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Integrated Sustainability, Life-Cycle Cost, and Regional Suitability Assessment of RC Skeletal and Masonry Load-Bearing Systems in Low-Rise Residential Buildings

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Keywords: Structural systems, Masonry load-bearing walls, Reinforced concrete frames, Sustainability, Life-cycle cost analysis, Embodied carbon, Value engineering, Decision-support framework, Sustainability Efficiency Index, Load-Bearing Suitability Index

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Integrated Sustainability, Life-Cycle Cost, and Regional Suitability Assessment of RC Skeletal and Masonry Load-Bearing Systems in Low-Rise Residential Buildings

Abstract

This study presents an integrated decision-support framework for evaluating two widely used structural systems in low-rise residential buildings: reinforced-concrete (RC) skeletal construction with masonry infill walls and masonry load-bearing construction. A three-story residential building was designed under identical geometric configurations, loading conditions, and Egyptian Code requirements to provide a consistent basis for comparison. The proposed framework integrates structural design, material quantification, life-cycle cost analysis (LCCA), embodied carbon assessment, sustainability evaluation, value-engineering principles, and regional suitability assessment within a unified methodology.

The results indicate that the direct wall-supported load-transfer mechanism of the masonry load-bearing system substantially improves resource efficiency. Compared with the RC skeletal alternative, concrete consumption decreased by approximately 59%, reinforcement steel demand by 82%, construction cost by 44%, life-cycle cost by 46.5%, and embodied carbon emissions by 52%. In contrast, the RC skeletal system demonstrated superior architectural flexibility, structural redundancy, and adaptability to future functional modifications.

To support systematic decision-making, an Analytic Hierarchy Process (AHP)-based evaluation was conducted and combined with a Sustainability Efficiency Index (SuEI) developed to integrate structural, economic, and environmental performance. In addition, a Load-Bearing Suitability Index (LBSI) was proposed to assess the applicability of masonry load-bearing systems under different geotechnical and planning conditions. The robustness of the proposed framework was further examined through Monte Carlo uncertainty analysis considering variability in cost and environmental parameters, while external comparative benchmarking was performed using representative published studies. Preliminary applicability assessment using independent Egyptian geotechnical case studies provided supporting evidence for the proposed framework as an early-stage structural-system screening tool.

The findings indicate that masonry load-bearing construction represents a highly competitive solution for regular low-rise residential developments where affordability, resource efficiency, and environmental sustainability are primary objectives. The study contributes a practical engineering decision-support framework that links building-scale performance evaluation with regional implementation suitability, supporting more informed structural-system selection during early design stages.

Keywords: Structural systems; Masonry load-bearing walls; Reinforced concrete frames; Sustainability; Life-cycle cost analysis; Embodied carbon; Value engineering; Decision-support framework; Sustainability Efficiency Index; Load-Bearing Suitability Index.

1. Introduction

The selection of an appropriate structural system is one of the most influential decisions in building design because it directly affects structural safety, serviceability, construction cost, resource consumption, project duration, environmental performance, and long-term functionality [1–4]. Among the structural systems commonly used in low-rise buildings, reinforced concrete (RC) skeletal structures and masonry load-bearing systems remain two of the most widely adopted alternatives. Each system offers distinct advantages and limitations that influence its suitability for specific project requirements.

RC skeletal structures have achieved widespread acceptance because they provide architectural flexibility, accommodate relatively large spans, and facilitate future modifications without significantly affecting the primary load-resisting system. In these structures, masonry walls are generally used as enclosure and partition elements, while gravity and lateral loads are resisted by beams, columns, and foundations. This arrangement supports diverse architectural layouts and allows greater adaptability throughout the service life of the building.

Although masonry infill walls are frequently treated as non-structural elements in conventional design practice, previous studies have shown that they can influence the overall response of framed buildings by contributing to stiffness enhancement, force redistribution, and global structural behavior [5–9]. Their interaction with surrounding structural members may affect the performance of the entire building system and should therefore be considered when evaluating alternative construction approaches.

In parallel with developments in framed construction, masonry load-bearing systems continue to represent an effective solution for residential applications. In these systems, walls serve as the primary vertical load-resisting elements, transferring loads directly from slabs to foundations. The elimination or significant reduction of beams and columns results in a shorter and more direct load path, which can improve material efficiency and simplify construction procedures [5–9]. Such characteristics make load-bearing masonry particularly suitable for regular low-rise buildings with moderate spans and repetitive floor layouts.

The use of load-bearing walls may also reduce the quantities of reinforced concrete, steel reinforcement, and formwork required during construction. Since achievedtaneously perform structural and architectural functions, the required building performance can

often be achieved with fewer structural components. Nevertheless, these advantages are accompanied by certain limitations. Compared with framed construction, load-bearing masonry provides less flexibility for future modifications and may be unsuitable for projects requiring large open spaces, irregular configurations, or substantial functional changes during the building service life.

Beyond structural considerations, sustainability has become a major factor in the selection of building systems. The construction sector is responsible for a significant proportion of global greenhouse-gas emissions, largely due to the extensive use of cement-based materials and steel reinforcement [10–15]. Consequently, reducing material consumption through efficient structural design has emerged as an important strategy for lowering embodied carbon and improving environmental performance. Recent studies have emphasized that structural-system selection should be evaluated not only in terms of strength and serviceability but also with respect to lifecycle environmental impacts and resource efficiency [10–18].

Embodied carbon assessment has therefore become an important decision-support tool during early design stages because material choices and structural configurations strongly influence the environmental footprint of buildings [11–18]. Systems requiring lower quantities of concrete and steel may offer significant environmental benefits; however, overall performance must also account for constructability, durability, functionality, and economic feasibility.

Value engineering provides an additional perspective by evaluating how effectively a structural system fulfills the required functions while minimizing unnecessary expenditure of resources. Rather than focusing solely on cost reduction, value engineering seeks to optimize the relationship between performance, quality, constructability, lifecycle cost, and sustainability [19–23]. Integrating value-engineering principles with environmental assessment and multi-criteria decision-making techniques allows a more comprehensive evaluation of alternative structural solutions.

Despite extensive research on RC frames, masonry construction, and sustainable building design, relatively limited attention has been devoted to direct comparisons between RC skeletal and masonry load-bearing systems under identical architectural layouts, loading conditions, and design-code requirements. Moreover, structural performance, economic considerations, and environmental impacts are often evaluated independently, limiting their usefulness during early-stage decision-making.

To address this gap, the present study develops a comprehensive comparative framework based on a three-story residential building designed using both structural systems in

accordance with Egyptian Code provisions. The assessment integrates structural behavior, material consumption, life-cycle cost, embodied carbon emissions, sustainability performance, and value-engineering principles within a unified decision-support approach. The proposed framework aims to assist engineers and practitioners in selecting the most appropriate structural solution based on project-specific priorities, resource efficiency, environmental impact, and long-term functional requirements.

The fundamental differences between the two structural systems considered in this study are illustrated in Figure 1.

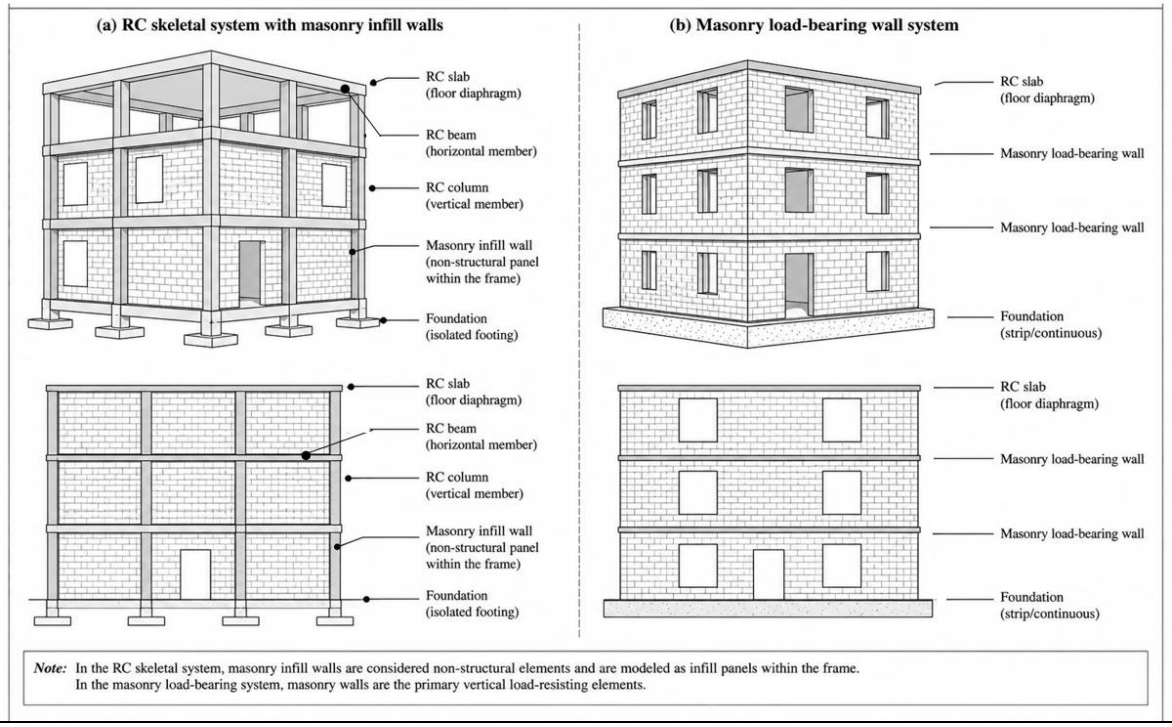


Figure 1. Typical structural configurations of (a) RC skeletal system with masonry infill walls and (b) masonry load-bearing wall system.

2. Literature Benchmarking and Research Gap

2.1 Comparative Positioning with Previous Studies

Numerous studies have investigated the sustainability implications of alternative building systems through environmental assessment, life-cycle costing, and multi-criteria decision-making approaches. However, most existing studies address individual aspects of sustainability and rarely integrate structural, economic, environmental, and regional suitability considerations within a unified framework.

Motuziene et al. integrated Life Cycle Assessment (LCA), Life Cycle Cost Analysis (LCCA), and multi-criteria decision-making techniques for sustainable residential design. However, their work did not address structural material quantification, sustainability-efficiency assessment, or regional suitability considerations.

Similarly, Santos et al. developed a BIM-based framework integrating LCA and LCC methodologies to support early-stage sustainability assessment. Although the framework improved environmental and economic evaluation efficiency, it did not include structural-system selection, material-efficiency assessment, or regional applicability analysis.

Vilutiene et al. investigated sustainable structural alternatives using multi-criteria assessment techniques and demonstrated the importance of balancing environmental and economic objectives during structural-system selection. Nevertheless, the proposed methodology did not incorporate sustainability-efficiency indicators or regional suitability assessment.

More recently, Esteghamati proposed a machine-learning-assisted framework integrating embodied-carbon evaluation and structural-system selection during conceptual design. While the study demonstrated the potential of data-driven sustainability assessment, it focused primarily on environmental and performance optimization rather than lifecycle economic evaluation or location-specific suitability analysis.

To highlight the contribution of the present study, Table 1 compares representative literature studies with the proposed framework.

Table 1. Comparative Positioning of the Proposed Framework Relative to Previous Sustainability-Oriented Studies

Study	Structural Comparison	LCCA	Embodied Carbon	Material Quantification	AHP/MCDA	Sustainability Index	Regional Suitability	External Validation
Motuziene et al.	✓	✓	✓	✗	✓	✗	✗	✗
Santos et al.	✗	✓	✓	✗	✗	✗	✗	✗
Vilutiene et al.	✓	✓	✓	✓	✓	✗	✗	✗

Study	Structural Comparison	LCCA	Embodied Carbon	Material Quantification	AHP/MCDA	Sustainability Index	Regional Suitability	External Validation
Present Study	✓	✓	✓	✓	✓	✓	✓	✓

In contrast, the present study integrates structural quantity estimation, embodied-carbon assessment, life-cycle cost analysis, AHP-based decision support, Sustainability Efficiency Index (SuEI) evaluation, Monte Carlo uncertainty analysis, external comparative benchmarking, and regional applicability assessment through the proposed Load-Bearing Suitability Index (LBSI). The methodology further incorporates independent Egyptian geotechnical case studies to support applicability assessment beyond the investigated building.

Consequently, the proposed framework extends beyond conventional sustainability assessment by linking building-scale structural performance and resource efficiency with regional implementation suitability.

2.2 External Benchmarking against Previous Studies

To further position the contribution of the present study within the existing body of knowledge, a benchmarking exercise was conducted using representative investigations comparing masonry-based and reinforced-concrete structural systems from structural, economic, environmental, and sustainability perspectives. Although direct numerical comparison is limited by differences in building configuration, materials, and assessment methodologies, the selected studies provide useful context for evaluating the consistency of the observed trends.

Table 2. External Benchmarking of the Proposed Framework Against Representative Masonry and RC Comparative Studies

Study	Structural Systems	Assessment Scope	Key Findings	Agreement with Present Study
Shashank & Raghunath (2014)	Reinforced Masonry vs RC Frame	Structural Design and Material Consumption	Lower concrete and steel demand	Strong

Study	Structural Systems	Assessment Scope	Key Findings	Agreement with Present Study
Puskás & Moga (2016)	Load-Bearing Masonry vs RC Frame	Cost and Environmental Assessment	Better economic and environmental performance	Strong
Vilutiene et al. (2020)	Alternative Structural Systems	Sustainability and MCDA	Sustainability-oriented selection improved decision-making	Methodological
Present Study	Masonry Load-Bearing vs RC Skeletal	Structural, Economic, Environmental and Regional Suitability Assessment	59% concrete reduction, 82% steel reduction, 44% cost reduction, 52% carbon reduction	—

The benchmarking results reveal a consistent pattern across independent investigations. Previous studies generally reported that structural systems requiring lower quantities of reinforced concrete and steel tend to achieve improved economic and environmental performance. The findings obtained in the present study follow the same trend, with the masonry load-bearing system demonstrating substantial reductions in material demand, embodied carbon emissions, and construction cost relative to the RC skeletal alternative.

Unlike previous investigations, the proposed framework combines comparative structural design, life-cycle cost analysis, embodied-carbon assessment, AHP-based decision support, Sustainability Efficiency Index (SuEI), Monte Carlo uncertainty analysis, external benchmarking, and regional suitability assessment through the proposed Load-Bearing Suitability Index (LBSI). Consequently, the contribution extends beyond conventional sustainability assessment by providing a unified engineering decision-support methodology for low-rise residential development.

2.3 Research Gap and Contribution

Existing studies have investigated sustainability assessment, life-cycle costing, embodied-carbon evaluation, and multi-criteria decision-making for buildings. However, direct comparisons between RC skeletal and masonry load-bearing systems designed under identical architectural layouts, loading conditions, and code requirements remain limited.

Furthermore, the literature contains very limited evidence regarding the combined evaluation of structural performance, material consumption, life-cycle cost, embodied carbon emissions, sustainability efficiency, uncertainty assessment, and regional implementation suitability within a single framework. Consequently, the influence of structural-system selection on overall sustainability performance remains insufficiently quantified for low-rise residential developments.

To address these limitations, the present study develops an integrated decision-support methodology combining comparative structural design, life-cycle cost analysis, embodied-carbon assessment, AHP-based evaluation, Sustainability Efficiency Index (SuEI), Monte Carlo uncertainty analysis, external comparative benchmarking, and Load-Bearing Suitability Index (LBSI) assessment. The proposed framework links building-scale performance with regional implementation suitability, thereby extending conventional sustainability assessment toward practical engineering decision support for low-rise residential developments.

3. Methodology

3.1 General methodological approach

A controlled comparative methodology was adopted to evaluate two alternative structural systems for the same residential building configuration: (i) a reinforced-concrete (RC) skeletal system with masonry infill walls and (ii) a masonry load-bearing wall system. Identical architectural layouts, loading assumptions, and design-code provisions were adopted to ensure that the comparison reflected differences in structural-system behavior rather than variations in building geometry or functional requirements.

The proposed framework consists of six sequential stages:

1. Comparative structural design of both systems in accordance with the Egyptian Code of Practice.
2. Quantification of material consumption, including concrete and reinforcement steel.
3. Economic assessment through construction-cost and life-cycle cost analysis.
4. Environmental assessment through embodied-carbon estimation.
5. Multi-criteria sustainability evaluation using AHP and the proposed Sustainability Efficiency Index (SuEI).

6. Framework robustness and applicability assessment through Monte Carlo uncertainty analysis, external benchmarking, and regional suitability evaluation using the proposed Load-Bearing Suitability Index (LBSI).

The overall workflow of the developed framework is presented in Figure 2.

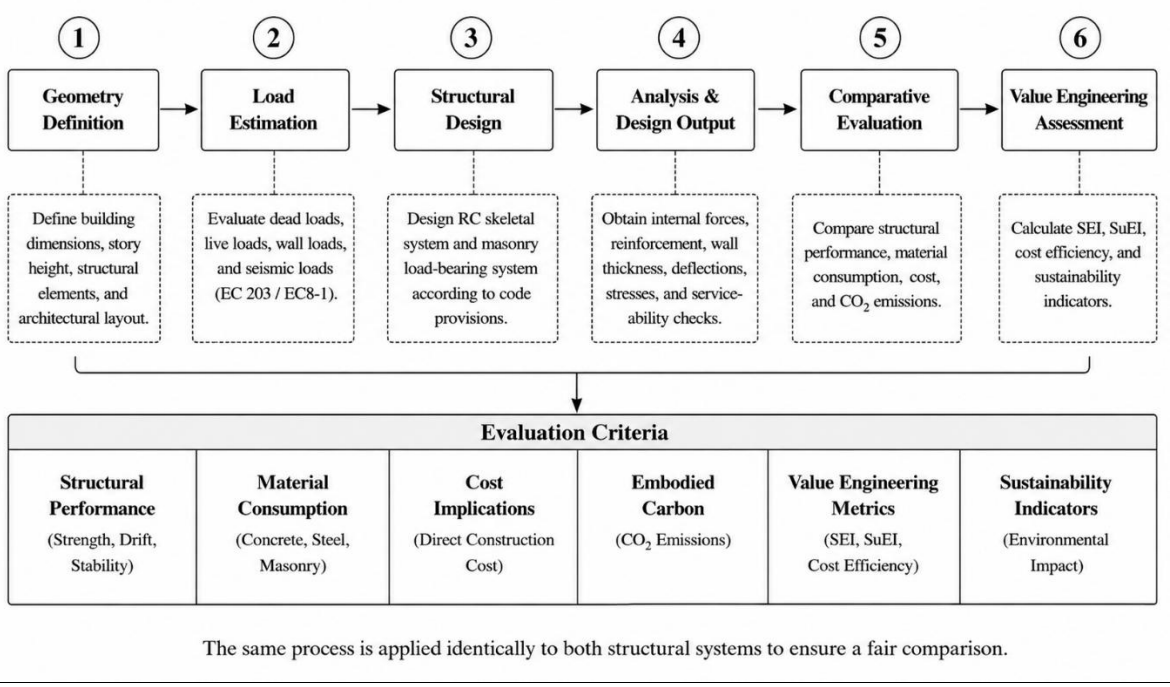


Figure 2. Workflow of structural design and comparative evaluation framework.

3.2 Case-Study Building and Structural Design Basis

The selected case study is a three-story residential building designed using both structural systems under identical geometric and loading conditions. The same architectural layout, floor configuration, occupancy classification, slab thickness, and loading assumptions were adopted to ensure a consistent basis for comparison.

Both alternatives were designed in accordance with the Egyptian Code of Practice. The design considered dead loads, live loads, slab self-weight, floor finishing loads, and load transfer to supporting structural elements. A slab thickness of 120 mm was adopted for both systems.

For the RC skeletal system, the design included solid slabs, beams, columns, and isolated footings. Structural design considered bending, shear, axial-load demands, bearing-capacity requirements, punching shear, and foundation performance.

For the masonry load-bearing system, the design focused on wall compressive capacity, wall slenderness, eccentricity effects, structural-wall load transfer, and wall-thickness adequacy.

The architectural layout adopted for both structural systems is presented in Figure 3.

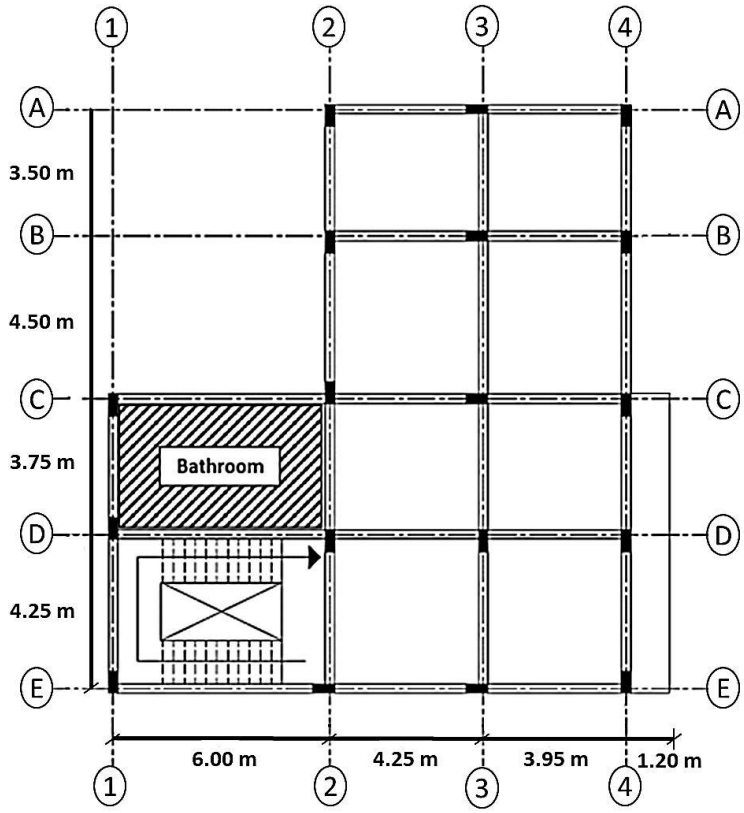


Figure 3. Architectural layout of the three-story residential building used for comparative study.

3.3 Structural Load-Transfer Mechanisms

The fundamental difference between the investigated systems lies in their load-transfer mechanisms.

For the RC skeletal system, gravity loads are transferred through:

Slabs → Beams → Columns → Footings → Soil

This hierarchical load path introduces bending moments, shear forces, reinforcement requirements, and multiple construction stages.

For the masonry load-bearing system, gravity loads are transferred through:

Slabs → Load-Bearing Walls → Foundations → Soil

This direct wall-supported load path reduces the need for beams and columns while enabling walls to perform both structural and architectural functions.

These differences form the basis for evaluating variations in material consumption, cost, embodied carbon emissions, and overall sustainability performance.

3.4 Comparative Evaluation Criteria

The investigated structural systems were evaluated using the following criteria:

- Structural behavior and load-path efficiency.
- Material consumption.
- Construction complexity and constructability.
- Construction and life-cycle costs.
- Embodied carbon emissions.
- Architectural flexibility and adaptability.
- Sustainability performance.
- Value-engineering efficiency.

Collectively, these criteria represent the principal technical, economic, environmental, and functional factors influencing structural-system selection in low-rise residential buildings.

3.5 Sustainability and Decision-Support Assessment

A multi-level sustainability assessment framework was developed to support systematic structural-system selection.

First, the Analytic Hierarchy Process (AHP) was applied to evaluate the relative performance of the investigated alternatives using multiple engineering criteria. Subsequently, a Sustainability Efficiency Index (SuEI) was developed to integrate structural performance, life-cycle cost efficiency, and environmental efficiency within a single composite indicator.

The proposed index enables direct comparison between competing structural systems during the conceptual design stage and provides a unified measure of overall sustainability performance.

3.6 Uncertainty and External Applicability Assessment

To evaluate the robustness of the obtained conclusions, a Monte Carlo uncertainty analysis was performed considering ±15% variability in unit material costs and embodied-

carbon coefficients. A total of 5000 simulations were conducted to quantify the stability of the identified economic and environmental advantages.

External benchmarking was additionally conducted using representative published studies comparing masonry and reinforced-concrete structural systems to examine the consistency of the observed trends with independent investigations.

To extend the applicability of the framework beyond the investigated case study, a Load-Bearing Suitability Index (LBSI) was developed to evaluate the suitability of masonry load-bearing systems under different geotechnical and planning conditions.

3.7 Summary of Design Quantities and Comparative Indicators

All comparative indicators presented in this study were derived from complete structural designs of both systems developed in accordance with the Egyptian Code of Practice. To improve readability and maintain focus on the comparative assessment, only consolidated design outputs are presented in the main manuscript, while detailed calculations may be provided as supplementary material.

Table 3 summarizes the principal design quantities and performance indicators obtained from the comparative structural-design process.

Table 3. Summary of design quantities and performance indicators.

Indicator	RC Skeletal	Masonry Load-Bearing	Reduction
Concrete Consumption	104.3 m^3	42.7 m^3	59%
Reinforcement Steel	14.8 t	2.6 t	82%
Construction Cost	1,380,000 EGP	770,000 EGP	44%
Embodied Carbon	55.4 tCO_2-eq	26.8 tCO_2-eq	52%

The results indicate that the masonry load-bearing system substantially reduces concrete consumption, reinforcement demand, construction cost, and embodied carbon emissions compared with the RC skeletal alternative. These reductions are primarily attributed to the elimination of most beams and columns and the adoption of a more direct gravity load-transfer mechanism through structural walls.

4.1 Structural Design Outputs

Table 4 summarizes the principal structural characteristics of the two investigated systems developed using identical architectural layouts, loading assumptions, and Egyptian Code

design provisions. The comparison highlights the fundamental differences in load-transfer mechanisms, structural-member requirements, construction complexity, and functional performance.

Table 4. Summary of structural design outputs for RC skeletal and masonry load-bearing systems.

Parameter	RC Skeletal System	Masonry Load-Bearing System	Engineering Interpretation
Building type	Three-story residential building	Three-story residential building	Same case-study basis
Design code	Egyptian Code provisions	Egyptian Code provisions	Same design framework
Slab system	Solid slab	Solid slab	Comparable floor system
Slab thickness	120 mm	120 mm	Same slab basis for comparison
Main vertical load-resisting elements	RC columns	Masonry walls	Different structural philosophy
Main horizontal supporting elements	RC beams	Mostly eliminated or minimized	Major reduction in RC elements
Load path	Slab → Beam → Column → Footing	Slab → Wall → Foundation	More direct load transfer
Reinforcement demand	Higher due to beams and columns	Lower due to reduced RC members	Significant steel reduction
Foundation type	Isolated footings	Strip/wall-supported foundations	Different load distribution mechanisms
Architectural flexibility	High	Limited	RC system advantage

Parameter	RC Skeletal System	Masonry Load-Bearing System	Engineering Interpretation
Construction complexity	Higher	Lower	Masonry system advantage
Suitability	Flexible or complex layouts	Regular low-rise layouts	Context-dependent selection

Table 4 demonstrates that both systems satisfy the same functional requirements while employing fundamentally different load-transfer mechanisms. The RC skeletal system relies on slabs, beams, columns, and footings, whereas the masonry load-bearing system transfers gravity loads directly through structural walls to the foundations. This distinction directly influences material consumption, reinforcement demand, construction complexity, and sustainability performance and forms the basis for the reductions in concrete consumption, reinforcement-steel demand, construction cost, and embodied-carbon emissions discussed in the following sections.

4.2 Comparative Performance Evaluation

To provide a comprehensive assessment of the investigated alternatives, the RC skeletal and masonry load-bearing systems were evaluated using structural, economic, environmental, and functional performance indicators. The assessment combines quantitative results obtained from the structural-design process with qualitative engineering considerations related to constructability, flexibility, and long-term functionality.

Table 5. Comparative performance evaluation of the structural systems investigated.

Evaluation Criterion	**RC Skeletal System**	**Masonry Load-Bearing System**	**Relative Difference / Preferred System**
Concrete consumption	**104.3 m^3**	**42.7 m^3**	**59% reduction (Masonry)**
Reinforcement steel	**14.8 t**	**2.6 t**	**82% reduction (Masonry)**
Construction cost	**1,380,000 EGP**	**770,000 EGP**	**44% reduction (Masonry)**

Evaluation Criterion	RC Skeletal System	Masonry Load-Bearing System	Relative Difference / Preferred System
Life-cycle cost	**1,578,229 EGP**	**843,711 EGP**	**46.5% reduction (Masonry)**
Embodied carbon	**55.4 tCO_2-eq**	**26.8 tCO_2-eq**	**52% reduction (Masonry)**
Load-path efficiency	**Indirect load transfer**	**Direct load transfer**	**Masonry preferred**
Construction complexity	**Higher**	**Lower**	**Masonry preferred**
Construction speed	**Moderate**	**Faster**	**Masonry preferred**
Structural redundancy	**Higher**	**Lower**	**RC preferred**
Architectural flexibility	**High**	**Limited**	**RC preferred**
Future modification	**Easier**	**More difficult**	**RC preferred**
Suitability for regular low-rise buildings	**Good**	**Very good**	**Masonry preferred**
Suitability for complex layouts	**Very good**	**Limited**	**RC preferred**

Table 5 demonstrates that the masonry load-bearing alternative consistently outperformed the RC skeletal system in terms of material efficiency, economic performance, and environmental sustainability. The most pronounced improvements were observed in reinforcement-steel demand (82% reduction), embodied-carbon emissions (52% reduction), and life-cycle cost (46.5% reduction).

In contrast, the RC skeletal system retained clear advantages in architectural flexibility, structural redundancy, and adaptability to future modifications. These characteristics make frame-based construction particularly suitable for buildings with irregular layouts, larger spans, mixed-use functions, or anticipated changes during their service life.

Overall, the results suggest that masonry load-bearing construction represents the more efficient solution for regular low-rise residential developments where affordability, resource efficiency, and sustainability are primary objectives. Conversely, RC skeletal

systems remain preferable when design flexibility and long-term adaptability are dominant project requirements.

4.3 Structural Behavior and Load-Transfer Mechanisms

The fundamental difference between the investigated systems lies in their load-transfer mechanisms. In the RC skeletal system, gravity loads are transferred through:

Slabs → Beams → Columns → Footings → Soil

This hierarchical load path provides structural redundancy and flexibility but requires additional beams, columns, reinforcement, and formwork.

In contrast, the masonry load-bearing system transfers loads through:

Slabs → Load-Bearing Walls → Foundations → Soil

Because walls act as both structural and architectural elements, the need for intermediate RC members is substantially reduced. This direct load-transfer mechanism improves material efficiency and contributes to lower concrete and reinforcement demand.

The conceptual difference between the two load-transfer mechanisms is illustrated in Figure 4.

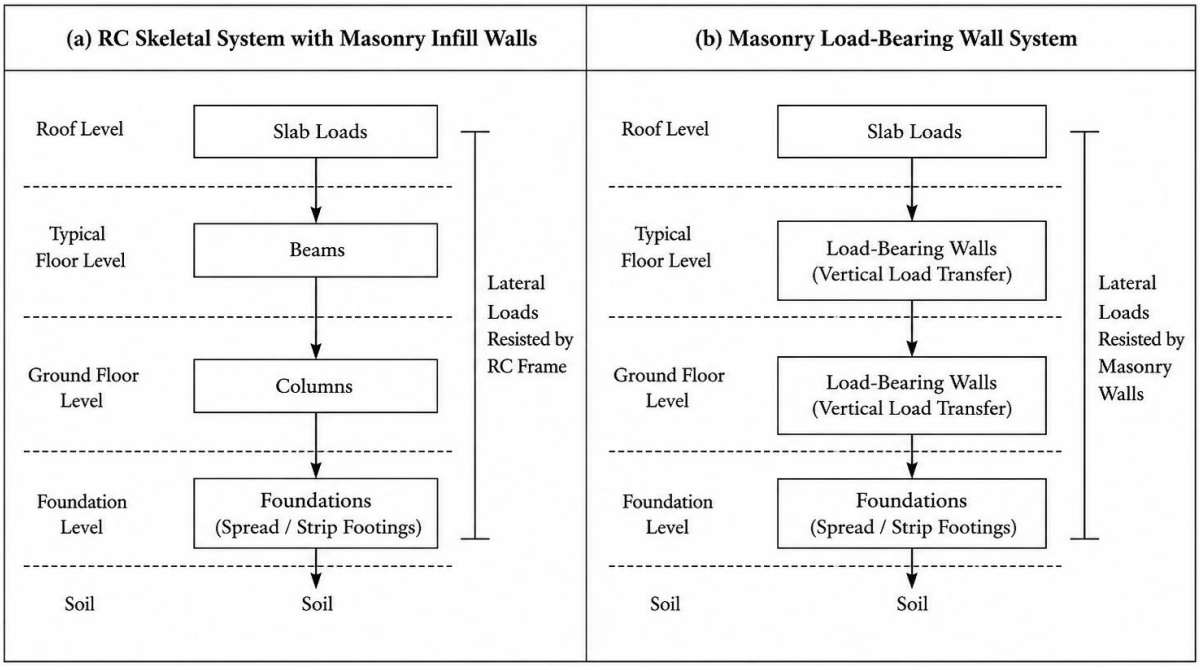


Figure 4. Load transfer mechanisms in RC skeletal and masonry load-bearing structural systems.

From an engineering perspective, the more direct load path of the masonry load-bearing system explains the substantial reductions observed in material consumption, construction cost, and embodied-carbon emissions. However, the RC skeletal system remains advantageous in terms of structural redundancy, architectural flexibility, and adaptability to future modifications.

4.4 Material consumption analysis

Material consumption represents one of the most important indicators for evaluating structural efficiency, economic performance, and environmental sustainability. The quantities of concrete and reinforcement steel required by the investigated systems were obtained from the complete structural designs summarized in Table 3.

The masonry load-bearing system demonstrated substantially lower material demand than the RC skeletal alternative. Concrete consumption decreased from 104.3 m^3 to 42.7 m^3, representing a reduction of approximately 59%, while reinforcement-steel demand decreased from 14.8 t to 2.6 t, corresponding to an 82% reduction. These reductions are primarily attributed to the elimination of most beams and columns and the adoption of a more direct load-transfer mechanism through structural walls.

The comparison of material quantities is illustrated in Figure 5.

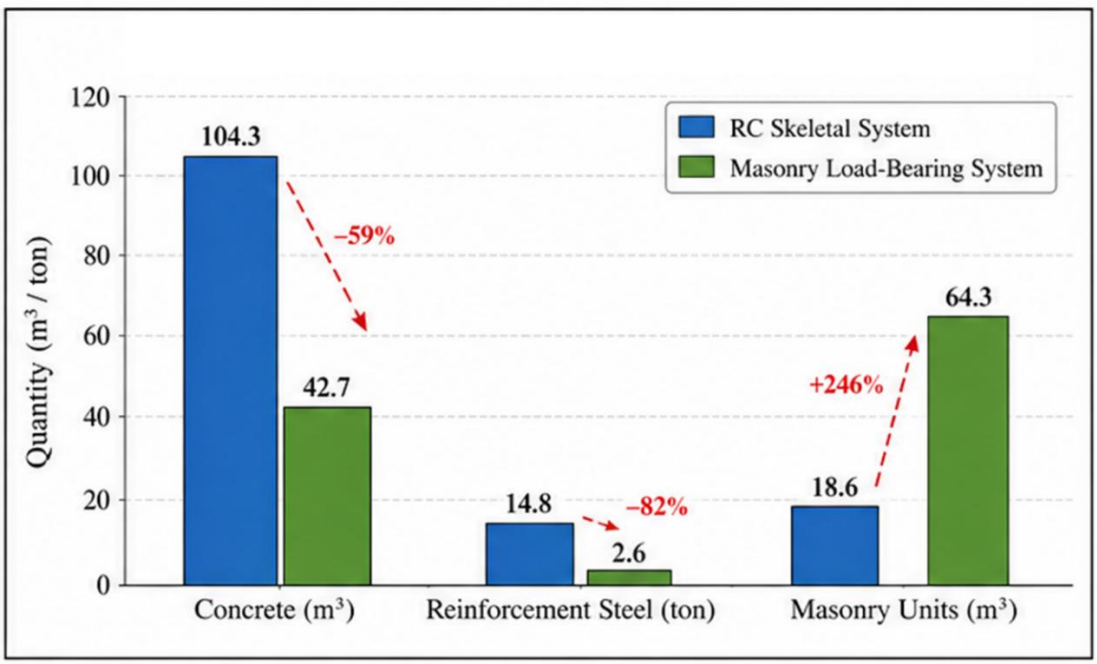


Figure 5. Comparison of material consumption between RC skeletal and masonry load-bearing systems.

The observed reduction in concrete and steel consumption has important practical implications. Lower material demand reduces construction cost, transportation requirements, reinforcement-fixing activities, and formwork operations. In addition, because cement production and steel manufacturing are highly carbon-intensive processes, the reduction in material consumption contributes directly to lower embodied-carbon emissions.

However, the improved material efficiency of masonry load-bearing construction should be evaluated together with project-specific architectural and structural requirements, including wall continuity, opening arrangements, and layout regularity.

4.5 Cost efficiency analysis

Construction cost represents one of the most influential factors in structural-system selection for low-rise residential buildings. Based on the complete structural designs, the masonry load-bearing system demonstrated a significant economic advantage over the RC skeletal alternative.

As illustrated in Figure 6, the total construction cost decreased from approximately EGP 1.38 million for the RC skeletal system to approximately EGP 0.77 million for the masonry load-bearing system, corresponding to a reduction of approximately 44%.

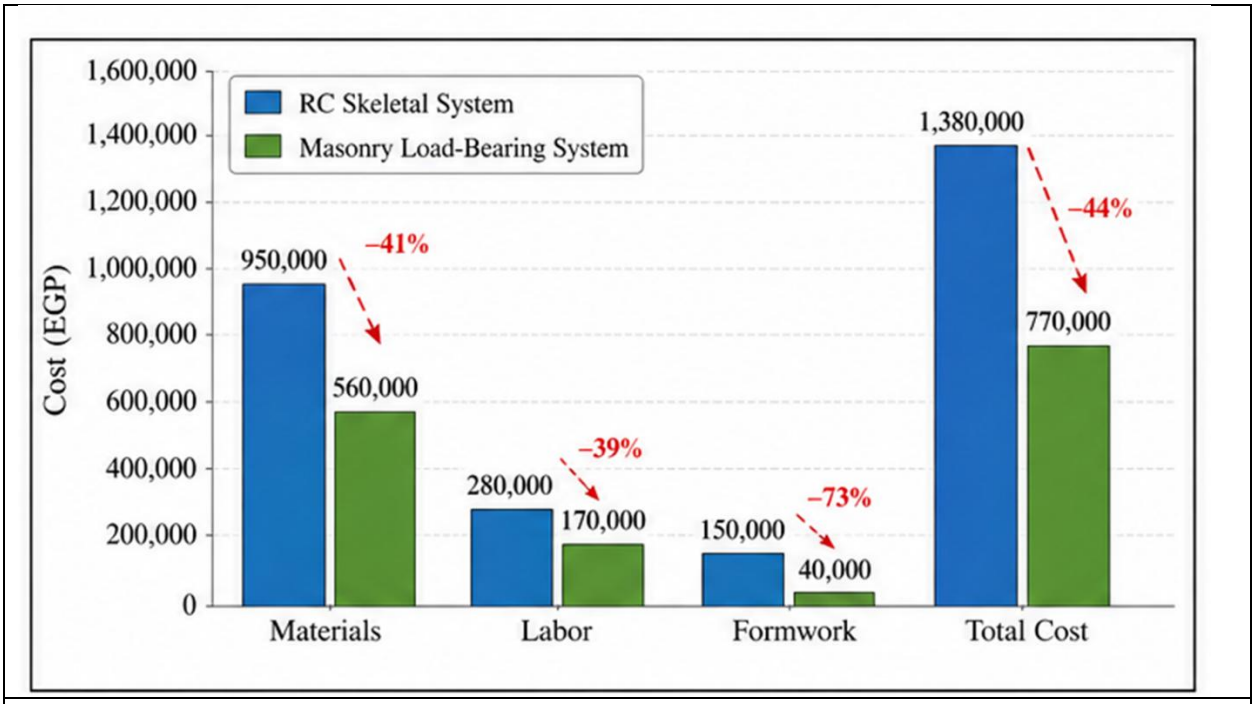


Figure 6. Cost comparison between RC skeletal and masonry load-bearing systems.

The observed cost reduction is primarily attributed to lower material demand, reduced formwork requirements, and simplified construction procedures. The elimination of most beams and columns decreases reinforcement installation, concrete-casting operations, and associated labor activities, resulting in a more economical construction process.

From a value-engineering perspective, masonry load-bearing construction provides an efficient balance between structural functionality and construction cost for regular low-rise residential developments. However, RC skeletal systems remain advantageous when architectural flexibility and future adaptability are primary project requirements. Therefore, structural-system selection should balance immediate economic benefits with long-term functional objectives.

4.6 Embodied Carbon Assessment

The environmental performance of structural systems is strongly influenced by material consumption because concrete and reinforcement steel are among the principal contributors to embodied carbon in building construction. Consequently, reducing the quantities of these materials can provide substantial environmental benefits.

As illustrated in Figure 7, total embodied carbon emissions decreased from 55.4 tCO_2-eq for the RC skeletal system to 26.8 tCO_2-eq for the masonry load-bearing alternative, corresponding to an overall reduction of approximately 52%.

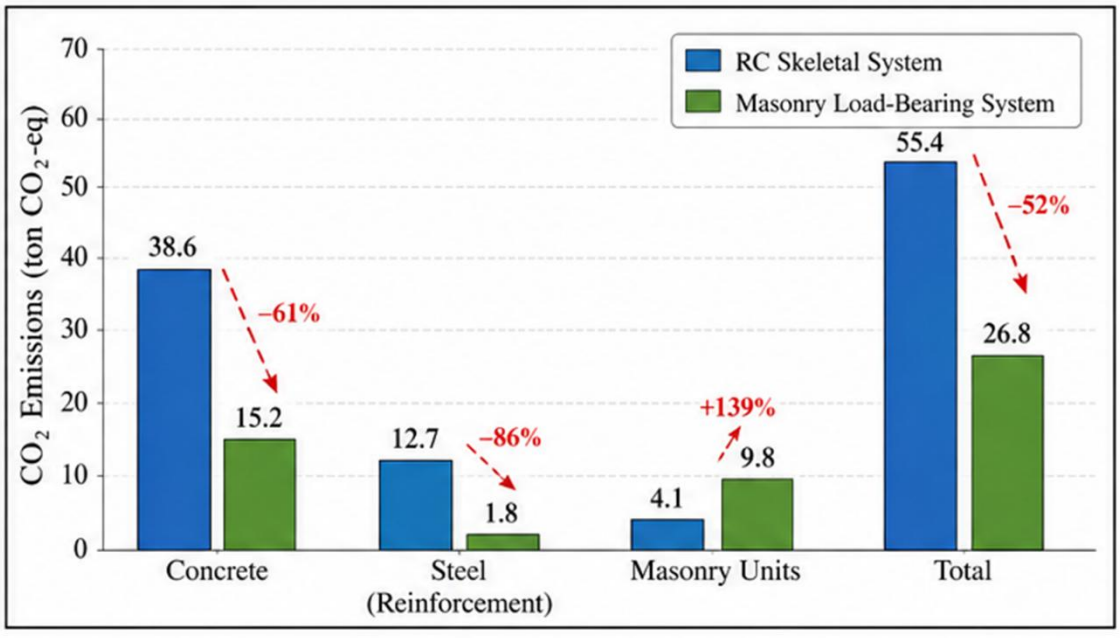


Figure 7. Comparative embodied CO_2 emissions of RC skeletal and masonry load-bearing systems.

The reduction is primarily attributed to the substantially lower quantities of concrete and reinforcement steel required by the load-bearing configuration. Given the carbon-intensive nature of cement production and steel manufacturing, the reduction in material demand translated directly into a lower environmental footprint.

These findings demonstrate that structural-system selection can significantly influence sustainability performance during the design stage. For regular low-rise residential developments, masonry load-bearing construction represents a more resource-efficient and lower-carbon alternative. Nevertheless, the present assessment is limited to embodied carbon associated with construction materials and construction-related activities. A comprehensive cradle-to-grave life-cycle assessment would additionally consider operational impacts, maintenance requirements, demolition processes, recycling potential, and end-of-life scenarios.

4.7 Sensitivity Analysis

A sensitivity analysis was conducted to evaluate whether the principal conclusions of the study remain valid under moderate variations in key design assumptions. The assessment considered changes in imposed loading conditions and masonry wall thickness, as these parameters directly influence the structural performance of load-bearing systems.

An increase in imposed loads results in higher structural demands in both alternatives. In the RC skeletal system, increased loads lead to greater bending, shear, and axial-force requirements, whereas the masonry load-bearing system primarily experiences increased compressive stresses within the structural walls. Similarly, increasing wall thickness improves load-carrying capacity and stability but increases masonry material consumption.

The results indicate that the principal conclusions remain unchanged under moderate variations in loading and wall-thickness assumptions. The masonry load-bearing system consistently retains advantages in material efficiency, construction cost, and embodied-carbon reduction. However, these advantages may diminish as building height increases, floor layouts become more irregular, or larger wall openings are introduced. Under such conditions, the flexibility and load-redistribution capacity of RC skeletal systems become increasingly beneficial.

5. Integrated Sustainability and Decision-Support Assessment

5.1 Sustainability and Value Engineering Assessment

Structural-system selection significantly influences the environmental, economic, and functional performance of buildings throughout their service life. Beyond satisfying

structural safety and serviceability requirements, contemporary design practice increasingly emphasizes resource efficiency, environmental responsibility, and long-term value. Consequently, sustainability assessment and value-engineering principles were integrated into the present comparative evaluation.

The results demonstrated that the masonry load-bearing alternative consistently outperformed the RC skeletal system in terms of material efficiency, construction cost, life-cycle cost, and embodied carbon emissions. These improvements were primarily associated with the reduction of reinforced-concrete elements and the adoption of a more direct load-transfer mechanism through structural walls.

From a value-engineering perspective, the masonry load-bearing system achieved the required structural functionality with substantially lower resource consumption and economic expenditure. At the same time, the RC skeletal system retained advantages related to architectural flexibility, structural redundancy, and future adaptability. Therefore, the selection of an optimal structural system should balance sustainability objectives with functional and project-specific requirements.

5.2 AHP-Based Multi-Criteria Evaluation

To support a systematic comparison, a multi-criteria decision analysis was conducted using the Analytic Hierarchy Process (AHP). Six evaluation criteria were considered: design efficiency, resource availability, ease of construction, construction progress rate, durability, and sustainability. Sustainability received the highest weighting factor (0.28), followed by durability and design efficiency (0.15 each), reflecting the increasing importance of environmental considerations in structural-system selection.

The pairwise comparison matrix was developed following the standard AHP procedure. The calculated consistency ratio (CR) was below the commonly accepted threshold of 0.10, indicating acceptable consistency of the assigned judgments and supporting the validity of the derived criteria weights.

The resulting AHP scores were 4.70 for the masonry load-bearing alternative and 3.90 for the RC skeletal system, indicating superior overall performance of the former for the investigated residential building. The higher score reflects the combined benefits of improved resource efficiency, lower economic burden, simplified construction, and enhanced sustainability performance.

5.3 Sustainability Efficiency Index (SuEI) and Decision-Support Evaluation

To provide a comprehensive sustainability assessment, a Sustainability Efficiency Index (SuEI) was developed by integrating engineering performance, economic efficiency, and

environmental performance into a single composite indicator. Unlike conventional sustainability metrics that focus on individual criteria such as cost or carbon emissions, the proposed index simultaneously considers structural functionality, life-cycle economic performance, and embodied-carbon efficiency. The proposed Sustainability Efficiency Index was formulated as:

$$SuEI = 0.40P_n + 0.30C_n + 0.30E_n$$

where:

- P_n= normalized structural-performance score;
- C_n= normalized life-cycle cost efficiency score;
- E_n= normalized environmental-efficiency score.

A slightly higher weighting was assigned to the performance component because structural adequacy remains the primary requirement of any building system.

The normalized indicators were calculated according to:

Structural performance normalization:

$$P_n = \frac{P}{P_{max}}$$

Life-cycle cost efficiency normalization:

$$C_n = \frac{LCC_{min}}{LCC}$$

Environmental efficiency normalization:

$$E_n = \frac{CO_{2,min}}{CO_2}$$

where:

- P= AHP performance score of the investigated structural system;
- P_{max}= maximum AHP score among all alternatives;
- LCC= life-cycle cost of the investigated structural system;
- LCC_{min}= minimum life-cycle cost among all alternatives;

- CO_2= embodied carbon emissions of the investigated structural system;
- $CO_{2,min}$= minimum embodied carbon emissions among all alternatives.

The resulting Sustainability Efficiency Index values are presented in Table 6.

Table 6. Sustainability Efficiency Index (SuEI) evaluation for the investigated structural systems.

Structural System	(Pn)	(Cn)	(En)	SuEI
RC Skeletal System	0.830	0.535	0.484	0.637
Masonry Load-Bearing System	1.000	1.000	1.000	1.000

The masonry load-bearing system achieved the highest SuEI value, reflecting its combined advantages in structural performance, life-cycle cost efficiency, and embodied-carbon reduction. In contrast, the higher life-cycle cost and environmental burden of the RC skeletal system resulted in a lower overall sustainability-efficiency score despite its advantages in flexibility and structural redundancy.

The results demonstrate that sustainable structural-system selection should not rely on individual indicators alone. Instead, integrating engineering, economic, and environmental criteria within a unified framework provides a more rational basis for decision-making during the early design stages of low-rise residential developments.

5.4 Sensitivity Analysis of the Sustainability Efficiency Index (SuEI)

To evaluate the robustness of the proposed Sustainability Efficiency Index (SuEI), a sensitivity analysis was conducted by varying the weighting factors assigned to the structural-performance, economic-efficiency, and environmental-efficiency components. The objective was to assess whether reasonable variations in decision-maker priorities would influence the ranking of the investigated structural systems.

The baseline SuEI formulation adopted weighting factors of 0.40, 0.30, and 0.30 for the normalized structural-performance score (Pn), life-cycle cost efficiency score (Cn), and environmental-efficiency score (En), respectively. To examine alternative decision-making preferences, two additional weighting scenarios were considered:

Sensitivity scenarios

$$SuEI_{Performance} = 0.50P_n + 0.25C_n + 0.25E_n$$
$$SuEI_{Balanced} = 0.40P_n + 0.30C_n + 0.30E_n$$

$$SuEI_{Sustainability} = 0.30P_n + 0.35C_n + 0.35E_n$$

The resulting SuEI values for both structural systems are presented in Table 7.

Table 7. Sensitivity analysis of the Sustainability Efficiency Index under alternative weighting scenarios.

Structural System	Scenario A	Scenario B	Scenario C
RC Skeletal System	0.670	0.638	0.606
Masonry Load-Bearing System	1.000	1.000	1.000

The results indicate that the masonry load-bearing system consistently achieved the highest SuEI value under all investigated weighting scenarios. Although moderate variations in weighting factors produced slight changes in the absolute SuEI values of the RC skeletal system, the relative ranking of the alternatives remained unchanged.

This stability demonstrates that the conclusions of the study are not highly sensitive to reasonable variations in stakeholder priorities. Whether greater emphasis is assigned to structural performance or to economic and environmental objectives, the masonry load-bearing system remains the preferred alternative for the investigated low-rise residential building. Consequently, the proposed SuEI framework provides a robust and practical decision-support tool for early-stage structural-system evaluation.

5.5 Weight-Sensitivity Analysis of the SuEI Framework

To further evaluate the robustness of the proposed Sustainability Efficiency Index (SuEI) against weighting subjectivity, a one-at-a-time sensitivity analysis was performed. The baseline weights assigned to structural performance, life-cycle cost efficiency, and environmental efficiency were varied by ±20%, followed by re-normalization to maintain a total weight of 1.0.

The normalized input scores used in the analysis were obtained from the SuEI evaluation, where the RC skeletal system achieved P_n = 0.830, C_n = 0.535, and E_n = 0.484, while the masonry load-bearing system achieved unity for all normalized indicators.

Table 8. ±20% weight-sensitivity analysis of the Sustainability Efficiency Index.

Scenario	Normalized Weights P/C/E	RC SuEI	Masonry SuEI	Preferred System
Baseline	0.400 / 0.300 / 0.300	0.638	1.000	Masonry

Scenario	Normalized Weights P/C/E	RC SuEI	Masonry SuEI	Preferred System
Performance +20%	0.444 / 0.278 / 0.278	0.652	1.000	Masonry
Performance −20%	0.348 / 0.326 / 0.326	0.621	1.000	Masonry
Cost +20%	0.377 / 0.340 / 0.283	0.632	1.000	Masonry
Cost −20%	0.426 / 0.255 / 0.319	0.644	1.000	Masonry
Environment +20%	0.377 / 0.283 / 0.340	0.629	1.000	Masonry
Environment −20%	0.426 / 0.319 / 0.255	0.648	1.000	Masonry

The results show that the RC skeletal system achieved SuEI values ranging from 0.621 to 0.652, whereas the masonry load-bearing system maintained a constant value of 1.000 under all weighting scenarios. Consequently, the relative ranking of the investigated alternatives remained unchanged.

This finding indicates that the preference for the masonry load-bearing system is not an artifact of the selected baseline weights but rather reflects its consistent advantages in life-cycle cost efficiency, embodied-carbon reduction, and overall sustainability performance. The stability of the ranking under all investigated weighting scenarios provides additional confidence in the robustness of the proposed decision-support framework and reduces uncertainty associated with subjective weighting assumptions.

5.6 Comparative Discussion with Previous Studies

To further evaluate the significance of the obtained findings, the proposed framework was benchmarked against representative sustainability-oriented studies reported in the literature. Although direct numerical comparison is limited by differences in building configurations, structural systems, and assessment methodologies, benchmarking provides useful context for assessing the contribution of the present study.

The comparison indicates that previous investigations primarily focused on environmental assessment, life-cycle costing, BIM-assisted sustainability evaluation, or multi-criteria decision-making. While these studies demonstrated the importance of integrating economic and environmental considerations into building design, most did not simultaneously evaluate structural-system selection, material efficiency, lifecycle

economic performance, and regional implementation suitability within a unified framework.

The proposed methodology extends previous research by integrating comparative structural design, material quantification, embodied-carbon assessment, life-cycle cost analysis, AHP-based decision support, Sustainability Efficiency Index (SuEI) evaluation, Monte Carlo uncertainty analysis, and Load-Bearing Suitability Index (LBSI) assessment within a single decision-support framework.

The benchmarking results further demonstrate that the reductions achieved in construction cost (44%), life-cycle cost (46.5%), and embodied carbon emissions (52%) are consistent with sustainability trends reported in previous investigations while providing a broader engineering perspective that incorporates both building-level performance and regional applicability considerations.

Unlike most previous studies, the proposed framework introduces a regional suitability component through the LBSI methodology, enabling structural-system selection to be evaluated not only from economic and environmental perspectives but also in relation to geotechnical and development-planning conditions.

5.7 Monte Carlo-Based Uncertainty Analysis

Although the comparative assessment presented in this study is based on deterministic material quantities, cost estimates, and embodied-carbon coefficients, practical construction projects are inherently affected by uncertainty associated with market conditions, material-price fluctuations, and environmental assessment parameters. To evaluate the robustness of the obtained conclusions, a Monte Carlo uncertainty analysis was performed.

The analysis considered variability in construction cost and embodied-carbon indicators, which are the sustainability metrics most directly influenced by external factors. Unit material costs and embodied-carbon coefficients were assumed to vary independently within ±15% of their baseline values. Uniform probability distributions were adopted because project-specific statistical records were unavailable.

A total of 5000 Monte Carlo simulations were conducted. For each simulation, modified cost and embodied-carbon factors were randomly generated and used to recalculate construction cost, life-cycle cost, and embodied carbon for both structural systems.

The results are summarized in Table 9. The masonry load-bearing system consistently maintained superior performance across all investigated indicators. The mean construction-cost reduction was approximately 43.9%, while the corresponding life-cycle

cost reduction reached 46.4%. Similarly, the mean embodied-carbon reduction remained approximately 51.5% relative to the RC skeletal system.

The calculated 95% confidence intervals further confirmed the stability of the obtained improvements. Construction-cost savings ranged from 35.3% to 51.6%, life-cycle cost savings varied between 38.2% and 53.7%, and embodied-carbon reductions remained within 44.1% to 58.0%. Most importantly, the probability that the masonry load-bearing system outperformed the RC skeletal alternative exceeded 99% across the investigated simulation space.

These findings demonstrate that the economic and environmental advantages of the masonry load-bearing system are not dependent on the deterministic assumptions adopted in the baseline assessment. Instead, the observed improvements remain highly robust under realistic uncertainty conditions, confirming the stability and reliability of the proposed decision-support framework.

The cumulative probability distributions obtained from the Monte Carlo simulations are illustrated in Figure 8, highlighting the statistical stability of the construction-cost and embodied-carbon reductions achieved by the masonry load-bearing system.

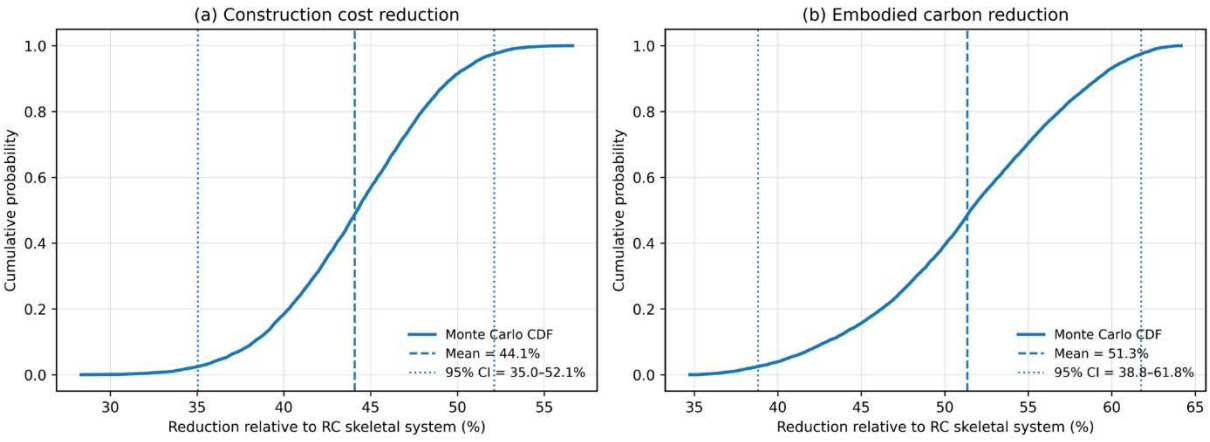


Figure 8. Probabilistic distributions of construction-cost and embodied-carbon reductions under ±15% parameter uncertainty.

Table 9. Monte Carlo uncertainty analysis considering ±15% variability in unit material costs and embodied-carbon coefficients (5000 simulations).

Performance Indicator	Mean Improvement (%)	95% CI (%)	Probability (%)
Construction Cost	43.9	35.3–51.6	>99
Life-Cycle Cost	46.4	38.2–53.7	>99
Embodied Carbon	51.5	44.1–58.0	>99

The Monte Carlo results further support the robustness of the Sustainability Efficiency Index (SuEI) and provide additional confidence that the preference for the masonry load-bearing system remains valid under uncertain economic and environmental conditions.

5.8 External Comparative Support Using Published Studies

To further examine the generalizability of the proposed framework beyond the investigated case-study building, an external comparative assessment was conducted using representative published studies comparing masonry-based and reinforced-concrete structural systems. The objective was not to establish direct numerical equivalence but rather to evaluate whether the trends identified in the present investigation are consistent with independent findings reported in the literature.

The comparison reveals a consistent pattern across independent investigations. Previous studies generally reported that structural systems requiring lower quantities of reinforced concrete and steel achieve improved economic and environmental performance. The findings obtained in the present study follow the same trend, with the masonry load-bearing system demonstrating substantial reductions in material consumption, construction cost, life-cycle cost, and embodied carbon emissions relative to the RC skeletal alternative.

The agreement observed between the present results and previously published investigations provides preliminary external support for the proposed framework. Although differences in building configuration, regional conditions, and design assumptions prevent direct numerical comparison, the consistency of the observed trends suggests that the advantages identified for masonry load-bearing construction are not solely attributable to the specific characteristics of the investigated case-study building.

6. Discussion

6.1 Why Did the Load-Bearing System Outperform the RC Frame?

The differences observed between the RC skeletal system and the masonry load-bearing system are primarily governed by their load-transfer mechanisms. In the RC skeletal system, loads are transferred through beams and columns, resulting in a hierarchical structural arrangement that provides redundancy and flexibility but requires larger quantities of reinforced concrete and steel.

In contrast, the masonry load-bearing system transfers loads directly through continuous structural walls. This compression-dominated behavior reduces the need for beams and columns and improves material utilization efficiency. Consequently, the masonry load-bearing alternative achieved substantial reductions in concrete consumption (59%), reinforcement-steel demand (82%), construction cost (44%), and embodied carbon emissions (52%).

However, the improved efficiency of load-bearing construction is accompanied by practical limitations. Because structural walls resist gravity loads directly, wall continuity and opening arrangements become critical design considerations. In addition, masonry systems generally provide lower ductility and adaptability than RC frame systems, particularly when future modifications, irregular layouts, or seismic performance requirements govern the design.

Therefore, neither system should be considered universally superior. Masonry load-bearing construction is most suitable for regular low-rise residential buildings where cost efficiency, resource optimization, and sustainability are primary objectives. Conversely, RC skeletal systems remain preferable when architectural flexibility, larger spans, structural redundancy, or future adaptability are dominant project requirements.

6.2 Flexibility–Sustainability Trade-Off

For regular low-rise residential buildings characterized by moderate spans and repetitive layouts, load-bearing masonry represents an efficient solution due to its lower material demand, reduced construction expenditure, and smaller carbon footprint.

Frame-based construction becomes more suitable when projects involve irregular geometries, large open spaces, mixed-use functions, or anticipated changes during the service life of the building. Under such conditions, the additional flexibility provided by the structural frame may justify the increased material and economic requirements.

Where both adaptability and environmental performance are desired, hybrid configurations combining reinforced-concrete frames with selected load-bearing masonry zones may provide a balanced alternative. The flexibility–sustainability trade-off between the investigated structural systems is illustrated in Figure 9.

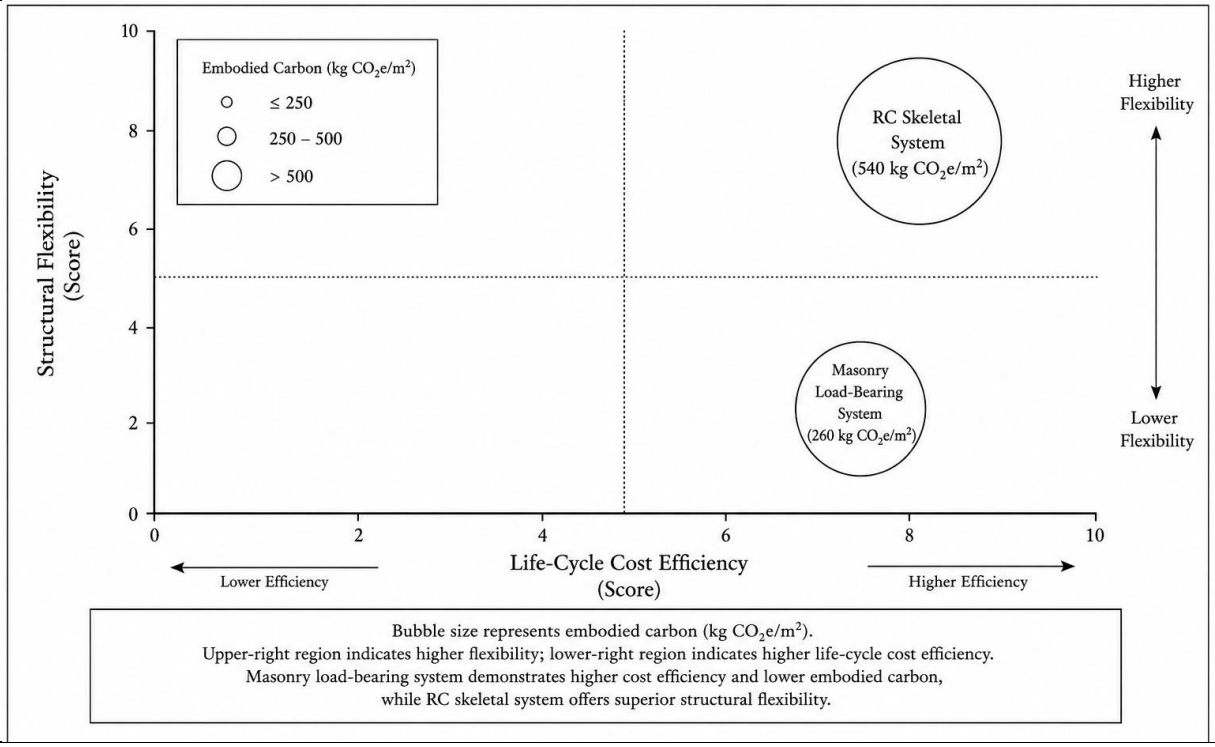


Figure 9. Trade-off between structural flexibility, life cycle cost efficiency, and embodied carbon

Figure 9 summarizes the relationship between cost efficiency and structural flexibility for the investigated systems. The masonry alternative occupies the region associated with lower cost and reduced environmental burden, whereas the RC frame system is positioned within the high-flexibility region. The figure highlights the fundamental trade-off between adaptability and resource efficiency and reinforces the need for project-specific structural-system selection based on technical, economic, environmental, and functional priorities.

7. Regional Applicability Framework for Low-Rise Housing Development in Egypt

7.1 Development of the Load-Bearing Suitability Index (LBSI)

To extend the applicability of the developed decision-support framework beyond the investigated case study, a Load-Bearing Suitability Index (LBSI) was developed to evaluate the suitability of masonry load-bearing systems under different geotechnical and planning conditions.

AHP-Based Derivation of LBSI Weights

The weighting factors were derived using the Analytic Hierarchy Process (AHP). Four criteria were considered: soil bearing capacity (SBC), groundwater level influence (GWL), building height requirement (BH), and future flexibility requirement (F). These criteria were selected

because they directly influence the feasibility, durability, and practical applicability of masonry load-bearing systems in low-rise residential buildings.

The pairwise comparison matrix was established based on structural and geotechnical engineering considerations. Soil bearing capacity received the highest weight because foundation support and settlement behavior directly govern the performance of wall-supported systems. Groundwater influence was assigned the second-highest weight because of its effects on durability and foundation conditions, whereas building height and future flexibility requirements received moderate weights reflecting their influence on structural complexity and long-term functionality.

Although the weighting factors were derived using the Analytic Hierarchy Process (AHP) and engineering judgment rather than calibration against a large historical performance database, the proposed framework was subsequently examined through sensitivity analysis and external applicability assessment using independent Egyptian geotechnical case studies. The obtained results demonstrated stable and logically consistent behavior across all investigated scenarios. Therefore, the LBSI should be interpreted as a preliminary engineering decision-support and screening tool, while future studies may further calibrate and validate the framework using larger datasets and observed project-performance records.

The consistency of the pairwise comparison matrix was verified using the AHP consistency procedure. The calculated consistency ratio (CR) was below the commonly accepted threshold of 0.10, indicating acceptable consistency and supporting the validity of the derived weights.

The resulting Load-Bearing Suitability Index was formulated as:

$$LBSI = 0.35(SBC) + 0.25(GWL) + 0.20(BH) + 0.20(F)$$

where all parameters are normalized on a 0–100 scale. Higher LBSI values indicate more favorable conditions for the application of masonry load-bearing systems. The AHP-derived weights adopted for the LBSI framework are presented in Table 10.

Table 10. AHP-derived weights for LBSI criteria

Criterion	Symbol	Weight	Engineering Justification
Soil bearing capacity	SBC	0.35	Governs foundation support and settlement behavior

Criterion	Symbol	Weight	Engineering Justification
Groundwater level influence	GWL	0.25	Affects durability, moisture exposure, and foundation performance
Building height requirement	BH	0.20	Controls vertical load demand and suitability for low-rise construction
Future flexibility requirement	F	0.20	Reflects limitations associated with future structural modifications

The relatively higher weighting assigned to SBC and GWL reflects the dominant influence of foundation and groundwater conditions on the long-term performance of masonry load-bearing structures.

7.2 LBSI Scoring Criteria

To ensure consistent evaluation across different development environments, a scoring framework was established for each LBSI parameter. The adopted ranges were developed based on engineering judgment, common geotechnical practice, and the practical limitations associated with low-rise load-bearing construction. Higher scores indicate more favorable conditions for the application of masonry load-bearing systems. The adopted scoring criteria are presented in Table 11.

Table 11. Scoring criteria adopted for LBSI calculation

(a) Soil Bearing Capacity (SBC)

SBC (kPa)	Score
>300	90–100
200–300	70–90
100–200	40–70
<100	<40

(b) Groundwater Level Influence (GWL)

Groundwater Depth	Score
>3 m	90

Groundwater Depth	Score
2–3 m	75
1–2 m	50
<1 m	25

(c) Building Height Requirement (BH)

Building Height	Score
≤3 Floors	90
4–5 Floors	70
6–8 Floors	40
>8 Floors	20

(d) Future Flexibility Requirement (F)

Requirement Level	Score
Minimal	90
Moderate	70
Significant	40
Extensive	20

The adopted scoring framework enables a unified assessment of site conditions and project requirements, thereby facilitating comparison between alternative development scenarios and supporting early-stage structural-system selection.

7.3 LBSI Suitability Classification

After calculating the Load-Bearing Suitability Index (LBSI), the resulting value is classified into one of three suitability categories representing the expected applicability of masonry load-bearing construction. Higher LBSI values indicate favorable combinations of foundation conditions, groundwater characteristics, building-height requirements, and future flexibility demands.

The proposed suitability classification is presented in Table 12.

Table 12. Proposed LBSI suitability classification framework.

LBSI Range	Suitability Level	Recommendation
>80	High	Strongly Recommended
60–80	Moderate	Recommended with Site Verification
<60	Low	RC Skeletal System Preferred

Projects classified within the High Suitability category are considered highly favorable for masonry load-bearing construction, whereas Moderate Suitability projects require additional site-specific verification. Locations within the Low Suitability category are generally characterized by geotechnical or functional constraints that make RC skeletal construction a more appropriate structural solution.

The proposed classification framework is intended as a preliminary decision-support tool and should complement, rather than replace, detailed geotechnical investigations and structural design procedures.

7.4 Case-Based Application: New Ismailia City

To demonstrate the applicability of the proposed framework, a representative low-rise residential development scenario was evaluated using published geotechnical information reported for New Ismailia City, Egypt. According to a recent geotechnical investigation involving field and laboratory testing, the site is predominantly characterized by medium-to-dense poorly graded sand layers with favorable geotechnical properties. The reported ultimate foundation bearing-capacity values ranged fom approximately 326.5 kPa to 490.3 kPa, indicating suitable foundation conditions for low-rise residential construction. Furthermore, the study concluded that the investigated soils are appropriate for both construction and pavement applications, provided that localized clayey lenses are properly treated or replaced. The proposed LBSI Evaluation for New Ismailia City is presented in Table 13.

Table 13. LBSI Evaluation for New Ismailia City

Parameter	Weight	Score	Weighted Contribution
Soil Bearing Capacity (SBC)	**0.35**	**90**	**31.50**
Groundwater Level Influence (GWL)	**0.25**	**90**	**22.50**

Parameter	Weight	Score	Weighted Contribution
Building Height Requirement (BH)	**0.20**	**90**	**18.00**
Future Flexibility Requirement (F)	**0.20**	**80**	**16.00**
Total LBSI	**—**	**—**	**88.00**

$$\boldsymbol{LBSI = 88.00}$$

which falls within the High Suitability category according to the proposed classification framework.

The obtained result indicates that masonry load-bearing construction represents a technically feasible and sustainable structural solution for low-rise residential developments in New Ismailia City. The favorable bearing-capacity characteristics, relatively deep groundwater conditions, and planned low-rise urban-expansion pattern collectively support the applicability of load-bearing masonry systems within similar Egyptian new-community developments.

The high LBSI value is consistent with the favorable economic and environmental performance identified for masonry load-bearing construction in the comparative assessment. Consequently, load-bearing masonry may represent an effective strategy for delivering affordable and sustainable housing within Egypt's emerging desert urban communities.

7.5 Engineering Interpretation

The calculated LBSI value for New Ismailia City is consistent with the favorable economic, environmental, and structural-performance trends identified for masonry load-bearing construction. The framework indicates that the suitability of load-bearing systems depends not only on building characteristics but also on geotechnical and planning conditions.

The results suggest that Egypt's new desert communities, including the New Administrative Capital, New Cairo, 6th October City, Sadat City, New Ismailia City, New Minia, and other Upper Egypt developments, represent favorable candidates for the application of low-rise load-bearing housing systems due to:

- Relatively stable foundation conditions.
- Lower groundwater influence.
- Planned urban expansion.

• Predominantly low-rise residential development patterns.
• Reduced need for future structural modifications.

Conversely, conventional RC skeletal systems remain preferable in situations involving:

• High-rise residential developments.
• Large-span architectural layouts.
• Significant future functional modifications.
• Soft compressible soils.
• Areas characterized by elevated groundwater levels or severe salinity exposure.

Therefore, the proposed Regional Applicability Framework extends the developed methodology beyond the investigated case study and provides a practical tool for identifying environments where masonry load-bearing construction can be implemented effectively.

Figure 10 illustrates the conceptual regional suitability map and the LBSI-based applicability framework for masonry load-bearing low-rise housing developments in Egypt.

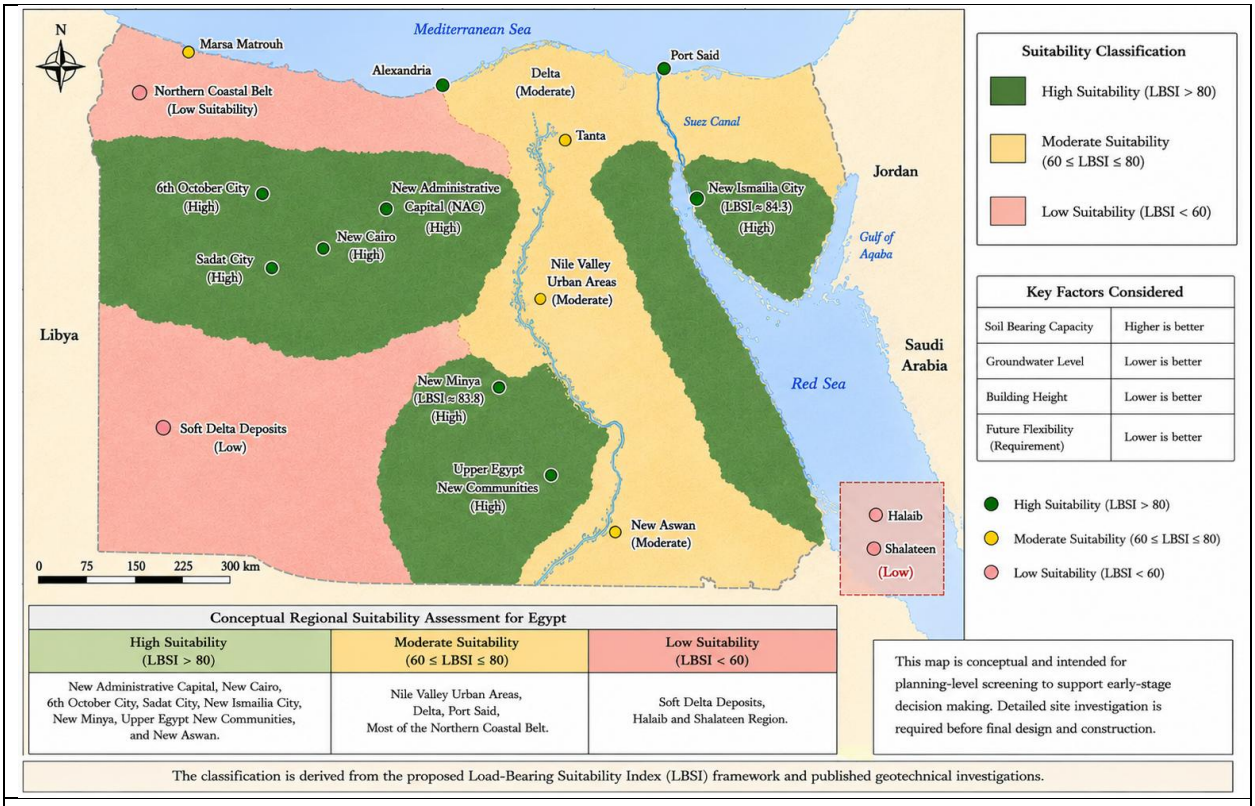


Figure 10. Conceptual regional suitability map and LBSI-based applicability framework for masonry load-bearing low-rise housing developments in Egypt.

7.6 Sensitivity Analysis of the Load-Bearing Suitability Index

To evaluate the robustness of the proposed Load-Bearing Suitability Index (LBSI), a sensitivity analysis was performed by varying the two most influential geotechnical parameters: Soil Bearing Capacity (SBC) and Groundwater Level Influence (GWL). Building Height Requirement (BH) and Future Flexibility Requirement (F) were maintained at constant values corresponding to the investigated low-rise residential building scenario (BH = 90 and F = 80). Table 14 presents the investigated sensitivity-analysis scenarios.

Table 14. Sensitivity Analysis Scenarios for LBSI Evaluation

Scenario	SBC Score	GWL Score	LBSI
S1	50	50	67.5
S2	50	75	73.8
S3	50	90	77.5
S4	70	50	74.5
S5	70	75	80.8
S6	70	90	84.5
S7	90	50	81.5
S8	90	75	87.8
S9	90	90	91.5

The results presented in **Table 14 and Figure 11** indicate that the suitability of masonry load-bearing construction is strongly influenced by geotechnical site conditions. Improvements in soil bearing capacity consistently resulted in higher LBSI values, reflecting the dominant influence of foundation support conditions on wall-supported structural systems.

For poor geotechnical conditions (SBC = 50), the calculated LBSI values ranged between 67.5 and 77.5, corresponding to the Moderate Suitability category. Under these conditions, masonry load-bearing construction remains feasible but may require additional geotechnical verification and foundation-improvement measures.

For moderate soil conditions (SBC = 70), the calculated LBSI values increased to 74.5–84.5, indicating a transition from Moderate to High Suitability depending on groundwater conditions. For favorable geotechnical conditions (SBC = 90), all investigated scenarios

produced LBSI values exceeding 80, indicating strong suitability for masonry load-bearing construction.

The groundwater parameter also exerted a noticeable influence on the suitability index. For a constant SBC value, increasing the groundwater score from 50 to 90 increased the LBSI by approximately 10 points, highlighting the importance of groundwater conditions during early-stage structural-system selection.

Overall, the sensitivity analysis demonstrates that the proposed framework responds logically to variations in key geotechnical parameters and successfully differentiates between favorable and constrained development environments. Consequently, the framework may serve as a practical decision-support tool for identifying locations where masonry load-bearing systems can provide the greatest economic, environmental, and structural benefits.

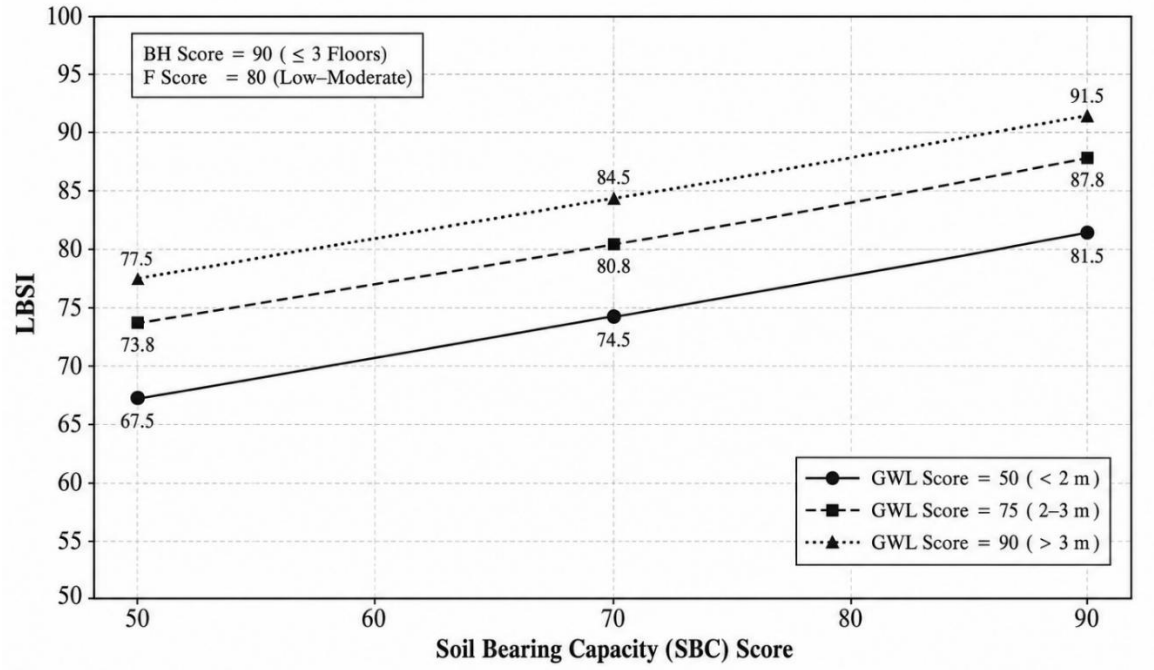


Figure 11. Sensitivity analysis of the Load-Bearing Suitability Index (LBSI) under varying soil bearing capacity and groundwater conditions.

7.7 Preliminary External Applicability Assessment of the LBSI Framework

To provide preliminary evidence regarding the applicability of the proposed LBSI framework beyond the investigated case study, independent geotechnical investigations reported in the Egyptian literature were examined. The selected locations represent a range of geological and engineering conditions, allowing the transferability of the proposed framework to be qualitatively assessed.

The applicability assessment dataset included New Ismailia City, New Minia City, Sadat City, East New Cairo, and the Cairo Supporting Ring Road Corridor. These locations were selected because published geotechnical and geophysical investigations provide sufficient information regarding foundation conditions, soil competence, geological hazards, and construction suitability.

Table 15 summarizes the resulting LBSI classifications.

Table 15. Preliminary applicability assessment of the proposed LBSI framework using published Egyptian geotechnical investigations.

Location	LBSI	Classification
New Ismailia City	84.25	High
New Minia City	83.75	High
Sadat City	84.00	High
East New Cairo	73.00	Moderate–High
Cairo Supporting Ring Road Corridor	60.25	Moderate

The obtained results demonstrate good agreement between the LBSI classifications and the geotechnical characteristics reported in the corresponding studies. The highest suitability levels were obtained for New Ismailia City, New Minia City, and Sadat City, where published investigations reported favorable foundation conditions, competent bearing strata, and generally suitable environments for urban development and construction activities.

In contrast, lower suitability levels were observed in East New Cairo and the Cairo Supporting Ring Road Corridor. Previous investigations identified heterogeneous subsurface conditions, fractured limestone, expansive clay deposits, fault-controlled geological structures, and localized geotechnical hazards capable of affecting foundation performance and long-term infrastructure stability. These conditions are consistent with the moderate suitability classifications produced by the proposed framework.

The evaluation exercise demonstrates that the proposed LBSI framework successfully differentiates between favorable and constrained development environments. Sites characterized by competent foundation materials and limited geotechnical hazards consistently achieved high suitability scores, whereas locations affected by problematic ground conditions received lower ratings.

The observed agreement between published geotechnical assessments and the calculated LBSI classifications provides preliminary support for the applicability of the proposed framework. Consequently, the proposed index may serve as an effective early-stage decision-support tool for screening the suitability of load-bearing masonry systems in newly planned Egyptian urban communities. Nevertheless, the framework is intended to complement rather than replace detailed geotechnical investigations, foundation design procedures, and project-specific engineering analyses.

The applicability of the proposed framework across different Egyptian regions is further illustrated in Figure 12.

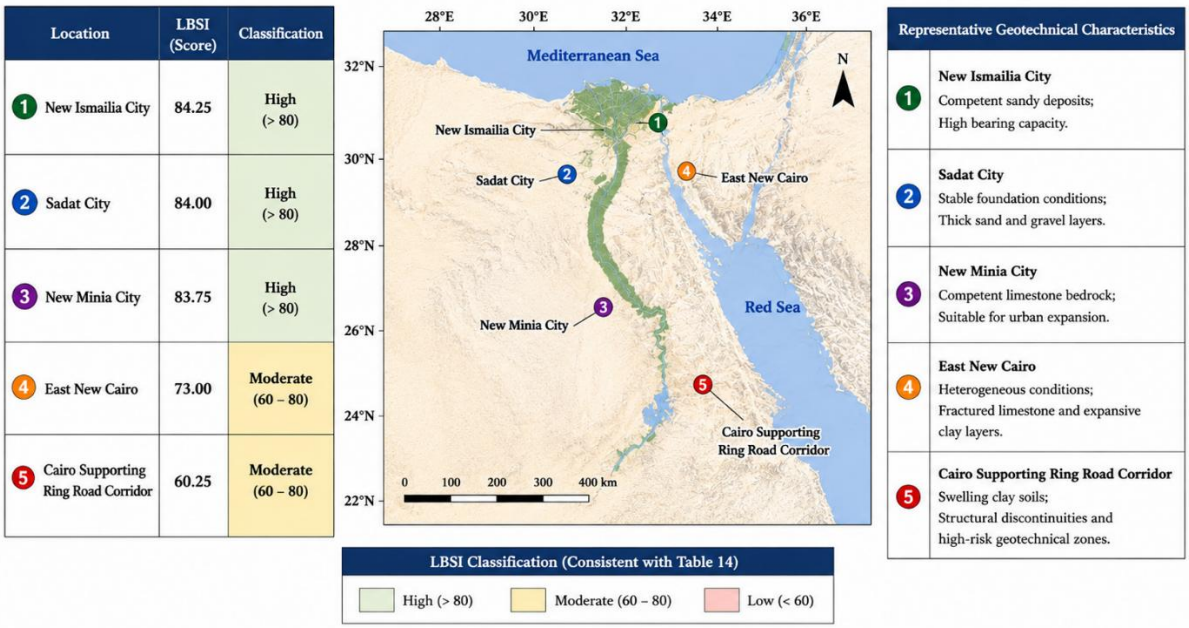


Figure 12. External comparative support for the proposed Load-Bearing Suitability Index (LBSI) using representative Egyptian geotechnical case studies.

7.8 Applicability of the Proposed Framework to Alternative Low-Rise Building Configurations

Although the present study focused on a three-story residential building, the proposed framework can provide useful guidance for a broader range of low-rise residential

developments. The identified advantages of masonry load-bearing construction are expected to be most applicable to buildings characterized by regular layouts, moderate spans, and limited future modification requirements.

For low-rise residential buildings consisting of two to four stories with repetitive floor plans, masonry load-bearing construction is expected to maintain favorable economic, environmental, and material-efficiency performance. However, as building height increases or architectural layouts become more complex, the relative advantages of load-bearing construction may gradually diminish because of increased wall-thickness requirements, larger openings, and greater flexibility demands.

Table 16 presents a qualitative applicability assessment of the proposed framework for representative low-rise residential building configurations.

Table 16. Qualitative applicability assessment for alternative low-rise residential building configurations.

Building Configuration	Expected Suitability of Masonry Load-Bearing Construction
2–3 story regular residential buildings	High
4-story regular residential buildings	Moderate to High
Buildings with moderate opening ratios	Moderate
Irregular layouts with larger spans	Low to Moderate
Buildings requiring extensive future modifications	Low

The assessment is intended to provide engineering guidance regarding the expected applicability of the proposed framework rather than a quantitative redesign of alternative building configurations. Detailed structural design, code verification, and project-specific evaluation remain necessary before selecting the most appropriate structural system for a particular development.

8. Practical Engineering Implications

The findings of this study provide several practical implications for engineers, developers, housing authorities, and decision-makers involved in low-rise residential construction.

From a structural perspective, masonry load-bearing systems can provide an efficient alternative to conventional RC skeletal construction for regular low-rise residential

buildings. The direct wall-supported load-transfer mechanism reduces dependence on beams and columns, resulting in lower material consumption while maintaining adequate structural performance.

From an economic perspective, the observed reductions in construction and life-cycle costs indicate that masonry load-bearing construction may contribute to improving housing affordability, particularly in large-scale residential developments where material demand and construction expenditure are major constraints.

From an environmental perspective, the substantial reduction in embodied carbon emissions demonstrates that structural-system selection can serve as an effective strategy for improving sustainability without requiring advanced construction technologies or expensive low-carbon materials.

The proposed Sustainability Efficiency Index (SuEI) and Load-Bearing Suitability Index (LBSI) provide practical decision-support tools for evaluating structural, economic, environmental, and geotechnical considerations during the early design stages.

Consequently, the developed framework may support sustainable housing policies, urban-expansion planning, and early-stage structural-system selection in emerging residential communities characterized by low-rise development patterns and favorable site conditions.

9. Limitations of the Study

This study is limited to a three-story residential building with a regular layout. Therefore, the findings are most applicable to low-rise residential buildings with similar architectural and loading characteristics and should not be directly generalized to high-rise buildings, highly irregular structures, or buildings with large open spans without additional investigation.

The study focused primarily on gravity-load design and did not include detailed nonlinear seismic analysis. Since masonry systems may exhibit brittle behavior under lateral loading, seismic performance should be investigated before extending the findings to regions where earthquake effects govern structural design.

The environmental assessment was limited to embodied carbon associated with construction materials and construction-related activities. A comprehensive cradle-to-grave life-cycle assessment incorporating transportation, operation, maintenance, demolition, and recycling impacts was beyond the scope of the present study.

Similarly, the economic assessment was based on representative material quantities and construction implications. Actual project costs may vary according to location, labor rates, material prices, construction technology, contractor experience, and market conditions.

The proposed LBSI framework should be interpreted as a preliminary screening tool rather than a calibrated predictive model. The adopted weighting factors were derived using engineering judgment and AHP analysis rather than calibration against a large historical performance database. Future studies should investigate statistical calibration and validation using larger datasets collected from different geotechnical environments.

Despite these limitations, the study provides a practical decision-support framework for evaluating alternative structural systems in low-rise residential developments.

10. Framework Generalization and Transferability

Although the proposed framework was developed using a representative three-story residential building in Egypt, the methodology itself is transferable and can be adapted to other regions and building typologies. The integrated assessment procedure, Sustainability Efficiency Index (SuEI), and Load-Bearing Suitability Index (LBSI) may be updated using region-specific design parameters, cost databases, embodied-carbon factors, and geotechnical criteria.

Therefore, the principal contribution of the present study lies not only in the comparative results obtained for the investigated case study but also in the development of a transferable decision-support methodology capable of supporting structural-system selection under different engineering, economic, environmental, and geotechnical conditions.

11. Conclusions

This study presented an integrated comparative assessment of RC skeletal structures with masonry infill walls and masonry load-bearing wall systems for a three-story residential building designed under identical conditions. The comparison incorporated structural behavior, material consumption, life-cycle cost, embodied carbon emissions, flexibility, sustainability, and value-engineering considerations.

The main conclusions are as follows:

1. The investigated systems exhibited fundamentally different load-transfer mechanisms. The RC skeletal system relies on a hierarchical load path through slabs, beams, columns, and footings, whereas the masonry load-bearing system transfers loads directly through structural walls to the foundations, resulting in a more efficient load-transfer mechanism for regular low-rise buildings.
2. The masonry load-bearing system reduced concrete consumption from 104.3 m^3 to 42.7 m^3 and reinforcement-steel demand from 14.8 t to 2.6 t, corresponding to reductions of approximately 59% and 82%, respectively.

3. The reduction in material demand resulted in substantial economic and environmental benefits, including a 44% reduction in construction cost, a 46.5% reduction in life-cycle cost, and an approximately 52% reduction in embodied carbon emissions compared with the RC skeletal alternative.
4. The AHP-based multi-criteria assessment, Sustainability Efficiency Index (SuEI), and life-cycle cost analysis consistently favored the masonry load-bearing alternative for the investigated case study, demonstrating its overall advantage in balancing structural performance, economic efficiency, and environmental sustainability.
5. Despite its economic and environmental advantages, masonry load-bearing construction remains most suitable for regular low-rise residential buildings. In contrast, RC skeletal systems remain preferable when architectural flexibility, structural redundancy, larger spans, irregular layouts, or future functional modifications are dominant project requirements.
6. The proposed Load-Bearing Suitability Index (LBSI) successfully integrated geotechnical and planning considerations into the decision-support framework. Preliminary applicability assessment using independent Egyptian geotechnical case studies demonstrated the ability of the framework to distinguish between favorable and constrained development environments.
7. Structural-system selection should not be based solely on structural adequacy. Instead, economic, environmental, functional, constructability, and geotechnical considerations should be integrated within a comprehensive decision-support framework to achieve more sustainable and cost-effective residential developments.

Overall, the study contributes a practical and transferable decision-support methodology for structural-system selection and highlights the importance of integrating sustainability, life-cycle economics, and value-engineering principles into early-stage building design decisions.

12. Future Work

Future research should extend the present study through nonlinear finite-element analysis to investigate cracking behavior, stress redistribution, serviceability performance, and failure mechanisms in both RC skeletal and masonry load-bearing systems. Additional studies should also evaluate seismic performance, particularly in regions where lateral loading governs structural design.

A comprehensive cradle-to-grave life-cycle assessment should be conducted to quantify environmental impacts associated with material production, transportation, construction, operation, maintenance, demolition, and recycling. Future investigations may also incorporate probabilistic cost assessment, uncertainty analysis, and expanded case studies involving different building heights, architectural configurations, and geotechnical conditions to further validate and generalize the proposed framework.

Ethics Declaration

Not applicable.

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Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Data Availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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