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RESEARCH ARTICLE

BIM–LCA integration for multi-scale sustainability assessment: Mapping the new European Bauhaus self-assessment framework

[version 1; peer review: 1 approved with reservations, 1 not approved]

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v1 **First published:** 29 Jul 2026, **6**:264
https://doi.org/10.12688/openreseurope.23481.1
Latest published: 29 Jul 2026, **6**:264
https://doi.org/10.12688/openreseurope.23481.1

Abstract

Background

The growing complexity of urban environments demands architectural practices that can address the environmental, economic, and social impacts of new construction projects. While the integration of digital tools and methods such as Building Information Modelling (BIM) and Life Cycle Assessment (LCA) enables the automation of environmental impact quantification, this approach remains limited to biophysical impacts and does not align with broader, multi-criteria sustainability frameworks. Currently, there is no standardised method for categorising which indicators can be automated using BIM and LCA tools. Addressing this gap requires integrated workflows, which are fundamentally outside typical BIM-LCA integration scope.

Methods

The present research investigates the role of BIM-LCA integration in supporting a norm-based, multi-criteria evaluation framework, using the New European Bauhaus (NEB) sustainability self-assessment tool as a case study. A systematic mapping and gap analysis has been performed to evaluate data dependencies and scope alignment among NEB sustainability indicators, LCA impact categories, and BIM data types.

Open Peer Review

Approval Status ? ✗

	1	2
version 1 29 Jul 2026	? view	✗ view

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Results

The analysis resulted in a triple taxonomy of indicators: 1) BIM-LCA Core (directly automatable), 2) BIM-LCA Informed (requiring integrated workflows), and 3) Beyond BIM-LCA which rely on parallel socio-economic or governance-based assessment methods.

Conclusions

The proposed taxonomy provides a strategic roadmap for integrating BIM–LCA workflows into multi-scale sustainability assessment, supporting practitioners in prioritising data requirements and informing tool developers about key interoperability challenges.

Keywords
BIM-LCA integration; Sustainability indicators; Multi-scale sustainability assessment; Buildings' environmental performance; New European Bauhaus



This article is included in the Horizon Europe gateway.



This article is included in the Marie-Sklodowska-Curie Actions (MSCA) gateway.

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Author roles: Tosi J: Conceptualization, Formal Analysis, Investigation, Methodology, Visualization, Writing – Original Draft Preparation; **Marzio S**: Conceptualization, Investigation, Visualization, Writing – Review & Editing; **Poggi F**: Investigation, Supervision, Validation, Writing – Original Draft Preparation; **Esteves L**: Conceptualization, Project Administration, Supervision, Writing – Review & Editing; **Amado M**: Methodology, Project Administration, Supervision, Validation, Writing – Review & Editing

Competing interests: No competing interests were disclosed.

Grant information: This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No [101073437] (GreeNexUS).

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How to cite this article: Tosi J, Marzio S, Poggi F *et al.* **BIM–LCA integration for multi-scale sustainability assessment: Mapping the new European Bauhaus self-assessment framework [version 1; peer review: 1 approved with reservations, 1 not approved]** Open Research Europe 2026, **6**:264 https://doi.org/10.12688/openreseurope.23481.1

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1. Introduction

The building sector is one of the major energy consumers and a key contributor to greenhouse gas (GHG) emissions in Europe. Addressing this challenge requires conducting a deep, comprehensive analysis of the environmental impacts of new construction and renovation projects. Life Cycle Assessment (LCA) is a widely recognized method for quantifying the environmental impacts of buildings (Potrč Obrecht et al., 2020), as it can identify the design and construction process with the lowest environmental burdens. However, identifying impactful strategies for implementation does not automatically lead to reducing the environmental footprint of the built environment or restoring biodiversity loss caused by human activities. For a construction project to adopt more comprehensive sustainability analyses, a more integrated methodological approach is necessary, rather than relying solely on LCA impact categories, which are the metrics used for evaluation in this method. This can be promoted by integrating sustainability analysis tools developed within EU frameworks that focus on the three dimensions of sustainability and incorporate socio-economic factors alongside environmental factors, assessed through LCA calculations.

In 2017, the European Commission has launched the Level(s) framework (European Commission, 2017) to standardise sustainability indicators for buildings, providing a three-dimensional advantage. First, it aligns with European standards and climate targets, bringing the building sector into line with them. Secondly, it facilitates the adoption of sustainability rating systems such as LEED or BREEAM and assists in aligning a building project with European legislative requirements. Third, it helps obtain green incentives or financing tools, which are essential drivers of transformation. Based on the Level(s) framework, the New European Bauhaus (NEB) initiative has developed a self-assessment tool to evaluate three main aspects of a building project: sustainability, inclusiveness, and aesthetic qualities.

The sustainability dimension aims to collect indicators and metrics commonly used in voluntary and commercial rating systems, then consolidate them into a reduced, manageable set of quantitative Key Performance Indicators (KPIs) to summarise the sustainability performance of a building project within the European context. The objective of this research is to investigate how sustainability indicators from the NEB self-assessment tool and LCA impact categories, to determine whether integration is needed for LCA indicators at the core of EN 15804:2012, and to address those flaws.

To do so, a cross-analysis of LCA impact categories and the NEB sustainability indicators has been performed to highlight which areas of sustainability analysis require further attention in LCA workflows. The paper is structured as follows: this first section introduces the research scope, objectives and structure. In Section 2, a brief literature review of the research topic is presented. Section 3 describes the research methodology, and Section 4 presents the results for the LCA impact categories and the analysed sustainability indicators. Section 5 discusses the cross-analysis performed, and Section 6 presents conclusions and future research directions.

2. State of the art

Recent literature has addressed integrating Life Cycle Assessment (LCA) into the design, construction, and management processes of the built environment, incorporating digital tools and methods to evaluate the environmental impacts of building projects. Studies from the last decade have explored the integration of Building Information Modelling (BIM) and LCA tools as a key technological advancement to facilitate environmental assessment by embedding relevant information into the digital design of buildings in the early phases (Soust-Verdaguer et al., 2024). The main purpose of BIM is to provide a shared environment for collaborative data management, yet it can increase the accuracy of a building project's environmental performance by embracing a comprehensive approach to its life cycle. These studies stems from the largely acknowledged potential of digitalization in providing rapid access to large amounts of information that is transforming anthropic activities sector (Negroponte, 1995) and human society itself (Han, 2022).

Dalla Mora et al. (2020) identified common parameters and workflows in LCA applications through analysis of academic literature. This review highlighted that most implemented tools, such as BIM and LCA software (e.g., Autodesk Revit) and MS Excel-developed spreadsheets, often result in fragmented and imprecise integration. Key barriers identified include limited interoperability among BIM and LCA software, as well as a lack of standardisation and retrievability in environmental databases. Emerging opportunities are arising related to the integration of Mixed Reality (MR) technologies during the design and construction phases. MR combines the characteristics of Virtual Reality (VR) and Augmented Reality (AR), and its implementation can enhance the visualisation and communication of environmental consequences of different design variables and construction scenarios (Kido et al., 2021; Sandagomika et al., 2024). Their work aims to provide practitioners with an easier path to CE objectives, while also reducing CO_2 emissions and embodied energy, among other benefits. The assessment of CE indicators can be further extended to waste generation analysis during the construction phase (Serrano-Baena et al., 2023), and help avoid discrepancies between the design and construction phases. Geographic Information System (GIS) digital tools can be integrated to support spatial analysis and optimise material flows and transport management in construction (Zubair et al., 2024).

Within this framework, recent studies identify emerging opportunities for novel digital tools that integrate algorithms for circular design and implement shared data Dervishaj and Gudmundsson (2023). In particular, Digital Twin (DT) are emerging as a promising technological solutions, by analyse design feasibility, monitoring project progress in construction phase and effectively managing facilities among other benefits (Piras et al., 2024). Digital Twin solutions built on BIM model can significantly improve a building project's environmental performance throughout the whole building lifecycle, yet this depends on real-time information exchange, for which is necessary to overcoming interoperability issues by adopting open data standards for BIM such as IFC, gbXML (Llatas et al., 2022; Okonta et al., 2024).

These technological developments can represent a significant opportunity to unlock automated or semi-automated sustainability assessment directly from BIM models and overcome operational barriers that currently limit the practical implementation of lifecycle assessment methods in the Architecture, Engineering and Construction (AEC) sector. The integration of BIM-LCA workflows with other software enables different stakeholders to align their strategies with sustainability principles, achieving benefits such as reduced production costs through increased material efficiency, minimised waste, optimised distribution channels, and reduced dependence on high-impact imported supplies (UNEP, 2016). Furthermore, combining BIM and LCA workflow with energy simulators and building management technologies, such as Building Energy Modelling (BEM), can contribute to greater energy efficiency while improving environmental conditions and occupant comfort (Di Santo et al., 2023). However, an important trade-off must be considered: improving a building's energy performance can significantly increase embodied emissions (Palumbo et al., 2024). Despite this challenge, improvements in operational energy performance remain a priority due to their substantial impact on energy consumption and the increasing regulatory pressure imposed by international climate policies (Pérez-Lombard et al., 2008).

Alongside these technological developments, recent literature has also explored the integration of sustainability rating systems as complementary methods for assessing additional sustainability dimensions of construction projects (Pai and Elzarka, 2021; Veselka et al., 2020). Sustainability rating systems consist of multi-criteria methodologies for assessing buildings' overall sustainability, aggregating results into a single score, enabling standardised outcomes, and aligning projects with national and international climate goals. Nonetheless, they are developed to evaluate the construction of a building only after it has been built and do not prove to be a suitable tool for assisting in the design of a building, which is the phase in which most consumption is determined and has the most potential for optimisation (Feria and Amado, 2019). The early adoption of BIM-LCA methodologies can support the attainment of sustainability certifications by informing design decisions in the early project stages (Azhar, 2011). Nevertheless, current research often focuses on achieving specific certification targets rather than adopting a comprehensive systems-based framework that aligns building design with broader environmental limits and planetary boundaries (Steffen, 2015).

To address these challenges, institutional frameworks are increasingly promoting standardised approaches to environmental assessment. The introduction of the Level(s) framework (European Commission, 2017) aims to support integrating LCA methods into building performance evaluation by providing a common set of indicators and methodological guidelines. In this context, De Wolf et al. (2022) proposed a categorisation of LCA tools available in Europe, extracting user-oriented information such as scope, consistency, cost, and accessibility. Their analysis focuses on tools directly aligned with Level(s) scope and requirements, providing supporting guidance to stakeholders in the AEC sector.

Despite the growing availability of digital tools, many challenges remain. While issues related to interoperability and the automation of information exchange across different software and tools are extensively discussed in recent academic literature, the role of a standardised framework in addressing practical barriers, such as the lack of a homogeneous dataset and consistent standards, remains underexplored. Technological advancements alone are unlikely to overcome persistent institutional, behavioural, and socio-economic barriers affecting sustainability practices in the construction sector (Tosi et al., 2025).

The present research addresses these gaps by investigating how integrating international standards can support the development of a structured protocol to improve the sustainability performance of building projects. In particular, this study explores how policy-based design frameworks, such as the New European Bauhaus (NEB), can be translated into a technical data workflow that supports BIM-LCA integration and enables the practical implementation of mitigation strategies during the design and development of buildings.

3. Research methodology and materials

The proposed research methodology consists of three steps and different materials, schematized in a figure. 1: 1) Source selection and data collection, 2) Information extraction, 3) Cross-analysis protocol.

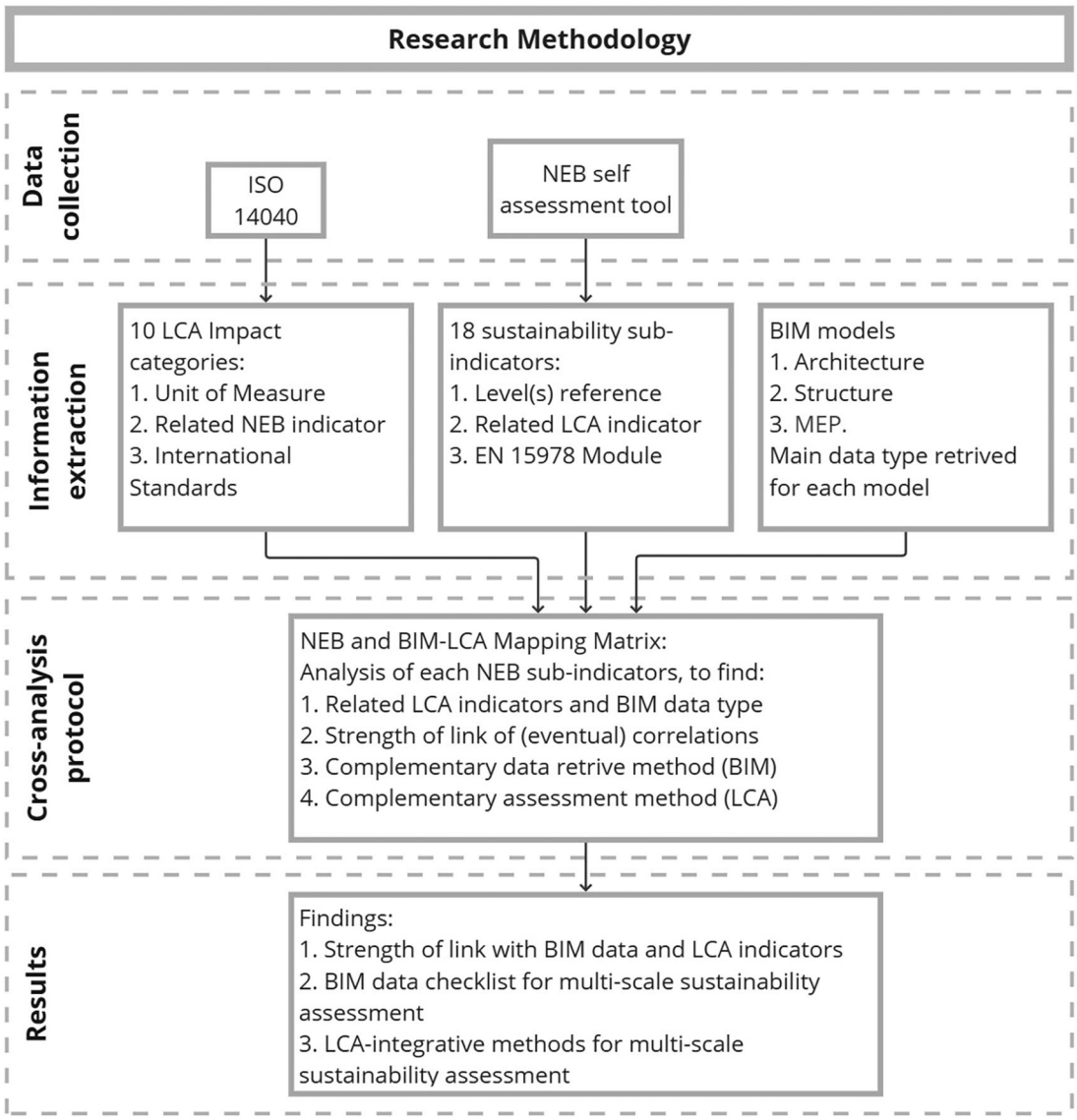

Fig. 1. Framework of the methodology implemented.

The cross-analysis consisted in firstly the analysis the NEB sustainability indicators to collect descriptive information, the information required that can be extracted from a BIM model, the unit of measurement encompassed, the life-cycle phase in which each indicator can be assessed. It encompassed three main phases:

1. **Data collection**: Data were collected from the core standards related to LCA methodology (ISO 14040:2006, EN 15978:2011) and the institutional documentation for the New European Bauhaus self-assessment tool (European Commission, 2021; Lourenço et al., 2024). The NEB framework was selected as the representative strategic framework due to its explicit design for use in early project phases and its direct policy alignment with Level(s) framework.

2. **Information extraction**: A qualitative content analysis was conducted using a structured procedure. For each NEB indicator, the following information was extracted:

    i. a brief description of the indicator, including the associated metrics and potential correlations with Level(s) indicators

ii. the life cycle phase where it can be initially evaluated and the cycle phase where it can be effectively assessed

iii. the assessment methodologies or digital tools required to calculate or support the evaluation of the indicator.A parallel analysis was conducted for LCA impact categories, for which the following information was extracted:

i. description of the impact category

ii. associated metrics

iii. reference international standards

Additionally, the BIM data types that could potentially support indicator calculation were identified. These data were retrieved from the main BIM model domains, including:

i. Architectural models

ii. Structural models

iii. Mechanical, Electrical and Plumbing systems.

The results of the first parallel analysis are schematized respectively in Table 1 and Table 2:

3. **Cross-analysis protocol**: after completing the information extraction process, a correlation analysis was conducted between each NEB sustainability sub-indicator, the corresponding LCA impact categories, and the relevant BIM data types. This cross-analysis enabled the identification of three levels of correlation:

   i. "Direct" correlation was identified if the NEB indicator's metric could be calculated primarily from LCA indicators (i.e. LCA *GWP* for NEB S.3.2 *Embodied GHG Emissions*); and if one or more BIM data type were sufficient information for calculating the selected NEB indicator as automated or semi-automated path (i.e. rooms data + plumbing data for NEB S.5.2 *Water Consumption*).

   ii. "Partial" correlation was linked to whether LCA indicators were: 1) necessary but insufficient input (for example, LCA Renewable share of *Cumulative Energy Demand* for NEB S.2.1 *Share of Renewables*) 2) more comprehensive metrics than the NEB corresponding indicator, requiring a breakdown of the NEB component's contribution (for example, LCA *Cumulative Energy Demand* for NEB S.2.1 *Share of Renewables*); 3) if more than one LCA impact category is needed (such as LCA HTP, Ecotoxicity Potential for NEB S.5.1 Indoor Air Quality). Regarding BIM analysis, the "partial" correlation occurs when the BIM data was required but insufficient input for NEB indicator calculation (for example, electrical systems for NEB S.1.2 Optimisation of Electricity Peak).

   iii. "Indirect" correlation was assigned for both LCA indicators and BIM data.

The methodology presented some limitations: the in-depth analysis allowed a critical evaluation of the two sets of indicators selected, yet it did not include complementary assessment methodologies for LCA calculations, such as Absolute LCA (Bjørn et al., 2015) and Life Cycle Sustainability Assessment (LCSA) (Soust-Verdaguer et al., 2022). These two methodologies can improve the comprehensiveness of impact assessment: Absolute LCA by aligning the environmental impact assessment to local budget of planet boundaries, LCSA by enriching the sustainability dimensions of LCA by implementing Life Cycle Costing (LCC) evaluation for economic assessment, and the social assessment (S-LCA) based on Guidelines for S-LCA and the Handbook for Product Social Impact Assessment (Goedkoop et al., 2020) developed by UNEP.

The choice behind focusing on the NEB methodology rather than on Absolute LCA and LCSA among others stem from three decisive factors: 1) Its direct policy relevance to the European context, as it intrinsically aligns with European standards of NEB indicators that represent a decisive factor to accelerate the decarbonization of the built environment, necessary for transition toward the net-zero greenhouse gas emissions envisaged within the European Green Deal; 2) It is a self-assessment tool for designers and practitioners, directly addressing some of the gaps observed in the State of the art

Table 1. Partial cross-analysis between NEB indictors and LCA impact categories.

	NEB sustainability sub-indicators	Related LCA impact category	Strength of link	EN 15978 module	Complementary assessment methods
S.1.1	Primary Energy Demand	Cumulative Energy Demand (**CED**)	Partial	A1–A3, B6	Energy Analysis Tools
S.1.2	Optimisation of Electricity Peak	-	Indirect	B6	Energy Analysis Tools
S.1.3	Smart Readiness of Buildings	-	Indirect	B6	-
S.2.1	Share of Renewables	Renewable share (part of **CED**)	Partial	A1–A3, B6	Sustainability Assessment Frameworks
S.2.2	Energy Storage Capacity	-	Indirect	B6	Simulation and Optimization Tools
S.3.1	Operational GHG Emissions	Global Warming Potential (**GWP**)	Direct	B6	Carbon Footprint Calculation Tools
S.3.2	Embodied GHG Emissions	Global Warming Potential (**GWP**)	Direct	A1–A5, B4, C1–C4	LCA Software
S.4.1	Electric Vehicle (EV) Parking)	-	Indirect	B6, B7	GIS Tools
S.4.2	Alternative Mobility: Bicycle	-	Indirect	B7	GIS Tools
S.5.1	Indoor Air Quality	**HTP**, Ecotoxicity Potential	Partial	B1	Sustainability Assessment Frameworks
S.5.2	Water Consumption	Abiotic Depletion Potential (**ADP**)	Direct	A1–A3, B6	Simulation and Optimization Tools
S.6.1	Construction and Demolition Waste	Abiotic Depletion Potential (**ADP**)	Direct	A5, C1–C4, D	Material and Resource Management
S.7.1	Social Return of Investment	-	Indirect	D (beyond boundary)	Sustainability Assessment Frameworks
S.7.2	Interdisciplinary Integration	-	Indirect	Design	Collaboration Platforms
S.7.3	Gross value added to local economy	-	Indirect	D (beyond boundary)	GIS Tools
S.8.1	Green Financial Tools	-	Indirect	Financial stage	Sustainability Assessment Frameworks
S.8.2	ESG and ESRS standards compliance	-	Indirect	Financial stage	Sustainability Assessment Frameworks
S.9.1	Secondary, Biobased, Recycled Materials	**ADP**, Ecotoxicity Potential	Partial	A1–A3	Material and Resource Management

section on the necessity of tools for the early phase, as the most impactful phase for reducing environmental impacts of construction projects; 3) Its structured inclusion of deeper social dimensions, such as cultural and aesthetic, inclusiveness and socio-economic implications, including the multi-dimensional aspects of LCSA, and also collect national threshold for various indicators, addressing the contextualization offered by A-LCA approaches. In summary, the NEB proposed methodology was chosen as it is both aligned with LCA and expands beyond it, integrating the potential upgrading offers by LCSA and A-LCA methodologies among others.

4. Results

This section presents the results of the cross-analysis by identifying recurring patterns between the New European Bauhaus (NEB) sustainability sub-indicators and the corresponding BIM and LCA data structures, and discussing the

Table 2. **Partial cross-analysis between NEB indictors and BIM data type.**

	NEB indicators	Related BIM data types	Strength of link	Minimum BIM information requirements (MIRs)	Complementary data method
S.1.1	Primary Energy Demand	**Architectural**: Geometry, Envelope, Rooms data **MEP**: HVAC, Lighting	Partial	Building volume and surfaces, U-values, HVAC system type & efficiency, lighting power density.	BEM Simulation + Operational/ Climate Data
S.1.2	Optimisation of Electricity Peak	**MEP**: Electrical Systems	Partial	Panel schedules, connected loads, renewable system specs.	Grid Interaction Analysis + Smart Meter Data
S.1.3	Smart Readiness of Buildings	**MEP**: HVAC, Electrical Systems, Lighting	Partial	System types, control devices, zoning information.	Functional Testing + Protocol Assessment
S.2.1	Share of Renewables	**MEP**: Electrical Systems	Partial	On-site renewable system capacity (kWp).	Energy Demand Simulation/ Measurement
S.2.2	Energy Storage Capacity	**MEP**: Electrical Systems	Direct	Storage system objects with 'Capacity' property (kWh).	Not Applicable (Direct from BIM)
S.3.1	Operational GHG Emissions	**Architectural**: Envelope **MEP**: HVAC, Lighting	Partial	Building volume/surfaces, U-values, HVAC system type & efficiency, lighting power density.	Emission factors database + Energy results
S.3.2	Embodied GHG Emissions	**Architectural**: Material Schedules **Structural**: Element Quantities, Material Specs	Direct	Material volumes/masses + material type specification.	LCA Database Linkage (automated)
S.4.1	Electric Vehicle (EV) Parking)	**Architectural**: Rooms data	Partial	Parking space objects with 'EV Capable'/'EV Ready' property.	Not Applicable (Direct from drawings)
S.4.2	Alternative Mobility: Bicycle	**Architectural**: Geometry (site plan)	Partial	Location and count of bicycle storage facilities.	Not Applicable (Direct from drawings)
S.5.1	Indoor Air Quality	**Architectural**: Rooms data, Geometry **MEP**: HVAC	Partial	Ventilation rates, filter specs, room volumes.	Sensor Data/ Contaminant Simulation
S.5.2	Water Consumption	**Architectural**: Rooms data **MEP**: Plumbing Data	Direct	Fixture counts and flow rate properties.	Occupancy Schedule/Usage Pattern
S.6.1	Construction and Demolition Waste	**Architectural**: Material Schedules **Structural**: Element Quantities	Partial	Material volumes/masses and material types.	Waste Factors + Deconstruction Plan
S.7.1	Social Return of Investment	-	Indirect	Not Applicable (Non-BIM Indicator).	Stakeholder Surveys + Economic Valuation
S.7.2	Interdisciplinary Integration	-	Indirect	Not Applicable (Meta-Process).	Process Audits + Collaboration Metrics

Table 2. *Continued*

	NEB indicators	Related BIM data types	Strength of link	Minimum BIM information requirements (MIRs)	Complementary data method
S.7.3	Gross value added to local economy	-	Indirect	Not Applicable (Non-BIM Indicator).	Economic statistics
S.8.1	Green Financial Tools	-	Indirect	Not Applicable (Non-BIM Indicator).	Financial Document Review
S.8.2	ESG and ESRS Standards Compliance	All: as a data source	Partial	Material and energy data from MIRs above.	Governance & Social Audits + ESG frameworks reporting
S.9.1	Secondary, Biobased, Recycled Materials	**Architectural**: Material Schedules **Structural**: Material Specs	Direct	Material property specifying recycled/ biobased content (%).	Supplier declarations

practical implications for integrating them into digital workflows. It is schematized in Table 3, and it arise from the two analysis presented in Table 1 and Table 2. It revealed three distinct types of relationships between NEB sub-indicators and BIM-LCA data and indicators:

1. ***BIM-LCA core indicators***, 4 out of 18 (~22%) of the NEB indicators presented a "Direct" link with both LCA impact categories and BIM data type, or one as "Direct" and the other one as "Partial".
   -- S.3.1 Operational GHG Emissions
   -- S.3.2 Embodied GHG Emissions
   -- S.5.2 Water Consumption
   -- S.6.1 Construction and Demolition Waste

This typology of indicators can therefore be automatically or semi-automatically be assessed trough BIM-LCA integration workflows.

2. ***BIM-LCA informed indicators***, more than half of the NEB indicators (10/18) reported "Direct" or "Partial" relationship with LCA indicators, and "Direct" or "Partial" relationship with BIM data. This degree of relationship describe NEB indicators for which BIM-LCA data provide necessary yet insufficient input to estimate them, therefore requiring further assessment methodologies:
   -- S.1.1 Primary Energy Demand
   -- S.1.2 Optimisation of Electricity Peak
   -- S.1.3 Smart Readiness of Buildings
   -- S.2.1 Share of Renewables
   -- S.2.2 Energy Storage Capacity
   -- S.4.1 Electric Vehicle (EV) Parking)
   -- S.4.2 Alternative Mobility: Bicycle
   -- S.5.1 Indoor Air Quality

Table 3. **Cross-analysis between NEB indicators and BIM-LCA data.**

	NEB sustainability sub-indicators	Strength of link: BIM	Strength of link: LCA	BIM-LCA integration	Complementary assessment methods	Complementary data method
S.1.1	Primary Energy Demand	Partial	Partial	**Informed**	Energy Analysis Tools	BEM Simulation + Operational data
S.1.2	Optimisation of Electricity Peak	Partial	Indirect	**Informed**	Energy Analysis Tools	Grid Interaction + Smart Meter Data
S.1.3	Smart Readiness of Buildings	Partial	Indirect	**Informed**	-	Functional Testing + Protocol Assessment
S.2.1	Share of Renewables	Partial	Partial	**Informed**	Sustainability Assessment Frameworks	Energy Demand Simulation/ Measurement
S.2.2	Energy Storage Capacity	Direct	Indirect	**Informed**	Simulation and Optimization Tools	-
S.3.1	Operational GHG Emissions	Partial	Direct	**Core**	Carbon Footprint Calculation Tools	Emission factors database + BEM
S.3.2	Embodied GHG Emissions	Direct	Direct	**Core**	LCA Software	LCA Database Linkage (automated)
S.4.1	Electric Vehicle (EV) Parking)	Partial	Indirect	**Informed**	GIS Tools	- (Direct from drawings)
S.4.2	Alternative Mobility: Bicycle	Partial	Indirect	**Informed**	GIS Tools	- (Direct from drawings)
S.5.1	Indoor Air Quality	Partial	Partial	**Informed**	Sustainability Assessment Frameworks	Sensor Data/ Contaminant Simulation
S.5.2	Water Consumption	Direct	Direct	**Core**	Simulation and Optimization Tools	Occupancy Schedule/Usage Pattern
S.6.1	Construction and Demolition Waste	Partial	Direct	**Core**	Material and Resource Management	Waste Factors + Deconstruction Plan
S.7.1	Social Return of Investment (SROI)	Indirect	Indirect	**Beyond**	Sustainability Assessment Frameworks	Stakeholder Surveys + Economic Valuation
S.7.2	Interdisciplinary Integration	Indirect	Indirect	**Beyond**	Collaboration Platforms	Process Audits + Collaboration Metrics
S.7.3	Gross Value Added to Local Economy	Indirect	Indirect	**Beyond**	GIS Tools	Economic statistics
S.8.1	Green Financial Tools	Indirect	Indirect	**Beyond**	Sustainability Assessment Frameworks	Financial Document Review
S.8.2	Compliance with ESG and ESRS Standards	Partial	Indirect	**Informed**	Sustainability Assessment Frameworks	Audits + ESG frameworks reporting
S.9.1	Secondary, Biobased, Recycled Materials	Direct	Partial	**Core**	Material and Resource Management	Supplier declarations

-- S.8.2 Compliance with ESG and ESRS Standards

In this category, BIM and LCA data provide necessary but insufficient input for full indicator evaluation, meaning that additional assessment methodologies or datasets are required.

3. ***Beyond BIM-LCA indicators***, four indicators (~22%) present no direct nor partial relationship with either BIM data or LCA impact categories.

   -- S.7.1 Social Return of Investment (SROI)

   -- S.7.2 Degree of Interdisciplinary Integration

   -- S.7.3 Gross Value Added to Local Economy

   -- S.8.1 Green Financial Tools.

These indicators address sustainability dimensions that extend beyond the environmental and technical scope typically covered by BIM-LCA workflows, focusing instead on economic, social, or governance aspects of sustainability.

Table 3 summarises the relationships identified between NEB sustainability sub-indicators, BIM data availability, LCA impact categories, and complementary assessment methods required for indicator evaluation.

The present classification proposes a novel categorisation of multi-scale sustainability indicators, namely the NEB sub-indicators across its sustainability dimensions, to identify the technologies and strategies that support their application, starting from a BIM model of a new construction project. This contribution offers a strategic implementation framework that identifies the digital support needed for each sustainability indicator within a multi-scale set, refining the often generic definition of holistic and comprehensive workflows into a well-defined workflow integration indicator.

An overview of the distribution of indicators reveals that BIM-LCA integration is a fundamental yet incomplete tool for holistic sustainability assessment, as it is not useful for a set of socio-economic indicators. On the other hand, it demonstrates its utility by directly serving as a core engine for some *core* indicators (4/18). This finding positions the multi-scale sustainability assessment issue not as an automation challenge, for which the barriers are mainly technical interoperability and data exchange between different software, (Teng, 2022) but as a workflow integration challenge, which requires a strategic coupling of the BIM-LCA workflow with further digital-based methods or tools. As showed in Tab. 1, *BIM-LCA core* indicators can rely on "Partial" BIM link and "Direct" LCA link revealing that the BIM model can mainly provide geometrical and characteristic of the project but needs further integration, as in the case of S.1.1 Primary Energy Demand that requires the critical energy simulation in BEMs environment, or for S.3.1 Operational GHG Emissions for which emission factor database are necessary (Anderson and Rønning, 2022). This demonstrates that the core challenge is not evolving individual tools, but rather coordinating reliable data flows between them.

The analysis of the *BIM-LCA informed* indicators, representing half of the total, reveals the research nexus that needs to be addressed to overcome the lack of practical implementation of digitally based practices that assess and, therefore, inform conscientious and sustainability-oriented choices for new construction projects. Energy-related indicators (i.e. Primary Energy Demand, Optimisation of Electricity Peak, Smart Readiness of Buildings, Share of Renewables), social and comfort indicators (i.e. Alternative Mobility: Bicycle, Indoor Air Quality) or compliance with national or EU standards can benefit from BIM-LCA integration practices, yet they require additional methods such as BEMs or environmental simulations, and information retrieval from technical drawings and schedules, interviews with stakeholders or quantities' schedules from construction phase.

The four retrieved *beyond BIM-LCA* indicators represent a frontier definition of the limits of BIM-LCA practices to grasp multi-scale sustainability assessment. Although BIM-LCA represents a useful tool for quantitative environmental assessment and does not integrate *per se*, holistic or multi-criteria sustainability assessment claims, drafting a demarcation line between the indicators that can be fed by BIM-LCA practices and the ones that require separate, usually qualitative governance processes is a result that can define future frameworks for comprehensive sustainability assessments.

5. Discussion

The state-of-the-art presented in this research highlights a fragmented debate regarding the integration of digital tools to assess and enhance the sustainability performance of new construction buildings, marked by strong focus on singular, promising solutions rather than a utmost overall view on the intrinsic complexity of the thematic debated. Some of the technical gaps encountered address interoperability and data exchange issues as the most relevant to the limited implementation in practice, without framing them within a broader perspective on strategic integration. The interdisciplinary integration of experts and tools across different phases of a project is as decisive for this implementation as it is underexplored in the academic debate. The results of the present study validated the need for further coordination, showing that half of the analysed multi-scale indicators required both complementary assessment methods and data acquisition beyond typical BIM-LCA practices. Future research should focus on new approaches to data exchange protocols and tools, such as open-source and vendor-neutral standards like IFC and gbXML, to enable transversal communication of software.

An additional gap identified in the literature review is that sustainability certification or rating systems (e.g., LEED, BREEAM) are usually more focused on post-construction evaluations of project sustainability performance, rather than informing practices in the early phases to reduce environmental impacts when the effects are highest. The novel characterisation proposed within this research aims to overcome the early-phase gap by providing guidance on indicators that can be automated using only the BIM-LCA application, which necessitates its integration and, therefore, multi-tool planning, and, finally, what needs to be assessed and managed in a parallel process. This next step could be addressed by practitioners by automating this integration via end-to-end framework, and describe these integration protocols into BIM technical documentation, such as BIM Execution Plans (BEPs), as a checklist of specific Minimum BIM Information Requirements (MIRs) for multi-scale sustainability assessment of new construction projects.

A final reflection concerns the nature of the indicators category recognised as outside traditional BIM-LCA approaches: the *beyond BIM-LCA* indicators are organisational and financial, confirming that recent technological advancements do not address the institutional, behavioural, and socio-economic barriers that still persist. Future research could further examine how to integrate socio-economic impact assessment, which usually relies on qualitative data and participatory processes, with quantitative data on biophysical impacts resulting from BIM-LCA practices. A decisive advancement could be a broader, more systematic adoption of LCSA practices to expand the scope to social dimensions, yet the operational steps required for this integration remain underexplored. The pivotal role that Common Data Environments (CDEs) or Digital Twins can play in evolving into a mixed-methods approach that spans multiple scales and integrates both qualitative and quantitative indicators can be further developed.

6. Conclusions

The framework proposed in this study aims to bridge the gap among technical BIM-LCA workflows, powerful operational tools for the quantitative assessment of the biophysical impacts of construction projects, and multi-scale sustainability assessment frameworks, such as the NEB self-assessment tool. The goal was to analyse the proposed set of sustainability indicators and to develop a process framework for understanding how BIM-LCA workflows can meet data requirements.

To achieve this objective, a cross-analysis was conducted, leading to the development of a tripartite typology of indicators and associated data requirements, and identifying complementary assessment tools and data extraction methods for indicators outside the traditional BIM-LCA scope. The proposed typological classification provides a clearer understanding of how BIM–LCA workflows can support multi-scale sustainability assessment. By defining the operational requirements for each indicator category, the framework establishes the procedural steps for evaluating indicators that can be directly supported by BIM–LCA data, those that require coordination with additional analytical tools, and those that must be addressed through parallel evaluation processes.

In this sense, the framework functions as a diagnostic taxonomy that can be translated into a project planning tool that practitioners can integrate into BIM technical documentations, such as BIM Execution Plans. In particular, the proposed approach can help define operational checklists specifying: 1) the data that need to be modelled for automating the *BIM-LCA core* indicators; 2) for *BIM-LCA informed* indicators, the integrative analysis to be performed with tools or to be externalised to commission, in case the expertise required fall outside a stakeholders domain; 3) the parallel processes to be established for the *beyond BIM-LCA* indicators.

This study faced some methodological and context-related limitations that frame its research boundaries and must be acknowledged. Firstly, it selected a set of multi-scale sustainability assessments, namely those developed by the NEB, to test how they could be integrated into BIM-LCA workflows. Although the selection of the NEB indicators guaranteed a

system-based framework that stems from their alignment with the European framework Level(s), all the specific instructions arising from the proposed classification are referred to the given set of indicators and cannot be automatically translated into a holistic and comprehensive approach for every sustainability assessment method. The study also proposes a theoretical and documentary framework; therefore, its operational validation will require application in different case studies across project contexts and typologies. The results of this study also open several directions for future research for technical, methodological and regulatory advancement, namely: 1) the development and validation of multi-tool workflows for automation or semi-automation of *BIM-LCA informed* indicators such as the data flow from BIM geometry, to BEM simulations, to LCA calculations for NEB S.3.1 *Operational GHG Emissions*; 2) investigate how the shared information within BIM CDEs can be upscaled to interconnect quantitative data from digital model to soft, often qualitative information from practitioners reports, documentation from construction phase or technical schedules of electrical equipment; 3) further explore the integration of broader assessment methodologies such as A-LCA or LCSA, that reshape the approach toward national and international sustainability goals.

In conclusion, the integration of international standards, such as the New European Bauhaus, has the potential to transform BIM-LCA workflows from standalone solutions into a quantitative environmental engine, and vice versa to respond to the information requirements necessary to align new building projects to such standards. By providing a structured map of the relationships between sustainability indicators and digital construction data, this research helps clarify how digital methodologies can support the transition toward more sustainable construction practices. Concretising this advancement can unlock the potential of digital tools to bridge the gap between current construction practices and the sustainability objectives established by international agreements such as the Paris Agreement, a gap that continues to widen within the Architecture, Engineering, and Construction sector.

Ethics and consent

Ethical approval and consent were not required.

Data availability statement

Zenodo. Underlying data for ORE_Framework review. https://doi.org/10.5281/zenodo.19565541 (Tosi, 2026).

This project contains the following underlying data:

- ORE_Framework_review_Tosi_underlyingdata.xlsx

Data is available under the terms of the license CC-BY 4.0.

Declaration of generative AI and AI-assisted technologies in the writing process.

During the preparation of this work the authors used ScopusAI in order to collect information regarding emerging themes of interest related to BIM-LCA integration, and DeepSeek tool in order to improve the language and readability of the paper. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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Open Peer Review

Current Peer Review Status: ? ✗

Version 1

Reviewer Report 25 September 2026

https://doi.org/10.21956/openreseurope.25416.r79333

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✗

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Summary of article
This article considers how an integrated BIM (Building Information Modelling, a significant process and design tool) and LCA (Life Cycle Assessment, a methodology for assessing environmental impacts) system maps to the definition of sustainability of the New European Bauhaus (NEB), as identified in the NEB self-assessment method and tool (Lourenço et al, 2024). The cross analysis (p6) describes how the correlation between 'each NEB sustainability sub-indicator, the corresponding LCA impact categories, and the relevant BIM data types' was categorised, as direct, partial, or indirect. 'Indirect' really means that there is no correlation. Two tables are presented which offer correlation levels between NEB indicators versus LCA, and NEB versus BIM. A further stage of analysis then brings these two tables together, and defines further 'Core indicators' within the NEB approach, in which at least one of LCA or BIM has a direct correlation and the other is either direct or partial, 'Informed', in which at least one is direct or both are partial, and 'beyond', where both LCA and BIM have no correlation (or 'indirect' as defined by the paper).

Is the work clearly and accurately presented and does it cite the current literature?

It is rather difficult to understand what the article is about, and it needs more careful signposting. For example, the title 'BIM–LCA integration for multi-scale sustainability assessment: Mapping the new European Bauhaus self assessment framework' suggests strongly that the focus is on the integration of LCA and BIM. However the introduction then suggests that the purpose of the paper is to consider how the NEB indicators (which specifically include social and economic as well as environmental indicators) are supported by the LCA method, defined as EN15804 which is the standard for Environmental Product Declarations.
The objective of the research is described (in the introduction) as 'to investigate how sustainability indicators from the NEB self-assessment tool and LCA impact categories, to determine whether integration is needed for LCA indicators at the core of EN 15804:2012, and to address those flaws.' This needs revising therefore as either there are missing words, or additional words. But even so this is rather baffling as an aim when the chosen LCA approach is limited to environmental

indicators, and the equivalent European Norms which do try to add social and economic dimensions (EN 16627 and EN16309) for example are not considered. (Later ISO14040 and EN15978 are used instead – both however are still specifically focused on environmental impacts), However in contrast the literature section starts by presenting the research on 'BIM-LCA integration', as part of a rather brief tour which includes VR and MR, and then adds in the Circular Economy indicators, and then Digital Twins, and Building Energy Modelling. A paragraph then mentions more holistic sustainability rating systems, and links these in part to 'BIM-LCA methodologies' (although the paper cited is a seminal work on BIM from 2011 rather than anything more recent). The following paragraph considers Level(s) and the paper cited (De Wolf et al, 2022) is about how different LCA tools support this environmental assessment.
The paper then explains that the research considers 'how policy-based design frameworks, such as the New European Bauhaus (NEB), can be translated into a technical data workflow that supports BIM-LCA integration and enables the practical implementation of mitigation strategies during the design and development of buildings.'
In the conclusions, this is rephrased again as 'The goal was to analyse the proposed set of sustainability indicators and to develop a process framework for understanding how BIM-LCA workflows can meet data requirements.'
This is really quite unfocused, therefore. The title, the introduction and the literature review imply that the paper is on three different things, and it is hard to then know what to expect of the paper. In addition in various places the sense is missing – this might be an English language issue, but simple editing isn't enough to correct it in some places. I would recommend a careful revision, ensuring that the fundamental purpose of the research is clear and consistent throughout, that all sentences are fully formed and make sense, that terms such as NEB, or NEB methodology, etc are consistent throughout, that if BIM-LCA is used as a term as well as BIM and LCA being used separately, the implications of this is discussed, and that the choice of LCA standard used as an example is consistent.

It would also be useful upfront to discuss the choice of an environmental LCA framework and why this might relate to non-environmental sustainability indicators included in the NEB framework, or rather why this is nevertheless a useful exercise. This is mentioned as a limitation at one point (p6). However the justification seems to be for the choice of the NEB indicators/methodology, rather than for the choice of the LCA approach.

Is the study design appropriate and does the work have academic merit?

The design is a fairly simple comparison, but the academic merit is rather lost at present. I believe it will be revealed is the paper is revised. The study design is defined in Figure 1 which suggests that data will come from ISO14040 and the NEB self assessment tool. For the 'information extraction stage' a third column adds in the rather unspecifically described 'BIM models'. These are then to be cross-analysed (or compared). The role of the Level(s) framework appears again in the description about 'information extraction', although it isn't clear why.
This returns to an earlier question. Either BIM-LCA is taken as one integrated beast, or (as later appears), the inputs to (or structure of) BIM models are a third 'thing' that is being compared.

Are sufficient details of methods and analysis provided to allow replication by others?
Are all the source data underlying the results available to ensure full reproducibility?

In response to both of these: Where does the 'BIM data type' identified in table 2 and compared with the NEB come from? The text merely states 'Additionally, the BIM data types that could potentially support indicator calculation were identified. These data were retrieved from the main BIM model domains...'

Are the conclusions drawn adequately supported by the results?

The discussion section is rather unfocused on the research, but it does include the undoubted conclusion that 'the beyond BIM-LCA indicators are organisational and financial, confirming that recent technological advancements do not address the institutional, behavioural, and socio-economic barriers that still persist.' This should be put into the conclusion, and the discussion section should be more focused (if left in at all). However the 'recent technological advancements' one might be led to think are the VR, etc approaches mentioned in the literature review, which don't then appear to be part of the analysis? If this just means the integration of LCA within BIM, perhaps that needs to be more specifically stated.

It is difficult to explain why the conclusion to this study isn't simply, that the sustainability indicators within the NEB framework that relate to social and economic aspects of sustainability are not supported by the use of BIM (a technical design tool) or by environmental LCA, while those that are measured within LCA (operational and embodied GHG, water, and waste) are supported. However the more interesting level is the partially supported categories, the additional information that is needed for these, and how 'plug-ins' to BIM might be used to fill in (some of) these gaps. This is not considered further, although the conclusions section does focus now (in contrast with the introduction) mainly on BIM, and suggests that, 'the framework functions as a diagnostic taxonomy that can be translated into a project planning tool that practitioners can integrate into BIM technical documentations, such as BIM Execution Plans'. While I would word it more carefully and concentrate on, what has this revealed, and what might be done about it, this middle ground (the partially supported categories) is worth emphasising as a finding of the study. However further muddle is then suggested by the final sentence of the paper which states 'Concretising this advancement can unlock the potential of digital tools to bridge the gap between current construction practices and the sustainability objectives established by international agreements such as the Paris Agreement, a gap that continues to widen within the Architecture, Engineering, and Construction sector.' The Paris agreement's specific focus is on reducing global greenhouse gas emissions, which are entirely measured by the 'BIM-LCA' indicators, rather than the wider sustainability objectives of the NEB framework. So again this needs more careful wording to make the point I think is intended.

In general this is not unnecessary work. However it needs more careful consideration and writing to make its purpose and conclusions clearer and more consistent, before it is indexed.

Is the work clearly and accurately presented and does it cite the current literature?
Partly

Is the study design appropriate and does the work have academic merit?

Partly

Are sufficient details of methods and analysis provided to allow replication by others?
Partly

If applicable, is the statistical analysis and its interpretation appropriate?
Not applicable

Are all the source data underlying the results available to ensure full reproducibility?
Partly

Are the conclusions drawn adequately supported by the results?
Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: I am an expert in LCA of buildings and in sustainable construction in general. I feel qualified to make this judgement.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to state that I do not consider it to be of an acceptable scientific standard, for reasons outlined above.

Reviewer Report 12 September 2026

https://doi.org/10.21956/openreseurope.25416.r80562

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General Evaluation & Title Alignment

Discrepancy between Title and Findings. The findings do not sufficiently reflect the promise implied in the title. While the title suggests the development of an actionable assessment or measurement framework, the manuscript primarily delivers a static taxonomy of indicators. The authors should either revise the title to accurately reflect the actual contribution or substantially expand the framework into an operational scoring or assessment model.Theoretical & Conceptual Framework (NEB Dimensions)

Operationalization of Core Pillars. The three foundational pillars of the New European Bauhaus (NEB)—sustainability, inclusiveness, and aesthetics/quality of experience—should serve as the primary overarching dimensions (latent variables). These core dimensions must be systematically

operationalized and broken down into sub-dimensions and measurable indicators, rather than presented as a loosely connected list.

Literature Currency and NEB Conceptualization. The New European Bauhaus is not adequately introduced or conceptualized in the Introduction section. Furthermore, given that the NEB initiative was officially launched in late 2020, the literature review relies heavily on outdated references (e.g., 1995, 2008, 2011, 2015, and 2017). The authors must update the references with current literature (particularly from the last 3–5 years) directly addressing the NEB, recent LCA standards, and modern openBIM workflows.

Methodology & Integration Process

Integration and Weighting Scheme. The methodological framework lacks a clear, standardized procedure for integrating qualitative NEB criteria with quantitative LCA metrics. The authors need to explicitly define the normalization, conversion, and weighting mechanisms (e.g., via MCDA/AHP or scoring rubrics) utilized to synthesize these disparate data types.

LCA System Boundary. The LCA system boundary (e.g., Cradle-to-Gate [A1–A3], Cradle-to-Grave [A–C], or Cradle-to-Cradle including Module D) is not clearly defined. The selected boundary must align rigorously with the circularity and life cycle claims advocated by the NEB principles.

BIM Modeling Specifications. Crucial BIM specifications are missing. The authors must specify the Level of Development (LOD), the BIM authoring software employed, and the underlying data schema (e.g., IFC property sets, parameters, or classification systems) used to host both environmental and non-geometric NEB data.

Data Interoperability & Workflow Reproducibility. The mechanism of data exchange from the 3D BIM model to the LCA environment is completely unaddressed. The authors should provide a step-by-step workflow diagram and clear descriptions detailing how quantities and parameters are transferred (e.g., via direct API plugins, Dynamo/Grasshopper visual scripting, or manual IFC/tabular exports) to ensure full reproducibility by other researchers.

Statistical Analysis

Statistical Relevance. Formal inferential statistical analyses are not relevant to the scope of this deterministic modeling/simulation study.

Is the work clearly and accurately presented and does it cite the current literature?
Partly

Is the study design appropriate and does the work have academic merit?
No

Are sufficient details of methods and analysis provided to allow replication by others?
No

If applicable, is the statistical analysis and its interpretation appropriate?

Not applicable

Are all the source data underlying the results available to ensure full reproducibility?
Partly

Are the conclusions drawn adequately supported by the results?
Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: My core academic and research expertise encompasses vocational education, TVET (Technical and Vocational Education and Training), building construction, and technology/engineering education.From this standpoint, I am well-qualified to evaluate the pedagogical and applied engineering dimensions of the study—specifically the practical integration of digital construction technologies (such as BIM), construction methodologies, material evaluation, and the operational clarity of assessment frameworks intended for engineering practice and education. However, my assessment focuses primarily on the methodological structure, technical construct validity, and applied construction workflows, rather than proprietary chemical life-cycle impact algorithms or macro-level socio-political European policy analyses

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.