Sustainable Processes Connect
ISSN: 3079-1421
2025, Article ID. 2025.0016, Cite as: https://doi.org/10.69709/SusProc.2025.155435

SCIFINITI PUBLISHING

Research Article

OPEN ACCESS

Data Delivery for Standardizing Sustainable Whole-Building Lifecycle Assessment Using the Proposed OpenBIM Framework

Farzad Jalaei[1,*] **Arash Hosseini Gourabpasi**[1] **Donya Mehran**[2]

[1] National Research Council Canada, Ottawa, ON K1A 0R6, Canada
[2] École de Technologie Supérieure (ÉTS), Montréal, QC H3C 1K3, Canada

Article History
Received: July 03, 2025 Accepted: December 09, 2025 Published: December 18, 2025

Abstract
Whole-Building Lifecycle Assessment (wbLCA) is an essential tool for evaluating the environmental impacts of buildings, including the benefits of material reuse. wbLCA can help the Architecture, Engineering, Construction, and Operation (AECO) industry reduce greenhouse gas (GHG) emissions. However, the effectiveness of wbLCA depends on the availability, quality, and exchange of data, leading to significant inconsistencies in LCA assessments and analyses. To address the issue of data consistency and reliability in wbLCA, this paper proposes a framework that uses the openBIM approach to standardize the required data. By using BIM to procure data for LCA, the framework ensures data accuracy and consistency, facilitates data transfer into wbLCA, and improves assessment reliability by minimizing redundancy and modeling errors. OpenBIM standards and tools are adopted to validate Industry Foundation Classes (IFC) submittals, and the models are checked for both geometric and non-geometric data needed for LCA. This comprehensive approach ensures that the model includes all necessary information for LCA analysis, assessment, comparison, and benchmarking. This openBIM-integrated approach is considered a key contribution to aid standardization of wbLCA practice and to add records to the bill-of-work database, which could host records for hundreds or even thousands of buildings. This sophisticated, flexible, and dynamic approach enables self-updating peer model identification, in contrast to static, generic 'archetype' baseline buildings. As the database grows, regional and building-type specificity will increase. The study provides practical recommendations for industry stakeholders and authorities.

Keywords:
whole-building lifecycle assessment (wbLCA); openBIM; standardization; benchmarking; industry foundation classes (IFC); GHG emission

1. Introduction

The built environment is responsible for more than one-third of global GHG emissions [1] and generates about 40% of the world's total annual CO_2 emissions [2]. Of this, 27% comes from the energy used to operate these buildings, and 13% comes from the materials and construction processes used to build them [2]. Buildings are significant contributors to rising carbon emissions and are responsible for approximately 37% of global energy and process-related GHG emissions [3]. It is estimated that by 2040, two-thirds of the global building stock will consist of existing buildings, which will continue to be substantial contributors to GHG emissions [2]. Also, for new buildings, the global building floor area is expected to double by 2060, to about 2.6 trillion ftt^2 (240 billion m2), equivalent to adding a city as large as New York every month for 40 years [3]. Thus, the built environment significantly contributes to global emissions, necessitating urgent mitigation strategies and sustainable construction practices to address the ongoing and future impact of increasing emissions.

* **Corresponding Author:**
Farzad Jalaei, National Research Council Canada, Ottawa, ON K1A 0R6, Canada,
farzad.jalaei@nrc-cnrc.gc.ca

The wbLCA, also known as Life Cycle Assessment (LCA) for buildings, has emerged as a vital method and is considered the most suitable way to assess the environmental impact of buildings [4]. The wbLCA consists of all building lifecycle stages, from production through construction, operation, and the end-of-life stage. This comprehensive approach enables the assessment of the impact of building-related activities on the environment. However, despite wbLCA being suitable for measuring and evaluating buildings' environmental impacts, in practice, the evaluation of buildings' wbLCA is solely reliant upon the sustainability certifications and green buildings requirements, such as BREEAM, LEED, etc., and is often neglected [5,6]. Additionally, the data needed for LCA are dispersed and often not prepared for direct use, requiring the analyst to assume, reproduce, and manipulate data to use existing information for assessment and analysis. These certifications are based solely on selected criteria with predefined thresholds and reference values and do not reflect the full life cycle of buildings. They evaluate building performance by comparing selected criteria against predefined thresholds or reference values. The main drawback is that these systems are not comparable due to several disparities in system boundaries, indicators, reference values, and calculation methods. Furthermore, these assessments are time-consuming, require extensive documentation for compliance, are costly, and often require experts recognized by the certifying organization to conduct them and achieve certification. Lorch (2017) [7] notes that the use of such systems in buildings has not led to significant reductions in CO_2 emissions. The wbLCA tools in the current market, such as Athena, Tally, one-click, etc., do not precisely use consistent resource and materials databases, resulting in varied results depending on the software platform [8] and typically do not provide harmonized benchmark reference values as they rely on different criteria in their assessment [5].

Over the last few years, significant efforts have been made globally to decarbonize buildings. Policies, regulations, and strategic goals are defined to reduce carbon emissions in the building and construction sector. The Paris Climate Agreement set a strategic goal of achieving zero embodied carbon in the building sector [9]. Architecture 2030's goal is to reduce embodied-carbon emissions from all new buildings, infrastructure, and associated materials up to 65% by 2030, and to zero by 2040. Additionally, various standards have been published to enable reductions in GHG emissions. For instance, EN 15978:2011 Sustainability of construction works-Assessment of environmental performance of buildings, ISO 21930:2017 Sustainability in building and civil engineering works, and ISO 21678:2020 [10]. Sustainability in buildings and civil engineering works. In Canada, recent decarbonization practices in the buildings and construction sector emphasize a comprehensive approach that integrates digitalization, productivity enhancement, and low-carbon solutions. Specifically, the National Research Council's (NRC) platform to decarbonize the construction sector at scale supports Canada's federal initiatives by advancing a low-carbon regulatory framework and reducing carbon impacts across the construction lifecycle. Through the construction sector digitalization and productivity program, the NRC focuses on digitalizing the construction sector, promoting modular low-carbon solutions, and encouraging performance-based codes. These efforts align with Canada's decarbonization goals by fostering innovation, improving construction productivity, and supporting the transition to sustainable building practices, all of which are essential to meeting the country's carbon reduction targets [11].

To achieve a reliable wbLCA, a reproducible, transparent benchmarking method is necessary. To do so, it is essential to establish reference values and benchmarks; having this information enables the evaluation and assessment of the environmental impact derived from wbLCA. [12,13]. Carbon Leadership Forum (2024) [14] defines benchmark as "a reference point against which comparisons can be made". Using this definition in the context of this study, a benchmark value can effectively serve as a reference point or range to enable comparisons among different models. On the other hand, benchmarking refers to the process of assessing and comparing the wbLCA of a building against these benchmark values. The wbLCA benchmarking provides a consistent and transparent framework for evaluating the environmental impacts of buildings and supports the development of effective strategies to reduce resource use and associated environmental impacts in the building sector. Moreover, wbLCA benchmark development enables setting realistic targets towards a more efficient use of resources and the minimization of related ecological impacts.

This paper aims to address the challenges of data quality and requirements in wbLCA by proposing a framework for standardizing data and model submissions in accordance with BIM standards, thereby extending their applicability to wbLCA as the industry increasingly adopts digitalized solutions for permitting and compliance checks. By adopting openBIM standards, the framework facilitates the standardization of input information, thereby enhancing the accuracy and reliability of wbLCA benchmarking. The significance of this study lies in its use of openBIM and in defining the Level of development (LOD), leveraging digital building models to improve data standardization, integration, and interoperability, ultimately boosting the overall efficiency of the wbLCA process.

The focus of this paper is solely on the conceptualization and detailed specification of the utility of openBIM-based data delivery for benchmarking and comparison. However, within the scope of this work, empirical simulation or case study validation is not covered and is expected to be addressed in future work.

2. Literature Review

Diversity of wbLCA benchmarking is known in both academia and industry [15–17]. In some instances, in Canada, the city of Vancouver published an absolute embodied carbon intensity value of 400 $kgCO_2e/m^2$ [18], and the city of Toronto defined an absolute embodied carbon intensity of 275 $kgCO_2e/m^2$ for commercial and residential buildings [19]. However, the defined benchmark values are not comparable, as the information used to identify them and the sample size (buildings studied to determine the benchmark values) are not standardized. A study by the University of British Columbia [20] on multiple buildings confirms this statement. It states that the wbLCA obtained from multiple buildings is generally not comparable, as there are numerous factors such as scope, data source, Bill of Materials (BoM) generation method, and tools. Gervasio et al. [16] and Feng et al. [21] address the complexity of data collection from buildings that limit the scope and accuracy of benchmarking values in terms of accuracy, consistency, measurability and verification as a significant barrier in the development of benchmarks for wbLCA. Additionally, the California Carbon report, which studied 30 buildings over a 60-year period, found a median lifetime total carbon value of 730 kg CO_2e/m^2 and revealed significant correlations between building type or categorization and higher or lower embodied carbon impacts [14]. Without wbLCA standardization, wbLCA results can be inconsistent and non-comparable, hindering efforts to reduce GHG emissions in the building sector. In other words, since the wbLCA benchmarking method heavily relies on standardizing both its methodology and the information used to determine the benchmarking value, a holistic and standardized approach to wbLCA benchmarking is needed.

Current practices in wbLCA involve various methodologies and tools, such as the Athena Impact Estimator for Buildings, One Click LCA, SimaPro, and GaBi. The availability of such tools enables users to perform LCA calculations based on different parameters, such as building shape, size, and types of materials, and to quantify the ecological impacts (EIs) associated with different building materials and methods, using available input information [22,23]. However, the main present challenge is that the input information used by these tools is not consistent, which in turn causes different wbLCA outcomes that are not directly comparable. This inconsistency leads to variations and potential inaccuracies in the reported environmental impacts, thereby undermining the reliability and comparability of wbLCA results. In current practice, benchmark values are defined as the process of collecting, analyzing, and relating performance data from comparable buildings or other types of construction works, typically used to assess and compare performance between or within objects of consideration (ISO21678, 2020). For wbLCA, these values are derived from these tools. However, the benchmarking methods used are also not comparable. On one hand, the input information for each tool is inconsistent; on the other hand, a consistent benchmarking method is not employed to enable comparability of results. Thus, two primary challenges that lead to concerns regarding the comparability and reliability of wbLCA benchmarking are: (1) the lack of information standardization for wbLCA, and (2) inconsistencies in benchmarking methodologies. These challenges are well recognized within both industry and practice. Several resolutions have been proposed to address these issues, which will be discussed in the following sections.

One way to address these challenges is by standardizing information through digital construction processes. With the increasing adoption of Building Information Modeling (BIM) in the built environment, significant opportunities are emerging to use BIM for extended use cases, such as Life Cycle Assessment (LCA), within the construction industry. The BIM Dictionary defines BIM as a set of technologies, processes, and policies that enable multiple stakeholders to collaboratively design, construct, and operate a building or facility in a virtual space. BIM serves as a pivotal tool for standardizing LCA by systematically sourcing the necessary data for assessment and analysis within the BIM environment. It enhances the assessment and management of environmental impacts throughout the lifecycle of buildings. By utilizing open exchange formats and reusing BIM processes across different building phases, users are enabled to perform detailed and advanced modeling. Adopting such an approach can yield significant improvements in LCA, enhancing accuracy, reproducibility, and traceability. Consequently, the utility of BIM for LCA, as it integrates these processes, has the potential to extend to Life Cycle Inventory (LCI) to minimize manual effort and reduce the time required to collect and compile data [24].

BIM standards adoption facilitates and streamlines data exchange among multiple stakeholders by creating a shared language for information exchange. By doing so, it reduces the number of times data needs to be translated [25,26], which often causes data loss. There are multiple tools available for applying BIM, such as Industry Foundation Classes (IFC), Information Delivery Specifications (IDS), the building Smart data dictionary (bsDD), and other relevant best practices, collectively known as openBIM standards [27]. One significant advantage is the elimination of manual LCA data entry, which is very time-consuming [4,28]. While BIM models provide a clear advantage in generating the Bill of Quantities (BoQ), they represent only one of the data inputs required for a wbLCA. According to the terminology and methodology of the European standard EN 15978 [29], additional required data include operational energy and water use, product service lives, transport, as well as maintenance and repair information.

However, it is essential to note that presently most data exchanges between BIM and LCA tools are still done manually [30]. This manual process necessitates further and additional advancements in the integration of these systems to fully realize the potential benefits of openBIM for wbLCA. The current practices mean that building modelers and life-cycle analysis work separately, and the current procedure causes redundancy and loss of information because data is not transferred systematically. While there are numerous methods for BIM-LCA integration, as shown in Figure 1, there is a need for a standardized, systematic approach to utilizing BIM for LCA [31,32]. The literature reviewed suggests that there are inadequate methodological details for implementing BIM for LCA integration; these gaps need to be addressed not only for knowledge organization but also to support decision-making in the construction sector and the built environment, and hence it is considered in its early stages [25–28].

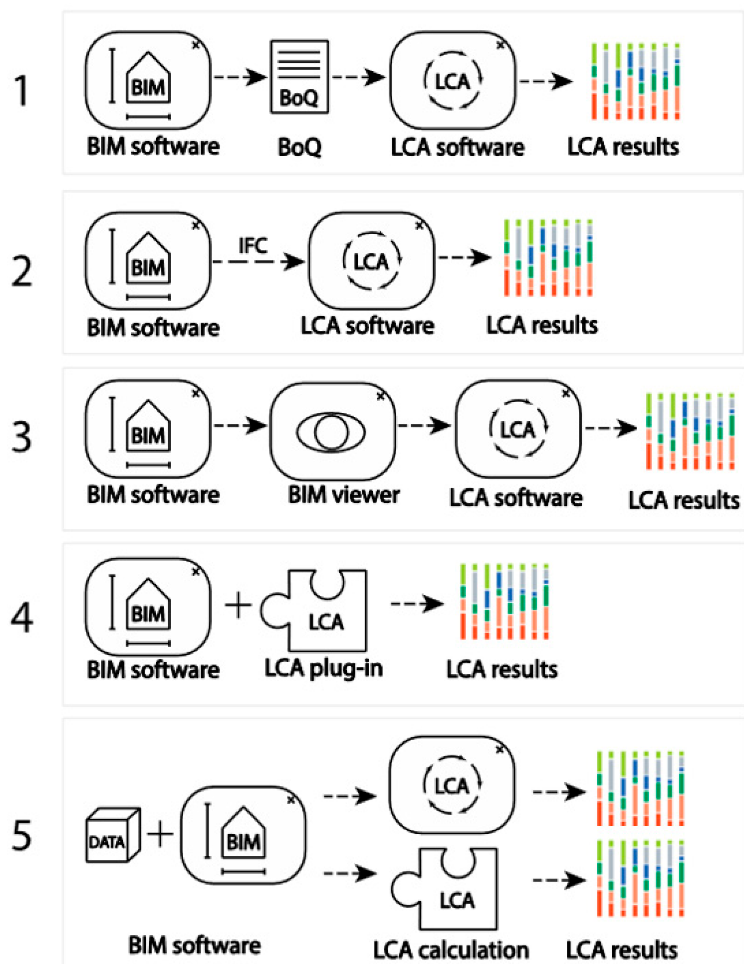

Figure 1: BIM-LCA integration types (adopted from Wastiels and Decuypere, [33]).

Although the integration of BIM and LCA significantly reduces time requirements and enhances the ability to evaluate environmental performance, several challenges persist. These challenges include methodological issues, such as the lack of standardized methods for integrating BIM and LCA, which makes it challenging to ensure consistency and reliability in assessments. Interoperability remains a significant hurdle, as ensuring seamless data exchange between different BIM and LCA tools is complex. Furthermore, the current state of BIM lacks comprehensive case studies and sufficient data to support robust LCA applications. In addition, the lack of a suitable methodology to allow verifying different material scenarios within the BIM-LCA framework remains a challenge. Research indicates that determining the appropriate level of detail and information required in BIM models for accurate LCA remains to be identified [34].

As indicated in the literature [35], LCA and organizational challenges can be broadly categorized as technical, informational, and functional requirements. In terms of technical issues, software compatibility, data exchange formats, and the technical capabilities of BIM and LCA tools are some of the pressing challenges. As for informational problems, the challenges can encompass the availability and quality of data within BIM models for performing LCA analysis. In the last category, organizational issues include the need for collaboration among stakeholders and the alignment of organizational processes to support the integration of BIM for LCA [30]. The challenges mentioned above are the main hurdles to integrating BIM and LCA.

The utility of BIM for LCA can be approached in two main ways. In the first approach, the necessary information needed for LCA is included in the BIM model itself. One issue with this approach is that models can become very large, but the method ensures that data is retained. In the second approach, Information from BIM is exported to other software and applications. In this approach, the risk of data integration loss remains significant.

The IFC format and other openBIM standards and tools can be leveraged to establish a framework for information exchange. While BIM provides information exchange standards and formats needed for transfer to the LCA application, in practice, the accuracy and quality of this information can vary depending on the building phase. For example, in the early design stages, models often have low levels of geometry (LOG). Research work indicates that the common granularity required for BIM elements and LCI data can be specified at the building element level. At this stage, LCA data is aggregated based on predefined material compositions [34,36].

The IFC is an open, vendor-neutral data exchange format, and it is essential to consider its standard structure to understand which information can be extracted from the BIM model [25]. Using a standard data structure will always restrict how data can be described and used in building performance tools [26]. Therefore, using a standard structure such as IFC requires all relevant software to translate their data into this format, creating a common language for data exchange and enabling standardized data structures in BIM models for LCA analysis.

The following resolution standardizing information via openBIM, the next step is to standardize the wbLCA benchmarking method, facilitated by a statistical method. Benchmarking in the context of wbLCA involves collecting, analyzing, and relating performance data from comparable buildings to evaluate and compare their performance (ISO21678, 2020). This is crucial for understanding the linkage between the economic value of an asset and sustainable development issues, thereby promoting sustainable building practices. However, existing wbLCA benchmarks often fall short of providing consistent parameters and factors, as they are usually developed for whole-building certification systems and do not offer design guidance at the material or element level [37,38]. Additionally, there remains a disconnect between the target values required for the whole-building assessment and the benchmarks for building elements. This can lead to inconsistencies when comparisons between different works are required. To address these challenges, benchmarking values such as limit value, reference value, best-practice value, target value, absolute value, and relative value are used, depending on the purpose and requirements of the assessment [39,40]. To accomplish wbLCA benchmarking, it is recommended to have external benchmarks rather than targeting new buildings against a broader range of buildings and updated construction standards. To develop benchmark models, building stock models need to be used, which are commonly categorized into top-down and bottom-up approaches. The bottom-up approach is preferred for wbLCA due to its detailed analysis capabilities [41].

Existing BIM–LCA methods and tools are not comparable due to inconsistent data requirements, manual, error-prone data transfer, insufficient detailed implementation guidance (e.g., LOD, classification, IDS), and non-standardized benchmarking. In addition to these, the scope is often on components rather than whole-building assessments. Hence, due to the reasons mentioned, the result is often non-comparable. The proposed framework attempts to address such issues by standardizing inputs through openBIM concepts and tools. By adopting these technologies and ideas, automation and data validation are enabled by aligning the Level of Detail (LOD) with functional requirements, facilitating a reproducible benchmarking module for the whole-building scope. This approach maintains a consistent, interoperable, and comparable wbLCA outputs, directly overcoming the shortcomings of prior approaches.

3. Methods

3.1. openBIM Framework and Standardized wbLCA Benchmarking Approach

In this section, an openBIM framework is identified and presented further. In addition, reference and best-practice values are considered for benchmarking purposes through a proposed framework comprising two interrelated modules. The first module, Module A, focuses on an openBIM-enabled wbLCA framework that standardizes the wbLCA process and the information used for all resources (materials, energy, and water) in environmental performance indicators. The second module, Module B, is dedicated to wbLCA benchmarking based on GWP. This approach enables standardizing the information required to identify benchmark values (reference and best-practice values) using a comprehensive dataset and an adequate sample size, determined by the desired margin of error. The integrative approach involving both modules in the framework aims to provide a standardized, reproducible framework for conducting wbLCA by enabling access to benchmark information. The framework facilitates sustainable building practices by enabling comparability of wbLCA results across multiple cases. Module A, the wbLCA process, and the information required for all resources, including materials, energy, and water, are considered for the environmental performance indicators. This standardization is crucial for ensuring consistency, reliability, and comparability of wbLCA results across different projects and tools. An overview of the proposed openBIM-enabled wbLCA framework is presented in Figure 2, which illustrates a comprehensive workflow for integrating BIM into LCA, ensuring a seamless, standardized process.

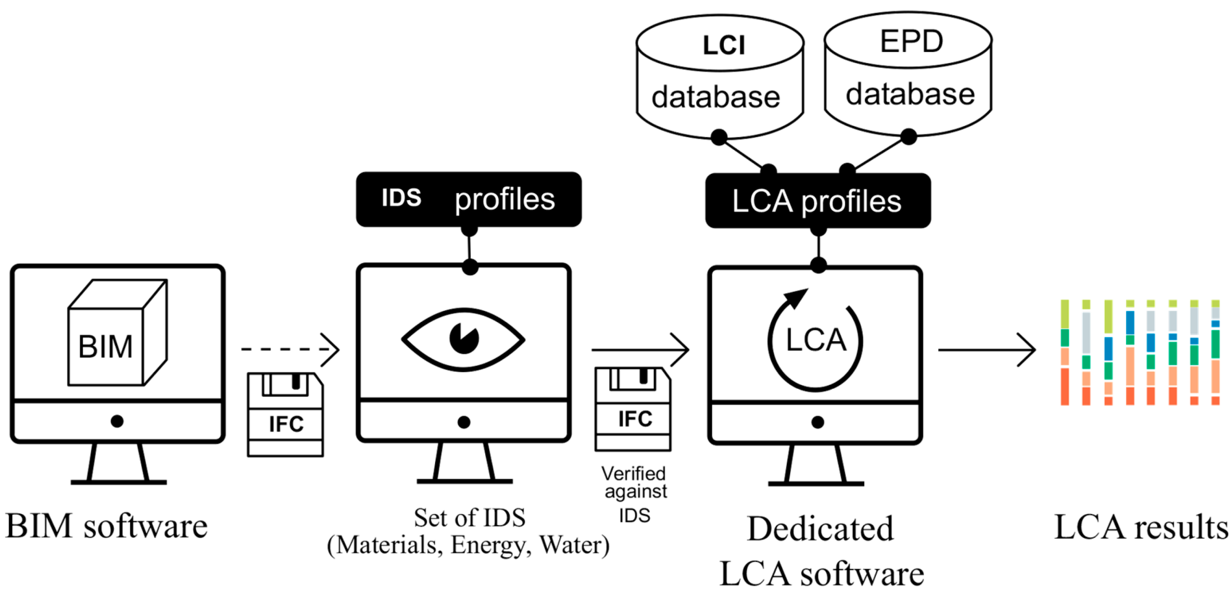

Figure 2: Overview of proposed standardized openBIM-enabled wbLCA.

To streamline the proposed framework, the following considerations are made. This framework treats the production stage of building materials as a single LCA stage rather than dividing it into various phases, i.e., A1-A3. The framework assumes that the Environmental Product Declarations (EPDs) of products at the end of the production stage, as provided by the manufacturer, are unknown and must be calculated.

The proposed procedure requires developing the model using existing tools that support IFC exports. In the second stage, the IFC data must be verified and checked against the data requirements identified for LCA. To achieve this, the framework proposes using Information Delivery Specifications (IDS) for materials, energy, and water. The adoption of IDS enables the identification of requirements that can be utilized across multiple projects and are accessible to both humans and computers due to their readability. The implementation of specifications ensures the availability and quality of data about materials, energy, and water. The availability of such information beforehand reduces time wasted in data gathering. This verification step allows the user to validate the IFC file, which is essential for maintaining data integrity and accuracy in the subsequent steps.

For example, in addressing the requirement for material specification as a standardized process for labeling material quantities in the BIM model, this approach ensures that quantities are accurately labeled and mapped, facilitating consistent data exchange and integration. Further Model checking verifies that the BIM model adheres to the specified standards and requirements.

The third step is the transition of information that can serve LCA from BIM. In this step, the analyst utilizes existing LCA tools to generate LCA profiles using LCI and EPD databases. The databases will enable the LCA analysis to provide and present the most accurate and up-to-date information about the environmental impacts of various building materials and processes. The final step of the proposed framework is used to produce comprehensive LCA results reports. These LCA-generated reports provide detailed insights into the building's environmental performance by ensuring that inputs are verified and results are comparable, covering all relevant indicators such as material use, energy consumption, and water use. The proposed framework achieves accuracy by using a standardized format to make the results interpretable and comparable across different projects.

As a prerequisite for creating BIM models, two categories support information delivery from BIM: the first is the Level of Development (LOD), and the second is the naming convention. This preliminary step is crucial as it must be defined before using BIM for LCA. Regarding the required LOD, literature analysis indicates that an element-based LOD is necessary, as LCA requires detailed information. For example, a door element may require a higher LOD than other elements depending on the use case, and therefore an element-based LOD is necessary. The two primary references for LOD used in this study are ISO 7817-1:2024 [42] and BIM Forum (2023) [43]. Defining such requirements enables data availability for LCA [35,44–47].

The second category is naming conventions and classifications, such as OmniClass in the USA and Uniclass in the UK, which are essential for accurately identifying information within the BIM model. [48]. Functional requirements challenges involve determining the goal and scope of the LCA, which in turn affects the information that must be integrated into the BIM model. The functional unit, often the whole building, varies in literature, and established standards help in identifying necessary inputs [30]. Organizational challenges, as noted by Bowick et al. (2022) [49], pertain to standardizing workflows for integrating BIM and LCA, which remains difficult despite available standards. The separation of BIM and LCA concepts, lack of detailed integration methodologies, and limitations of current studies hinder practical implementation [31,50].

OmniClass (US-based) is commonly used to identify the Bill of Materials (BoM) from the BIM model, where Uniformat Level 3 is mapped to Masterformat Level 4, and then connected to a relevant product from EPD and/or LCI tools, whichever is available. This study adapts and improves the earlier work of Bowick et al. [49] by proposing a new material quantity labeling method, as shown in Figure 3, that enables a direct mapping between the Uniformat table Level 3 and the related Uniclass 15 labeling classification. This method is adapted from the LOD Specification by BIM Forum [43] and establishes a direct relationship with the .IFC file. Additionally, the IFC version to be used should be identified to ensure consistency and compatibility.

By integrating these elements, the framework aims to provide a robust, standardized approach to conducting wbLCA. This approach promotes sustainable building practices and enhances the comparability of wbLCA results across different studies, thereby facilitating informed decision-making and policy development in the construction sector.

The proposed openBIM-enabled wbLCA framework, which standardizes data and information flow, is comprehensively depicted in Figure 4. This figure shows the proposed pipeline for conducting wbLCA in a standardized manner. The first step of the process begins with IFC format generation, which serves as the standard input format. The second step utilizes the BIM data stored in IFC to undergo a quality check using a validation service or tool provided by buildingSMART International, which is currently available in Beta [51]. This step can be considered a prerequisite, as the BIM model's data structure is verified to ensure the necessary data is available for further processing.

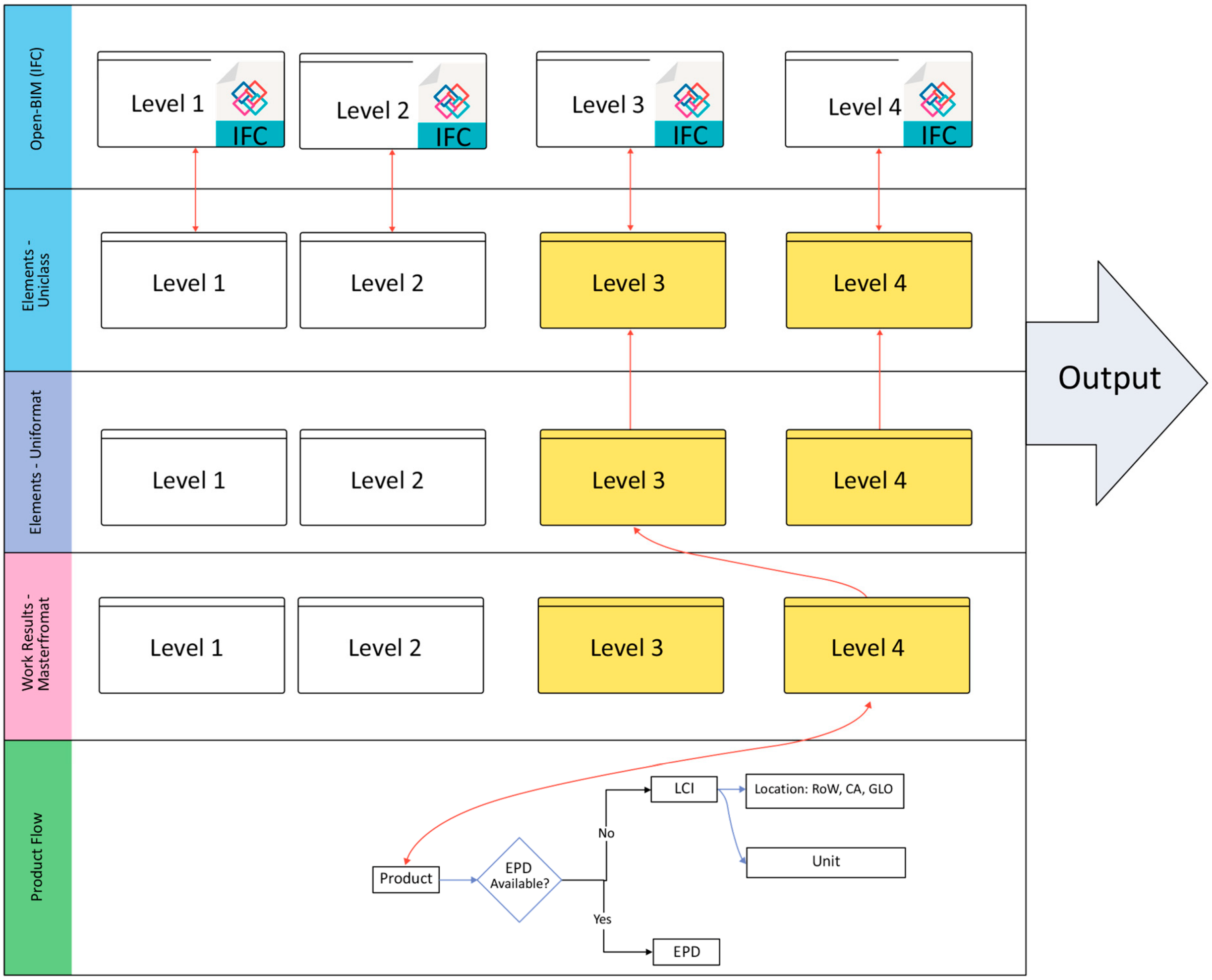

Figure 3: Proposed labelling for material quantities.

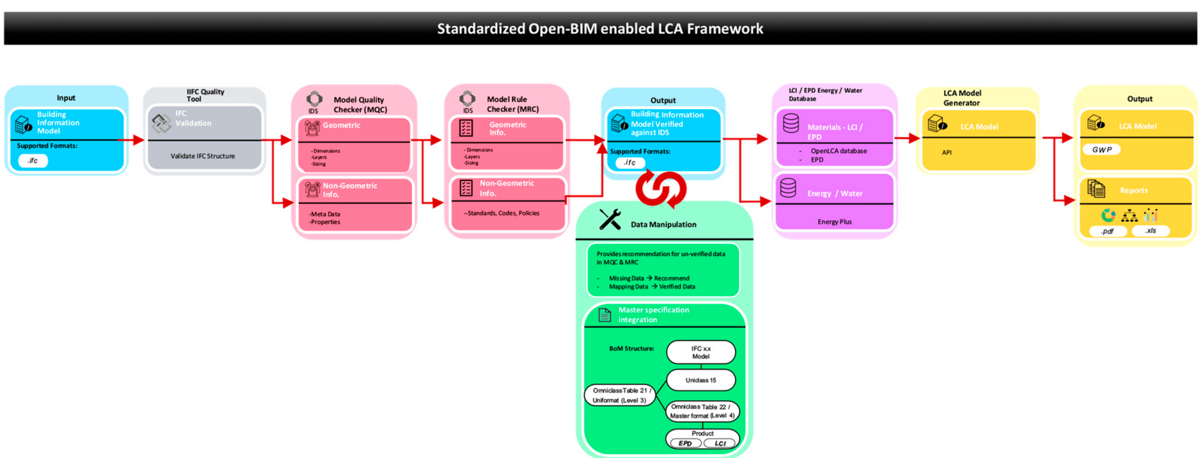

Figure 4: Data delivery for LCA using the openBIM approach.

Next, the framework employs a Model Quality Checker (MQC) to assess the BIM data. The MQC contains two components: one checks geometric information, including spatial and dimensional elements, and the second checks non-geometric information, which examines requirements associated with building elements. After this stage, a Model Rule Checker (MRC) applies the predetermined rules to both types of information to ensure compliance with relevant standards and codes.

In the data manipulation stage, users can address any discrepancies or missing information, as project information is made available during different building phases. This step can be used to provide recommendations for unverified data and suggestions for missing data based on a structured hierarchy and data verification steps. The next step involves using master specifications to map BIM elements to product data, such as Environmental Product Declarations (EPDs) and Life Cycle Inventory (LCI) data, using Uniformat, OmniClass, and Masterformat specifications. This mapping phase enables bidirectional data flow to BIM as LCA is conducted.

The next stage allows the user to check the enhanced, verified BIM model against the requirements using Information Delivery Specifications (IDS), ensuring the data can be used for all phases of LCA. The LCA Model Generator is the step where LCA analysis generally utilizes its respective LCA tools; in this case, the analysts have access to readily available input data to create an LCA model through an API, integrating materials, energy, and water data, as well as databases like ecoinvent [52].

The output is the final step of the process, containing the verified LCA model and relevant LCA reports. The LCA model is based on the BIM-based input data. The reports, available in various formats (e.g., .pdf, .xls), provide detailed results on environmental impacts, including Global Warming Potential (GWP). This framework is designed to standardize the wbLCA process by integrating openBIM data with LCA tools, ensuring data quality and consistency throughout the assessment. This standardized approach facilitates reliable and comparable environmental performance assessments, thereby contributing to more sustainable building practices.

Since the process for deriving the wbLCA outputs is standardized, the next step to derive the benchmark number is to select the appropriate path from the various benchmarking approaches (top-to-bottom, bottom-to-top, gradual). The modified version of the graduated approach to standardize wbLCA benchmarking (Module B) is illustrated in Figure 5. This approach is enabled through the adoption of two key elements: (1) a list of information requirements ensuring similar functional equivalency, and (2) the identification of the desired sample size of buildings, to determine reference values and best practice values. The process begins with the initiation of Module B, which focuses on data collection and benchmark definition. The first step involves collecting data from Module A to provide a set of whole-building Life Cycle Assessments (wbLCA). This dataset includes multiple wbLCA results, denoted as wbLCA1, wbLCA2, wbLCA3, ..., wbLCAn, representing assessments from various buildings or scenarios. The next step is to define benchmarking requirements, including the aim and scope of the benchmarking exercise, setting objectives, and identifying the specific life cycle phases, building types, or geographic regions to be considered. Additionally, it involves determining the optimal sample size needed to create statistically valid and meaningful benchmarks, ensuring the robustness and reliability of the benchmarking process. Based on Sauro [53], this method is proposed for this purpose, with a 95% confidence level suitable for publication.

The subsequent step involves quantifying benchmarks based on key environmental indicators (e.g., GWP, which measures the building's impact on climate change over its life cycle), with consideration of whether to include or exclude biogenic carbon in line with guidelines from the JRC [5] and NRC [49] reports. The final step is to establish initial benchmarks and targets based on statistical analysis. This includes setting reference values, represented by the median of the sample set, and best-practice values, identified as the top 25% of the sample set, indicating superior performance in terms of GWP. Statistical analysis of GWP, expressed in kg CO_2 eq./m^2.yr, is undertaken using probabilistic methods, including uniform and Gaussian distributions, with Monte Carlo simulation over 1000 iterations.

The information for the definition of benchmarking requirements shall be adopted based on the following Table 1.

4. Results and Discussion

The outcome of this research is the identification and proposal of a framework that standardizes the data required for wbLCA, ultimately enabling the benchmarking of the Canadian building stock. The proposed framework leverages existing best practices and standards collectively known as openBIM standards, which enable data exchange through IFC. It ensures the completeness of data present in the BIM model through IDS authored for LCA assessment and satisfies local requirements, such as those specific to Canada. Additionally, both geometrical and non-geometrical data are validated to meet Canadian regulatory requirements for building construction throughout the entire lifecycle. The advantages of adopting the proposed framework include the use of BIM extended to LCA use cases and, potentially, to other applications. This approach avoids redundancy, increases productivity, maintains the quality and accuracy of submittals, and reduces the time and effort required by authorities for model checking, thereby enhancing collaboration and data exchange.

Table 1: Definition of benchmarking information requirements.

	Process Flow	Input Data
1.	Defining building by type for Function	OmniClass (Level 3)
2.	Defining building by type for Form	OmniClass (Level 3)
3.	Categorizing each type of building function	For residential buildings, there are 3 categories: ■ Single family (SI) ■ Multi-family apartment (MF) less than or equal to 5 stories ■ High-rise building (HR) more than 5 stories For office buildings, consider one type of category
4.	Location	City, Province, Country
5.	Total gross area (According to NRC Guideline)	■ Gross External area ■ Gross internal area ■ Net floor area
6.	Building Structure	■ Wood ■ Concrete ■ Steel
7.	Number of floors	N/A
8.	Pattern of use / No. of occupants / working places	■ Residential—number of permanent living people ■ Office—number of people with respective working hours
9.	Estimated design working life	■ Number of years
10.	Date of construction / reference year	■ Number of years
11.	required service life	■ declared by the owner ■ ISO 15686
12.	Seismic area	
13.	Climate area	■ Based on geographical zone
14.	Technical requirements	■ Relevant codes ■ Standards ■ Policies
15.	Functional requirements	■ description of building functions
16.	Reference unit	■ User Input
17.	Building model scope	■ User Input
18.	State of the project and available information	■ User Input

2025, Vol. 1, Article ID. 2025.0016
https://doi.org/10.69709/SusProc.2025.155435

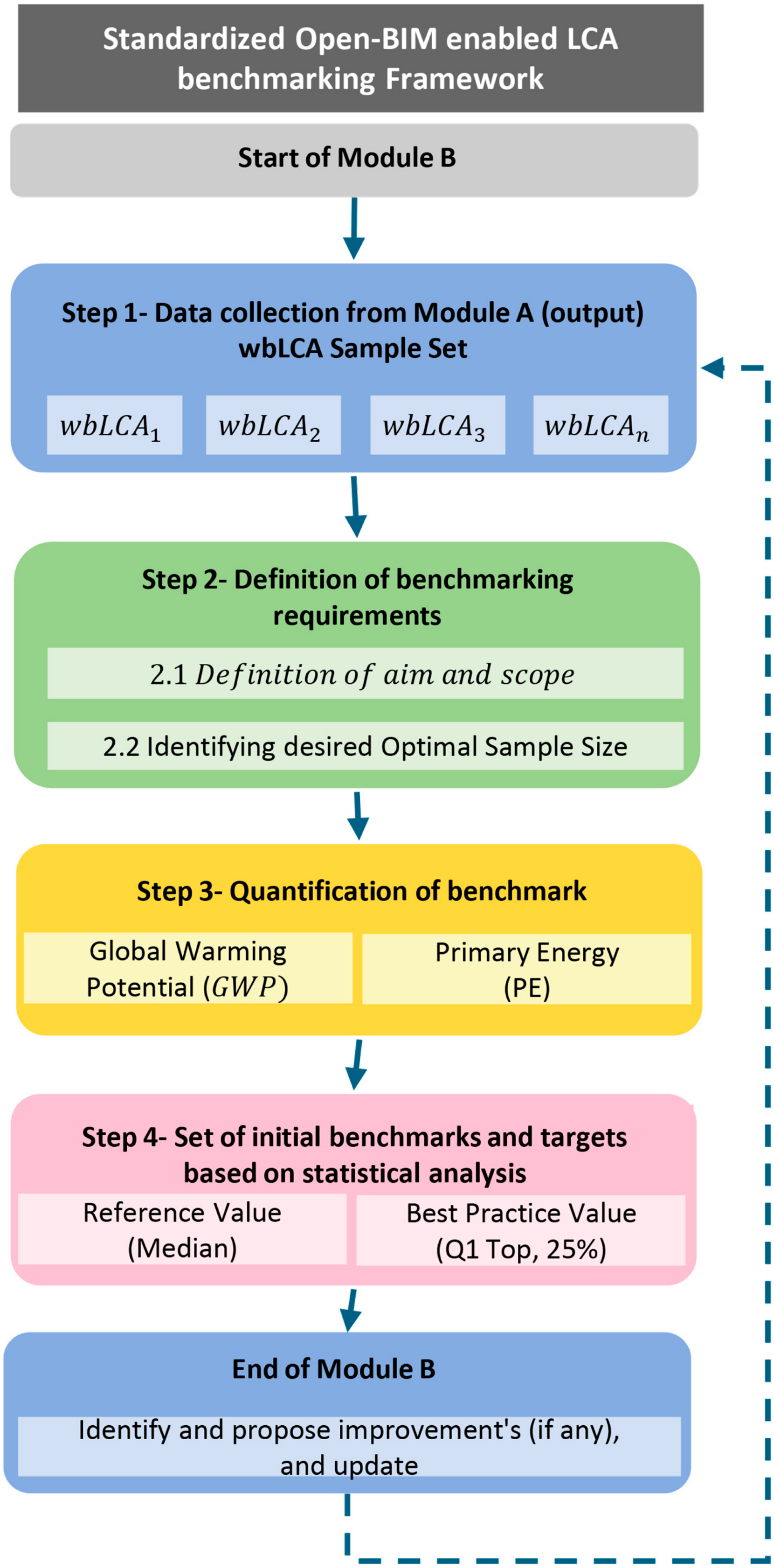

Figure 5: Standardized openBIM wbLCA benchmarking framework.

The literature review highlights several challenges that need to be addressed to achieve effective integration. One of the primary challenges is the varying LODs within the BIM model and across LCA stages. The LOD Specification, based on the BIM Forum 2023 Parts I and II, provides a structured approach to BIM modeling, ensuring that the necessary data is accurately captured and exchanged. By predefining and aligning the functional requirements of LCA analysis with the BIM model LOD at each stage, adopting appropriate BIM model classifications, and using IFC to translate BIM model information to meet wbLCA requirements, information standardization for wbLCA can be achieved. This approach facilitates a more efficient and reliable integration of BIM and LCA, enabling comprehensive environmental impact assessments.

Current procedures are found to have following shortcomings: (a) they often focus on specific building components rather than the whole structure, (b) they rely on annual electricity and water consumption data from similar buildings, which can vary widely, (c) they oversimplify or omit complex construction and renovation processes, and (d) they offer limited automation and interoperability with formats like IFC and gbXML, which do not significantly reduce manual effort. Tools and plug-ins for exporting material quantities from BIM models to LCA are available but limited in their ability to analyze the environmental effects and integrate with BIM tools, reducing their effectiveness in the early design stages [46,54]. The study suggests that building modelers use IDS requirements to identify LOD requirements before and during model development. Compliance with the LOD requirements minimizes rework and the time required to find relevant information during LCA analysis stages. Hence, the framework facilitates the transfer of available information to LCA by connecting it with BIM. This integration builds upon the best practices for enhancing the wbLCA for benchmarking and comparative analysis.

In addition to the issue of data transfer to further implement a standardized benchmark method, there is a need to implement statistical approaches. A dual approach is suggested, with external benchmarks for broader industry comparisons and internal benchmarks for building assessments. This dual approach provides a complete view by integrating top-down and bottom-up models. By doing so, it ensures that benchmarks are relevant to the project and maintain a way for broader comparison, addressing the specific needs of different building components while aligning with broader sustainability goals.

To do so, an adequate sample size must be defined based on the desired precision and confidence level for benchmarking. As suggested by the literature, to harmonize the wbLCA practices, the use of specifications is recommended. For example, OmniClass tables can be used for consistent data inputs. Having uniform inputs allows for broader comparisons and moves toward more reliable wbLCA results and reporting. Ensuring an adequate sample size that meets the desired precision and confidence levels is crucial for reliable benchmarking. The literature underscores the importance of harmonizing wbLCA practices through standardized specifications and, as such, the use of OmniClass tables for consistent data input. This harmonization facilitates the comparability and reliability of wbLCA results. By adopting the standard LOD definitions found in documents such as the BIM Forum 2023 and a dual-approach to benchmarking. This resultant method and framework can provide a robust, standardized approach for conducting wbLCA and establishing reliable benchmarks.

5. Conclusions and Future Research Direction

The proposed framework for OpenBIM-enabled wbLCA can provide its users, such as LCA analysts, with a robust, standardized approach for conducting analyses and generating comparable results. This is achieved by ensuring consistency, accuracy, and interoperability through standardized data inputs from BIM. This approach facilitates more reliable environmental performance assessments, ultimately contributing to more sustainable building practices and enabling more effective comparisons. The inclusion of standardized processes for model checking ensures that all relevant data is accurately captured and utilized in the LCA process, with the added ability of reproducibility. The use of IFC files and IDS profiles ensures that data can be easily exchanged and understood across different software tools and platforms for specific use cases, such as wbLCA. The verification of IFC files against IDS profiles, along with the use of LCI and EPD databases, ensures that the LCA analysis is based on accurate and reliable data. This approach leads to more precise results. In addition to what is stated, the framework covers all relevant environmental performance indicators, providing a holistic view of the building's ecological impact.

The built environment generally contributes significantly to GHG emissions. It can be beneficial for both existing and new buildings that require implementing mitigation strategies and sustainable construction practices into the workflows. The proposed framework aims to address the pressing issue of data quality by defining LOD requirements in advance. Further, using openBIM tools such as IFC for data translation and adopting a dual-approach to benchmarking further eases interoperability

2025, Vol. 1, Article ID. 2025.0016
https://doi.org/10.69709/SusProc.2025.155435

and reproducibility. The proposed approach implements an accurate data capture and reliable integration of BIM and LCA. Doing so facilitates sustainable building practices. Furthermore, by integrating global sustainability targets with detailed component-specific benchmarks, as achieved through the dual approach of combining top-down and bottom-up models, it is possible to move towards holistic benchmarking while simultaneously recording building performance. The developed framework provides recommendations to users by illustrating the importance of an adequate sample size based on desired precision and confidence levels, as well as the use of standardized specifications to enable benchmarking. This comprehensive approach facilitates the identification of reference and best-practice values and provides support for informed decision-making by stakeholders such as policymakers and industry practitioners.

This study highlights the importance of identifying reference and best-practice values for residential and office buildings in the Canadian building domain. By adopting statistical approaches in combination with the proposed framework, this framework enables users to produce reliable comparisons and support informed decision-making. By attempting to address the present challenges of wbLCA benchmark and adopting the proposed framework, it facilitates the move towards achieving sustainable standardized practices. This research provides the foundation for reducing the environmental impact of the built environment by laying the framework for a more sustainable, environmentally conscious construction industry. Future research is intended to focus on developing flexible LCA methodologies and building lifecycle assessments that encompass all stages, including planning, design, construction, and operation. Additionally, implementing the proposed framework through case studies will be essential to illustrate and validate the solution's effectiveness, especially for defining a benchmark. This approach will enable the researchers to further refine it for real-world scenarios, ultimately promoting more sustainable building practices.

List of Abbreviations

AECO	Architecture, Engineering, Construction, and Operation
API	Application Programming Interface
BoM	Bill of Materials
BoQ	Bill of Quantities
bsDD	buildingSMART Data Dictionary
CSDP	Construction Sector Digitalization and Productivity
EN 15978	European Standard 15978
EPD	Environmental Product Declaration
GHG	Greenhouse Gas
GWP	Global Warming Potential
IDS	Information Delivery Specifications
IFC	Industry Foundation Classes
ISO 21678	International Standard 21678
ISO 21930	International Standard 21930
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LOD	Level of Development
LOG	Level of Geometry
Masterformat	Masterformat Specification System
MQC	Model Quality Checker
MRC	Model Rule Checker
NRC	National Research Council Canada
OmniClass	Construction Classification System
UNEP	United Nations Environment Programme
Uniclass	Unified Classification System
wbLCA	Whole-Building Life Cycle Assessment

Author Contributions

Conceptualization, methodology: F.J., A.H.G.; Software: A.H.G., D.M.; Validation: F.J., A.H.G., D.M.; Formal analysis: F.J., D.M.; Funding Acquisition: F.J.; Investigation: D.M.; Resources: F.J., A.H.G., D.M.; Data curation: D.M.; Visualization: D.M. All authors have read and agreed to the published version of the manuscript.

Availability of Data and Materials

Data supporting the results of this study are available upon request from the corresponding author.

Consent for Publication

No consent for publication is required, as the manuscript does not involve any individual personal data, images, videos, or other materials that would necessitate consent.

Conflicts of Interest

The authors declare no conflicts of interest.

Funding

This study has been supported by the Construction Sector Digitalization and Productivity (CSDP) program under the project “A1-025516- BIM-based integrated framework to standardize how a whole-building life cycle assessment (LCA) benchmark serves as a reference for comparing the performance of a building under the study”.

Acknowledgments

This study has been supported by the National Research Council Canada Platform to Decarbonize the Construction

Sector at Scale- Construction Sector Digitalization and Productivity (CSDP) program. The authors would like to extend their sincere gratitude to all the stakeholders who participated in this research and contributed to the findings presented in this paper.

AI Declaration

The authors confirm that no AI tools were used to generate any content of this manuscript.

References

[1] Alwan, Z.; Ilhan, B. IFC-Based Embodied Carbon Benchmarking for Early Design Analysis. *Autom. Constr.* **2022**, *142*, 104505. [CrossRef]

[2] Architecture, "Embodied Carbon Actions—Architecture 2030". Available online: https://www.architecture2030.org/embodied-carbon-actions/ (accessed on 22 July 2024).

[3] U. N. United Nations. 2022 Global Status Report for Buildings and Construction | UNEP—UN Environment Programme. 2022. Available online: https://www.architecture2030.org/embodied-carbon-actions/ (accessed on 23 July 2024).

[4] Nizam, R.S.; Zhang, C.; Tian, L. A BIM Based Tool for Assessing Embodied Energy for Buildings. *Energy Build.* **2018**, *170*, 1–14. [CrossRef]

[5] Dos Santos Gervasio, H.; Dimova, S. Model for Life Cycle Assessment (LCA) of buildings; EUR 29123 EN. Publications Office of the European Union: Luxembourg, 2018. JRC110082. Available online: https://publications.jrc.ec.europa.eu/repository/handle/JRC110082 (accessed on 5 March 2025).

[6] Wu, W.; Issa, R.R.A. BIM Execution Planning in Green Building Projects: LEED as a Use Case. *J. Manag. Eng.* **2014**, *31*, A4014007. [CrossRef]

[7] Lorch, R. Climate Policies for Buildings. *Build. Res. Inf.* **2017**, *45*, 475–477. [CrossRef]

[8] Goodland, H.; Walsh, K. *The Circular Built Environment in Canada: A Review of the Current State, Gaps and Opportunities*; CSA Group: Toronto, ON, Canada, 2024. Available online: https://www.csagroup.org/article/research/the-circular-built-environment-in-canada-a-review-of-the-current-state-gaps-and-opportunities/ (accessed on 23 July 2024).

[9] Architecture. On Track to Meet the Paris Agreement–Architecture 2030. 2025. Available online: https://www.architecture2030.org/on-track-to-meet-the-paris-agreement/ (accessed on 9 December 2025).

[10] *ISO 21678:2020*; Sustainability in Buildings and Civil Engineering Works—Indicators and Benchmarks—Principles, Requirements and Guidelines. International Organization for Standardization: Geneva, Switzerland, 2020. Available online: https://www.iso.org/standard/71344.html (accessed on 23 July 2025).

[11] Jalaei, F.; Masoudi, R.; Guest, G. A Framework for Specifying Low-Carbon Construction Materials in Government Procurement: A Case Study for Concrete in a New Building Investment. *J. Clean. Prod.* **2022**, *345*, 131056. [CrossRef]

[12] Jalaei, F.; Sultan, Y.; Poirier, E.; Staub-French, S.; Bhonde, D.; Davari, S. *Digitalization and Productivity Research and Development Roadmap*; National Research Council Canada: Ottawa, ON, Canada, 2024. Available online: https://nrc-publications.canada.ca/eng/view/ft/?id=fe42611a-8cc7-4721-8282-02460ad01245 (accessed on 21 October 2024).

[13] Joint Research Centre (European Commission); Dimova, S.; Gervasio, H. *Environmental Benchmarks for Buildings: EFIResources—Resource Efficient Construction Towards Sustainable Design*; Publications Office of the European Union: Luxembourg, 2018. [CrossRef]

[14] Benke, B.; Roberts, M.; Shen, Y.; Carlisle, S.; Chafart, M.; Simonen, K. *The California Carbon Report*. Available online: https://carbonleadershipforum.org/california-carbon/ (accessed on 23 May 2024).

[15] Simonen, K.; Rodriguez, B.X.; De Wolf, C. Benchmarking the Embodied Carbon of Buildings. *Technol. Archit. Des.* **2017**, *1*, 208–218. [CrossRef]

[16] Gervasio, H.; Dimova, S.; Pinto, A. Benchmarking the Life-Cycle Environmental Performance of Buildings. *Sustainability* **2018**, *10*, 1454. [CrossRef]

[17] Trigaux, D.; Allacker, K.; Debacker, W. Environmental Benchmarks for Buildings: A Critical Literature Review. *Int. J. Life Cycle Assess.* **2021**, *26*, 1–21. [CrossRef]

[18] City of Vancouver. *Embodied Carbon Guidelines v1*; City of Vancouver: Vancouver, BC, Canada, 2023. Available online: https://vancouver.ca/files/cov/embodied-carbon-guidelines.pdf (accessed on 20 October 2023).

[19] City of Toronto. *Buildings Energy, Emissions & Resilience (Toronto, Ontario, Canada)*; City of Toronto: Toronto, ON, Canada, 2022. Available online: https://www.toronto.ca/city-government/planning-development/official-plan-guidelines/toronto-green-standard/toronto-green-standard-version-4/mid-to-high-rise-residential-non-residential-version-4/buildings-energy-emissions-resilience/ (accessed on 23 July 2024).

[20] UBC. Embodied Carbon Pilot | Campus as a Living Lab. The University of British Columbia (UBC). 2022. Available online: https://livinglabs.ubc.ca/projects/embodied-carbon-pilot (accessed on 22 July 2024).

[21] Feng, H.; Zhao, J.; Zhang, H.; Zhu, S.; Li, D.; Thurairajah, N. Uncertainties in Whole-Building Life Cycle Assessment: A Systematic Review. *J. Build. Eng.* **2022**, *50*, 104191. [CrossRef]

[22] Li, J.; Lützkendorf, T.; Balouktsi, M.; Bi, X.; Alaux, N.; Obrecht, T.P.; Passer, A.; Han, C.; Yang, W. Identifying Uncertainties in the Whole Life Carbon As-

sessment of Buildings: Sources, Types, and Potential Actions. *Build. Environ.* **2023**, *244*, 110779. [CrossRef]

[23] Li, Q.; Yang, W.; Kohler, N.; Yang, L.; Li, J.; Sun, Z.; Yu, H.; Liu, L.; Ren, J. A BIM–LCA Approach for the Whole Design Process of Green Buildings in the Chinese Context. *Sustainability* **2023**, *15*, 3629. [CrossRef]

[24] Ajayi, S.O.; Oyedele, L.O.; Ceranic, B.; Gallanagh, M.; Kadiri, K.O. Life Cycle Environmental Performance of Material Specification: A BIM-Enhanced Comparative Assessment. *Int. J. Sustain. Build. Technol. Urban Dev.* **2015**, *6*, 14–24. [CrossRef]

[25] Zimmermann, R.K.; Bruhn, S.; Birgisdóttir, H. BIM-Based Life Cycle Assessment of Buildings—An Investigation of Industry Practice and Needs. *Sustainability* **2021**, *13*, 5455. [CrossRef]

[26] Toth, B.; Janssen, P.; Stouffs, R.; Chaszar, A.; Boeykens, S. Custom Digital Workflows: A New Framework for Design Analysis Integration. *Int. J. Archit. Comput.* **2012**, *10*, 481–499. [CrossRef]

[27] Cozzitorto, C.; Jalaei, F.; Sultan, Y.; Davari, S.; Bhonde, D. *openBIM Implementations for a Canadian Roadmap*; National Research Council Canada: Ottawa, ON, Canada, 2024. Available online: https://nrc-publications.canada.ca/eng/view/ft/?id=04722ff6-3ebd-42dc-9458-b4bcb873c946 (accessed on 1 October 2024).

[28] Soust-Verdaguer, B.; Llatas, C.; García-Martínez, A. Critical Review of BIM-Based LCA Method to Buildings. *Energy Build.* **2017**, *136*, 110–120. [CrossRef]

[29] *BS EN 15978:2011*; Sustainability of Construction Works. Assessment of Environmental Performance of Buildings. Calculation Method. British Standards Institution (BSI): London, UK, 2011. Available online: https://www.en-standard.eu/bs-en-159782011-sustainability-of-construction-works-assessment-of-environmental-performance-of-buildings-calculation-method/ (accessed on 12 January 2024).

[30] Potrč Obrecht, T.; Röck, M.; Hoxha, E.; Passer, A. BIM and LCA Integration: A Systematic Literature Review. *Sustainability* **2020**, *12*, 5534. [CrossRef]

[31] Najjar, M.; Figueiredo, K.; Palumbo, M.; Haddad, A. Integration of BIM and LCA: Evaluating the Environmental Impacts of Building Materials at an Early Stage of Designing a Typical Office Building. *J. Build. Eng.* **2017**, *14*, 115–126. [CrossRef]

[32] Xu, J. *Block Trace Analysis and Storage System Optimization: A Practical Approach with MATLAB/Python Tools*; Apress: Berkeley, CA, USA, 2018. Available online: https://link.springer.com/book/10.1007/978-1-4842-3928-5 (accessed on 12 December 2024).

[33] Wastiels, L.; Decuypere, R. Identification and Comparison of LCA-BIM Integration Strategies. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *323*, 012101. [CrossRef]

[34] Röck, M.; Hollberg, A.; Habert, G.; Passer, A. LCA and BIM: Integrated Assessment and Visualization of Building Elements' Embodied Impacts for Design Guidance in Early Stages. *Procedia CIRP* **2018**, *69*, 218–223. [CrossRef]

[35] Volk, R.; Stengel, J.; Schultmann, F. Building Information Modeling (BIM) for Existing Buildings—Literature Review and Future Needs. *Autom. Constr.* **2014**, *38*, 109–127. [CrossRef]

[36] Cabeza, L.F.; Barreneche, C.; Miró, L.; Morera, J.M.; Bartolí, E.; Fernández, A.I. Low Carbon and Low Embodied Energy Materials in Buildings: A Review. *Renew. Sustain. Energy Rev.* **2013**, *23*, 536–542. [CrossRef]

[37] Hollberg, A.; Lützkendorf, T.; Habert, G. Using a budget approach for decision-support in the design process. In *IOP Conference Series: Earth and Environmental Science*; Passer, A., Lutzkendorf, T., Habert, G., Kromp-Kolb, H., Monsberger, M., Eds.; Institute of Physics Publishing: Bristol, UK, 2019; Volume 323. [CrossRef]

[38] Hollberg, A.; Lützkendorf, T.; Habert, G. Top-Down or Bottom-Up? – How Environmental Benchmarks Can Support the Design Process. *Build. Environ.* **2019**, *153*, 148–157. [CrossRef]

[39] Ganassali, S.; Lavagna, M.; Campioli, A. LCA Benchmarks in Building's Environmental Certification Systems. In Proceedings of the 41st IAHS World Congress, Albufeira, Portugal, 13–16 September 2016. Available online: https://www.researchgate.net/publication/308606167_LCA_BENCHMARKS_IN_BUILDING%27S_ENVIRONMENTAL_CERTIFICATION_SYSTEMS (accessed on 21 October 2024).

[40] Stephan, A.; Crawford, R.H. The Relationship between House Size and Life Cycle Energy Demand: Implications for Energy Efficiency Regulations for Buildings. *Energy* **2016**, *116*, 1158–1171. [CrossRef]

[41] Shinde, R.; Kim, A.; Hellweg, S. Bottom-Up LCA Building Stock Model: Tool for Future Building-Management Scenarios. *J. Clean. Prod.* **2024**, *434*, 140272. [CrossRef]

[42] *ISO 7817-1:2024*; Building Information Modelling—Level of Information Need—Part 1: Concepts and Principles. ISO: Geneva, Switzerland, 2024. Available online: https://www.iso.org/standard/82914.html (accessed on 9 April 2025).

[43] Level of Development Specification—BIM Forum. Available online: https://bimforum.org/resource/lod-level-of-development-lod-specification/ (accessed on 2 July 2025).

[44] Schneider-Marin, P.; Harter, H.; Tkachuk, K.; Lang, W. Uncertainty Analysis of Embedded Energy and Greenhouse Gas Emissions Using BIM in Early Design Stages. *Sustainability* **2020**, *12*, 2633. [CrossRef]

[45] Theißen, S.; Höper, J.; Drzymalla, J.; Wimmer, R.; Markova, S.; Meins-Becker, A.; Lambertz, M. Us-

ing Open BIM and IFC to Enable a Comprehensive Consideration of Building Services within a Whole-Building LCA. *Sustainability* **2020**, *12*, 5644. [CrossRef]

[46] Yang, X.; Hu, M.; Wu, J.; Zhao, B. Building-Information-Modeling Enabled Life Cycle Assessment, a Case Study on Carbon Footprint Accounting for a Residential Building in China. *J. Clean. Prod.* **2018**, *183*, 729–743. [CrossRef]

[47] Ramaji, I.; Gultekin, P.; Crowley, R.; Lambert, J. Investigation of Leveraging BIM Standards to Facilitate Sustainability Evaluations from Early Stages of Design. In Proceedings of the ASCE International Workshop on Computing in Civil Engineering, Seattle, WA, USA, 25–27 June 2017; pp. 175–183. [CrossRef]

[48] Athena Sustainable Materials Institute. A Proposed Construction Product Nomenclature for Use in LCA for Buildings. 2023. Available online: https://www.athenasmi.org/wp-content/uploads/2023/11/Construction_Product_Nomenclature_for_Use_in_LCA_for_Buildings_202311.pdf (accessed on 2 July 2025).

[49] Bowick, M.; O'Connor, J.; Salazar, J.; Meil, J.; Cooney, R. *National Guidelines for Whole-Building Life Cycle Assessment*. National Research Council of Canada: Ottawa, ON, Canada, 2022. [CrossRef]

[50] Peng, C. Calculation of a Building's Life Cycle Carbon Emissions Based on Ecotect and Building Information Modeling. *J. Clean. Prod.* **2016**, *112*, 453–465. [CrossRef]

[51] BuildingSMART International. IFC Validation Service. Available online: https://www.buildingsmart.org/users/services/ifc-validation-service/ (accessed on 28 June 2024).

[52] *Life Cycle Assessment (LCA)*. Available online: https://support.ecoinvent.org/ecoinvent-use-cases (accessed on 2 July 2025).

[53] Sauro, J. *Benchmarking the User Experience: A Practical Guide to Benchmarking Websites, Software, and Product Experiences*; MeasuringU Press: Denver, CO, USA, 2018. Available online: https://www.booksamillion.com/p/Benchmarking-User-Experience/Jeff-Sauro/9780692149096.

[54] Xue, K.; Hossain, M.U.; Liu, M.; Ma, M.; Zhang, Y.; Hu, M.; Chen, X.; Cao, G. BIM Integrated LCA for Promoting Circular Economy towards Sustainable Construction: An Analytical Review. *Sustainability* **2021**, *13*, 1310. [CrossRef]