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# The Integration of Building Information Modelling and Life Cycle Assessment: Progress, Challenges, Future Directions

Ting Pan[a], Peter Nemeth[b], Yee Van Fan[a,c] , Ling Shao[d], Zekun Yang[e], Bohong Wang[f], Petar Sabev Varbanov[a,b]

[a]Sustainable Process Integration Laboratory – SPIL, NETME Centre, Faculty of Mechanical Engineering, Brno University of Technology - VUT Brno, Czech Republic
[b]Széchenyi István University, Egyetem tér 1, 9026 Győr, Hungary
[c]Environmental Change Institute (ECI), University of Oxford, Oxford, OX1 3QY, United Kingdom
[d]School of Economics and Management, China University of Geosciences, Beijing, 100083, China
[e]Centre for Process Integration, Department of Chemical Engineering and Analytical Science, The University of Manchester, Manchester, M13 9PL, UK
[f]National & Local Joint Engineering Research Center of Harbor Oil & Gas Storage and Transportation, Technology/Zhejiang Key Laboratory, Zhejiang Ocean University, 316022, Zhoushan, P.R. China
pan@fme.vutbr.cz

Building Information Modelling (BIM) plays a key role in the digitisation of the building sector, facilitating the design and construction of buildings. Environmental impacts have become an important factor to consider in building design and construction, often analysed through Life Cycle Assessment (LCA). The integration of BIM and LCA is crucial for supporting sustainable building design and construction. However, there is a lack of up-to-date reviews that consider the role of artificial intelligence (AI) in the integration of BIM and LCA. This paper addresses this gap by examining the recent progress, challenges, and future directions in building carbon emission accounting for buildings. The integration of the BIM-LCA for environmental impact accounting is explored, including goal and scope definition, life cycle inventory, impact assessment, interpretation, interoperability, and integration AI. The results identify gaps in BIM-LCA integration, including transparency issues and reliance on non-local databases. Future directions emphasise enhancing data quality, refining models, and developing AI methods for carbon emission predictions to explore decarbonisation strategy in the building sector. The review contributes to early-stage analysis, facilitating informed decision-making in sustainable building design and construction.

## 1. Introduction

The building sector accounted for one-third of total final energy use and $CO_2$ emissions in 2023, making it crucial for decarbonisation efforts. Additionally, energy use in buildings is projected to increase by 46 %-73 % by 2050 from 2019 levels due to population growth and higher living standards (Camarasa et al., 2022). To reduce the environmental impact of the building sector and achieve the climate mitigation targets proposed by the Intergovernmental Panel on Climate Change (IPCC), several strategies are explored to analyse demand-side mitigation approaches. The low energy demand (LED) strategy is proposed, promising to reduce carbon emissions by 40 % from 2020 to 2050. Digitalisation is one of the key trends of the LED strategy (Mastrucci et al., 2023). The digitalisation of the building sector is crucial for infrastructural interventions and technological development. The building sector model, defined as computer-based modelling in the building sector, is an important tool to quantify the environmental impacts. The building sector models are developed and grouped as top-down, bottom-up models or hybrid methods. (Li et al., 2020). Top-down models describe emissions for the entire building stock at an aggregated level, using carbon emissions, macroeconomic, or other statistics (Huo et al., 2021). Bottom-up models assess individual stock components, offering more detailed insights into the impact of technological upgrades on building carbon emissions (Mastrucci et al., 2017). Life Cycle Assessment (LCA) is a common bottom-up method used to analyse the carbon emissions generated by the building sector,

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assessing environmental impacts throughout its lifecycle. The LCA method exhaustively evaluates the entire building life cycle, analysing the environmental impacts of the input of materials and energy for the defined function unit. However, manual data input for analysing building carbon emissions remains a significant challenge, resulting in time-consuming tasks and potential data gaps. Therefore, integrating LCA with building information is essential for efficiency and accuracy. Building Information Modelling (BIM) offers a promising avenue for integrating LCA into sustainable development within the building sector. BIM focuses on modelling and managing both graphical and non-graphical information, facilitating the extraction of quantities, properties, and cost estimates of materials for construction projects in facilities and infrastructure (Röck et al., 2018). Seamless integration of BIM and LCA tools enhances overall efficiency (Najjar et al., 2017).

However, most previous research focuses on exploring the model integration of LCA and BIM, including technologies, methods of integration (e.g., exporting quantities, plugins), and applications in various building types (e.g., offices and residential), neglecting the role of artificial intelligence (AI) tool in optimising carbon emission for the building sector. This paper aims to review recent studies to analyse progress, challenges, and future directions in carbon emission accounting for the building sector, aiming to enhance accurate carbon emission accounting and target key aspects for improvement. The contributions of this work are:

(1) Conduct an up-to-date analysis of carbon emission accounting methods in the building sector, encompassing both current condition assessment, optimisation and prediction.

(2) Identify technological and application gaps in the integration of BIM-LCA and discuss the future directions.

## 2. BIM with LCA

To provide up-to-date insights into digitalisation carbon emission accounting for the building sector, we define the related keywords across various databases, with the selection process completed in 2024. Specifically, the keywords “building”, “life cycle assessment”, “building information model”, and ”building energy model” were defined, and searches were conducted across databases such as ScienceDirect, Scopus, Springer, and Web of Science, with the selection process completed in 2024. This yielded a set of 45 peer-reviewed articles, which were further refined based on their relevance. Ultimately, 28 papers were included in this study for review.

Figure 1 integrates the BIM-LCA across the building life cycle stages defined by EN 15978 (Ireland, 2011), covering stages from raw material supply to end-of-life. It follows ISO 14040 for environmental impact assessment (ISO, 2006), and ISO 19650 for BIM information management (ISO, 2018). The building life cycle stages defined by EN 15978, includes the product stage (A1-A3), construction stage (A4-A5), operation stage (B1-B5), and end-of-life stage (C1-C3), along with the benefits and loads beyond the system boundary (D). The building information management according to ISO 19650 includes planning and mobilisation (E5), production, collaborative production and delivery of the information model (E6-E7), closing and activities performed after the delivery of the contract (G8). The integration of the building life cycle stages (A-D) with the information management stages (E5-G8) ensures a seamless flow of data and enhances the environmental performance of the building.

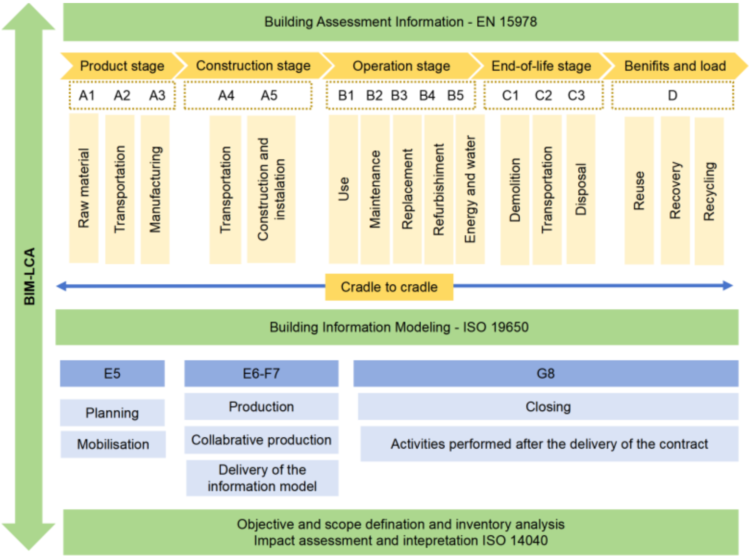

*Figure 1: Framework of BIM-LCA integration*

BIM-LCA integration enhances design efficiency and environmental performance in buildings in five integration types: (1) Bill of quantity export from the BIM environment; (2) IFC file format use; (3) IFC and BIM viewer processing; (4) BIM plug-ins like Tally; (5) Second tool development in BIM environment (Cheng et al., 2024). BIM accuracy is determined by the Level of Development (LOD), aiding in defining geometric complexity and data across project stages. LODs range from 100 (conceptual design stage) to 500 (as-built stage). LOD 300 and 400 is often used, which corresponds to the detailed design stage and provides more detailed data, including quantity, shapes, size, location, orientation, fabrication and assembly. When considering the environmental impacts, previous studies focus on global warming potential (GWP), primary energy demand (PE), and acidification potential (ADP). More details can be found in Table 1.

*Table 1: Integration of BIM-LCA for multiple environmental impacts of buildings*

| Authors | LCA database; tool | BIM software; LOD | Objective | Environmental impact | Case study |
|---|---|---|---|---|---|
| Marrero et al., 2020 | Ecoinvent, ACCD;<br>Simapro | BIMVision by Datacomp;<br>The highest level | Urbanisation process | WF, CF, EE | A small urban project including playgrounds, parking lots, sidewalk |
| Theißen et al., 2020 | ÖKOBAUDAT | Autodesk Revit, linear, external BIM-object databases (Open BIM)<br>LOD:300/400 | Environmental assessment of building services within an open BIM integrated WBLCA | GWP, ADP, EP, POCP, PE-Re, PE-NRe | Office building with a net floor area is 1849 $m^2$.<br>Lifetime: 50 y |
| Phillips et al., 2020 | EPDs;<br>Tally plugin, DOE's EnergyPlus | Autodesk Revit | Assess the environmental, economic, and social effects of various WWR levels using a triple-bottom line approach | ADP, EUP, GWP, ODP, SFP | US DOE's large office (12-story) prototype building.<br>Lifetime: 60 y |
| Su et al., 2020 | Chinese reference life cycle database (CLCD);<br>eBalance | Autodesk Revit<br>LOD: 300 | Quantify the dynamic life cycle environmental impacts of buildings | GWP, ADP, EUP, PE, WR, ore. | Multi-family residence, with the area of 16,650 $m^2$.<br>Lifetime: 50 y |
| Soust-Verdaguer et al., 2020 | Ecoinvent;<br>SimaPro | ArchiCAD<br>LOD: 300 | Present a quantitative method based on LCA to compare the environmental impacts produced by two building types | GWP, ADP, EUP, FWE, HT, ODP | Two alternative houses: one built with a timber frame and the other with concrete masonry.<br>Lifetime: 60 y |
| Tushar et al., 2021 | EPDs;<br>Tally | Autodesk Revit | Develop an integrated workflow between BIM and energy simulation software to get an in-depth analysis of the construction scenarios | ADP, EUP, GWP, ODP, SFP, PED, PE-Re, PE-NRe | A typical detached residential dwelling in the suburban terrain of Melbourne city with a gross floor area of 230 $m^2$ |

### 2.1 BIM-LCA integration: The goal and scope definition

The goal and scope definition in a building LCA involves comparing materials and building components to assess environmental impacts. Each building is unique, affecting results significantly due to factors like building type (residential and commercial), contract type (integrated project delivery), model complexity, and project stage (Rezaei et al., 2019). Under the building type category, residential buildings and office buildings are usually analysed particularly those with concrete structures. Literature shows a higher proportion of studies on low-rise and residential buildings (1-6 floors). Most BIM-LCA studies focus on early design stages due to increasing costs of changes as projects progress. The lifespan of the building varies from 50 to 100 y.

### 2.2 BIM-LCA integration at life cycle inventory (LCI) step

The BIM-LCA integration has the advantage of reducing the need to manually input the LCI and improving assessment efficiency. The life cycle inventory in building LCA is time-consuming and involves collecting data on elementary and intermediate flows across product life cycles (Llatas et al., 2020). Database for the LCI is from the following source: (1) Generic database (e.g. Ecoinvent); (2) Specific data sources (e.g. Athena, which is popular in North America; EUBUCOO v0.1 for Europe (Milojevic-Dupont et al., 2023); RASMI for global ranges of building material (Fishman et al., 2024)); (3) Region database, including China (Su et al., 2020), Korea (Shin and Cho, 2015), the UK, and Germany. LCA results often change throughout the building design process, necessitating updating the level of development of BIM. Notably, the level of development (LOD) correlates with the precision of the LCI. Lower LOD simplify the LCI because of utilising average data. The complexity and detail of the LCI determine the credibility of LCA results, posing a key challenge in early-stage building design. Therefore, utilising a regionalised and updated database is crucial for improving LCI quality. The integration approach for BIM-LCA integration is categorised into conventional (MS Excel), static BIM-LCA (plugins like GFC), and dynamic BIM-LCA (Programming Language) methods, establishing a bidirectional relationship between building information and LCI while considering temporal variations.

### 2.3 BIM-LCA integration at life cycle impact assessment

Life cycle impact assessment reveals environmental impacts, identifies constraints, and suggests improvements. Many studies focus on limited environmental indexes, obtained from various impact assessment methods like Recipe 2016 midpoint and CML 2001. Climate change, especially greenhouse gas emissions, is a key focus of the impact assessment. Hollberg et al. (2020) analyses BIM-LCA tools' potential for environmental assessments, highlighting embodied global warming potential in building design. Kiamili et al. (2020) find HVAC systems contribute 15-36 % of total greenhouse gas emissions. Some studies integrate economic and environmental factors in design, confirming walls' significant emissions impact, and emphasising wood frames' sustainability in Brazil. Few studies comprehensively address environmental factors or compare renovation with reconstruction for long-term development.

### 2.4 BIM-LCA integration at interpretation phase

BIM-LCA requires substantial data and expertise, especially in early decision-making stages. Uncertainties arise from models, design parameters, and assumptions, impacting the robustness of conclusions. Despite international standards emphasising uncertainty reduction, few studies incorporate uncertainty and sensitivity analysis in building design. Integrating sensitivity analysis on key parameters into BIM-LCA processes enhances comprehension of methodological choices and impacts. Some parameters such as design parameters, building lifetime and electricity intensity are commonly analysed (Pan et al., 2024). Rezaei et al. (2019) utilise Monte Carlo analysis to allocate material uncertainty in the early design stage. In all, conducting sensitivity and uncertainty analyses in the BIM-LCA process is crucial for enhancing the reliability of LCA decision-making.

### 2.5 Integrate BIM-LCA with artificial intelligence

BIM-LCA studies often use retrospective data, ignoring future technology improvements, potentially leading to inconsistencies in future decision-making. However, future technologies can drastically alter building operation and energy consumption results, differing up to 70 % from retrospective outcomes (Safari and AzariJafari, 2021), highlighting the necessity to predict the building energy consumption of buildings. AI methods are gaining popularity due to the advantage of predicting carbon emissions by learning from available data and could be used to model complex relationships without expert knowledge. The most common AI approaches used in the modelling of building energy consumption are Artificial Neural Networks (ANN) and Support Vector Machines (SVMs) (Zhao and Magoulès, 2012). Wang et al. (2023) estimate mid-century hourly building energy consumption in 277 U.S. urban areas using a bottom-up approach. It finds that projected future climate change leads to heterogeneous changes in energy use intensity among urban areas. However, these methods may result in higher prediction errors, especially with non-linear patterns, due to the need for large data sets, complex hyperparameter tuning, high computational cost, and lack of real-time adaptation (Lu et al., 2022). Hybrid models are becoming increasingly popular to address these gaps. Specifically, ANNs are combined with meta-heuristic algorithms for optimising weights, biases, and hyperparameters. Additionally, deep learning methods such as Convolutional Neural Networks (CNNs) and Recurrent Neural Networks (RNNs) are used to capture the spatial and temporal dependencies of buildings. Moreover, transfer learning leverages knowledge from similar buildings, and (generative adversarial network) GANs are employed for data augmentation and enhancing training data variety.

## 3. Challenges and future directions

The challenge in BIM-LCA integration encompasses several key aspects. Firstly, the importance of BIM model quality, particularly the LOD, is highlighted. However, only a quarter of the reviewed studies reported LOD, indicating a gap in model transparency. The complexity of technical systems poses another hurdle, often leading to incomplete LCA calculations. Secondly, in terms of life cycle inventory, reliance on non-local databases and incomplete regionalised databases impacts the accuracy of environmental assessments. Data extraction from BIM models presents challenges, with interoperability issues and data loss during exchange being common. Moreover, interpretation of results is hindered by uncertainties and changes over time, with little effort made to reduce uncertainties or conduct sensitivity analysis.

For the operational carbon emission caused by the building energy system, BIM-BEM interoperability faces limitations, with simulation results often unreliable. Native BEM tools yield more accurate results, highlighting existing challenges in interoperability. Predicting future carbon emissions in building energy systems is complex, often overlooking future scenarios and using limited frameworks. AI methods offer promise, though they may result in higher prediction errors, especially with non-linear patterns. Deep learning approaches are gaining traction for their potential to enhance prediction accuracy. The future investigations may focus on the following points:

(1) Data quality enhancement: Emphasize transparency in BIM model quality, particularly Level of LOD, to ensure accuracy and reliability. Improve regionalized databases and data extraction methods from BIM models to enhance the accuracy of environmental assessments.

(2) Model refinement: Address challenges related to technical system complexities, ensuring comprehensive LCA calculations without missing components. Explore interoperability solutions to improve data match during exchange and enhance the integration of BIM and LCA tools.

(3) Methodological advancements: Develop frameworks for predicting future carbon emissions in building energy systems, considering diverse scenarios and non-linear patterns. AI methods needs to be integrated in BIIM-LCA, to enhance prediction accuracy.

(4) Practical Application: Practical examples demonstrating the real-world integration of BIM-LCA need to be discussed.

## 4. Conclusion

This paper reviews recent studies to analyse progress, challenges, and future directions in carbon emission accounting for the building sector, aiming to enhance accurate carbon emission accounting and target key aspects for improvement. It shows that the challenge in BIM-LCA integration involves issues like LOD transparency, incomplete LCA calculations, and reliance on non-local databases. BIM-BEM interoperability faces limitations while predicting future carbon emissions requires refined methodologies and AI exploration, especially deep learning. Future directions in the digitalisation of the building sector might benefit from three key aspects. Future directions could focus on emphasising BIM transparency and improving data methods for environmental assessments. This includes addressing technical complexities for LCA, enhancing BIM-LCA integration, and developing AI frameworks for accurate carbon emission prediction and optimisation. Practical examples demonstrating the real-world application of BIM-LCA integration need to be discussed. The limitation of this review is that the references are limited, and few practical applications of the model are analysed. Future work will expand this review and provide more analysis on practical applications.

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