A Multi-Criteria Framework for Sustainable Structural Design Tools in Early-Stage Design

Mohammed Hamdallah[1], Sarah Nasser Asad[2], Jukka Heinonen[3]

1. PhD Researcher, Department of Civil and Environmental Engineering, University of Iceland, Reykjavík, Iceland
2. MBUILD Master of Science in Sustainable Design, Construction and Management of the Built Environment (FEUP Faculdade de Engenharia da Universidade do Porto, Portugal; THM Technische Hochschule Mittelhessen, Germany; UC Universidad de Cantabria, Spain), an Erasmus Mundus Joint master's degree co-funded by the European Union.)
3. Professor, Department of Civil and Environmental Engineering, University of Iceland, Reykjavík, Iceland.

[*]mah118@hi.is

Abstract

The construction industry's digital maturity remains critically low in early-stage structural design, the phase where decisions most significantly dictate a building's total lifecycle impact. While a plethora of digital tools claim to facilitate sustainability, practitioners lack a systematic, evidence-based framework for tool selection, often leading to sub-optimal workflows and a "tool-choice paradox." This study addresses this gap by presenting a qualitative evaluation of three prominent tools representing distinct digital paradigms: Carbon Designer 3D (cloud-based schematic estimation), Structural PANDA (generative optimization), and Carbo-Life Calculator (BIM-integrated evaluation). Using the Analytic Hierarchy Process (AHP), these tools are assessed against three core pillars: efficiency, decision support, and user experience, decomposed into 11 specific functional criteria. To ground the model, performance scoring was derived from a real-world office building case study. Our findings reveal a critical trade-off between automation and accessibility: Structural PANDA demonstrates superior generative design integration but requires high computational literacy, whereas Carbon Designer 3D excels in rapid estimation but lacks geometric flexibility. Meanwhile, Carbo-Life Calculator provides robust BIM integration for carbon tracking but fails to offer the comparative trade-off capabilities essential for iterative design. By isolating these qualitative performance drivers, this article contributes a streamlined selection matrix and a decision-support framework. This enables engineering firms and researchers to align tool selection with specific project requirements and institutional technical capacity, ultimately fostering a more effective transition toward low-carbon structural design.

Keywords: *Sustainable Structural Design, Construction Automation, AHP, BIM, LCA Tools Comparison.*

1. Introduction

Human-induced greenhouse gas emissions, especially CO_2, remain the primary driver of global warming. Their impacts are already visible through more frequent extreme weather events and widespread effects on human health, ecosystems, and economies (IPCC, 2023). Between 1970 and 2021, more than 11,700 climate-related disasters caused over 2 million deaths and US$4.3 trillion in economic losses (WMO, 2023). These figures highlight the urgent need for rapid emission reductions. The buildings and construction sector is a major contributor, responsible for 34% of global final energy use and 34% of energy-related CO_2 emissions. Yet, instead of declining, emissions in the sector have increased by about 5% since 2015 due to slow and uneven progress in efficiency and decarbonization (UNEP, 2025). As improvements in operational energy efficiency reduce operational emissions, embodied carbon across a building's life cycle becomes increasingly important (Ürge-Vorsatz *et al.*, 2020), making Life Cycle Assessment (LCA) a key tool for evaluating environmental impacts and supporting holistic, sustainable building design (Anand & Amor, 2017; ISO 14040:2006).

Decisions made during the early design phase play a decisive role in determining a building's environmental performance. Studies have shown that embodied carbon can be reduced by 40-60% through optimized design choices related to materials and structural systems (Dunant *et al.*, 2021). Parametric analyses further demonstrate that parameters such as structural system type, building geometry, number of storeys, and floor height strongly influence embodied emissions, emphasizing the value of early-stage LCA in low-carbon design strategies (Torabi and Evins, 2024). However, generating and evaluating multiple design alternatives remains challenging due to the large number of possible configurations and the time- and resource-intensive nature of early-stage LCA (Gauch *et al.*, 2022; Jusselme *et al.*, 2020). Consequently, automating LCA assessments during early structural design is essential to support sustainable decision-making and reduce embodied carbon.

Different types of commercial Life Cycle Assessment (LCA) tools have been developed for environmental assessment in the building sector, differing in their work models, levels of automation, workflows and strategies for integrating Building Information Modelling (BIM). Stand-alone tools such as SimaPro and GaBi which rely on detailed life cycle inventories and extensive manual data input (Roberts *et al.*, 2020). This limits their suitability for early structural design characterized by high uncertainty and incomplete information (Meex *et al.*, 2018). Building-specific tools, including stand-alone software (e.g., Athena Impact Estimator) and BIM plug-ins (e.g., Tally and Carbo Life Calculator), partially automate data handling. However, they still face interoperability issues, lack of standardized data structures (Jrade and Jalaei, 2013) and the limited availability of regionally consistent LCA databases (Peng, 2016). Several studies have conducted comparative analyses of digital LCA tools in the built environment, examining their workflows, functionalities, limitations, and development pathways. Dervishaj and Gudmundsson (2024) analyzed a range of tools, including web-based platforms, visual programming tools, CAD plug-ins, and BIM plug-ins. However, the study perspective is primarily academic rather than industry-oriented and applies evaluation criteria tailored to circular economy objectives. This limits its applicability in early-stage structural design. Moreover, it does not employ a multi-criteria comparison framework to support companies and practitioners in selecting suitable tools. Other studies have focused on specific LCA tools and identified features and gaps without supporting tool selection for early structural design (Meex *et al.*, 2018; Prideaux *et al.*, 2022) or examined parametric design-oriented tools largely within the Grasshopper® environment (Säwén *et al.*, 2022). None of these studies apply a multi-criteria methodology aimed at guiding practitioners and companies in choosing LCA tools for early-stage structural design and decision-making.

The aim of this study is to evaluate sustainability assessment tools for early-stage structural design. To achieve this aim, the study conducts a qualitative comparison of selected tools using the Analytic Hierarchy Process (AHP), complemented by technical validation and a case study implementation to identify the functional challenges encountered when implementing sustainable measures during the conceptual phase.

2. Methods and Data

The decision-making process involves selecting the most appropriate option among alternatives based on multiple criteria, typically through steps such as problem definition, identification of alternatives, determination of criteria and weights, problem solving, and implementation (Munier et al., 2019). As the number of alternatives and criteria increases, this process becomes more complex, making Multi-Criteria Decision Making (MCDM) methods essential for providing structured, analytical frameworks grounded in defined criteria, weights, and a decision matrix (Shahsavarani and Azad Marz Abadi, 2015). These methods use weighted criteria to assess each alternative's performance and generate a ranked list of options, supporting robust and informed decision-making (Keisler and Linkov, 2021).

MCDM includes both quantitative and qualitative criteria within a unified framework. Quantitative criteria are directly measurable, while qualitative criteria rely on expert judgment and are converted into numerical values using defined indicators and scales (Mulliner *et al.*, 2016). Among MCDM methods, the Analytic Hierarchy Process (AHP) is one of the most widely applied due to its simplicity and hierarchical structure (Munier and Hontoria, 2021; Taherdoost and Madanchian, 2023), employing pairwise comparisons to derive criteria weights and priorities for alternatives (Saaty, 1987). Given inherent uncertainties in data and subjective inputs, sensitivity analysis is used to examine how changes in criteria weights or performance scores affect ranking stability, thereby assessing model robustness (Benford *et al.*, 2018). Because MCDM results are highly sensitive to weighting assumptions, sensitivity analysis is used to assess how variations in inputs affect the final ranking and to identify which uncertainties most strongly influence the results (Saltelli *et al.*, 2008).

2.1 Case Study

The selected case study is the SAERO office building, a new headquarters developed by SENER to integrate sustainable design practices into its internal workflow. The project is located on plots SZI-3.1.1 and SZI-3.1.2 in the Zamudio Technology Park, Bizkaia, Spain. The building has a rectangular footprint of 18 × 53 m, four above-ground storeys, and a reinforced concrete structural system selected after comparison with alternative solutions. The structure comprises rectangular concrete columns, L-shaped reinforced concrete core walls, and solid reinforced concrete slabs.
The SAERO building was selected as a representative case study because its reinforced concrete structural system and rectangular geometry provide a baseline performance 'benchmark,' allowing for a clear isolation of tool-specific estimation variances without the noise of extreme architectural complexity

2.2 Tool Identification

A wide range of digital tools exists to support sustainability assessment in building design, particularly for embodied carbon and material circularity. Many rely on Environmental Product Declarations (EPDs) from proprietary or open-access databases, while others allow manual Global Warming Potential (GWP) input from sources such as ECO Platform, IBU-EPD, or the Digital Environmental HUB. However, most tools operate at LOD 300-400 and require detailed 3D BIM models, limiting their suitability for rapid early-stage comparison of design alternatives.

To represent the diversity of current digital approaches, three tools were selected:

– Carbon Designer 3D (One Click LCA): A cloud-based tool for schematic-stage (LOD 200) embodied carbon estimation. It enables partial automation and rapid exploration of structural alternatives without a full BIM model, integrates with the One Click LCA database, and supports early decision-making. Limitations include reduced applicability to complex geometries and the absence of structural performance assessment.

– Structural PANDA: A generative design and numerical optimisation tool developed by the University of Cambridge and Price & Myers. It automatically generates and structurally verifies thousands of alternatives, simultaneously assessing embodied carbon and material cost. Structural PANDA provides fully automated model generation and evaluation without requiring a BIM model and supports environmental, economic, and structural performance assessment.

– Carbo Life Calculator: A Revit-integrated plug-in that quantifies embodied carbon directly from BIM models by mapping Revit materials to EPD datasets. It provides real-time LCA feedback and detailed material-level results suitable for advanced design stages but is less effective for early-stage exploration due to its reliance on a complete 3D model.

These tools were selected to reflect three dominant digital paradigms: conceptual cloud-based assessment, fully automated generative optimisation, and BIM-integrated evaluation. The Tally plug-in was considered but excluded due to limited automation, manual material-to-EPD mapping, reliance on North American datasets, lack of automatic parameter export to Revit, and an export-import workflow incompatible with the study’s automation requirements.

The tools were evaluated during the period of 22/03/2024 to 31/07/2024.

2.3 Qualitative Assessment

A qualitative assessment was conducted to evaluate how effectively the three tools support early-stage sustainable structural design. Due to differences in methodology, functionality, and automation level, a structured comparison was performed using an AHP model. The assessment addressed three layers of uncertainty.

2.4.1 Criteria Definition (Selection Uncertainty)

Eleven evaluation criteria were defined to capture functional and sustainability requirements relevant to schematic structural design. The criteria were initially derived from the literature and subsequently refined through exploratory testing of the three tools, with emphasis on early-stage LCA integration and the ability to generate and compare sustainable structural alternatives. This iterative process ensured alignment with actual software capabilities rather than theoretical benchmarks.

2.4.2 Weighting Strategy and Sensitivity Analysis (Weighting Uncertainty)

The relative importance of each criterion was established through pairwise comparisons based on the researcher's technical judgment, informed by two years of building engineering practice and specialized training in the MBUILD Master's program. To account for the subjectivity inherent in single-expert weighting, a sensitivity analysis was performed. This step is critical to the study's robustness, as it demonstrates how the tool rankings shift under different organizational priorities (e.g., a "speed-focused" workflow versus a "data-rigor" workflow), thereby mitigating the impact of individual judgment bias.

2.4.3 Performance Scoring (Judgment Uncertainty)

Tool performance was scored using a triangulated data collection approach comprising: (1) hands-on implementation of the case study within each tool, (2) detailed review of technical documentation to verify underlying logic and data sources, and (3) semi-structured interviews with technical representatives from One Click LCA and Structural PANDA to validate findings and clarify non-obvious functionalities. Final scores were processed using an AHP matrix, maintaining a Consistency Ratio ($CR < 0.1$) to ensure logical consistency.

Table 1. Criteria for Qualitative Assessment of Sustainable Structural Design Tools.

No.	Criterion	Definition
1	Efficiency	Measures the speed and ease with which the tool can perform calculations and provide results. The ideal tool offers rapid calculations with minimal data input, enabling quick assessment of various design alternatives.
2	Data Reliability and Accuracy	Evaluates the dependability and precision of the data sources used by the tool. Reliable tools use data from credible sources such as EPDs and various comprehensive databases, ensuring accurate environmental impact assessments.
3	Decision Support	Assesses the tool's ability to aid in decision-making by comparing multiple structural solutions or design alternatives simultaneously, facilitating informed choices based on detailed analysis.
4	Integration with Other Software	Looks at how well the tool can export its results and integrate with other software tools. Good integration allows seamless data transfer and utilization in various software environments, enhancing workflow efficiency.
5	User Interface	Examines the usability and accessibility of the tool's interface. A user-friendly interface ensures ease of use, enabling users to interact with the tool effectively and without requiring extensive training.
6	Sustainable Solutions	Evaluates the tool's ability to identify and support sustainable design solutions. Effective tools provide comprehensive comparisons and detailed analysis, aiding in the selection of low-carbon and environmentally friendly materials.
7	Complex Geometries	Considers how well the tool handles buildings with complex and irregular geometries. The best tools maintain accuracy and efficiency even when dealing with non-rectangular or intricate designs.
8	LCA (Life Cycle Assessment)	Assesses the scope and thoroughness of the LCA performed by the tool. Comprehensive tools cover the entire life cycle of materials from Cradle to Grave, including sequestration for biobased materials.

9	SSD (Sustainable Structural Design)	Examines the integration of structural performance with environmental and economic assessments. Effective tools provide detailed environmental data and support sustainable structural design integration.
10	Flexibility	Looks at the ability of the tool to adapt to different analysis scenarios and allow modifications. Highly flexible tools enable manual entry, database customization, and modification of analysis parameters, facilitating tailored assessments.
11	Implementation Feasibility	Evaluates the practical prerequisites and operational constraints of tool adoption, including licensing models, hardware resource demands, technical maturity (software stability), and the utility of secondary outputs such as automated reporting or Bills of Quantities (BOQ).

3. Results

Structural PANDA emerged as the preferred alternative (46% priority), primarily driven by its dominance in Sustainable Solutions (22.8%) and Decision Support (18.5%). While Carbon Designer 3D (24%) outperformed in technical reliability and user interface, these criteria were weighted lower for early-stage conceptual exploration. The model achieved a Consistency Ratio (CR) of 0.071, confirming that the pairwise judgments follow a transitive and logical hierarchy. The criteria weights are shown in Figure 1.

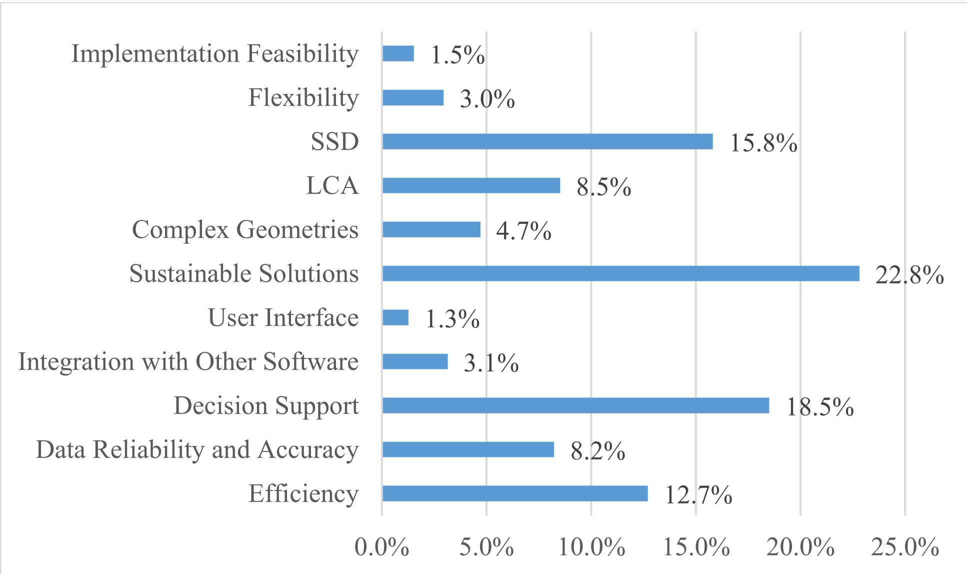

Figure 1. Weights Assigned to the Qualitative Evaluation Criteria in the AHP Model

3.1 Criterion-Level Results

Although Structural PANDA achieved the highest overall score, performance varied significantly across individual criteria. Carbon Designer 3D demonstrated the strongest performance in Efficiency, Data Reliability, and Accuracy, and User Interface, reflecting its data accuracy and streamlined workflow. In contrast, Carbo Life Calculator emerged as the top performer in criteria such as Integration with Other Software, Complex Geometry Handling, LCA Depth, Flexibility, and Other Workflow Features, indicating its strength in detailed environmental assessment and adaptability. These criterion-level results are summarised in Table 2.

3.2 Sensitivity Analysis

The findings of the sensitivity analysis are represented in the rank reversal points, which are the values at which the ranking of alternatives changes due to adjustments in the weight of a specific criterion. The model showed no sensitivity to criteria 5 and 8. However, it displayed high sensitivity to the other criteria, with various reversal points summarized in Table 3.

Table 2. Criterion-Level Performance of the Three Tools in the Qualitative AHP Assessment.

NO.	**Aspect**	**Carbon Designer 3D**	**Structural PANDA**	**Carbo Life Calculator**	**Best Alternative (Pairwise Comparison)**
1	Efficiency	Provides rapid calculations with minimal data input, typically under 5 minutes per alternative.	Offers quick calculations of carbon emissions and structural costs with minimal data, proportional to the number of generated alternatives.	Delivers rapid results for carbon footprint assessments, though some modifications in materials mapping may delay the analysis.	Carbon Designer 3D
2	Data Reliability and Accuracy	Uses Environmental Product Declarations (EPDs) generated by OneClick LCA manufacturers.	Utilizes predefined data for various materials, with limitations in the material database.	Relies on embodied carbon values sourced from multiple databases.	Carbon Designer 3D
3	Decision Support	Allows comparison of up to four structural solutions simultaneously.	Capable of generating up to 50,000 structural alternatives.	Facilitates detailed embodied carbon analysis.	Structural PANDA
4	Integration with Other Software	Can export results only as diagrams in JPG format, lacking integration with other tools.	Able to export results to Tekla Structural Designer and Excel.	Seamlessly integrates with Revit Common Data Environment (CDE) and Excel.	Carbo Life Calculator
5	User Interface	Features a user-friendly web interface, accessible from various devices.	Provides a user-friendly desktop interface.	Offers an intuitive interface but requires familiarity with Revit and LCA.	Carbon Designer 3D
6	Sustainable Solutions	Helps identify sustainable solutions early in the design process based on assumptions about structural layouts that affect material quantities.	Provides solutions based on basic structural calculations.	Offers comprehensive material comparisons during mapping, obtaining quantities from a 3D model.	Structural PANDA
7	Complex Geometries	Accuracy decreases with complex buildings having irregular geometries; only suitable for rectangular geometries.	Accuracy decreases with complex buildings having irregular geometries; however, it can define cores for the structure and L-shaped geometries.	Effectively manages complex geometries through Revit integration.	Carbo Life Calculator
8	LCA	Limited to Cradle to Gate analysis.	Uses the Whole Process of Construction (WPC) LCA type, relies on predefined emissions databases up to Cradle to Cradle (A-D), but lacks sequestration	Employs the Whole Process of Construction (WPC) LCA, assesses up to Cradle to Grave (A-D + Sequestration).	Carbo Life Calculator

			for biobased materials.		
9	SSD	Only considers the second step of the SSD (environmental assessment).	Integrates structural performance with environmental and economic assessments.	Exports environmental data into Revit parameters, aiding SSD integration.	Structural PANDA
10	Flexibility	Allows changing the material type of each building component after analysis.	Enables changes in analysis definitions and comparisons of different parameter sets; however, it lacks flexibility in controlling each alternative.	Provides high flexibility through manual entry, database customization, and modification of information to tailor the analysis.	Carbo Life Calculator
11	Implementation Feasibility	Requires subscription to the main tool of OneClick LCA.	The software is under development, with potential bugs and high CPU/memory usage.	Capable of exporting comprehensive reports and Bills of Quantities (BOQ).	Carbo Life Calculator

Table 3. Sensitivity Analysis of Criteria Weights

No.	Aspect	Actual Weights	Rank Reverse Point 1 (between Carbon Designer 3D and Structural PANDA)	Rank Reverse Point 2 (between Carbon Designer 3D and Carbo Life Calculator)	Rank Reverse Point 3 (between Structural Panda and Carbo Life Calculator)
1	Efficiency	12.7%	41%	21%	-
2	Data Reliability and Accuracy	8.2%	33%	21.6%	47%
3	Decision Support	18.5%	-	43.4%	-
4	Integration with Other Software	3.1%	-	-	24%
5	Sustainable Solutions	22.8%	-	-	-
6	Complex Geometries	4.7%	-	-	29%
7	LCA Maturity	8.5%	-	-	30%
8	SSD Methodology	15.6%	-	-	-
9	Flexibility	3.0%	61%	-	22.4%
10	Implementation Feasibility	1.50%	-	-	35%
11	User Interface	1.3%	37.4%	12.6%	-

4. Discussion

4.1 Key findings

The study aims to support design firms in selecting a suitable sustainability-based decision support tool for early-stage structural design through the evaluation of three different LCA digital tools representing different digital approaches used in the AEC market. The tools were qualitatively compared on a case study and ranked using AHP across 11 operability criteria, including efficiency, data reliability, and accuracy. The AHP results show that Structural PANDA had the highest priority weight with 46%, followed by Carbo Life Calculator with 30%, and lastly, Carbon Designer 3D with 24%. Besides the overall ranking, the AHP model identifies the strengths and weaknesses of each tool distinctively, which provides room to understand each tool's limitations and therefore for tool development.

4.2 Comparison with Previous Studies

The AHP-based tool evaluation quantifies the technical strengths and limitations of three different methodological types of existing tools. Structural PANDA's first rank reflects its strong decision-support capacity for its trade-off comparative assessment for cost and embodied carbon of a large number of design alternatives generated by the software and the sustainable solution it offers based on the basic structural calculations automatically generated. This facilitates optimization in both structural component selection (e.g., materials, decking, foundations) and early-stage sustainability assessment. Consequently, it addresses key industry challenges regarding the time and resources required for conducting LCA at LOD 200 (Gauch et al., 2022; Jusselme et al., 2020). Although the tool is sought as an early-stage design optioneering tool rather than an LCA software (Structural Panda Ltd, 2026), studies tracking projects in a design firm using Structural PANDA show a systematic reduction in embodied carbon for using better early-design choices generated by the software (Dunant, 2024). The high overall ranking of Structural PANDA in our AHP model is supported by recent applications where PANDA is used as a parametric optioneering tool to rapidly explore low-carbon structural DfA solutions at the concept stage (Watt et al., 2025). Despite the Structural PANDA's overall ranking, the Carbon Designer 3D demonstrated superior results in Efficiency, Data Reliability and Accuracy, and User Interface, while Carbo Life Calculator outperformed in Integration with other software, Complex Geometry Handling, LCA depth, Flexibility, and Workflow features. The varied performance suggests that no single tool comprehensively satisfies all project requirements.

Several outcomes of the AHP model are consistent with the findings of Dervishaj & Gudmundsson (2024b), particularly regarding the strong performance of Carbon Designer 3D in User Interface and Data Reliability and Accuracy. However, their analysis was primarily academically oriented rather than industry-focused, with evaluation criteria driven by research trends rather than the practical needs of companies seeking to implement LCA with the early sustainable design workflows. As a result, practitioners may find it difficult to apply their comparisons to tools aligned with the specific organizational requirements, especially when relevant tools are not included in the study. Moreover, while their work identifies tool gaps and proposes areas of improvement, it didn't employ a multi-criteria decision-making approach or provide a structured framework to support companies in conducting their own tool evaluations, gaps that the present study explicitly addresses.

4.3 Limitations

A key limitation of this study stems from the methodological limitation of the Analytic Hierarchy Process (AHP) (Tan *et al.*, 2021), as the selection of criteria, the assessment of criteria weights, and the comparative assessment of tools were based on the author's professional judgment. These judgments were shaped by the author's organizational context and needs of implementing LCA in practice, direct experience with early-stage structural design processes, and familiarity with digital sustainability assessment tools. Although the consistency ratio of the AHP model was below the accepted 10% threshold, this approach inherently introduces subjectivity and associated uncertainty. To mitigate uncertainty related to criteria weighting, a sensitivity analysis was conducted, allowing alternative weighting scenarios to be explored. Tool- level evaluations were based on the author's hand-on application of each tool to the case study and were further supported by interviews with the development teams of One Click LCA and Structural PANDA, as well as a detailed review of available documentation. Involving a broader range of practitioners in the assessment process would further reduce potential bias and increase the robustness of the results. However, rather than claiming universal applicability of the specific ranking presented, this study positions the proposed AHP-based framework as a practical guide that enables practitioners to conduct their own assessment based on their organization's specific requirements, priorities, and workflows.

4.4 Future Recommendations

This study represents the inaugural phase of a multi-stage research initiative. While the current work provides a qualitative assessment of sustainability tools, subsequent research will undertake a rigorous quantitative evaluation to benchmark tool outputs and assess their operational feasibility within professional workflows. To enhance the robustness of the AHP model, future iterations should expand the validator pool to include a broader range of practitioners, further refining criteria selection, weighting assignments, and tool performance judgments.

Building upon these findings, the research aims to develop and validate a three-phase integration framework designed to optimize sustainable decision-making within corporate BIM environments. Ultimately, this effort will culminate in the development of a user-friendly, open-access interface. This digital platform will empower practitioners to conduct bespoke qualitative evaluations by defining criteria that align with their specific organizational requirements and unique project constraints.

5. Conclusion

This study establishes a systematic, multi-criteria framework for evaluating digital tools in early-stage sustainable structural design. By applying the AHP method, the research successfully navigated the "tool-choice paradox," identifying Structural PANDA as the most effective solution for generative design optimization, while recognizing Carbon Designer 3D and Carbo-Life Calculator as leaders in computational efficiency and BIM-integrated documentation, respectively.
The primary contribution of this work is the development of a streamlined selection matrix that moves beyond academic software reviews toward a practitioner-oriented decision-support model. The sensitivity analysis confirms that while no single tool currently satisfies every project requirement, the AHP framework is robust enough to remain valid across varying organizational priorities, whether a firm prioritizes rapid schematic estimation or high-fidelity environmental data.

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