different outcomes.

Second, the accuracy of the life-cycle carbon assessment depends on the quality of the material quantities and carbon emission factors used in the analysis. Carbon factors can vary according to material production processes, energy sources, transportation distances, geographical location, and end-of-life treatment. Consequently, changes in these parameters can influence calculated whole-life carbon emissions. The paper's underlying methodology similarly relies on linking BIM quantities with corresponding carbon information.

Third, the life-cycle cost assessment depends on long-term economic parameters such as unit costs, discount rates, maintenance requirements, replacement intervals, and operational expenditure. These parameters may change during the building service life, creating uncertainty in long-term cost estimates. Life-cycle costing is nevertheless an established component of the research framework and is supported by ISO 15686-5 in the paper's reference base.

Fourth, the construction alternatives were limited to selected interventions involving low-carbon concrete, recycled steel, building-envelope improvement, and their integrated application. Other potential strategies, including alternative structural systems, renewable energy technologies, construction methods, and circular material strategies, were outside the present assessment boundary.

Finally, the MCDM results are influenced by the selected criteria and their relative weights. Although the sensitivity analysis demonstrated that A4 maintained the highest ranking across the evaluated weight variations, different criteria or stakeholder priorities could affect the relative performance of the alternatives. MCDM therefore supports structured decision-making but does not eliminate the influence of decision preferences [14], [16], [17].

These limitations define the applicability of the findings without affecting the primary contribution of the study: the integration of BIM, LCA, LCC, MCDM, and sensitivity analysis within a unified carbon–cost decision framework.

### 7.2 Future Research Directions

Future research should extend the integrated BIM–LCA–LCC–MCDM framework to a broader range of construction projects to examine its applicability across different building types, structural systems, project scales, and regional conditions. Applying the framework to multiple case studies would enable comparison of carbon–cost performance under different material, operational, and economic conditions.

Further research should also incorporate more detailed regional and project-specific carbon data, including material production, transportation distance, construction processes, energy sources, maintenance activities, and end-of-life pathways. This would improve the resolution of whole-life carbon assessment while maintaining the BIM-based quantity linkage established in the present study. The existing research framework specifically establishes BIM quantities as the basis for linking project information with carbon and cost assessment.

The range of construction alternatives can also be expanded beyond the material and envelope strategies evaluated in this research. Future studies may investigate alternative structural systems, prefabricated construction, recycled and reusable materials, renewable energy integration, material recovery, and circular construction strategies within the same carbon–cost evaluation framework.

Future LCC analysis should additionally examine uncertainty in material prices, energy costs, discount rates, maintenance intervals, and replacement costs. Scenario-based analysis of these parameters would provide a more comprehensive understanding of long-term economic performance and complement the life-cycle costing principles used in the present framework [20].

The MCDM component can be extended by incorporating a wider range of criteria, including construction duration, material availability, durability, resource efficiency, and constructability, together with environmental and economic indicators. Stakeholder-specific weighting can also be investigated to examine how the priorities of clients, designers, contractors, cost consultants, and sustainability professionals influence alternative selection [14], [16], [17].

Finally, future research can focus on greater automation of the BIM–LCA–LCC data exchange, allowing changes in BIM quantities to update carbon and cost assessments more efficiently. This would strengthen the practical application of the framework as a dynamic decision-support approach throughout project design and planning.

Overall, future development should focus on broader project validation, improved life-cycle datasets, expanded construction alternatives, uncertainty assessment, stakeholder-based MCDM, and BIM-based automation.

## CONCLUSIONS

This research developed an integrated BIM–LCA–LCC–MCDM framework for evaluating and optimizing the carbon and economic performance of construction projects. BIM-based material quantities provided a common data foundation for life-cycle carbon and cost assessment, while MCDM enabled alternative construction strategies to be evaluated using multiple environmental and economic criteria. Sensitivity analysis was subsequently used to examine the robustness of the final decision. This integrated approach directly addresses the research objective of connecting BIM-derived quantities, carbon emissions, life-cycle costs, construction alternatives, and decision-making within a unified assessment framework.

The baseline case-study building recorded a whole-life carbon emission of 1,867.7 t $CO_2e$, with operational carbon accounting for 50.6% and embodied carbon for 32.8% of the total emissions. The baseline life-cycle cost was £9.496 million. These findings demonstrate the importance of considering both embodied and operational impacts and evaluating economic performance beyond initial construction cost.

Among the evaluated construction alternatives, individual material interventions produced moderate improvements. The low-carbon concrete alternative A1 reduced whole-life carbon by 5.9%, while the recycled-steel alternative A2 achieved a 4.2% reduction. The enhanced building-envelope alternative A3 provided greater improvement, reducing whole-life carbon by 11.4% and life-cycle cost by 4.0%.

The strongest performance was achieved by A4 – Integrated Low-Carbon Design. Whole-life carbon decreased from 1,867.7 to 1,482.6 t $CO_2e$, representing a 20.6% reduction and a saving of 385.1 t $CO_2e$. At the same time, life-cycle cost decreased from £9.496 million to £8.983 million, producing a 5.4% reduction and approximately £0.513 million in life-cycle cost savings. Although A4 required a higher initial investment, its long-term operational and economic benefits resulted in superior whole-life performance.

The MCDM evaluation further confirmed this outcome, with A4 achieving the highest performance score of 0.914, followed by A3, A1, A2, and A0. The final ranking was:

A4>A3>A1>A2>A0

Sensitivity analysis showed that A4 maintained Rank 1 across all evaluated criterion-weight variations, confirming that the preferred alternative remained stable under changing environmental and economic priorities.

The principal research contribution is therefore the integration of BIM, LCA, LCC, MCDM, and sensitivity analysis into a single carbon–cost optimization process. Rather than selecting construction solutions solely on the basis of initial cost or carbon emissions, the framework supports decisions based on whole-life environmental and economic performance. This extends the BIM-based carbon and cost integration discussed in the existing literature [1], [2] by incorporating alternative evaluation, multi-criteria ranking, and decision robustness.

From a practical perspective, the framework can support project managers, cost consultants, designers, contractors, and sustainability professionals in material selection, design comparison, life-cycle budgeting, value engineering, and sustainable procurement. The findings demonstrate that low-carbon construction does not necessarily require a long-term economic penalty; appropriately integrated design strategies can simultaneously achieve lower whole-life carbon and lower life-cycle cost.

Overall, the research demonstrates that BIM-enabled life-cycle assessment combined with economic and multi-criteria evaluation provides a systematic basis for achieving low-carbon, cost-efficient, and **sustainable construction decision-making.**

## REFERENCES

1. Y. Zhang, X. Jiang, C. Cui, and M. Skitmore, “BIM-based approach for the integrated assessment of life cycle carbon emission intensity and life cycle costs,” Building and Environment, vol. 226, Art. no. 109691, 2022. doi: 10.1016/j.buildenv.2022.109691. ScienceDirect
2. K. Lu, X. Jiang, J. Yu, V. W. Y. Tam, and M. Skitmore, “Integration of life cycle assessment and life cycle cost using building information modeling: A critical review,” Journal of Cleaner Production, vol. 285, Art. no. 125438, 2021. doi: 10.1016/j.jclepro.2020.125438.
3. K. Lu, X. Jiang, V. W. Y. Tam, M. Li, H. Wang, B. Xia, and Q. Chen, “Development of a carbon emissions analysis framework using building information modeling and life cycle assessment for the construction of hospital projects,” Sustainability, vol. 11, no. 22, Art. no. 6274, 2019. doi: 10.3390/su11226274.
4. X. Yang, M. Hu, J. Wu, and B. Zhao, “Building-information-modeling enabled life cycle assessment, a case study on carbon footprint accounting for a residential building in China,” Journal of Cleaner Production, vol. 183, pp. 729–743, 2018. doi: 10.1016/j.jclepro.2018.02.070.
5. C. K. Chau, T. M. Leung, and W. Y. Ng, “A review on life cycle assessment, life cycle energy assessment and life cycle carbon emissions assessment on buildings,” Applied Energy, vol. 143, pp. 395–413, 2015. doi: 10.1016/j.apenergy.2015.01.023.
6. A. Hollberg and J. Ruth, “LCA in architectural design—a parametric approach,” The International Journal of Life Cycle Assessment, vol. 21, pp. 943–960, 2016. doi: 10.1007/s11367-016-1065-1.
7. E. Alasmari, P. Martinez-Vazquez, and C. Baniotopoulos, “A systematic literature review of the adoption of Building Information Modelling (BIM) on Life Cycle Cost (LCC),” Buildings, vol. 12, no. 11, Art. no. 1829, 2022. doi: 10.3390/buildings12111829.

8. M. N. Nwodo, C. J. Anumba, and S. Asadi, “BIM-based life cycle assessment and costing of buildings: Current trends and opportunities,” in Computing in Civil Engineering 2017, 2017. doi: 10.1061/9780784480847.007.
9. “A systematic review of the integration of building information modeling into life cycle assessment,” Building and Environment, vol. 221, Art. no. 109260, 2022. doi: 10.1016/j.buildenv.2022.109260.
10. “BIM-based life cycle assessment: A systematic review on automation and decision-making during design,” Building and Environment, vol. 282, Art. no. 113248, 2025. doi: 10.1016/j.buildenv.2025.113248.
11. “Carbon emission reduction in prefabrication construction during materialization stage: A BIM-based life-cycle assessment approach,” Science of the Total Environment, 2020.
12. “A multi-objective optimization strategy for building carbon emission from the whole life cycle perspective,” Energy, vol. 262, Art. no. 125373, 2023. doi: 10.1016/j.energy.2022.125373.
13. “Developing a multi-objective optimization model for improving building's environmental performance over the whole design process,” Building and Environment, vol. 246, Art. no. 110996, 2023. doi: 10.1016/j.buildenv.2023.110996.
14. “Building information modelling application for developing sustainable building (Multi criteria decision making approach),” Ain Shams Engineering Journal, vol. 12, no. 1, pp. 293–302, 2021. doi: 10.1016/j.asej.2020.06.006.
15. “Research on low carbon during the construction design process based on BIM and Life Cycle Assessment,” Buildings, vol. 16, no. 13, Art. no. 2653, 2026. doi: 10.3390/buildings16132653.
16. T. L. Saaty, The Analytic Hierarchy Process. New York, NY, USA: McGraw-Hill, 1980.
17. C. L. Hwang and K. Yoon, Multiple Attribute Decision Making: Methods and Applications—A State-of-the-Art Survey. Berlin, Germany: Springer-Verlag, 1981.
18. International Organization for Standardization, ISO 14040: Environmental Management—Life Cycle Assessment—Principles and Framework. Geneva, Switzerland: ISO, 2006.
19. International Organization for Standardization, ISO 14044: Environmental Management—Life Cycle Assessment—Requirements and Guidelines. Geneva, Switzerland: ISO, 2006.
20. International Organization for Standardization, ISO 15686-5: Buildings and Constructed Assets—Service Life Planning—Part 5: Life-Cycle Costing. Geneva, Switzerland: ISO. 3