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AN ENABLING TOOL FOR BIM-BASED EMBODIED CARBON ASSESSMENT IN HIGH-RISE CONSTRUCTION

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SUMMARY: *The escalating contribution of buildings to global greenhouse gas (GHG) emissions necessitates urgent measures to mitigate their environmental impact. High-rise buildings present a unique challenge in managing embodied carbon during construction with their pronounced material intensity. Addressing embodied carbon in the early stages of design and construction is imperative to mitigate its long-lasting environmental consequences. However, assessing embodied carbon involves navigating through the complexities and uncertainties inherent in the construction process, creating a necessity for different tools and methods. While existing tools offer varying functionalities for assessing embodied carbon in buildings, they fail to fully address the complexities of high-rise structures. Therefore, there is a pressing demand for a specialised Building Information Modelling (BIM) tool to assess embodied carbon, which is tailored to address the unique challenges of high-rise buildings. This research adopts the design science research methodology, which encompasses problem explication, requirements definition, design and development of the artefact, demonstration, and evaluation phases. Through a comprehensive literature review and questionnaire survey, the specific features required for the new BIM tool were identified. Development is conducted using Figma for the front-end, with industry experts participating in the demonstration and subsequent evaluation of the artefact. This research aims to contribute to the advancement of sustainable practices in the construction industry by integrating cutting-edge technologies and methodologies. The resulting BIM tool promises to offer enhanced capabilities for visualising and calculating embodied carbon in high-rise buildings and facilitate informed decision-making towards a more sustainable built environment.*

KEYWORDS: *building information modelling, embodied carbon, high-rise buildings, design science methodology, software development.*

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1. INTRODUCTION

Buildings play a significant role in global GHG emissions, contributing to approximately 40% of the total (Zhu et al., 2020). Embodied carbon is equally significant, while operational energy consumption (such as heating, cooling, and lighting) has traditionally been a focus (Waldman et al., 2020). Unlike operational energy, which accumulates over time, embodied carbon emissions are immediate, entering the atmosphere when materials arrive at the project site (Gauch et al., 2023; Jalaei et al., 2015). Moreover, carbon from construction materials persists for decades to centuries, impacting the climate long after the building's completion. High-rise buildings pose particular challenges regarding embodied carbon due to their material intensity (Xiao et al., 2018). These structures require substantial amounts of materials such as concrete, steel, and glass, resulting in higher embodied carbon compared to low-rise buildings. Additionally, the sheer volume of materials required for high-rise construction amplifies the environmental impact (Kumari et al., 2022). Furthermore, materials for high-rise buildings often travel long distances, increasing emissions associated with transportation. This underscores the significance of tracking embodied carbon during the design and construction phases to alleviate its enduring effects.

Various tools in the construction industry aid in assessing embodied carbon, including Revit and Dynamo (Alzara et al., 2023), BHoM Lifecycle Assessment Toolkit, Embodied Carbon in Construction Calculator (EC3) (Nguyen & Morgan, 2021; Perrier et al., 2020), IES-VE software (Che-Ani & Raman, 2019), and LCAlink (LCAlink, 2023). These tools enable evaluations of environmental impacts and assist in material selection and procurement decisions. However, limitations exist, such as the need for proficiency in software tools, reliance on BIM models and EPD datasets (Alzara et al., 2023), lack of consideration for transportation and installation emissions significance (Nguyen & Morgan, 2021; Otranto et al., 2025), and compatibility issues (Säwén et al., 2022). Additionally, some tools lack comprehensive analyses across all lifecycle stages and impact categories, visualisation capabilities, support for structural modelling or analysis, and flexibility in material substitution (Nguyen & Morgan, 2021). Despite their value, further development is necessary to enhance their effectiveness in high-rise building projects.

This research aims to develop a novel Building Information Modelling (BIM) tool for accurately assessing embodied carbon in buildings by addressing the limitations of existing tools. The objectives to achieve this aim include analysing current embodied carbon assessment tools to identify their features and limitations, developing innovative features to enhance accuracy and usability, designing and implementing a new BIM tool with these features, conducting rigorous validation and usability testing to ensure accuracy and user-friendliness, and evaluating the tool's impact on sustainable practices while recommending future research and development directions.

2. LITERATURE REVIEW

2.1 Existing embodied carbon calculation tools

The literature review has revealed a set of existing embodied carbon calculation tools, including EC3, Tally, Athena, OneClick LCA, Beacon, EnviCASE, IES-VE, Revit with Dynamo, BHoM, and LCAlink. Their primary functions are delineated in Table 1.

With EC3, Tally, Athena, OneClick LCA, Beacon, EnviCASE, IES-VE, Revit, Dynamo, BHoM and LCAlink, people can use multiple features such as visualising embodied carbon, benchmarking, comparing materials, doing whole-building LCA and carrying out preliminary designs (Ayman Mohamed et al., 2023; Ekundayo et al., 2019; Sheng et al., 2024). With EC3, it is possible for users to compare the carbon content of different materials in EPDs and choose those that produce less carbon. With Tally and Revit integrated, it's possible to analyse whole-building LCA and compare designs and materials in a familiar BIM environment. The Embodied Carbon Pathfinder helps to experiment early on, whereas EcoCalculator assesses fossil energy used at the start of conceptual design (Leicht et al., 2009; Maassarani et al., 2017; Primasetra et al., 2022). Through its benchmarking and 3D analytical viewpoints, OneClick LCA gives guidance for reducing emissions at the start of design and Beacon and EnviCASE supply general feedback and early checks for structural initiatives (Gavotsis & Moncaster, 2014; Nikologianni et al., 2022). IES-VE, which includes the VE Gaia module, does early-stage analysis and connects to other life cycle tools, whereas Revit and Dynamo, as well as BHoM, help manage data by giving architects the chance to study embodied carbon for individual building elements and join up architectural information with external programs

(Ayman Mohamed et al., 2023; Jackson & Brander, 2019; Potnis & Ben-Alon, 2024). What makes LCAlink special is its ability to pull detailed information from BIM models and link to LCA systems, allowing for better carbon accounting (Hu & Ghorbany, 2024).

Table 1*: Features of existing embodied carbon calculation tools.*

Tool	Features
EC3 (Nguyen & Morgan, 2021)	- Visualisation of embodied carbon emissions. - Find and Compare Materials: Sorting and visualising material EPDs.
Tally (Che-Ani & Raman, 2019)	- Whole-building LCA within Revit. - Evaluation of design options and materials.
Athena (Jrade & Abdulla, 2012)	- Embodied Carbon Pathfinder: Early-stage design experimentation. - EcoCalculator: Assessing fossil energy use.
OneClick LCA (Newberry et al., 2023)	- Planetary: Benchmarking embodied carbon. - Early Design Decarbonization: 3D model-based insights.
Beacon (Dror et al.; Marcy & Iordanova, 2022)	- Structural project tracking. - High-level feedback on embodied carbon.
EnviCASE (Degenkolb, 2024)	- Excel-based LCA tool for structural materials. - Early-stage embodied carbon assessment.
IES-VE (Che-Ani & Raman, 2019)	- VE Gaia: Early-stage analysis for architects. - Integration with OneClick LCA.
Revit and Dynamo (Alzara et al., 2023)	- Assessing embodied carbon at BIM element level. - Integration with BHoM.
BHoM (Säwén et al., 2022)	- Building Human-Object Model for embodied carbon assessment. - JSON, Excel, or MongoDB results.
LCAlink (LCAlink, 2023)	- Integrates with BIM software to extract detailed building data. - Exports extracted BIM data to BRANZ LCAQuick for LCA. - Allows users to adapt an existing model or create a new one.

Although these advances have been reported, the articles consistently show ongoing challenges that reduce how effective these tools are on large buildings and in challenging places. The inconsistency present in startup databases, system boundaries and calculation formulas makes it possible for different tools to report very different carbon numbers (Chen et al., 2022; Sheng et al., 2024). For example, when looking at open-source and commercial tools side by side, their ways of defining system limits and data sources become an issue when trying to compare and assess them (Ekundayo et al., 2019). Because of this, while the amount of available information has grown, there are still gaps in the data for innovative and unique materials that may not be featured in global datasets. There is evidence that many tools are designed for common low-rise projects, but do not support the mix of approaches and special needs seen in high-rise architectures (Quaglio et al., 2024; Sheng et al., 2024). Even though more tools now link with BIM systems, these connections are often not flawless. This can happen because engineers have to input data manually, the tool relies on only a few automation options, and the graphical mapping of materials is insufficient. Also, some integrations include upfront display and advice, though they typically do not fully address modelling scenarios on the fly, suggesting materials based on AI or changing possible design settings to find the best combination of carbon and cost results (Hu & Ghorbany, 2024; Lamberti et al., 2024; Scott & Broyd, 2024).

Several new technologies are working on solving these issues. Uses of artificial intelligence and machine learning in embodied carbon and cost tools allow for quicker, more accurate and easier evaluations during the early design phase when results impact lifecycle emissions the most (Al-Habaibeh et al., 2024; Hu & Ghorbany, 2024). Building science is adapting to digital systems, which in turn helps ensure the correctness of data, improves its traceability and makes modelling decarbonization faster. There are new ways being developed to measure how much of the carbon in timber and bio-based materials is biogenic, as well as the special needs for infrastructure and landscape, which increases the use of carbon embodied analysis in the built environment (Ekundayo et al., 2019; Nikologianni et al., 2022). Nevertheless, studies stress that stronger consistency in engineering, a larger collection of materials and more flexible BIM methods are needed to support new trends in sustainable construction in high-rise buildings. In fact, though current tools for measuring embodied carbon in construction are reliable, more improvement work is needed to maintain their effectiveness.

2.2 Limitations of existing embodied carbon calculation tools

Although embodied carbon assessment tools provide valuable insights into the environmental impact of construction activities, their suitability for high-rise buildings presents unique challenges. However, their effectiveness in assessing embodied carbon in high-rise structures may be limited by factors such as complex structural systems and diverse material usage. Based on findings from the literature, Table 2 provides an overview of the constraints these tools face when applied to high-rise buildings.

The gap between what current tools for embodied carbon calculation can do and what high-rise construction involves is well described in recent publications. Certain constraints found in EC3, Tally, Athena, OneClick LCA, Beacon, EnviCASE, IES-VE, Revit and Dynamo, BHoM or LCAlink reduce their suitability for designing high-rise projects. A major challenge comes from Environmental Product Declarations (EPDs), since they are rarely available for the specialised components found in high-rise buildings, making the analysis incomplete and missing important areas areas (Haymaker, 2006; Maassarani et al., 2017; Resalati et al., 2019). For instance, establishing the environmental profile of many high-rise-specific materials is complicated by the absence of EPD data for EC3 and EnviCASE, while both Athena and OneClick LCA find it difficult to deal with changes in data and differences in databases when dealing with rare or region-specific materials (Galimshina et al., 2024; Maassarani et al., 2017). Because Tally does not fully integrate with BIM, users must input changes manually for complex design elements and upper levels, which may lead to errors in results. These tools, such as Revit and Dynamo, together with BHoM, were created for general BIM uses and miss the precise automation required for accurate element-level embodied carbon assessments in tall buildings, which can demand slow and difficult management of the data (Maassarani et al., 2017; Saad et al., 2020; Wu & Issa, 2012).

Furthermore, the common tools used for assessments often leave out the various effects of different structures and local material differences in building high-rises (Ferguson et al., 2016; Resalati et al., 2019). Beacon and EnviCASE mainly study the structure in tall buildings, which means they might not fully consider essential contributions from non-structure, but IES-VE, though it covers many aspects of building performance, does not give a detailed analysis of embodied carbon in high buildings (Kouka et al., 2024; Li et al., 2021). Because LCAlink works only with certain versions of Autodesk Revit and requires high computing power, it is not available to all potential users (Maassarani et al., 2017). The fact that these tools work separately and are not connected well with BIM aids causes extra difficulty for professionals carrying out detailed, time-efficient, accurate embodied carbon evaluations during the early design stage. For this reason, sustainable high-rise projects require new BIM-connected tools that contain large material databases, automatically gather data, enable advanced visualisation and use better design ideas (Arslan et al., 2023; Asdrubali et al., 2024; Dore & Murphy, 2014).

Findings from recent research show that due to the complexity and diversity in high-rise construction, more complicated and flexible methods are necessary for assessment (Adu et al., 2025; Getuli et al., 2024; Resalati et al., 2019). Since tools for early carbon assessment in buildings are not yet widely available, sustainability consultants are often called in at the last minute in design, meaning their impact is reduced (Maassarani et al., 2017; Saad et al., 2020). Besides, unclear and fluctuating measurements of embodied energy and carbon from things like EPD and material differences add more difficulty to comparing and choosing between buildings (Asdrubali et al., 2024; Resalati et al., 2019). Reviews of green building research regularly state that there is a need for tools that combine several assessment methods to connect carbon analysis for use and construction, make scenario planning easier and support worldwide sustainability objectives (Asdrubali et al., 2024; Kouka et al., 2024). The development of advanced tools based on BIM, which automate information transfer, widen materials lists, provide 3D views and give useful design advice, will be key to solving the current difficulties and promoting the use of low-carbon approaches in making high-rise buildings (Arslan et al., 2023; Asdrubali et al., 2024; Van Berlo & Natrop, 2015).

Table 2: Limitations of existing embodied carbon calculation tools.

Tool	Limitations
EC3 (Nguyen & Morgan, 2021)	- Relies on available EPDs. *[EPDs are the foundation for the assessment performed by this tool, and on some occasions, they may not exist for certain materials used in high-rise construction.]* - Limited material coverage. *[While EC3 covers materials typically found in the supply chain, selected materials that may be unique to high-rise buildings may be excluded.]*
Tally (Che-Ani & Raman, 2019)	- BIM element limitations. *[Tally's interfacing is limited to BIM, which makes it difficult to determine embodied carbon for high-rise and complicated structures.]* - Manual adjustments needed for upper floors. *[It may still have inputs to be manually keyed depending on the frequency of material usage, type of structural systems and floors; this increases the probability of errors.]*
Athena (Jrade & Abdulla, 2012)	- Simplified approach. *[Athena LCA due diligence simplicity seems to lack a certain depth that is important while handling high-rises, denying the role of variety in structures and the regional materials.]* - Data variability. *[The tool operates on life cycle inventory data points means that the quality of the respective data can be poor and/or irrelevant, hence compromising the results obtained.]*
OneClick LCA (Newberry et al., 2023)	- Data challenges. *[The tool is likely to encounter challenges in aligning it with the material database since sometimes it may not encounter rare materials which are used in high-rise construction.]* - Software constraints. *[There are aspects of OneClick LCA where the methods of how it is set up to work may not be ideal for the high-rise projects and its compatibility with the other designing and certifying tools.]*
Beacon (Dror et al.; Marcy & Iordanova, 2022)	- Limited granular details. *[Beacon may not provide the level of detail required for accurately assessing the embodied carbon of intricate structural systems in high-rise buildings.]* - Focus on structural projects. *[The tool is primarily designed for structural assessments, potentially neglecting the carbon impact of non-structural elements that are significant in high-rise buildings.]*
EnviCASE (Degenkolb, 2024)	- Data reliance on EPDs. *[EnviCASE's effectiveness is tied to the availability of EPDs, which may not cover the full range of materials used in high-rise construction.]* - Limited scope beyond structural materials. *[The tool focuses on structural materials, potentially overlooking the embodied carbon associated with other critical components in high-rise buildings.]*
IES-VE (Che-Ani & Raman, 2019)	- Broader focus beyond embodied carbon. *[IES-VE is a versatile tool for building performance simulation, but its broader focus means that it may not offer the depth needed for detailed embodied carbon assessments specific to high-rise buildings.]* - Integration challenges. *[Integrating IES-VE with other tools and data sources for embodied carbon assessment can be complex and may limit its effectiveness.]*
Revit and Dynamo (Alzara et al., 2023)	- Element-level assessment. *[These tools are designed for general BIM workflows and do not provide the specificity needed for accurate embodied carbon assessments in complex high-rise structures.]* - Data updates needed. *[Regular updates and manual data management are required to ensure accuracy, which can be time-consuming and prone to errors, especially in high-rise projects.]*
BHoM (Säwén et al., 2022)	- Data challenges. *[BHoM may struggle with data consistency and availability, particularly for materials not commonly used in standard building projects.]* - Requires Dynamo setup. *[Effective use of BHoM in LCA workflows requires a custom setup in Dynamo, which can be complex and may require specialised knowledge, making it less accessible for some users.]*
LCAlink (LCAlink, 2023)	- Specific software Requirements. *[LCAlink requires specific versions of Autodesk Revit (2023 or 2024) and operates on 64-bit Microsoft Windows 10 or 11.]* - Demand a high-performance system. *[The tool demands a relatively high-performance computer system, which has a powerful CPU and GPU]* - Limited software compatibility. *[LCAlink is designed to work with specific versions of Autodesk Revit, which may limit its use for projects using different or older versions of BIM software.]*

3. METHODOLOGY

The study utilises design science research as it is the optimum research method for artefact development-related research (see Figure. 1), systematically addressing each step with clear processes (Hevner et al., 2004).

An online questionnaire survey was employed to gather expert suggestions for the proposed BIM-based tool, followed by the validation phase. The snowball sampling method was used to identify qualified respondents, ensuring that participants possessed relevant expertise in Building Information Modelling (BIM), sustainability, and embodied carbon assessment. Invitations were distributed via email to 62 industry experts, including architects, engineers, sustainability consultants, and BIM managers from a range of countries such as Canada, the United Kingdom, the Republic of Ireland, Kuwait, the United Arab Emirates, India, Sri Lanka, Australia, and New Zealand. The sample size of 62 experts was considered appropriate for this study because the focus was not on achieving statistical generalisation, but rather on obtaining high-quality, informed, and contextually relevant insights from professionals with specialised expertise.

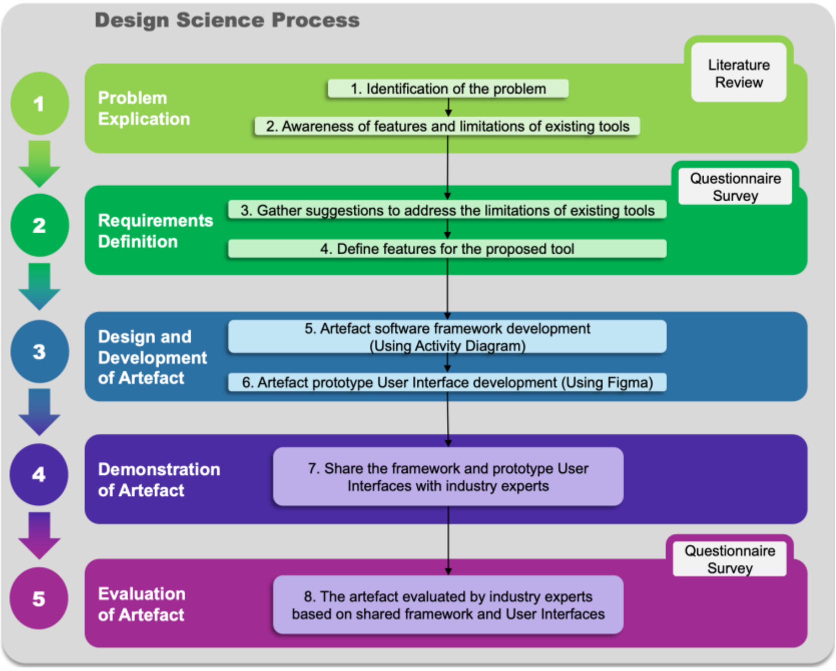

Figure. 1: Design Science Research methodology.

The questionnaire included a combination of closed-ended and open-ended questions designed to collect both quantitative and qualitative data. Closed-ended questions were used to obtain measurable feedback on the importance, relevance, and usefulness of proposed features. These items typically use a five-point Likert scale to assess expert agreement with specific tool functionalities. Open-ended questions allowed respondents to provide detailed qualitative input, offering suggestions for additional features, improvements to the tool interface, and strategies for overcoming limitations in existing BIM systems with justifications.

Descriptive statistics and qualitative thematic analysis were used for data analysis. Descriptive statistics summarised the frequency of responses to closed-ended items, whereas thematic analysis was applied to identify expert insights in open-ended responses.

For validation, the developed framework and user interface of the proposed BIM tool were shared with the same panel of experts. Respondents were then asked to map which features of the proposed tool address the limitations of existing tools to evaluate the practical relevance and comprehensiveness of the proposed solution.

4. RESULTS AND DISCUSSIONS

From the pool of 62 invited experts, 44 valid responses were received, representing a 71.0% response rate.

4.1 Experts' suggestions for the proposed tool

In the questionnaire, each respondent was asked to rate the importance, relevance, and usefulness of each feature in relation to high-rise construction and sustainability aspects on a five-point Likert scale. The mean of these Likert scores was then calculated under each category (importance, relevance, usefulness) and multiplied together with each other and the frequency percentage to derive the final score for each feature. Finally, the features were ranked based on the scores they obtained, as presented in Table 3.

Table 3: Summarised results of questionnaire survey.

Feature	Frequency % (F)	Likert score means			Score = (F*I*R*U)	Rank
		Importance (I)	Relevance (R)	Usefulness (U)		
BIM Model Integration	86.36%	4.8	4.9	4.7	95.47	1
Embodied Carbon Assignment	84.09%	4.7	4.8	4.6	87.27	2
Material Quantities Extraction	81.82%	4.6	4.7	4.5	79.60	3
Total Embodied Carbon Calculation	75.00%	4.5	4.6	4.4	68.31	4
3D Visualisation in BIM Model	68.18%	4.4	4.5	4.3	58.05	5
Manual Material Changes	68.18%	4.3	4.4	4.2	54.18	6
Comprehensive Material Database	65.91%	4.2	4.3	4.1	48.80	7
AI-Based Design Suggestions	52.27%	4.5	4.6	4.4	47.61	8
Lifecycle Assessment Integration	38.64%	4.6	4.5	4.3	34.39	9
Real-Time Carbon Footprint Feedback	38.64%	4.3	4.2	4.1	28.61	10
Geolocation-Based Material Sourcing	36.36%	4.3	4.2	4.1	26.93	11
Version Control for Material Changes	29.55%	4.4	4.3	4.2	23.48	12
Regulatory Compliance Checker	27.27%	4.2	4.1	4	18.79	13
Cloud-Based BIM Collaboration	27.27%	4.1	4.0	3.9	17.44	14

Table 4: Selected high-scoring features for the tool.

Feature	Description
BIM Model Integration	Accepts the BIM model of the high-rise building as input. Identifies building materials within the model.
Embodied Carbon Assignment	Utilises a database to assign relevant embodied carbon amounts to each material. Uses data from the database to estimate the carbon impact of different materials.
Material Quantities Extraction	Retrieves material quantities (such as areas and volumes) from the tool. Incorporates these quantities into the embodied carbon calculations.
Total Embodied Carbon Calculation	Systematically computes the total embodied carbon for the entire building. Aggregates the carbon contributions from all materials.
3D Visualisation in BIM Model	Displays the results within the BIM model. Utilises a colour code to indicate materials with varying levels of embodied carbon.
Manual Material Changes	Allows users to manually modify materials within the BIM model. Facilitates material substitutions to achieve lower embodied carbon. Automatically updates the BIM model based on user changes.
Comprehensive Material Database	Includes data for nearly all construction materials. Covers both conventional and low-carbon alternatives. Enables informed decision-making during design iterations.
AI-Based Design Suggestions	Incorporates a simple Artificial Intelligence (AI) model. Provides design and material change recommendations. Makes the tool accessible even to users with limited knowledge in embodied carbon assessment.

As suggested by the experts in the online questionnaire survey, the features for the prototype were selected for the proposed tool, as presented in

Table 4. While selecting features from those suggested by experts, only the features that received scores above 40% were chosen. A threshold of 40% was used as the passing score for selection. The selected features are shown in

Table 4.

The justifications for recommending these features specifically for high-rise constructions were also described by the experts through open-ended questions in the survey. After analysing the justifications from the survey, the summarised justifications are presented below.

1) BIM Model Integration

High-rise buildings require coordination across numerous floors and systems such as mechanical, electrical, plumbing, structural and fire safety. BIM model integration enables centralised management of these systems, ensuring consistency and reducing errors. In low-rise buildings, the spatial and system complexity is significantly lower, making manual coordination more feasible. Therefore, high-rise projects demand precise vertical alignment and integration, especially in core areas like elevator shafts and service risers.

2) Embodied Carbon Assignment

High-rise structures use large volumes of carbon-intensive materials such as concrete and steel to meet structural and fire safety requirements. Assigning embodied carbon values to these materials allows designers to assess environmental impact and explore alternatives. This is less critical in low-rise buildings, which often use lighter materials and have simpler structural demands.

3) Material Quantities Extraction

In high-rise construction, material estimation is complicated by the repetition of components across multiple floors and the need for bulk procurement. This feature automates quantity take-offs, improving accuracy and efficiency. Low-rise buildings typically have fewer floors and simpler layouts, making manual estimation more manageable. For high-rise projects, this feature supports logistics planning, cost control, and waste reduction, which are critical when dealing with large volumes of material and tight construction schedules.

4) Total Embodied Carbon Calculation

Calculating total embodied carbon in a high-rise building involves aggregating data from a vast number of components and systems. This is a complex task due to the scale and diversity of materials used across floors. In low-rise buildings, the number of components is limited, and carbon calculation is more straightforward.

5) 3D Visualisation in BIM Model

Understanding spatial relationships in high-rise buildings is more difficult due to vertical complexity and the interaction of systems across floors. 3D visualisation helps stakeholders grasp the design intent, especially for structural cores and facade elements. In low-rise buildings, spatial relationships are simpler and easier to interpret. This feature improves the communication and reduces errors in visualising and validating design decisions in complex structures as high-rise buildings.

6) Manual Material Changes

Manual adjustments to materials are more challenging in high-rise buildings due to the cascading effects across floors and systems. This feature allows for controlled changes while maintaining consistency throughout the model. In low-rise projects, such changes are easier to manage and less likely to affect other systems.

7) Comprehensive Material Database

A rich material database supports informed decision-making, especially in high-rise projects where material selection impacts structural integrity, fire safety, and sustainability. High-rise buildings often require specialised materials not commonly used in low-rise construction, such as high-strength concrete or fire-rated assemblies.

Moreover, high-rise buildings consist of different types of multifunctional and complex spaces in order to fulfil functions specific to high-rise buildings. This feature addresses the challenges of selecting appropriate materials for complex and multifunctional spaces in high-rise buildings.

8) AI-Based Design Suggestions

AI-driven design suggestions can optimise layouts and structural systems, where manual design interaction is time-consuming due to scale and complex layouts. While useful in low-rise buildings, the impact is more pronounced in high-rise projects, where design decisions affect multiple floors, systems, and overall building stability.

A prototype for the proposed tool, including framework and user interfaces, is then developed based on the selected features.

4.2 Prototype development (Framework + User interface)

The framework was developed using an "Activity Diagram" to outline the basic functional processes of the prototype, as presented in Figure 2. The user interfaces to illustrate the main functions of the prototype were designed by "Figma" as presented in Figure 3.

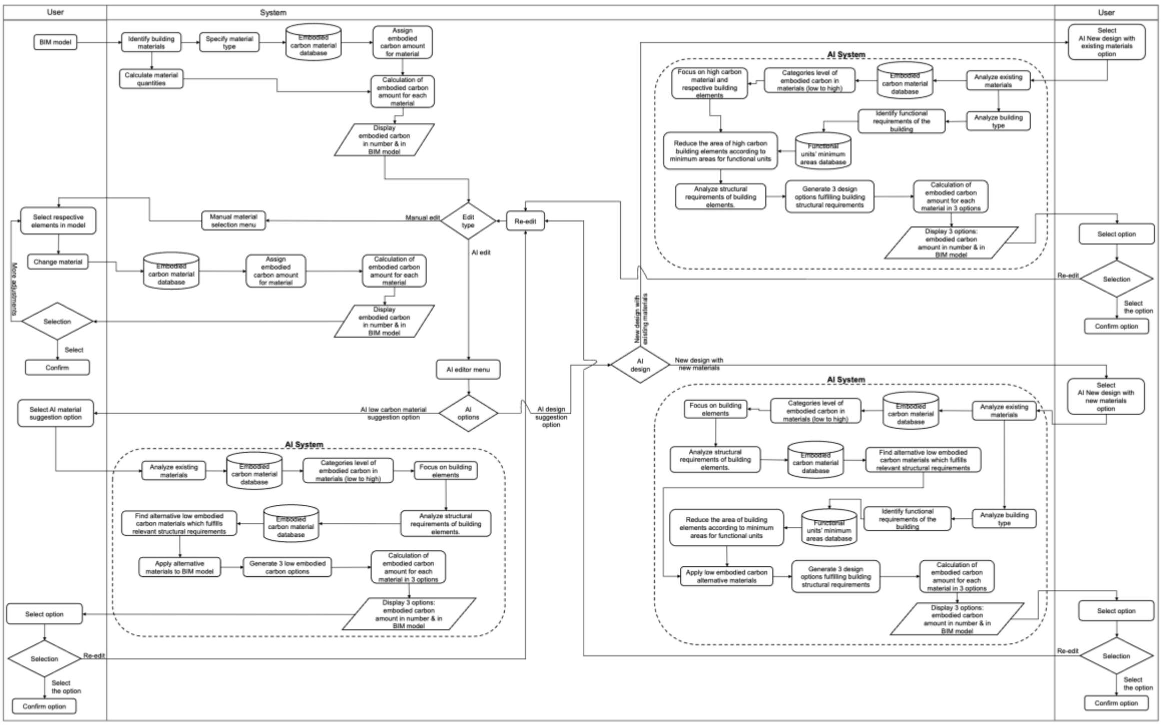

Figure 2: Activity diagram framework for the proposed BIM tool – shows the overall workflow of processes of the proposed tool.

With the activity diagram, the framework illustrates the core workflows involved in the prototype of the BIM-based tool for calculating embodied carbon. The visual chart of each step and vote in the activity diagram helps explain how data is entered, materials chosen, carbon is counted, and the results are shown. By using this structure, the process becomes more open, understandable and helps people communicate well indeed, which benefits the tool's further progress.

The proposed system has four (04) main functions that generate different options for building materials and design, aiming to minimise the amount of embodied carbon, as illustrated in Figure 3.

When the user imports a BIM model of a high-rise building to the system, it reads the BIM data and calculates the embodied carbon amount (kg CO_2e). A heatmap is then generated on top of building materials in the visualised model, ranging from green to red, to visually indicate materials with low to high embodied carbon. The user can then modify the building materials, adjust the design, or apply both changes simultaneously using the main functions of the proposed tool, as shown in Figure 3, in order to minimise the embodied carbon. The four (04) main functions of the proposed tool are briefly explained below.

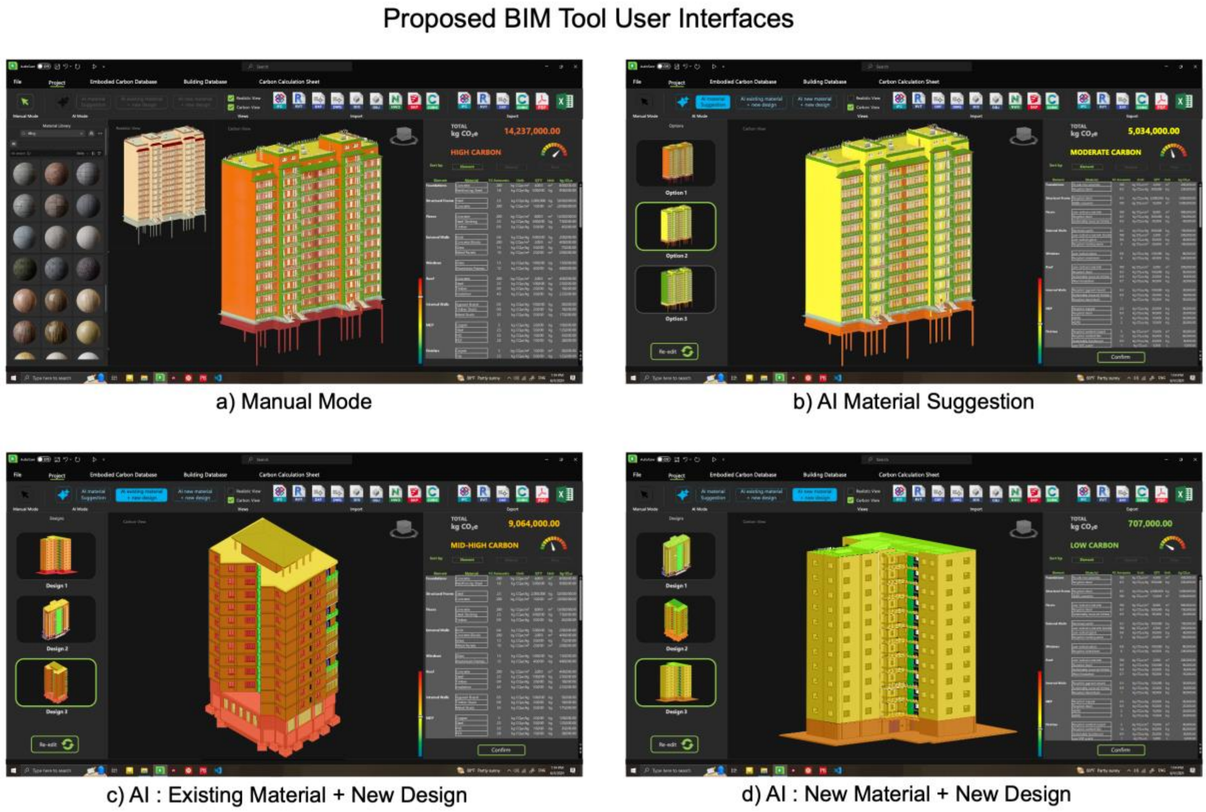

Figure 3: User interfaces of the proposed BIM tool – show the four (04) main functions for generating building material and design options to reduce the embodied carbon amount.

a) Manual Mode

The user can manually select low-carbon materials from the material library and replace them with existing materials.

b) AI Material Suggestion

The built-in AI automatically detects and applies the most suitable low-carbon materials to the model, aiming to achieve the lowest possible total embodied carbon.

c) AI: Existing Material + New Design

The integrated AI modifies the building design while retaining the original materials, aiming to minimise the total embodied carbon as much as possible.

d) AI: New Material + New Design

The built-in AI system modifies both the building design and materials to achieve the lowest possible embodied carbon.

Although the AI modifies the building design, it preserves key elements such as the number of floors, room types, and room count.

4.3 Validation of the developed prototype

The developed framework and the user interfaces were shared with the same 44 industry experts who responded earlier through email. Subsequently, a questionnaire survey was distributed to the same experts. The respondents were tasked with mapping which feature addresses what limitations in existing tools, with justifications. The results are presented in Table 5 with summaries of justifications.

Table 5: Results of the developed prototype validation by experts through the survey.

Existing Tool	Limitations of Existing Tool	Feature/s of the proposed tool that address the limitations and a summary of justifications	Response %
EC3	- Relies on available EPDs. EPDs are the foundation for the assessment performed by this tool, and on some occasions, they may not exist for certain materials used in high-rise construction.	**Embodied Carbon Assignment** No need to rely on EPDs. Embodied carbon amounts ($kgCO_2e$) are linked with materials in the large material library specific to high-rise construction in the proposed tool.	**100.00%**
	- Limited material coverage. While EC3 covers materials typically found in the supply chain, selected materials that may be unique to high-rise buildings may be excluded.	**Comprehensive Material Database** The material library is specific to high-rise construction materials.	**100.00%**
Tally	- BIM element limitations. Tally's interfacing is limited to BIM, which makes it difficult to determine embodied carbon for structures that are high-rise and complicated structures.	**BIM Model Integration** Almost all high-rise building models are made using BIM software.	**97.73%**
	- Manual adjustments needed for upper floors. It may still have inputs to be manually keyed depending on the frequency of material usage, type of structural systems and floors; this increases the probability of errors.	**Material Quantities Extraction** Automates taking off for the whole building.	**100.00%**
		3D Visualisation in BIM Model Visualise all types of structural elements in the building.	**95.45%**
		Manual Material Changes Materials can be manually changed depending on the complexity of structural elements.	**100.00%**
Athena	- Simplified approach. Athena LCA due diligence simplicity seems to lack a certain depth that is important while handling high-rises, denying the role of variety in structures and the regional materials	**Material Quantities Extraction** Automates taking off in complex high-rise buildings.	**79.55%**
		Total Embodied Carbon Calculation Automates total embodied carbon for entire high-rise construction, including complex structures within.	**90.91%**
	- Data variability. The tool operates on life cycle inventory data points means that the quality of the respective data can be poor and/or irrelevant, hence compromising the results obtained.	**Material Quantities Extraction** Building material data is automatically extracted from the BIM model.	**100.00%**
		Total Embodied Carbon Calculation Total embodied carbon amount automatically calculated based on BIM data.	**68.18%**
		AI-Based Design Suggestions Built-in AI suggest innovative design changes without being limited to BIM data.	**79.55%**
OneClick LCA	- Data challenges. The tool is likely to encounter challenges in aligning it with the material database, since it may not	**Embodied Carbon Assignment** All materials in the material library are linked with corresponding embodied carbon data.	**95.45%**

Existing Tool	Limitations of Existing Tool	Feature/s of the proposed tool that address the limitations and a summary of justifications	Response %
	encounter rare materials that are used in high-rise construction.	**Comprehensive Material Database** The material database is big and specific to high-rise building materials.	**97.73%**
	- Software constraints. There are aspects of OneClick LCA where the methods of how it is set up to work may not be ideal for the high-rise projects, and its compatibility with the other designing and certifying tools.	**AI-Based Design Suggestions** Automates design suggestions with AI, removing the need for compatibility with other designing tools.	**70.45%**
Beacon	- Limited granular details. Beacon may not provide the level of detail required for accurately assessing the embodied carbon of intricate structural systems in high-rise buildings.	**Total Embodied Carbon Calculation** Automatically accurately calculate the total embodied carbon amount, including all structural elements. **Manual Material Changes** Allows for changing materials manually in complex structural elements in high-rise buildings.	**88.64%** **72.73%**
	- Focus on structural projects. The tool is primarily designed for structural assessments, potentially neglecting the carbon impact of non-structural elements that are significant in high-rise buildings.	-	-
EnviCASE	- Data reliance on EPDs. EnviCASE's effectiveness is tied to the availability of EPDs, which may not cover the full range of materials used in high-rise construction.	**Embodied Carbon Assignment** No need to rely on EPDs. Embodied carbon amounts ($kgCO_2e$) are linked with materials in the large material library specific to high-rise construction in the proposed tool.	**100.00%**
	- Limited scope beyond structural materials. The tool focuses on structural materials, potentially overlooking the embodied carbon associated with other critical components in high-rise buildings.	**Embodied Carbon Assignment** All materials in the material library are linked with corresponding embodied carbon data. **Comprehensive Material Database** The material database is broad and specific to high-rise building materials.	**84.09%** **93.18%**
IES-VE	- Broader focus beyond embodied carbon. IES-VE is a versatile tool for building performance simulation, but its broader focus means that it may not offer the depth needed for detailed embodied carbon assessments specific to high-rise buildings.	**3D Visualisation in BIM Model** Visualise all types of structural elements, including complex ones in the high-rise building, in a 3D environment, providing depth and increasing the understandability of complex structures for the users.	**81.82%**
	- Integration challenges. Integrating IES-VE with other tools and data sources for embodied carbon assessment can be complex and may limit its effectiveness.	**BIM Model Integration** Data from the BIM model is integrated and linked with embodied carbon amounts.	**100.00%**
Revit and Dynamo	- Element-level assessment. These tools are designed for general BIM workflows and do not provide the specificity needed for accurate embodied carbon assessments in complex high-rise structures.	**BIM Model Integration** Data from the BIM model is integrated and linked with embodied carbon amounts. **3D Visualisation in BIM Model** Visualise complex structures specific to high-rise buildings, improving the understandability.	**93.18%** **75.00%**
	- Data updates needed.	-	-

Existing Tool	Limitations of Existing Tool	Feature/s of the proposed tool that address the limitations and a summary of justifications	Response %
	Regular updates and manual data management are required to ensure accuracy, which can be time-consuming and prone to errors, especially in high-rise projects.		
BHoM	- Data challenges. BHoM may struggle with data consistency and availability, particularly for materials not commonly used in standard building projects.	**Embodied Carbon Assignment** Material embodied carbon data are linked consistently. **Comprehensive Material Database** The large library of high-rise construction materials ensures that most materials are readily available.	**72.73%** **81.82%**
	- Requires Dynamo setup. Effective use of BhoM in LCA workflows requires a custom setup in Dynamo, which can be complex and may require specialised knowledge, making it less accessible for some users.	**AI-Based Design Suggestions** Automates design suggestions with AI, removing the need for other plugins.	**72.73%**
LCAlink	- Specific software Requirements. LCAlink requires specific versions of Autodesk Revit (2023 or 2024) and operates on 64-bit Microsoft Windows 10 or 11.	**AI-Based Design Suggestions** Built-in AI eliminates the necessity of specific software versions.	**90.91%**
	- Demand a high-performance system. The tool demands a relatively high-performance computer system, which has a powerful CPU and GPU	-	-
	- Limited software compatibility. LCAlink is designed to work with specific versions of Autodesk Revit, which may limit its use for projects using different or older versions of BIM software.	**AI-Based Design Suggestions** Built-in AI eliminates the necessity of specific software.	**93.18%**

According to the validation survey, the existing limitations namely, lack of focus on structural projects in Beacon software, need for data updates in Revit and Dynamo, and demand for a high-performance system in LCAlink were not addressed by the proposed tool, which can be regarded as limitations of it. However, all remaining features had response rates exceeding 65%. All experts agreed that features such as Embodied Carbon Assignment, Comprehensive Material Database, Material Quantities Extraction, Manual Material Changes, and BIM Model Integration in the proposed tool effectively address most of the limitations found in existing tools. The AI-Based Design Suggestions feature held a special place among the other features, as it independently addressed any of the limitations found in existing tools, such as data variability, software constraints, the need for plugins, and dependency on specific software and versions.

The new tool addresses various limitations in existing tools with its advanced features. It integrates seamlessly with BIM models, improving data synchronisation and addressing integration challenges. The tool assigns embodied carbon values using a broad material database, enhancing material coverage and accuracy. It automates the extraction of material quantities, reducing manual adjustments and variability. The tool ensures detailed and accurate total embodied carbon calculations for all building components. It enhances 3D visualisation within BIM models, providing detailed carbon data integration. The tool allows for precise manual material adjustments, improving flexibility. A comprehensive material database offers an extensive, up-to-date repository of materials. Lastly, AI-based design suggestions simplify decision-making and reduce complexity.

A graphical representation of the mapping of these limitations with the corresponding features is illustrated in Figure 4.

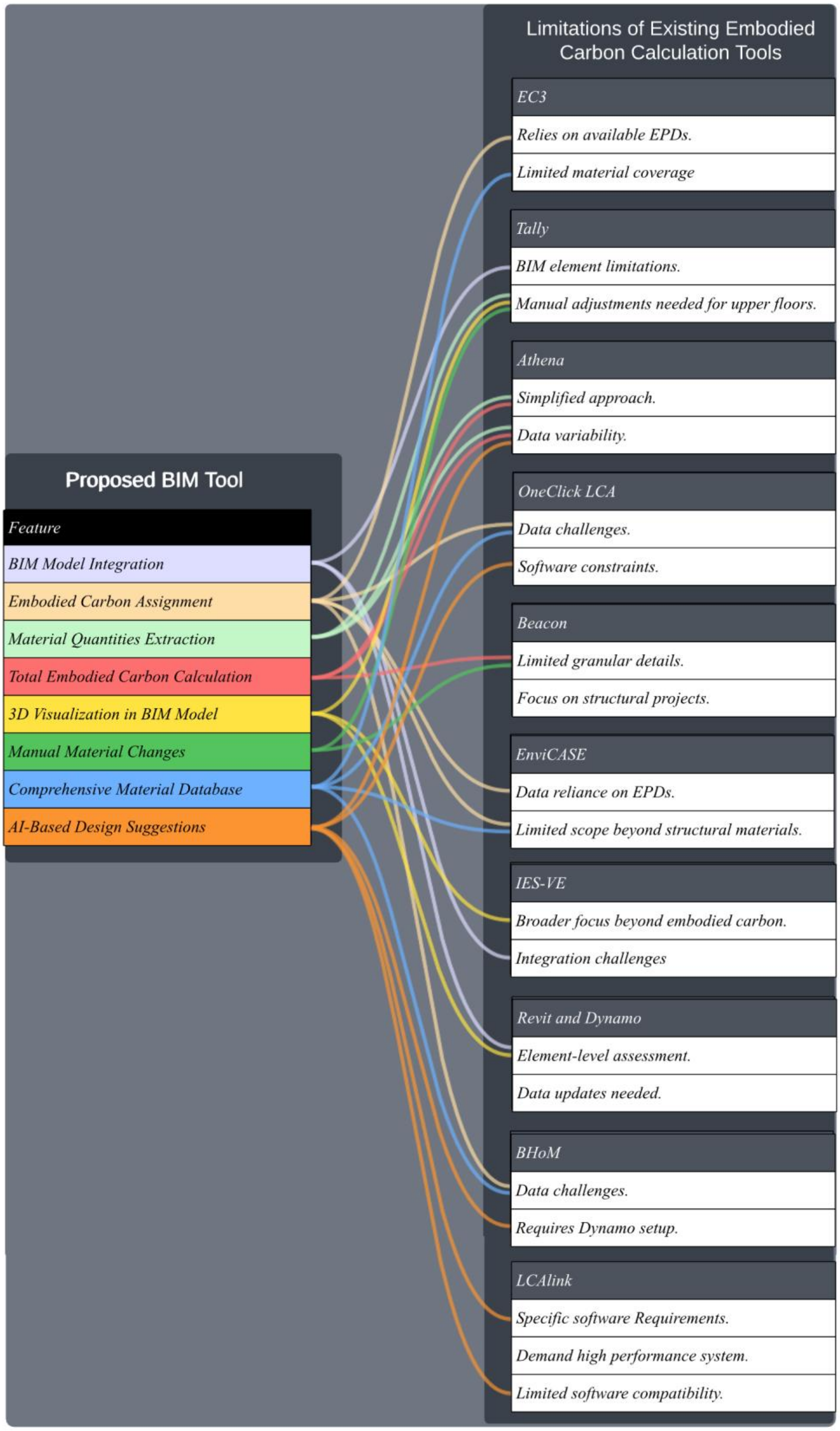

Figure 4: Expert validation – Mapping which limitations in existing tools are addressed by the features of the proposed tool.

5. CONCLUSION

The research findings indicate that because high-rise buildings emit a large amount of greenhouse gases, the use of innovative digital tools is important for assessing their carbon footprint. It is now understood that little of a building's carbon footprint comes from operating it; instead, much of it happens when materials are produced, transported, and installed. Because high-rise buildings depend so much on concrete, steel, and glass, they bring much greater and more difficult challenges than typical projects. Within BIM, existing tools EC3, Tally, Athena, OneClick LCA, Beacon, EnviCASE, IES-VE, Revit, Dynamo, BHoM and LCAlink give users the ability to model, analyse and evaluate environmental aspects at each phase of design. Yet, the available literature points out that continued limitations exist, such as relying on not-completed Environmental Product Declarations (EPDs), not having enough materials information, insufficient automation, and not having direct connections with Building Information Modelling (BIM) tools, which lessen their usefulness for high-rise projects.

Specific features identified by consultants and analysed in the current market were added directly to the novel BIM tool developed in this research to solve these issues. Innovative features include easy integration of BIM models for the right material selection, a large, updated materials list that curtails the need for EPDs, automated extraction of the amount of each material needed and intricate carbon calculations for single materials as well as the entire project. BIM software makes it easy to communicate about carbon hotspots, as well as experiment with different energy-saving designs during the design process. Confirmation from industry experts reveals that the tool helps correct data errors, needs less manual action, and encourages smarter, more adaptable choices, all needed for the fast and repetitive work in high-rise design. According to the research, the time to make decisions during conceptual and schematic design is most important for reducing emissions.

Going forward, the reports and advice underline the importance of including cost analysis, options for biogenic and new technologies and the merging of both embodied and operational assessments in such platforms. As digital tools and AI-backed approaches develop, future studies should work on aligning assessment strategies, widening the range of databases and creating better accessibility for these tools to be effective in construction projects all over the globe. When BIM and LCA approach their tasks guided by accurate data and effective visual tools, they can greatly support moving the construction sector towards sustainability and lower carbon footprints in high-rise construction. The proposed tool for BIM offers a complete, automated, and simple service that pushes forward efforts to make the built environment more environmentally friendly.

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