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Research Article

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

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Highlights:

- Developed a standardized OpenBIM-enabled framework to improve data quality and reproducibility in whole-building life cycle assessment (wbLCA).
- Integrated Information Delivery Specifications (IDS) and Industry Foundation Classes (IFC) to ensure verified, consistent inputs for LCA modeling.
- Proposed a dual benchmarking approach (top-down and bottom-up) to establish reliable reference and best practice values for Canadian building stock.
- Enhanced interoperability between BIM and LCA tools, minimizing manual data transfer and reducing modeling errors.
- Facilitated sustainability-oriented decision-making through comparable and transparent wbLCA results across projects.

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 is contingent upon the availability, the quality, and the exchange of data, leading to significant inconsistencies in LCA assessments and analyses.

To address the issue of consistency and reliability of data in wbLCA, this paper proposes a framework that utilizes the openBIM approach to standardize the necessary data. By using BIM to procure data for LCA, the framework ensures data accuracy and consistency, facilitating data transfer into wbLCA and improving 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 required for LCA analysis, assessment, comparison, and benchmarking purposes.

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, contrasting with 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 total world's yearly CO2 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 the rising levels of 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 buildings that already exist today, which will continue to be substantial contributors to GHG emissions [2]. Also, in the case of new buildings, the global building floor area is expected to double by 2060, that is, about 2.6 trillion ft^2 (240 billion m^2), which is 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.

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 lifecycles, from production through construction, operation, and the end-of-life stage. This comprehensive approach enables to 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 and etc., and is often neglected [5, 6]. Additionally, the availability of data needed for LCA is dispersed and often not ready for direct utility, and requires the analyst to assume, reproduce, and manipulate data in order to use existing information for assessment and analysis. These certifications are solely based on the selected criteria with predefined thresholds and reference values, which do not reflect the whole lifecycle of buildings. They are based on the evaluation of selected criteria by comparing the performance of the building with 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 necessitate experts recognized by the certifying organization to conduct the assessment and achieve certification. Lorch (2017) [7] addresses that the use of such systems in buildings has not led to significant reductions in terms of CO2 emissions. The wbLCA tools in the current market such as Athena, Tally, one-click and etc., do not precisely use consistent resource and materials databases, resulting in varied results depending on the software platform [8] and do not provide reference value benchmark to set benchmark reference value as they are relied on different criteria in their assessment [5].

Over the last few years, significant efforts have been made globally towards decarbonization in buildings. Policies, regulations, and strategic goals are defined to reduce carbon emissions in the building and construction sector. The Paris Climate Agreement developed a strategic goal of achieving zero-embodied carbon in the building sector [9a]. 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 are published to enable GHG emissions reduction. 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 [9b]. Sustainability in buildings and civil engineering works. In Canada, the most recent practices towards decarbonization 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 [10].

To have a reliable wbLCA, it is necessary to have a reproducible and transparent benchmarking method. To do so, it is important to establish reference values and benchmarks; having this information enables to evaluation and assessment of the environmental impact derived from wbLCA. [11, 12]. Carbon Leadership Forum (2024) [13] 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 yardstick for the assessment of the environmental impacts of buildings and strives towards an effective reduction strategy for the use of resources and relative 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 environmental impacts.

This paper aims to address the challenges of data quality and requirements in wbLCA by proposing a framework for standardization of data and model submission by adhering to BIM standards to extend its applicability to wbLCA as the industry is moving towards permitting and compliance checks by moving towards digitalized solutions. By adopting Open-BIM 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 utilization of Open-BIM and defining the Level of development (LOD), which leverages 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 to be used for benchmarking and comparisons. 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 [14-16]. In some instances, in Canada, the city of Vancouver published an absolute embodied carbon intensity value of 400 kgCO2e/m2 [17], and the city of Toronto defined an absolute embodied carbon intensity of 275 kgCO2e/m2 for commercial and residential buildings [18]. However, the defined benchmark values are not comparable, as the information that was used to identify these benchmark values and the sample size (buildings studied to define benchmark values) are not standardized. A study by the University of British Columbia [19] on multiple buildings confirms this statement and 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. [14] and Feng et al. [20] 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 major barrier in the development of benchmarks for wbLCA Additionally, the California Carbon report study on 30 buildings over 60-year study period result in median lifetime total carbon value of 730 kg CO2 e/m2 and revealed significant correlations between building type or categorization of buildings and higher or lower embodied carbon impacts [13]. Without wbLCA standardization, the results of wbLCA 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 share, size, types of materials, and quantification of environmental impacts (EI) associated with different building materials and processes, when using available input information [21, 22]. However, the main present challenge is that the input information used by these tools is not consistent, which in turn causes to have 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 defined as the process of collecting, analyzing, and relating performance data of comparable buildings or other types of construction works, typically used for evaluating and comparing performance between or within objects of consideration (ISO21678, 2020) for wbLCA are derived from these tools. However, the methods of benchmarking 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 wellrecognized within both industry and practice. Several resolutions have been proposed to address these issues, which will be discussed in the following sections.

One resolution to address the described challenges is through the standardization of information facilitated by digital construction processes. With the increasing adoption of Building Information Modeling (BIM) in the built environment, significant opportunities are emerging to utilize 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 to move toward standardizing LCA by systematically sourcing the required data for assessment and analysis through the BIM environment. It enhances the assessment and management of environmental impacts throughout the lifecycle of buildings. By utilizing open exchange formats and reuse of BIM processes, which encompass different building phases which enabling users detailed and advanced modeling capabilities. Adopting such an approach can provide significant improvements that can help with LCA in terms of accuracy, reproducibility, and trackability. 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 efforts and reduce time associated with collecting and compiling data [23].

BIM standards adoption facilitates and streamlines the exchange of data among multiple stakeholders by creating a shared language for the exchange of information. By doing so, it reduces the number of times data needs to be translated [24, 25], which often causes data loss. There are multiple tools available to apply BIM, such as Industry Foundation Classes (IFC), Information Delivery Specifications (IDS), buildingSmart data dictionary (bsDD), and other relevant best practices known collectively as openBIM standards [26]. One significant advantage is the elimination of manual data entry for LCA, which is very time-consuming [4, 27]. While BIM models have a clear advantage in creating the Bill of Quantities (BoQ), this is not the only data input required for a wbLCA. According to the terminology and methodology from the European standard EN 15978 [28], additional data required includes operational energy and water use, service lives of products, transport, and maintenance and repair.
However, it is important to note that presently most data exchanges between BIM and LCA tools are still done manually [29]. This manual process necessitates further and additional advancements in the integration of these systems to fully realize the potential benefits of Open-BIM for wbLCA. The present practices mean that the building modelers and life cycle analysis work separately, and hence current procedure causes redundancy and loss of information as the 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 and systematic method of utilizing BIM for LCA [30, 31]. Literature reviewed indicates that there are insufficient methodological details for the

implementation of BIM for LCA integration; these gaps need to be addressed not just 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 [24-27].

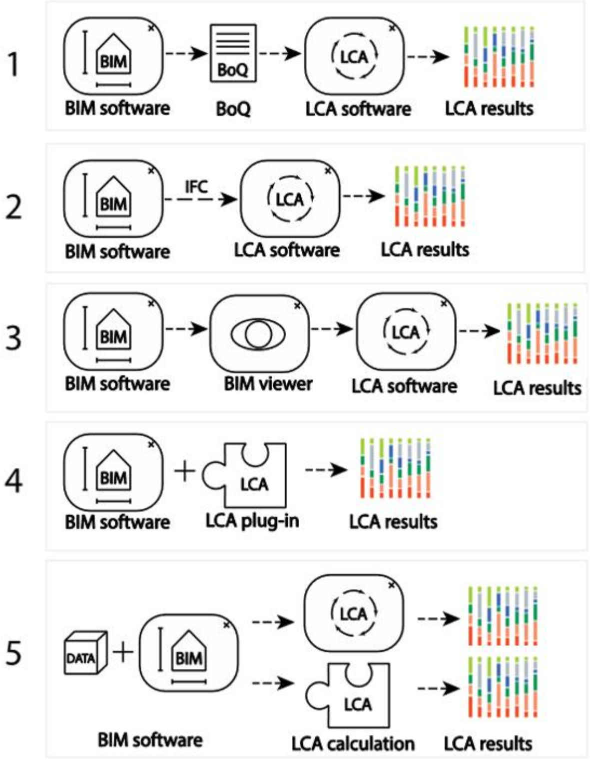

Figure 1: BIM-LCA integration types (Adopted from Wastiels and Decuypere, [53])

Although the integration of BIM and LCA significantly shortens the time required and enhances the applications for evaluating environmental performance, several challenges still persist. These challenges include methodological issues, such as the lack of standardized methods for integrating BIM and LCA, which makes it difficult 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. In addition to above mentioned, at its present state, there is a lack of comprehensive case studies and sufficient data within BIM 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 [32].

As indicated in the literature [33], 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 issues, the challenges can encompass the availability and quality of data within BIM models for performing LCA analysis. In the last category, organizational issues contain the need for collaboration between stakeholders and the alignment of organizational processes to support integrating BIM for LCA [29]. The above-mentioned challenges are the main hurdles to integrating BIM and LCA.

The utility of BIM for LCA involves two main approaches. 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 usually become large in size, but this method ensures data retention. In the second approach, Information from BIM is exported to other software and applications. In this approach, loss of data integration remains a large risk.

The use of 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 to be transferred to LCA application, in practice, the accuracy and quality of this information can vary, depending on the phase of the building. For example, in early design stages, often the models 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 [32, 34].

The IFC is an open standard and vendor-neutral data exchange format, and it is important to consider its standard structure to understand what information can be extracted from the BIM model [24]. Using a standard data structure will always restrict how data can be described and used in building performance tools [25]. Therefore, using a standard structure like IFC requires all relevant software to translate their data into this standard structure, creating a common language for data exchange and enabling the standardization of data structures in BIM models for LCA analysis.

The next resolution after standardizing the information facilitated by openBIM will focus on standardizing the wbLCA Benchmarking method, facilitated by a statistical method. Benchmarking in the context of wbLCA involves the process of collecting, analyzing, and relating performance data of 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 in providing consistent parameters and factors, as they are typically developed for certification systems at the whole building level and do not offer design guidance at the material or element level [35, 36]. Additionally, there remains a disconnect between target values needed for the whole building assessment and defining benchmarks for building elements. This leads to inconsistencies when comparison between different works is needed. To address such challenges, benchmarking values are targeted, such as limit value, reference value, best-practice value, target value, absolute value, and relative value, which will depend upon the application and requirement of the assessment [37, 38]. 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 [39].

Existing BIM–wBIMCA methods and tools are not comparable due to inconsistent data requirements, manual and error-prone data transfer, lack of detailed implementation guidance (e.g., LOD, classification, IDS), and non-standardized benchmarking. In addition to these mentioned 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 openIM concepts and tools. By adopting these technologies and concepts, it enables the automation and data validation by aligning LOD with functional requirements to enable 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 Open-BIM framework and standardized wbLCA benchmarking approach

In this section, an openBIM framework is identified and presented further. In addition, reference values and best practice values are taken into consideration for benchmarking purposes through a proposed framework that consists of two interrelated modules. The first module, which is Module A, focuses on an open-BIM enabled wbLCA framework, standardizing the wbLCA process and the information used for all resources (materials, energy, and water) in environmental performance indicators. The second module, named Module, is dedicated to wbLCA benchmarking based on GWP. This approach enables standardizing the information required to identify benchmark values (reference value and best practice value) 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 and reproducible approach for conducting wbLCA by having access to benchmark information. The framework facilitates sustainable building practices by enabling the comparability of wbLCA results among multiple cases. The module A, the wbLCA process, and the information required for all resources, which can include materials, energy, and water in 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 standardized Open-BIM enabled wbLCA framework is presented in Figure 2, which illustrates a comprehensive workflow for integrating BIM for LCA, ensuring a seamless and standardized process.

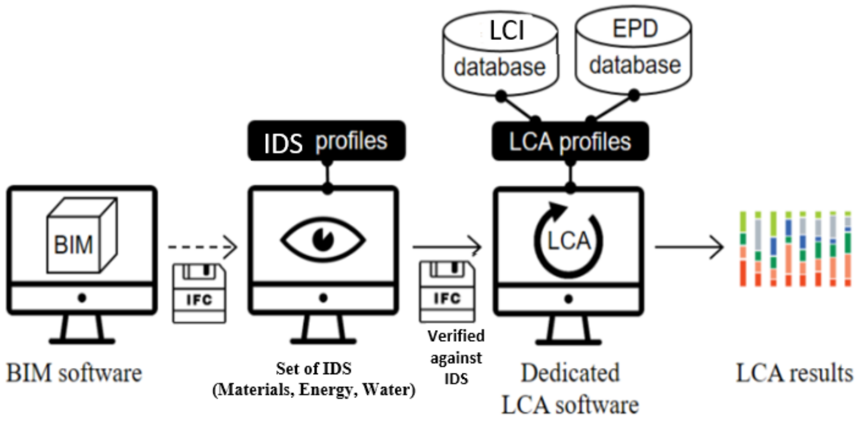

Figure 2: Overview of proposed standardized Open-BIM enabled wbLCA

To streamline the proposed framework following considerations are made: this framework defines the production stage of building materials as a single LCA stage rather than separating it into multiple individual phases, i.e., A1 to A3. The framework assumes that the Environmental Product Declarations (EPD) of products at the end of the production stage, provided by the manufacturer, are unknown and need to be calculated.

The proposed procedure requires the development of the model using existing tools that support IFC exports. In the second stage, the IFC data needs to 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 pertaining to materials, energy, and water. The availability of such information beforehand reduces the waste in terms of time needed for 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, when looking at the requirement for material specification as a standardized process for material quantity labeling from the BIM model, the process ensures that material quantities are accurately labeled and mapped within the BIM model, 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 pertaining to 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 environmental performance of the building by making sure that the input is verified and the results are comparable, covering all relevant indicators such as material usage, energy consumption, and water usage. The proposed framework achieved accuracy by using a standardized format to make the results interpretable and comparable across different projects.

As a prerequisite for the creation of the BIM models, two categories can help with information delivery from BIM: the first being the Level of Development (LOD), and the second is the naming convention. This preliminary step is important as it must be defined prior to using BIM for LCA. In terms of LOD required, literature analysis indicates that element-based LOD is needed, as LCA needs detailed information. For example, in the case of a door element, this element may require a higher LOD than other elements, depending on the use case, and hence it would require element-based LOD. The two main references for LOD used in this study are ISO 7817-1:2024 [40] and BIM Forum (2023)[41]. By defining such requirements it enables data availability for LCA [33, 42-45].

The second category identified is the Naming conventions and classifications, such as Omniclass in the USA and Uniclass in the UK, which are crucial for information identification within the BIM model [46]. Functional requirements challenges involve determining the goal and scope of the LCA, which affects what information 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 [29]. Organizational challenges, as noted by Bowick et al. (2022) [47], 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 in current studies hinder practical implementation [30, 48].

Omniclass (US-based) is commonly used for identifying the Bill of Materials (BoM) from the BIM model, where Uniformat Level 3 is mapped with Masterformat Level 4, and then proceeds to be 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. [47] by proposing a new material quantity labeling method, as shown in Figure 3, that enables direct mapping of the Uniformat table Level 3 with the related Uniclass 15 labeling classification. This method is adapted from the LOD Specification by BIM Forum [41] and establishes a direct relationship with the .ifc file. Additionally, the version of IFC to be used should also be identified to ensure consistency and compatibility.

By integrating these elements, the framework aims to provide a robust and standardized approach for 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.

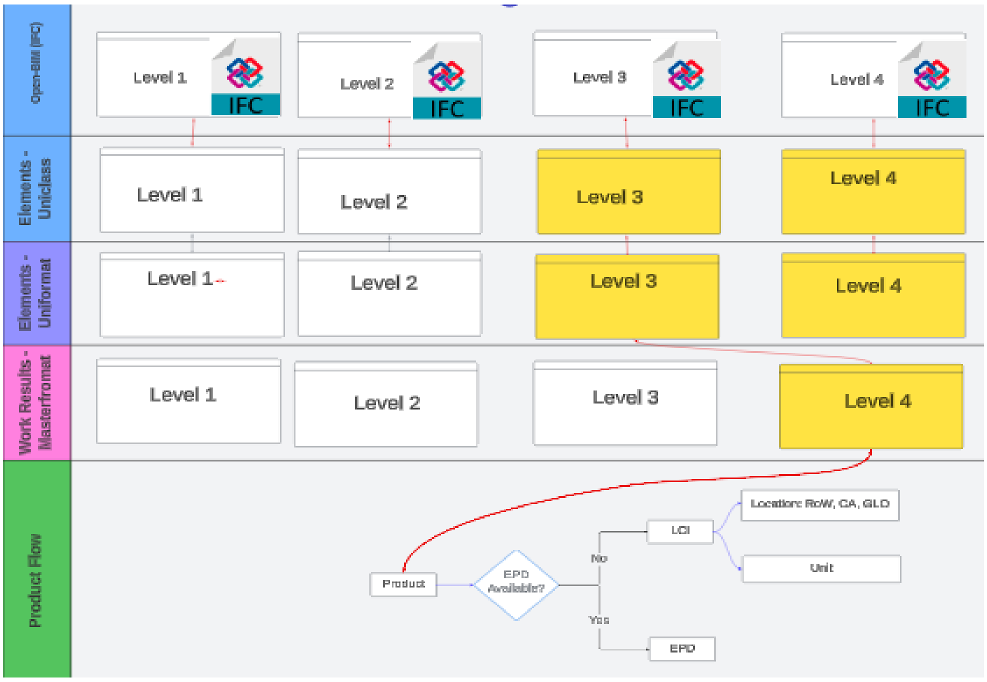

Figure 3: Proposed labelling for material quantities

The proposed Open-BIM enabled wbLCA framework that standardizes the data and information flow is comprehensively depicted in Figure 4. This figure shows the pipeline proposed to conduct 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 steps utilize 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 its Beta version [49]. This step can be considered as a pre-requisite step where the data structure of the BIM model is verified to make sure the necessary data is available for further processing.

Next, the framework employs a Model Quality Checker (MQC) to assess the BIM data. The MQC contains two components, where one checks the geometric information, including the spatial and dimensional aspects, and the second component checks the non-geometric information, which looks at requirements identified in association 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, the users are allowed to address any inconsistencies or missing information as the 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 the usage of master specifications for mapping BIM elements with product data, such as Environmental Product Declarations (EPDs) and Life Cycle Inventory (LCI) data via Uniformat, Omniclass, and Masterformat specifications. This mapping phase enables a bi-directional flow of data to BIM as LCA is conducted.

The next stage allows the user to use the enhanced and verified BIM model to be checked against the requirements via Information Delivery Specifications (IDS), ensuring the data can be used for all phases of LCA. The LCA Model Generator basically is the step where LCA analysis generally utilizes their respective LCA tools, only in this case, the analysts have access to readily available input data to create an LCA model through an API, integrating materials, energy, water data, and databases like ecoinvent [50].

The output is the last and final step of the process, which contains 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 Open-BIM data with LCA tools, ensuring data quality and consistency throughout the assessment. This standardized approach facilitates reliable and comparable environmental performance assessments, contributing to more sustainable building practices.

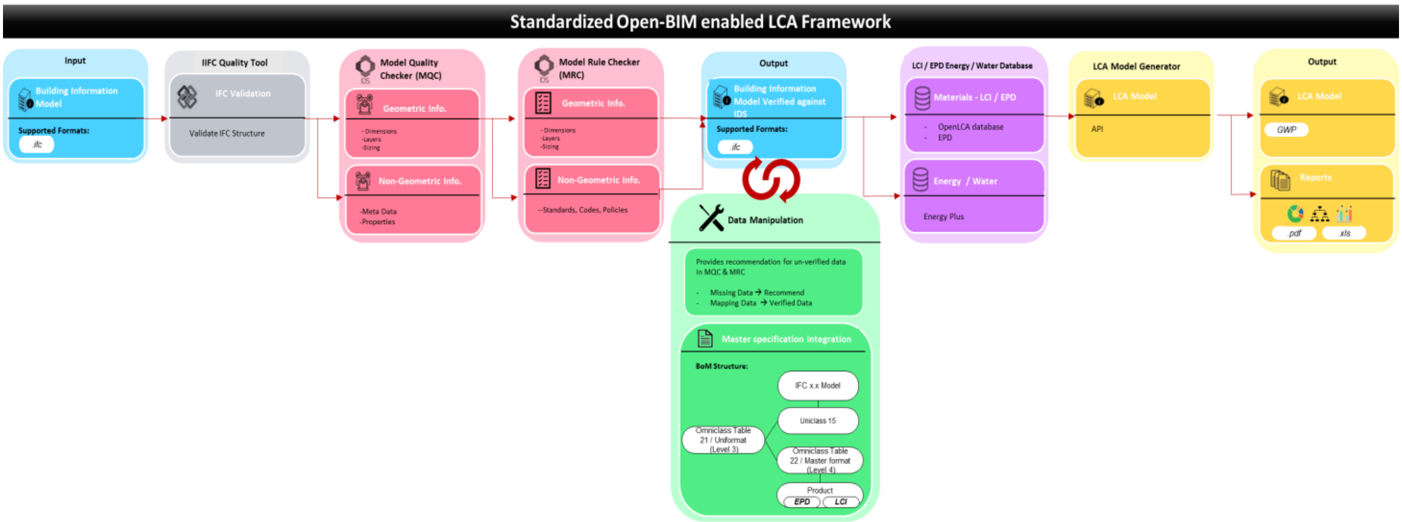

Figure 4: Data delivery for LCA using the openBIM approach

Since the process of reaching the wbLCA outputs is standardized, the next step in order to derive the benchmark number is to adopt the right pathway from 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, with the aim of determining reference values and best practice values. The process begins with the initiation of Module B, which focuses on collecting data and defining benchmarks. The first step involves data collection from Module A, providing 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 the definition of benchmarking requirements, which includes defining the aim and scope of the benchmarking exercise, setting objectives, and identifying 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 [51], for this purpose is proposed to use this method with a 95% confidence level suitable for publication.

The subsequent step involves the quantification of benchmarks based on key environmental indicators (i.e., GWP, which measures the building's impact on climate change over its life cycle), with considerations for including or excluding biogenic carbon based on guidelines from the JRC [5] and NRC [47] reports. The final step is the establishment of initial benchmarks and targets based on statistical analysis. This includes setting reference values, represented by the median value 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 for GWP, expressed in kg CO_2 eq./m².yr, is conducted using probabilistic analysis methods such as uniform distribution and Gaussian distribution, with Monte Carlo Simulation performed over 1000 iterations.

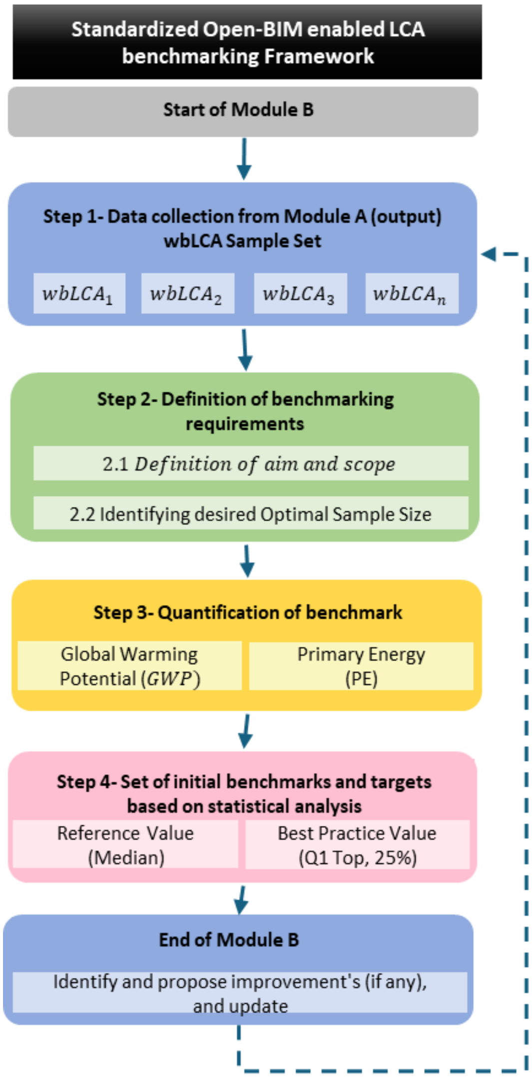

Figure 5: Standardized open-BIM WB-LCA benchmarking framework

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

Table 1: Definition of benchmarking information requirements

Process Flow	Input data
1. Defining building by type for Function	Omnicalss Table 11 (Level 3)
2. Defining building by type for Form	Omnicalss Table 12 (Level 3)
3. Categorizing each type of building function	For residential buildings, there are 3 categories: ▪ Single family (SI) ▪ Multi-family apartment (MF) less or equal to 5 story ▪ High rise building (HR) more than 5 story 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 – no. of permanent living people ▪ Office – no. 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 owner ▪ ISO 15686
12. Seismic area	
13. Climate area	▪ Based on geographical zone
14. Technical requirements	▪ Relevant codes ▪ Standards ▪ Polices
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

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 leading to 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 utilization of BIM extended to LCA use cases and potentially 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.

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 at each LCA stage. The LOD Specification based on 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 requirements at each stage, adopting appropriate BIM model classification, and using IFC to translate BIM model information to meet the requirements of wbLCA, the standardization of information 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 analyzing environmental impacts and integrating with BIM tools, reducing their effectiveness in early design stages [44, 52]. The study suggests that building modelers utilize IDS requirements to identify the LOD requirements prior to and during model development. Compliance with the LOD requirements results in minimizing the rework and time needed to find the 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 weLCA 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 in which external and internal benchmarks are formed, where external benchmarks serve broader industry comparisons and internal benchmarks can be used for building assessments. This dual approach provides a complete view by integrating top-down and bottom-up models. By doing so, it is ensured 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 needs to be defined based on the precision and confidence level desired 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 to achieve broader comparison and move toward more reliable wbLCA results and reporting. Ensuring an adequate sample size based on 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, 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 BIM Forum 2023, and adopting a dual-approach to benchmarking. This resultant method and framework can provide a robust and standardized method for conducting WB-LCA and establishing reliable benchmarks.

5. Conclusion and Future Research Direction:

The proposed framework for OpenBIM-enabled wbLCA can provide its users, such as LCA analysts, a robust and standardized approach to conduct analysis and generate comparable results. By ensuring consistency, accuracy, and interoperability through a standardized data input from BIM. This approach facilitates more reliable environmental performance assessments, ultimately contributing to more sustainable building practices, which can be compared more effectively. 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 the 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 and the use of LCI and EPD databases ensure that the LCA analysis is based on accurate and reliable data. This approach leads to more precise results. In addition to stated, the framework covers all relevant environmental performance indicators, providing a holistic view of the building's environmental impact.

Given that generally built environment generally contributes largely 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 attempts to address the pressing issue of data quality by predefining Levels of LOD requirements. Further, the use of openBIM tools such as IFC for data translation, and adopting a dual-approach to benchmarking, further eases interoperability and reproducibility. The proposed approach implements an accurate data capture and reliable integration of BIM and LCA. Doing so facilitates sustainable building practices. Further, by integrating global sustainability targets with detailed component-specific benchmarks, as described by the dual-approach of combining top-down and bottom-up models, we can move towards benchmarking with a holistic view and 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, and the use of standardized specifications to enable benchmarking. This comprehensive approach facilitates the identification of reference values and best practice values and also provides support to enable informed decision-making for stakeholders such as policymakers and industry practitioners.

This study indicates the importance of the identification of reference values 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 its users to produce reliable comparisons and provide support for 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 to reduce the environmental impact of the built environment by laying the framework for a more sustainable and 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, the implementation of the proposed framework by developing case studies will be essential to illustrate and validate the effectiveness of the solution, especially to define a benchmark. This approach will enable the researchers to further refine the approach to real-world scenarios, ultimately promoting more sustainable building practices.

List of Abbreviations:

wbLCA: Whole-Building Life Cycle Assessment
LCA: Life Cycle Assessment
AECO: Architecture, Engineering, Construction, and Operation
GHG: Greenhouse Gas
IFC: Industry Foundation Classes
IDS: Information Delivery Specifications
LOD: Level of Development
BoM : Bill of Materials
BoQ: Bill of Quantities
EN 15978: European Standard 15978
ISO 21930: International Standard 21930
ISO 21678: International Standard 21678
LCI: Life Cycle Inventory
EPD: Environmental Product Declaration
bsDD: buildingSMART Data Dictionary
Omniclass: Construction Classification System
Uniclass: Unified Classification System
Masterformat: Masterformat Specification System

GWP: Global Warming Potential
MQC: Model Quality Checker
MRC: Model Rule Checker
API: Application Programming Interface
LOG: Level of Geometry
CSDP: Construction Sector Digitalization and Productivity
NRC: National Research Council Canada
UNEP: United Nations Environment Programme

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Availability of Data and Materials

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

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Conflicts of Interest

The authors declare no conflicts of interest regarding this manuscript.

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