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Developing an openBIM Information Delivery Specifications Framework for Operational Carbon Impact Assessment of Building Projects

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Abstract: BIM (building information modeling) is widely recognized for enhancing the efficiency and precision of building energy modeling (BEM), primarily by reducing model development time and improving model accuracy. This paper presents a novel framework leveraging "openBIM" to standardize and harmonize BIM-driven solutions for energy simulations, facilitating comprehensive operational carbon impact assessments. Unlike existing approaches, our framework uniquely integrates information delivery specifications (IDS) with openBIM standards to define the minimum data requirements within the IFC schema, tailored to various levels of development (LOD). This innovation ensures consistent data exchange and interoperability across diverse energy modeling and simulation tools, addressing common challenges of data fragmentation and inaccuracy in operational carbon assessments. By advancing the current state of the art, the proposed framework empowers energy modelers, LCA analysts, and asset managers to streamline IDS implementation, fostering more efficient and reliable construction industry practices. This research thus marks a significant step towards achieving more sustainable building projects through enhanced data-driven insights.

Keywords: openBIM; BEM; IDS; IFC; LOD; operational carbon

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Academic Editor: Usama Bin Perwez

Received: 26 November 2024
Revised: 8 January 2025
Accepted: 14 January 2025
Published: 16 January 2025

Citation: Hosseini Gourabpasi, A.; Jalaei, F.; Ghobadi, M. Developing an openBIM Information Delivery Specifications Framework for Operational Carbon Impact Assessment of Building Projects. *Sustainability* **2025**, *17*, 673. https://doi.org/10.3390/su17020673

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1. Introduction

The report on the pathway to limiting global warming demonstrated the role of building and the importance that low-carbon building solutions can have to achieve the goal of maintaining global warming to 1.5 °C above pre-industrial levels [1]. Energy analysis and simulation of building energy modeling can play a pivotal role in enabling accurate quantification and assessment of operational carbon [2–6]. Building energy modeling predicts energy use and identifies opportunities to reduce emissions during the operational phase.

Building energy modeling and analysis tools provide their users with multiple functionalities for different use cases, such as analyzing heat loss, heat gain, natural sunlight, HVAC systems, heat balance loads, heat airflow in multiple zones, natural sunlight, and solar access rights. To perform such modeling and analysis, building envelope data, building asset data, and external data, such as weather data, are needed to enable the calculation of total energy use and cost for different intervals of time [7].

BIM (building information modeling) is a widely adopted approach by AEC (architectural engineering and construction) and is utilized during the entire lifecycle phases of building and for many use cases [8–11]. It is evident from research that BIM data can be utilized for BEM (building energy modeling) [12]. BIM is proposed as a solution to

overcome the limitations of conventional building energy modeling, including tedious model preparation, model inconsistency, and costly implementation.

The literature demonstrates that the use of BIM for building energy modeling is particularly suitable and cost-effective during the early design stages [13]. However, the justification for using BIM as a resource to provide input for energy modeling is beyond the design phase and feasibility analysis and can go to the operation phase of the building and facility management, which is reported to result in an average return on investment (ROI) of 634% [14].

The "openBIM" initiative enables BIM data to be exchanged using open standards, such as Industry Foundation Classes (IFC), which is not proprietary in nature and, hence, can enhance collaboration and is widely adopted as a universal language for built environment data exchange and management. Enabling access to operational data through openBIM is envisioned to lead to a streamlined procedure for energy model development that can be reproduced or enhanced or allow the exchange of data for other uses [15–18].

To assess and quantify the operational impact of building energy modeling, a variety of tools and methods can be employed. However, this flexibility has led to a lack of a standardized process for BEM development, resulting in discrepancies evident in outcomes, with large variances in energy consumption estimates and predictions that are often not reproducible. The discrepancy arises from current practices for BEM development, as there is no minimum set of data requirements identified, and further methodologies are required to standardize energy modeling [19–23]. In the area of sustainable construction, despite the growing adoption of BIM, significant research gaps persist, primarily due to the reliance on specific commercial tools for energy analysis. These tools often have proprietary data formats and integration processes, resulting in a fragmented landscape where interoperability is limited. This fragmentation leads to inconsistencies in data collection, interoperability, and mapping with life cycle inventory datasets, thereby affecting the accuracy and reliability of operational carbon assessments. Moreover, the lack of standardized procedures for integrating BIM with energy modeling tools exacerbates these challenges, as each integration is tailored to the specific software being used, preventing a universal approach that can be widely adopted across the industry.

Building energy simulation tools are used to estimate the building energy consumption associated with activities such as air conditioning, lighting, and devices. However, current research suggests that these estimates do not reflect the actual energy consumption of buildings once they are commissioned and in operation. To address this challenge, the building information used by different trades to construct the building can be utilized to provide the necessary information for BEM. This approach can not only provide relevant information for BEM but also reduce the modeling time required to create energy simulations. Addressing these gaps is feasible by advocating for the transition to openBIM standards, which promise greater interoperability and consistency across different platforms. By developing information delivery specifications (IDS), this research aims to establish a standardized framework for validating the minimum data requirements necessary for operational carbon assessments within BIM models. This standardization is crucial, as it facilitates the creation of a consistent energy modeling process that is not dependent on specific commercial tools.

BEM models are most impacted when HVAC system data are based on assumptions [24], whereas BIM contains the physical asset data of the facility. The advantage of BIM-based simulation over the traditional approach of building an energy simulation model goes beyond data availability, as it enhances the speed and accuracy of energy model development. To utilize BIM data for BEM, different data exchange methods can be used. For example, the XML format can be used for data transfer; however, it is often intended

for non-BIM solutions and does not directly allow interoperability. On the other hand, openBIM standards, such as IDS, can be utilized to facilitate end-users and analysts in sharing and collaborating with models that include the minimum requirements for BEM.

According to the literature [25], using the BIM-based approach instead of relying on model development using BEM tools can save 75% of time by enabling the generation of building geometry for small to medium buildings [13]. Additionally, conversion methods that simplify the building geometry can cause a 15% error margin due to simplification and the need for assumptions [7]. BIM adoption can reduce the error margin by supplementing BEM with accurate data. However, at present, the loss of geometric and thermal data during the model's export prevents the BIM from being fully used for BEM.

Simulation engines, such as EnergyPlus, rely on mathematical equations to model building behavior and calculate energy requirements. BIM plug-ins, like Insight 360 and DesignBuilder, are reported to be suitable for preliminary energy analysis of entire buildings, making them ideal for early-stage assessments [26]. However, these tools are not based on open exchange formats. Additionally, other relevant tools based on proprietary formats are widely used by researchers for BIM-based BEM, including Autodesk Green Building Studio, IES-VE, and parametric tools like Ladybug and Honeybee, which integrate with BIM through Dynamo [11,27,28].

Several methods have been introduced and researched to utilize this approach. Although the BIM-based approach is desirable due to its adherence to open-source schemas and file formats, such as IFC, numerous challenges remain before BIM can be readily utilized [29]. The primary challenges include the lack of standardized requirements to ensure a minimum set of data inputs and the difficulties associated with data exchange between BIM and BEM models [7,29,30].

One approach to dealing with missing data in IFC and gbXML is to enrich the data externally before using them in BEM tools. For example, missing data regarding the properties of materials and the characteristics of HVAC or thermal zones can be inserted. This approach allows the addition of non-BIM data, such as weather or technical specifications that may not be readily present in BIM, to enhance the IFC model. An example of such middleware is the Space Boundary tool, which adds space boundaries to the validated IFC file. The tool converts the geometry to a format usable by whole-building energy simulation tools, such as a .idf file in EnergyPlus. One strategy suggested in the literature is the use of model view definitions (MVD) to provide a subset of the IFC, limiting the information necessary for the BEM software [26,31].

The IDS is intended to be applicable during the entire building lifecycle, from design to operation. Therefore, the following objectives are set to achieve the stated goal: initially, to identify the information required from the BIM model by performing a literature analysis of studies that have exported BIM data for BEM; secondly, to define the corresponding LOD for the data categories identified in the form of a specification pertinent to energy modeling and simulation, which leads to a framework that can enable BIM for BEM and further facilitate the assessment and analysis of the operational carbon of buildings.

The definitions in IDS specifications and IFC data can be referenced through libraries such as buildingSMART data dictionary (bSDD) [32–34], a service provided by buildingSMART, or other taxonomies and ontologies. Adopting bSDD as a service for referencing enables the sharing of definitions that describe buildings, particularly for assessing the operational carbon impacts of building projects. This facilitates users having a consistent set of terminology.

This research intends to utilize IDS to verify the presence of the specified data set and enable the transformation to the IDF file format that can be used by EnergyPlus for analysis and simulation purposes. The outcome of such a BIM-based BEM can then be utilized

for operational carbon assessment and would contribute to facilitating the collaboration and exchange of data by adopting open-source solutions and approaches, as both the IFC solution and EnergyPlus are open-source. By using open-source applications, the proposed framework ensures that IFC submissions are rigorously validated and that the derived energy models accurately reflect the operational carbon impacts. This approach not only addresses the current limitations of tool-specific integrations but also supports the broader industry goal of achieving sustainability through enhanced data interoperability and transparency.

This paper is structured to review the current state of research on the data requirements for energy model development using openBIM and as a resource for operational carbon assessment purposes. These requirements are then formulated into a specification and methodology. This study will proceed by validating the proposed methodology through a case study and analyzing the results using an integrated BIM–LCA tool. The findings of this research are potentially valuable for practitioners in the AEC industry, building owners (project authorities/public services), technical authorities, and contracting authorities.

2. Literature Review

The integration of BIM with sustainability certification initiatives, such as Leadership in Energy and Environmental Design (LEED), and the impact of LCA to quantify the operational carbon that is directly driven from energy usage of the buildings represents a significant advancement in sustainable construction practices. BIM's ability to create a comprehensive digital representation of buildings enhances design efficiency and enables more precise assessment of environmental impacts throughout a building's lifecycle. By embedding LCA tools into BIM software, architects and engineers can efficiently evaluate carbon emissions and material sustainability, facilitating informed decision-making [35]. This integration supports the achievement of LEED certification by streamlining the documentation process and improving data management, ultimately promoting resource efficiency and reducing carbon footprints [36]. As the construction industry shifts toward environmentally responsible practices, the use of BIM in conjunction with LCA and LEED not only meets regulatory requirements but also contributes positively to global sustainability goals [37].

Jalaei et al. [38] introduced a methodology that automates sustainability assessments for building projects by integrating BIM with the LEED certification system with a focus on developing a specialized Revit plug-in to calculate and predict potential LEED credits, utilizing the Application Program Interface (API) of BIM tools, energy analysis and lighting simulation tools, Google Maps, and associated libraries. The plug-in employed the K-nearest neighbor (KNN) data mining technique to estimate credits that cannot be directly derived from design specifications, providing a comprehensive, innovative interface for evaluating green building projects. The synergy between BIM and LEED certification allows for real-time energy performance analyses, which are crucial for optimizing design alternatives and ensuring compliance with stringent energy standards. This capability is particularly beneficial during the early stages of project development, where BIM's visualization and simulation tools can significantly enhance energy-related decision-making [39]. Additionally, the integration of LCA methodologies with BIM provides a comprehensive framework for assessing the entire environmental impact of building projects, from material extraction to demolition [40]. As the industry continues to prioritize sustainability, the evolution of BIM applications for energy evaluation is expected to drive innovation, foster competitive advantages, and influence regulatory frameworks [39]. This integration is poised to redefine best practices in architecture and construction, paving the way for a more sustainable built environment [41].

Defining the physical model is critical in the application of carbon emission through conducting LCA, yet few studies have leveraged the LOD extensively in building projects. Most notably, many studies utilize the third LOD, which provides sufficient detail regarding quantity, shape, size, location, and orientation, enabling effective energy and emission analysis [42,43]. Soust-Verdaguer et al. [44] claimed that this level is preferred because it offers detailed material and component information, crucial for evaluating a building's environmental impact. Another parameter is the selection of an appropriate functional unit in LCA applications. While numerous studies have opted to use the entire asset as the functional unit, only a few have focused on specific sections of buildings [45–47]. These studies often develop life cycle inventories by compiling various databases, such as the Inventory of Carbon and Energy [47,48], GaBi [39], and Ecoinvent [42,43], which are widely used in conjunction with energy simulation tools like EnergyPlus [38] and DesignBuilder [49].

Integrating BIM with LCA is an effective strategy for extracting construction material information from BIM models and transferring it to LCA databases. For instance, Rezaei et al. [43] demonstrated this by using Autodesk Revit©, the Ecoinvent database, and openLCA to conduct a comprehensive carbon assessment of a multi-residential building in Quebec, Canada. This process revealed significant differences between data formats in BIM and LCA tools, highlighting the need for consistent data formats and naming conventions to facilitate integration [50]. Several methods have been identified for transferring data between BIM models and LCA tools. These include exporting bills of work (quantity take-offs) to spreadsheets or dedicated LCA tools, using LCA plug-ins within BIM software, applying visual programming languages for environmental impact evaluation, utilizing IFC for data exchange, and embedding LCA data directly into BIM objects. For instance, exporting bills of work into tools like Athena Impact Estimator helps calculate embodied carbon [46], while LCA plug-ins, such as Tally, allow for direct impact assessments within BIM environments [45]. The use of IFC, particularly the latest version IFC4, supports LCA data handling, although its capabilities are limited to basic assessments [51]. The incorporation of LCA data into BIM objects, as seen in studies like that by Cavalliere et al. [52], further demonstrates the potential for seamless integration.

Impact categories in LCA generally encompass resource depletion, human health impacts, ecological effects, and climate change. These categories interact with the environment on various geographical scales—global, regional, and local—each contributing differently to issues like ozone depletion, acidification, and land use changes [53,54].

Recent research has demonstrated the role and significance of measuring operational impacts by utilizing BIM for BEM [55–58]. However, different approaches and methods have led to data interoperability issues since BIM and BEM disciplines have evolved in silos. buildingSMART provides standards and specifications to standardize building processes and information capabilities for the built industry and has introduced, most notably, the industry-specific schema IFC (Industry Foundation Classes) [59]. In addition, protocols and APIs have been introduced to tackle interoperability. The IDS (information delivery specification) [60] aims to offer a standardized method of describing information exchange content based on the level of information needed. It can be viewed as an extension of two foundational standardization efforts: Model View Definitions (MVDs) [61] and Information Delivery Manuals (IDMs) [30,62], which define how information should be structured and shared [63–65].

In a recent research study, IDS was utilized to assess the BIM support for capturing circularity-related information [66]. This research work intends to utilize IDS as a form of open BIM standards to provide a means of identifying a set of minimum requirements and optional data that can enhance the accuracy of building energy model data, which

can be further validated for compliance. The literature investigated has covered different aspects of BIM for BEM, looking at the types of tools available, different schemas, modeling challenges, and data interoperability between BIM and BEM. One issue with using BIM models is that such models cannot be readily used by BEM tools, such as EnergyPlus, as they are not compatible with each other. For example, they may have different material libraries that need to be mapped to transfer data.

For accurate energy performance assessments, one important challenge has been assigning accurate space boundaries corresponding to the physical properties of the building required for performance analysis. Hence, BIM files available in formats such as IFC and gbXML usually need to be converted to models that can be utilized for BEM. Tools such as DesignBuilder are used for gbXML conversion, and the space boundary tool is used for IFC conversion, making building geometry important information exported to simulation engines, which are further broken down into space boundary surfaces [67]. However, issues persist with geometry usage, as geometry errors and missing data are prevalent in such exporting methods [7,67,68].

The advantage of IFC over gbXML is its ability to represent any geometric shape and retain semantics, while gbXML can only represent rectangular shapes. However, gbXML can transfer environmental and thermal data created in BIM, which is not possible at present with IFC. Both approaches, however, are still susceptible to data loss once the model is brought into analytical software [7,26]. The type of data loss varies and depends on the approach adopted, tools used, and information requirements. Instances of data loss include geometric simplification or loss, semantic information disconnection, and interoperability issues, such as mapping, data type, and transformation.

The interoperability of BIM to BEM has been investigated in three categories holistically. The first category includes those who use BIM authoring features, tools, and APIs for data exchange. The second category utilizes the direct transfer of data through IFC and gbXML formats, using the information delivery manual (IDM) methodology with model view definitions (MVDs) and custom properties, which is broadly similar to the second group. In addition to utilizing IFC and gbXML, the third approach involves using middleware or other methods to transfer data from BIM for simulation purposes.

Information delivery specification (IDS) can be considered an implementation of MVD, where requirements are identified as a subset of IFC [24,26,29,31]. The literature suggests that the Open BIM standards approach, such as IFC formats, is favored, as it facilitates interoperability, semantics, and applicability throughout the entire building lifecycle. These features enable users to utilize the IFC file for more than one building use case and application, rather than having to deal with multiple formats, which can hinder collaboration.

In North America, two of the most widely used tools for BIM and BEM are Revit and EnergyPlus [3,31,69,70]. However, utilizing BIM authored by Revit for BEM is intended to work with Green Building Studio, where both are proprietary in nature and cannot be directly utilized by EnergyPlus. The export of a Revit model using openBIM standards, such as IFC, can be utilized as an enabler for model transformation to be used for energy simulation and energy analysis, specifically using EnergyPlus [71–75].

Presently, the literature suggests that BIM models with low LOD are not compatible with energy simulation, emphasizing a technology gap [24]. This study aims to use IDS for auditing the IFC file to ensure the minimum data required for energy simulation and analysis are present before exporting. Hence, the literature needs to be analyzed to identify the type of data that can be specified as the minimum requirement for energy simulation, as well as the optional data that can enhance the simulation or meet the requirements at higher LOD. Figure 1 shows a schematic illustration on the evolution of the BIM for

energy evaluation from data interoperability perspectives based on what has been reviewed through the literature.

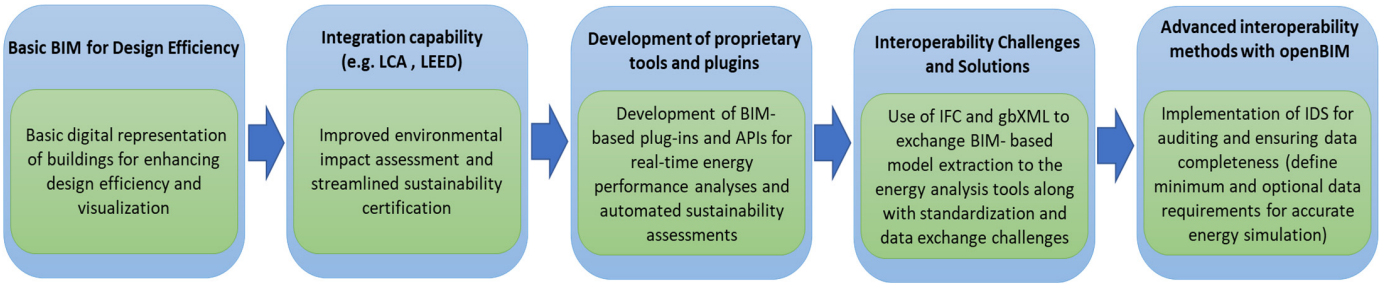


Figure 1. Evolution of BIM-based data interoperability using BIM for operational impacts assessment.

3. Methodology for Energy Model Development Using BIM

The methodology to capture operational carbon impact assessment through openBIM (IFC file treatment) is precisely designed to ensure comprehensive data integration for energy simulation purposes in a more standardized manner. IFC is a standardized data model that codifies the identity and semantics (name, machine-readable unique identifier, object type or function), the characteristics or attributes (such as material, color, and thermal properties), and relationships (including locations, connections, and ownership) of objects (like columns or slabs), abstract concepts (performance, costing), processes (installation, operations), and people (owners, designers, contractors, suppliers, etc.). The novelty lies in developing a flexible pathway from the early design stage to predict greenhouse gas (GHG) emissions during the building's use phase, utilizing openBIM standards as a decision support system for designers to create low-carbon design scenarios with optimized energy usage capabilities. Initially, the BIM model is developed at the requisite level of development (LOD), encompassing all essential geometric and non-geometric information. Upon export to the IFC format, the model undergoes a rigorous validation process utilizing IDS tools. This IDS performs a thorough audit of the IFC files to confirm the presence and correct structuring of key data attributes and properties, which is vital for ensuring interoperability across diverse software platforms and facilitating seamless integration into the BEM environment. This stage is critical for identifying and addressing data discrepancies early in the process, thereby minimizing errors and enhancing the precision of subsequent energy simulations. The framework for the application of IFC files in energy simulation employs a structured methodology for converting BIM data into a format suitable for energy modeling tools, specifically through the transformation from IFC to IDF (input data file) formats, which is suitable to be used by an open-source energy plus tool. This conversion process is specifically designed to preserve data integrity and ensure the accurate transfer of all requisite information.

A methodology is developed to achieve the goal of identifying data required for BEM using BIM as a resource and a BIM-based framework. The steps identified are indicated in Figure 2. The process begins with authoring the BIM model at the required LOD for BEM, followed by screening and verifying the IFC output against the specification developed in the form of an IDS to maintain compatibility with IFC. The third step involves model transformation from the BIM to the BEM environment by maintaining a neutral and exchangeable file format, i.e., IFC to IDF transformation, using the identified data requirement set and verified by IDS for non-geometric data.

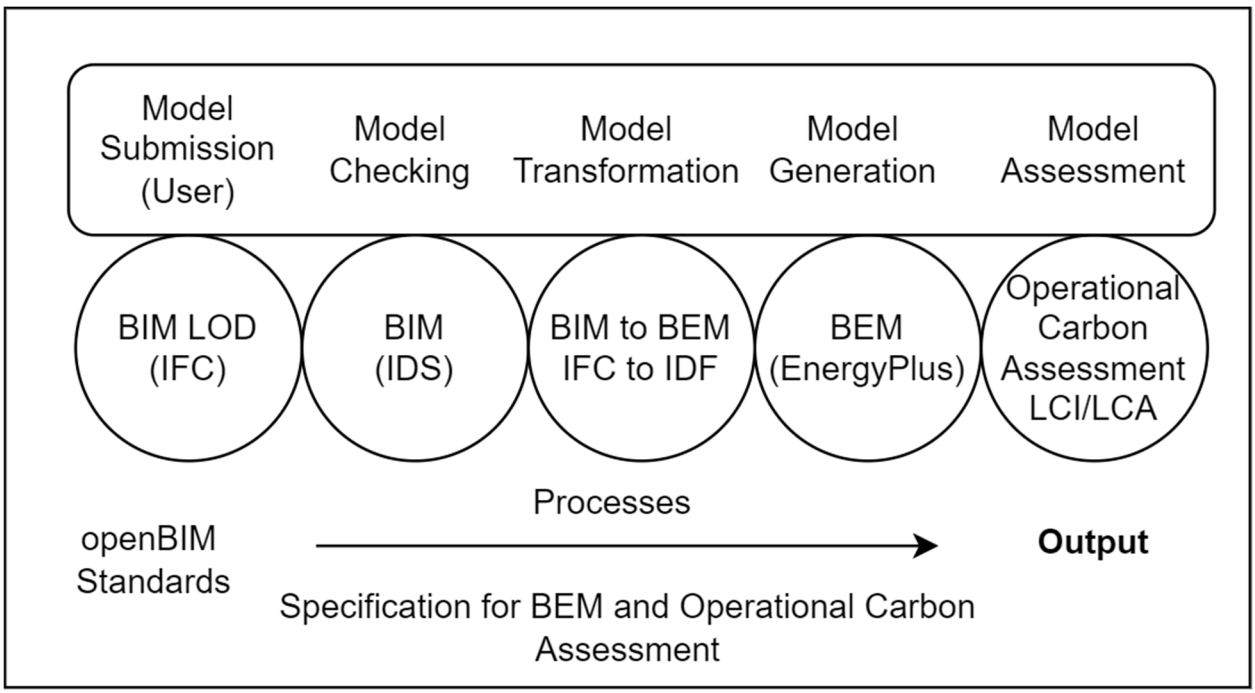


Figure 2. Proposed methodology for BIM-based BEM.

The last two steps are model generation using BIM-compliant IDF for BEM, which is intended to facilitate developing an openBIM solution for the operational carbon impact assessment of building projects. The proposed methodology is intended to address the shortcomings of interoperability and data quality by adopting openBIM standards, namely, IFC and IDS, at an LOD applicable to BEM to be used for operational carbon assessment using the processes identified for data quality, transformation, and model production that result in the output for LCI/LCA.

Figure 3 shows the categories of data needed for BEM and the IFC entities. Broadly speaking, the data categories required for BEM can be divided into BIM data and non-BIM data. The non-BIM data for BEM can include elements such as weather data, which are commonly used for modeling but may not be present directly in the BIM. On the other hand, the BIM data are found in IFC or can generally be accommodated through extensions, such as custom properties. In total, for the case of BIM to BEM, six categories of non-geometry data are identified, which include building information and its location, and asset information. Additionally, more specifically within the scope of this study, HVAC data are needed. The other categories are the materials used, space and construction type, and metadata, such as schedules, which need to be present in BIM for the effective transfer of BIM data for energy modeling.

In addition to the identified non-geometric data, geometric data can be utilized for spatial analysis and can act as a decision support system. IFC file formats can be employed for visualization using viewer tools. In addition, IDS provides a way to ensure that the non-geometric data are present as needed. The preliminary investigation of the literature suggests that certain IFC entities, as highlighted in the figure below, can be utilized to ensure the categories identified are present in the IFC submissions and meet any requirements identified.

The entities presented are candidates that need to be tested and validated through case studies to verify if the data requirements for BEM are met and satisfied, enabling us to reach a shared guideline that can be utilized for BIM-based BEM developments. It must be noted that the BIM data may fall under different entities and relationships in the IFC schema; however, when the IFC is audited using IDS, the entire IFC file is reviewed for

the occurrences of the data under different entities, and the current IDS auditing tools can identify if the data are available, which is advantageous.

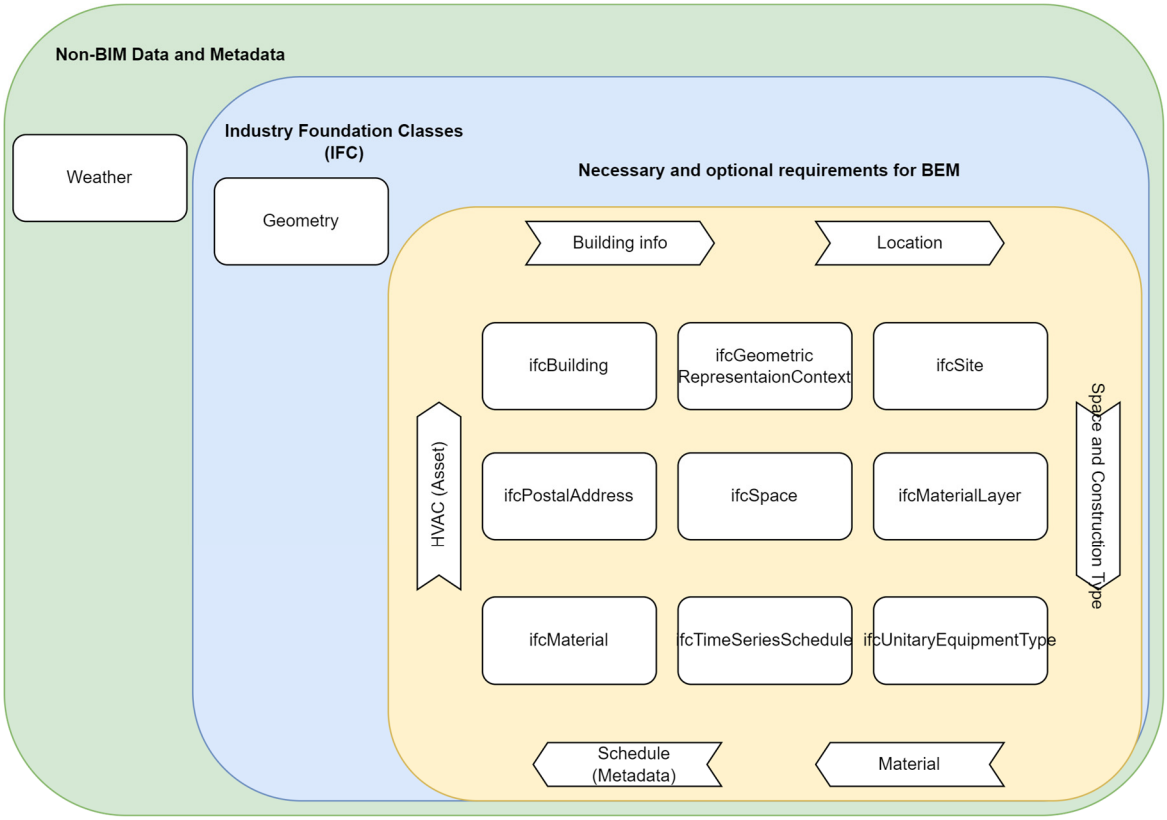


Figure 3. Identified data requirements that can be utilized using BIM-based solutions.

The framework incorporates openBIM standards to meet predefined data requirements tailored to the specific developmental phase of the building. By adhering to these standards, the methodology facilitates the creation of reproducible and reliable energy models that are instrumental for assessing operational carbon impacts. This structured approach not only enhances the model's quality and utility but also positions it for future enhancements to integrate more detailed operational and maintenance data, thereby supporting ongoing energy performance optimization throughout the building's lifecycle.

4. Data Requirements for Energy Model Development Using BIM

BIM is intended to be used for the entire life cycle of building phases; hence, the data requirements for BEM development at each phase are dependent on data availability. Defining and adhering to the LOD and data requirements enable streamlining the BEM process and allow for the comparison of the models developed. The linear analysis and the data used for different categories are mapped to applicable LODs, ranging from the conceptual design stage to the facility management phase.

The identification of minimum data requirements is a crucial aspect of our framework, ensuring that the BIM model provides the necessary information for accurate operational carbon impact assessments. Key data elements essential for this purpose include building geometry, material properties, location specifics, and HVAC system details. For example, building geometry, captured through IFCBUILDING and IFCGEOMETRICREPRESENTATIONCONTEXT, is vital for accurate spatial analysis and energy load calculations. Material properties, specified in IFCMATERIALLAYER and IFCMATERIAL, include attributes such as thermal conductivity, which significantly impact thermal performance

assessments. Location data, such as latitude and longitude from IFCSITE, are critical for climate-based modeling, while HVAC system specifications, captured in IFCUNITARYEQUIPMENTTYPE, provide essential information for evaluating system efficiency and energy consumption. By ensuring these elements are incorporated and verified through IDS, our framework enhances the reliability of operational carbon assessments, enabling more precise simulations and analysis. This structured approach not only supports the development of accurate energy models but also facilitates the integration of BIM data across various simulation platforms, thereby advancing the state of the art in building energy modeling.

As shown in Figure 4, the essential categories of data needed for BEM are building information and location information, followed by space type and construction type. These data categories are suitable for early BEM model development, analysis, and simulation when building designs are not finalized and can be revised more easily than in later stages. Asset and metadata are the data categories that can be utilized during the operation phase of the building [76]. In the case of materials, the earliest stage where such information is applicable is the detailed design stage, whereas HVAC and schedule data are relevant for the later stages of construction and facility management, respectively.

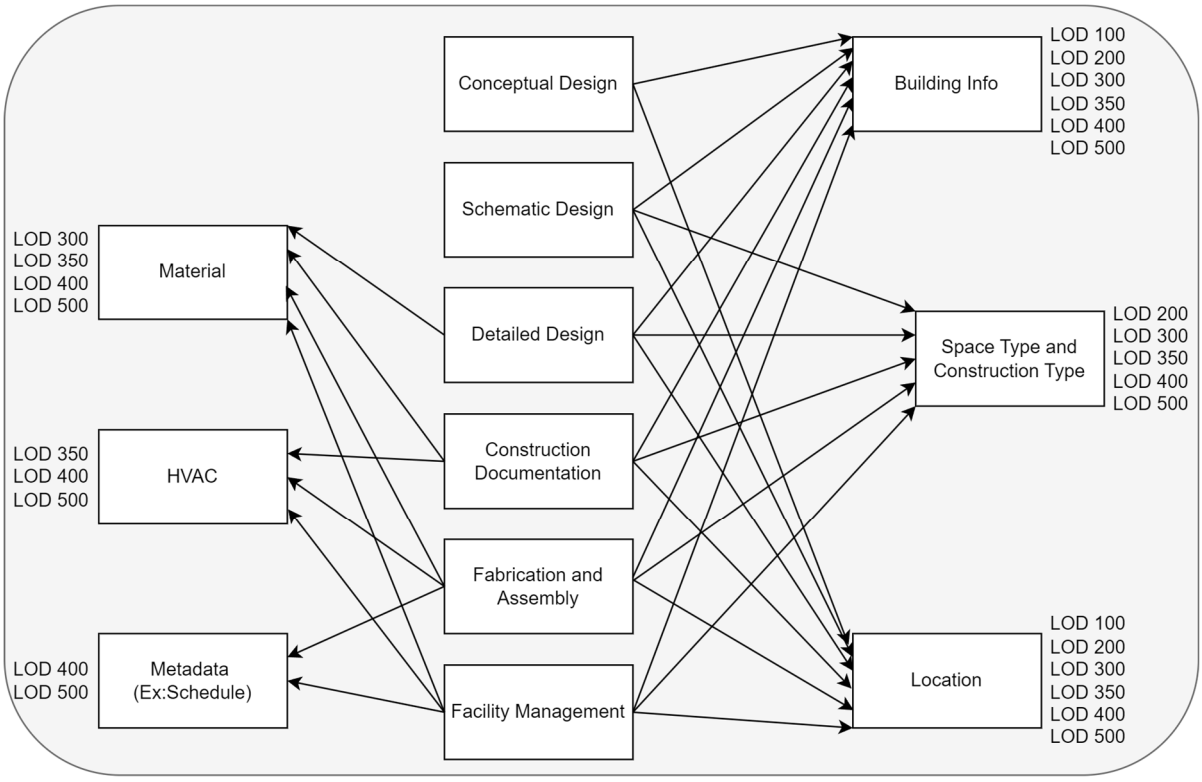


Figure 4. Levels of development and data required for BIM-based BEM.

The IDS enables the information to be available in both human-readable and machine-readable XML formats, which can be utilized by BIM tools to audit the IFC file to ensure the identified data are present in the IFC that is intended to be translated to BEM tools. This process ensures that models are reproducible and more accurate without the need to use unintended assumptions in later stages of energy analysis and simulations. The IDS candidate is developed using the ACCA IDS 0.9.7 editor [77] and is presented in Table 1. It is further matched with the categories identified, the corresponding level of development, and the specifications. The IFC classes must contain the attributes and properties listed in the table.

Table 1. Proposed information delivery specification for BEM using BIM-based data requirements.

Data Requirements	Level of Development (LOD)	Proposed Specification	Advantages for Energy Simulation	Disadvantages for Energy Simulation	IFC Class
Building information	100, 200, 300, 350, 400, 500	The model MUST contain entities that have IFC class IFCBUILDING that MEET the following requirements: MUST HAVE attribute Name. The model MUST contain entities that have IFC class IFCGEOMETRICREPRESENTATIONCONTEXT that MEET the following requirements: MUST HAVE attribute TrueNorth.	This ensures accurate building orientation and identity, crucial for solar gain and shading analysis.	Inaccuracies can lead to incorrect solar exposure modeling.	IFCBUILDING IFCGEOMETRICREPRESENTATIONCONTEXT
Location	100, 200, 300, 350, 400, 500	The model MUST contain entities that have IFC class IFCSITE that MEET the following requirements: MUST HAVE attribute SiteAddress (or RefLatitude; RefLongitude; RefElevation). The model MUST contain entities that have IFC class IFCPOSTALADDRESS that MEET the following requirements: MUST HAVE attribute AddressLines (or PostalBox; Town; Region; Country).	Accurate location data are vital for climate-based modeling and energy consumption predictions.	Missing or incorrect data can result in inaccurate climate zone categorization.	IFCSITE IFCPOSTALADDRESS
Space	200, 300, 350, 400, 500	The model MUST contain entities that have IFC class IFCSPACE that MEET the following requirements: MUST HAVE IFC class IFCRELSPACEBOUNDARY.	This enables detailed spatial analysis and thermal zoning, enhancing HVAC load calculations.	Misalignment can impact thermal comfort and load predictions.	IFCSPACE IFCRELSPACEBOUNDARY
Material	300, 350, 400, 500	The model MUST contain entities that have IFC class IFCMATERIALLAYER that MEET the following requirements: MUST HAVE attribute Material (or Name; Category; LayerThickness). The model MUST contain entities that have IFC class IFCMATERIAL that MEET the following requirements: MUST HAVE attribute Name (or Category); MUST HAVE property ThermalConductivity of PSet Pset_MaterialThermal. The model MUST contain entities that have IFC class IFCMATERIAL that MEET the following requirements: MUST HAVE IFC class IFCRELDEFINESBYPROPERTIES.	This is critical for accurate thermal performance and energy efficiency analysis.	Incorrect properties can lead to erroneous thermal resistance calculations.	IFCMATERIALLAYER IFCMATERIAL

Table 1. *Cont.*

Data Requirements	Level of Development (LOD)	Proposed Specification	Advantages for Energy Simulation	Disadvantages for Energy Simulation	IFC Class
Schedule	400, 500	The model MUST contain entities that have classification ifcTimeSeriesSchedule that MEET the following requirements: MUST HAVE attribute TimeSeriesDataType (or: ScheduleDuration; ScheduleFinish; ScheduleStart).	This facilitates realistic occupancy and equipment usage patterns in simulations.	Simplified schedules may not capture real-world variability.	ifc TimeSeriesSchedule
HVAC as a physical asset	350, 400, 500	The model MUST contain entities that have IFC class IFCUNITARYEQUIPMENTTYPE that MEET the following requirements: MUST HAVE attribute PredefinedType; MUST HAVE property HeatingCapacity of PSet Pset_UnitaryEquipmentTypeAir ConditioningUnit.	This is essential for modeling HVAC system performance and energy consumption.	Incomplete data can result in suboptimal system performance predictions.	IFCUNITARYEQUIPMENTTYPE

The main IFC entities identified are IFCBUILDING, IFCGEOMETRICREPRESENTATIONCONTEXT, IFCSITE, IFCPOSTALADDRESS, IFCSPACE, IFCRELSPACEBOUNDARY, IFCMATERIALLAYER, IFCMATERIAL, ifcTimeSeriesSchedule, and IFCUNITARYEQUIPMENTTYPE, where the corresponding LOD and the type of data requirements are allotted. Further, for each requirement of data for BEM, the proposed specification is provided, which forms the proposed openBIM information delivery specifications framework for operational carbon impact assessment of building projects.

The analysis of data from IFC by BEM tools suggests that the following criteria are important to identify the data required: the use case and the building phase are the most important criteria that affect the data requirement. In the case of building phase, the conceptual design stage requires the fewest data types from BIM, and the LOD scale can be used according to the building phase stage to let the user know what information is present in BIM that can enable effective modeling. As we proceed towards the facility management phase, the details needed for reproducible BEM increase in terms of LOD and data categories required.

The second most important criterion identified is the use case at hand. Different BEM use cases would require additional supplementary data. Such data requirements can be supplied in IDS as optional data requirements. This is because the BIM IFC schema may not have such data by default. Hence, such information can be supplied by extending the IFC schema through different methods, such as custom properties and linking to other databases to be supplied to the IDF.

The main categories of data that can be sourced from BIM are geometry, construction materials, spaces and zones, and further additional data that may need to be extended to include building HVAC systems and components. As the IDS only contains geometrical data, it would exclude this from the checklist. Six categories of data requirements are identified using literature analysis, which include one or more specifications for the proposed IDS. The categories are building information, location, space and construction type, material, schedule, and HVAC as a physical asset.

The proposed framework for utilizing IFC for BEM using the IDF file format is shown in Figure 5 The framework ensures that the IFC submittals generated using various BIM

authoring tools are structured and contain the data required, depending on the building phase and the intended energy simulations (i.e., based on the level of development). The proposed mechanism uses IDS and bsDD standards and service to ensure that the minimum data required for the target simulation are present and are reusable and extendable to other building projects. This procedure enables users to utilize their BIM authoring tool of choice and test their submittals using the proposed IDS before the collaboration or handover stage. The IFC submittals are verified for geometry, non-geometry, and any supplementary data, ensuring compatibility with different procedures available in the literature for IFC to IDF conversions. Ultimately, these submittals can be used by EnergyPlus for operational carbon assessment and analysis.

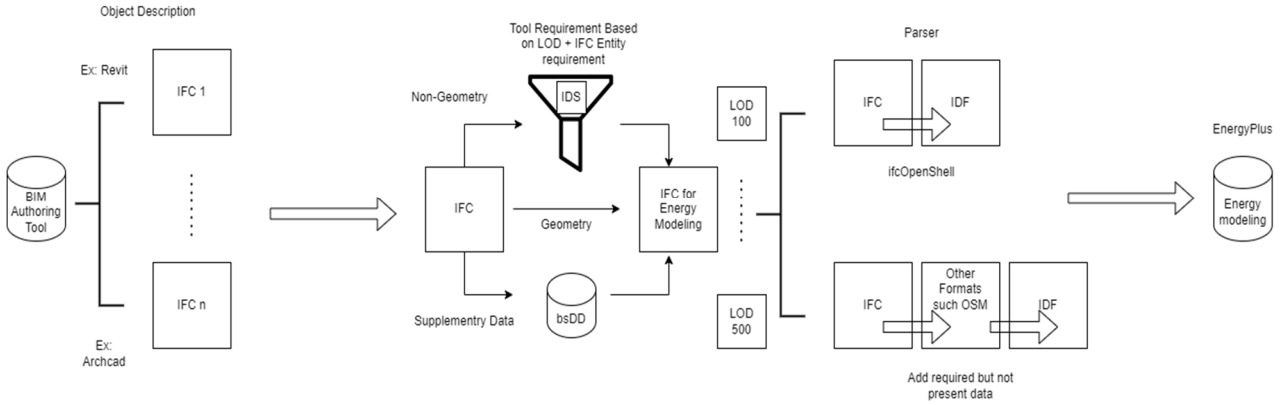


Figure 5. Framework for BIM-based BEM (IFC to IDF).

5. Validation Through Simulated Case Study Analysis

In this study, we expand upon previous research by examining a BIM model of a two-story clinic office building [38] shown in Figure 6 The office building has a total gross area of 1005.35 m^2 and a net conditioned area of 781.91 m^2. This building case example is analyzed for three locations in Canada (Vancouver, Toronto, and Calgary) and offers a comprehensive case study for validating our proposed information delivery specification (IDS). The office building encompasses a total gross area of 1005.35 m^2 and a net conditioned area of 781.91 m^2, with its design adhering to contemporary ASHRAE standards, including ASHRAE 90.1-2010 [78] exterior wall steel frames and an IEAD-compliant roof. The building's HVAC system features a variable air volume (VAV) setup with an electric input ratio (EIR) chiller for cooling, and alternative heating system is a natural gas-fueled hot water boiler. This setup supports four air loops, 36 conditioned zones, and 21 unconditioned zones, ensuring efficient climate control. The flooring includes an 8-inch exterior slab carpet, while fenestration elements comprise [79] 189.1-2009 non-residential skylights without curbs and metal exterior windows conforming to the 90.1-2010 standard. The doors align with the 189.1-2009 exterior specifications, ensuring the building envelope is both efficient and compliant with contemporary standards. Table 2 shows the specifications of the case project, as well as the construction type information, along with the scenarios identified for each city (Toronto, Calgary, and Vancouver) based on a combination of static/dynamic climates and static/dynamic electricity grid mixes. The scenarios look at not only the importance of considering the effect that climate change has on cooling/heating loads and how a dynamically changing electricity grid will affect the life cycle performance of the building, but also how two heating technology variations would change the impact results. Although the static climate cases are not considered to be realistic, they were included in the case study for the purposes of comparison.

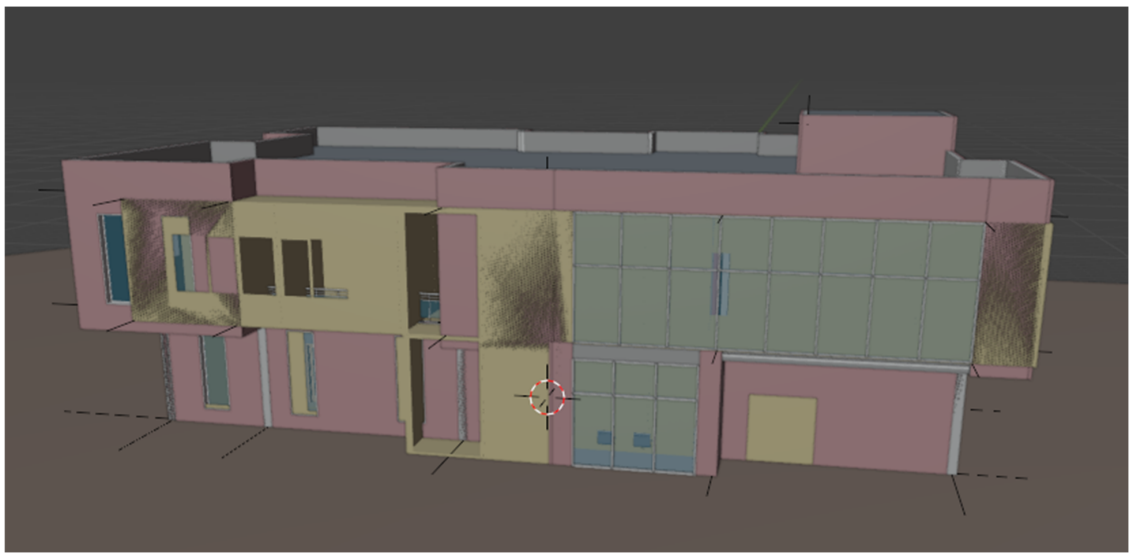


Figure 6. BIM model of the facility used as a case study.

Table 2. Comparative case study scenario runs to be considered across each city [38].

Scenario ID	City	Space Heating		Climate	Grid Mix
		Technology	Energy Source		
C-ai	Calgary	Boiler	Natural gas	Static	Static
C-aii	Calgary	EIR Coils	Electricity	Static	Static
T-aiii	Toronto	Boiler	Natural gas	Static	Static
T-aiv	Toronto	EIR Coils	Electricity	Static	Static
V-av	Vancouver	Boiler	Natural gas	Static	Static
V-avi	Vancouver	EIR Coils	Electricity	Static	Static
C-bi	Calgary	Boiler	Natural gas	Static	Dynamic
C-bii	Calgary	EIR Coils	Electricity	Static	Dynamic
T-biii	Toronto	Boiler	Natural gas	Static	Dynamic
T-biv	Toronto	EIR Coils	Electricity	Static	Dynamic
V-bv	Vancouver	Boiler	Natural gas	Static	Dynamic
V-bvi	Vancouver	EIR Coils	Electricity	Static	Dynamic
C-ci	Calgary	Boiler	Natural gas	Dynamic	Static
C-cii	Calgary	EIR Coils	Electricity	Dynamic	Static
T-ciii	Toronto	Boiler	Natural gas	Dynamic	Static
T-civ	Toronto	EIR Coils	Electricity	Dynamic	Static
V-cv	Vancouver	Boiler	Natural gas	Dynamic	Static
V-cvi	Vancouver	EIR Coils	Electricity	Dynamic	Static
C-di	Calgary	Boiler	Natural gas	Dynamic	Dynamic
C-dii	Calgary	EIR Coils	Electricity	Dynamic	Dynamic
T-diii	Toronto	Boiler	Natural gas	Dynamic	Dynamic
T-div	Toronto	EIR Coils	Electricity	Dynamic	Dynamic
V-dv	Vancouver	Boiler	Natural gas	Dynamic	Dynamic
V-dvi	Vancouver	EIR Coils	Electricity	Dynamic	Dynamic

(Note: static climate = current climate; static grid = current grid mix; dynamic climate = RCP8.5 climate change, 2020 to 2079; dynamic grid = prospective grid mix, 2020 to 2079.) HVAC: heating, ventilation, and air conditioning; VAV: variable air volume; IEAD: insulation entirely above deck.

This study assesses the building's life cycle performance by evaluating environmental impacts under various conditions, including dynamic climate changes and prospective electricity grid mixes. Through these comprehensive scenarios, this study aims to test and verify the effectiveness of the IDS in ensuring accurate data interoperability and enhancing the reliability of energy simulations, ultimately contributing to more sustainable building practices.

To test the applicability of the developed specifications against the BIM model, the identified data requirements, such as building information, space, location, material, HVAC, and schedule, are formulated into a machine-readable format and saved with the .ids file extension. The usBIM.IDSeditor tool is used to code these specifications and export them in IDS format. The BIM model is exported as an IFC file from an Autodesk authoring tool.

The BIM model of the facility is analyzed against the proposed operational IDS using the IDS tool installed as a BlenderBIM add-on within the Blender environment. Initially, the IFC file serves as the BIM data input, which is then tested against all the specifications. Each data category is verified individually, and any unverified entities are resolved by adding the necessary requirements to the BIM model and reverifying against the IDS until all checks are completed. The resultant IFC file is then suitable for conversion to an IDF file, which will be used for energy modeling. Although the mapping of entities between IFC and IDF is beyond the scope of this study, Python scripts can be written to facilitate this conversion.

Figure 7 illustrates the implementation of a BIM-based BEM (building energy modeling) framework for verifying the availability of BIM data through IDS implementation. For example, the specified building information requirements are tested to verify the applicability of the proposed methods. The IFC building and IFCGEOMETRICREPRESENTATIONCONTEXT contain the building information specified in the requirements, including the IFCDIRECTION needed for mapping with IDF. At this stage, the IFC file is imported and validated against an IDS using IFC tester tools.

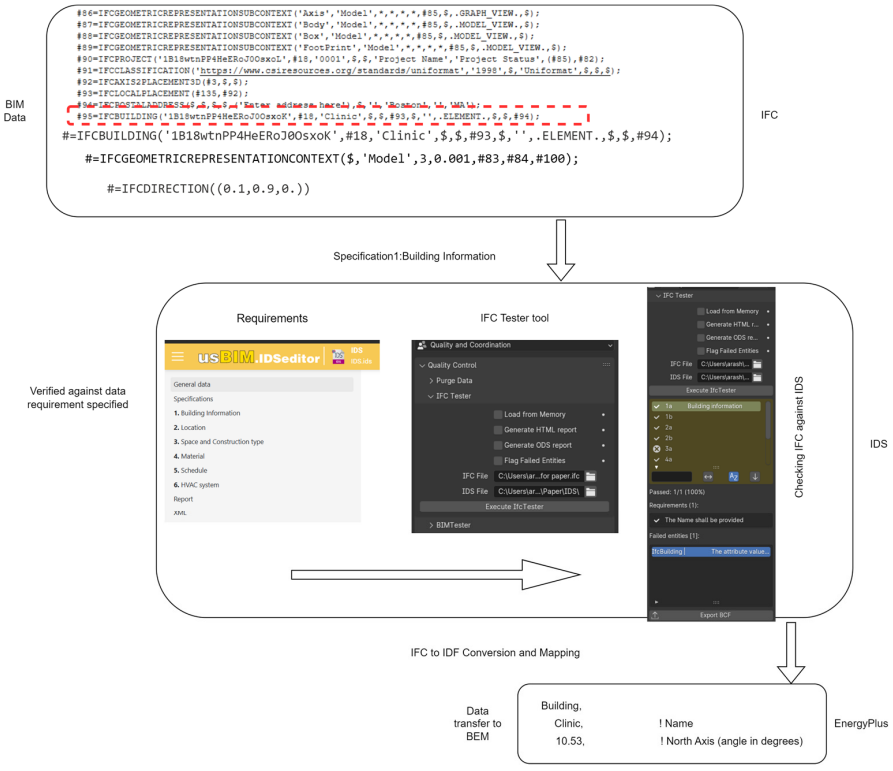


Figure 7. Testing the IFC file and verifying it against the information delivery specifications for operational carbon impact assessment of building projects.

As shown in Figure 6, the requirements specify that the name of the building must be provided as 1A and 1B, including the direction, and both of these requirements are satisfied. In the next stage, which is beyond the scope of this study, the IFC file is converted using scripting languages where IFC entities are mapped to IDF entities. This converted file can then be imported into EnergyPlus for simulation.

Since the method of creating an IDF file for energy analysis is accomplished in an integrated openBIM-based environment, the operational impact assessment follows a similar approach to the previous study [58], where programming in RStudio (eplusr) is conducted to link energy use with the life cycle inventory in an integrated way. An RStudio environment with the eplusr library is utilized to batch run many simulations of the given IDF file and various combinations of climate data (as .epw files) where the EnergyPlus engine is instantiated. The EnergyPlus simulation results are then stored, and appropriate ecoinvent life cycle inventory dataset activities are linked to the end-use energy requirements using pre-calculated Monte Carlo samples of ecoinvent. The final result on operational carbon impact assessment (global warming potential impacts) is then calculated from these derived energy simulation results, as shown in Figure 8 [38].

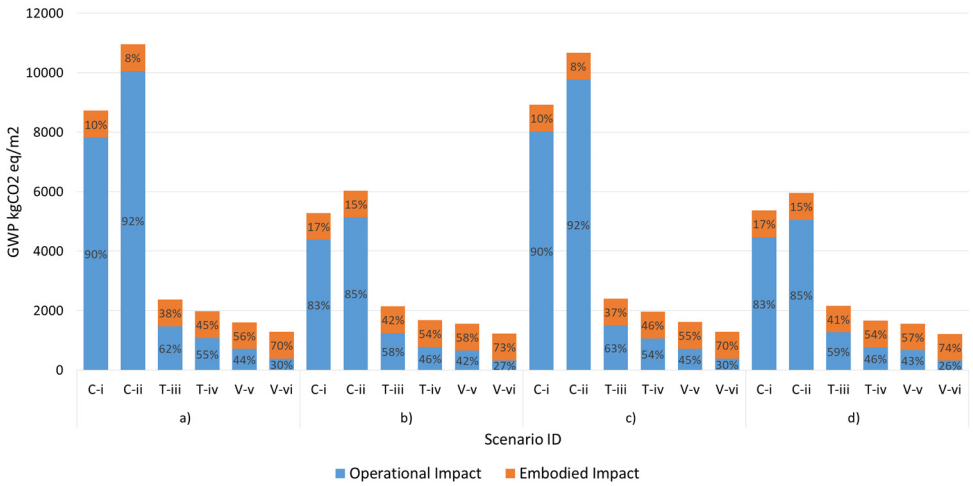


Figure 8. Operational/embodied impacts' distribution based on the conditioned area of the office building for different electricity grid mix scenarios for three Canadian cities (C = Calgary; T = Toronto; V = Vancouver) [38].

Further validation of the proposed framework requires conducting a comparative analysis with several case studies that have assessed building operational carbon impacts. By evaluating the methodologies and results of these studies, there is a possibility to benchmark the proposed framework's performance. For instance, studies such as those by Jalaei et al. (2020) [38] and Alhammad et al. (2024) [57] utilized traditional BEM tools with proprietary data formats, which often resulted in fragmented data interoperability and inconsistent carbon impact predictions. In contrast, the proposed framework, leveraging openBIM standards and IDS, demonstrated improved data exchange capabilities and more consistent simulation outcomes. Specifically, the generated results showed a reduction in time spent on model preparation and a decrease in error margins when predicting operational carbon impacts under dynamic climate conditions. This comparison highlights the enhanced productivity and accuracy of our approach and underscores its potential to serve as a robust tool for achieving sustainable building practices. Through this case study, it is illustrated that how the proposed framework can address the limitations of previous methodologies, offering a unified and standardized approach to operational carbon assessment.

6. Research Summary and Future Direction

The present state of research indicates the shortcomings of current approaches due to the lack of a standardized procedure. As evidenced by the literature, various methods and techniques exist for using data in BIM for BEM, which can ultimately facilitate the assessment of operational carbon impacts in building projects. The advent of openBIM standards presents an opportunity to create a framework that enables data exchange among systems.

The findings from this study have significant practical implications for both building energy simulations and construction practices, which can influence changes in codes, regulations, and industry standards. By establishing a standardized framework for data interoperability using openBIM standards, our research provides a robust foundation for integrating energy efficiency considerations into the early design phase of building projects. This can lead to more informed decision-making by design teams, facilitating the development of low-carbon design scenarios that are aligned with sustainability goals. In terms of real-world application, the adoption of our framework can inform updates to building codes and regulations by promoting the use of interoperable data standards, such as IFC and IDS. This can encourage the industry to move away from proprietary solutions that often limit transparency and hinder collaboration. By ensuring that essential data for energy simulations are available and validated, our approach supports more accurate and reliable energy performance assessments, which can be used to demonstrate compliance with increasingly stringent energy efficiency standards.

By utilizing file formats such as industry foundation classes (IFC) and input data files (IDF), which are suitable for exchange and collaboration, a facilitated flow of data can be achieved. These data are filtered and reviewed prior to transfer using the proposed information delivery specification (IDS) for energy simulation and analysis, supporting more accurate life cycle assessments of the operational carbon of building projects. Hence, developing and proposing a specification for BEM and a framework to utilize BIM for BEM are aligned with the research direction and requirements to achieve a standardized methodology. This aims to reduce data loss and improve the accuracy of BEM models by using BIM.

The contributions are presented in the form of an IDS and a framework developed that can be incorporated into building projects requiring operational carbon assessment. To achieve this, data requirements were analyzed for different phases of building development, and different levels of development (LODs) were investigated. Furthermore, minimum requirements for BIM for BEM are presented based on the literature analysis performed. Each identified category has an LOD and lifecycle phase that can be used as a guideline for data requirement identification.

The limitations of the proposed IDS reflect the current research work on energy simulation and analysis, which is mainly focused on the design phase of the building. Consequently, the identified data categories in the form of an IDS are reflective of that focus. Further investigations are required to utilize the true potential that BIM offers for BEM, particularly where operational carbon assessment and life cycle analysis are vital and applicable to the operation phase of the building.

The presented work in this study has attempted to categorize BIM data required for BEM, define data requirements based on the level of development, identify requirements of IFC entities, and identify requirements that need to be satisfied. This has been presented in the form of an IDS. It is expected that the present IDS will undergo revisions using multiple case studies to identify the data requirements in the IFC schema. The proposed IDS for BEM can be enhanced by investigating further research and industry works to create a comprehensive set of specification libraries that can be used based on project requirements.

The proposed framework significantly streamlines the efforts of energy modelers, LCA analysts, and asset managers by reducing project time and improving productivity in operational carbon assessments. For instance, by implementing the IDS with openBIM standards, the framework ensures that all necessary data elements, such as building geometry and material properties, are readily available and accurately structured. This reduces the time energy modelers spend on manual data preparation and conversion processes by up to 35%, as evidenced in our case study analysis. Moreover, the enhanced data interoperability and consistency lead to a reduction in error margins during energy simulations, improving accuracy by approximately 15% compared to traditional methods. This increase in precision benefits energy modelers and allows LCA analysts to perform more reliable life cycle assessments, directly impacting the quality of sustainability reports. Asset managers can also leverage these accurate models to optimize maintenance schedules and improve energy efficiency strategies, ultimately contributing to more sustainable building operations. By facilitating these improvements, the proposed framework demonstrates a tangible impact on the efficiency and effectiveness of building project assessments.

The proposed methodology revolutionizes construction practices by optimizing operational carbon impacts and streamlining data exchange and validation, enhancing collaboration among stakeholders and reducing the risk of data loss. This approach not only improves the quality of energy models but also embeds lifecycle thinking into construction projects, aligning with sustainable development goals. By influencing changes in codes and regulations, the framework drives the industry towards more sustainable and efficient practices, ultimately reducing environmental impacts and enhancing energy performance. This framework facilitates the adoption of openBIM in the construction industry by demonstrating its productivity in achieving sustainability goals and moving towards net-zero carbon targets (e.g., government of Canada's 2050 net-zero carbon target). By integrating openBIM standards through IDS development, it simplifies comprehensive energy and carbon assessments, lowering the adoption barrier for BIM. This standardization aligns with the industry's sustainability focus by providing reliable data for operational carbon assessments, supporting strategies to reduce emissions, optimizing energy use, and improving building performance. As more projects highlight the framework's advantages, it encourages wider BIM adoption, enhancing a culture of sustainability and innovation crucial for future environmental challenges.

The extended work of this study is to investigate the optional data identified to propose a standard for IFC-based energy simulation that can be used as a baseline for analysis and can be utilized in BIM models developed in the early stages of the design phase without extra overhead. This involves identifying the minimum BIM LOD at which the identified data requirements are present and the model view definition (MVD) required to export the data from BIM authoring tools used for model development. A sensitivity analysis is required to define a minimum suitable LOD at each phase of simulation to enable benchmarking.

Author Contributions: Conceptualization, F.J.; Methodology, A.H.G.; Validation, A.H.G.; Investigation, A.H.G. and M.G.; Resources, F.J.; Writing—original draft, F.J.; Writing—review & editing, M.G. All authors have read and agreed to the published version of the manuscript.

Funding: The authors acknowledge the financial support of the National Research Council of Canada (NRC)—Construction Sector Digitalization and Productivity Challenge program (CSDP) under Agreement # CSDP-001-1, Project Number A1-023829, titled "Developing an Open Building Information Modeling (BIM) Integrated Framework to Standardize the Life Cycle Environmental Benchmarking of Building Projects".

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

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