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Bridging Interoperability Gaps Between LCA and BIM: Analysis of Limitations for the Integration of EPD Data in IFC

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Abstract

The construction industry is a major consumer of raw materials and a significant contributor to environmental emissions. Life cycle assessment (LCA) using digital models is a valuable tool for conducting a science-based analysis to reduce these impacts. However, transferring data from environmental product declarations (EPDs) to BIM for the purpose of sustainability assessment requires significant resources for its interpretation and integration. This study is founded on a comprehensive review of the scientific literature and standards, an analysis of published digital EPDs, and a thorough evaluation of IFC (industry foundation classes), identifying twenty gaps for the automated incorporation of LCA data from construction products into BIM. The identified limitations were assessed using the digital model of a building pilot, applying simplifications to incorporate actual EPD data. This paper presents the identified barriers to the automated incorporation of digital EPDs into BIM, and proposes eleven concrete actions to improve IFC 4.3. While prior studies have analyzed the environmental data in IFC, this research is significant in two key areas. Firstly, it focuses on the direct machine interpretation of environmental information without human intervention. Secondly, it is intended to be directly applicable to a revision of the IFC standards.

Keywords: EPD; LCA; automatization; BIM; IFC

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1. Introduction

Buildings accounted in 2023 for 34% of global energy demand and 37% of energy- and process-related CO_2 emissions according to UNEP [1]. The construction sector is also a major generator of waste and, just in the EU-27 in 2018, the total construction and demolition waste accounted for nearly $8.5 \cdot 10^8$ tons according to the EU Science Hub [2]. Digitalization of the construction sector is increasingly recognized as a potential game changer in relation to resource and energy efficiency.

The sustainability challenges posed by climate change, resource depletion, waste generation and other environmental aspects can be addressed by integrating a life cycle perspective into decision-making processes related to the design, construction and operational management of built assets.

Life cycle assessment (LCA) is a standardized, comprehensive methodology used to calculate the environmental impacts associated with a product, system, process or service considering its entire life cycle. LCA can be used to compare different construction methods or materials, and the results can be the basis for public and private procurement, thereby promoting the selection of environmentally preferable products or services. However, both LCA and green procurement must be based on reliable data calculated according to internationally accepted standards.

The international and European standardization organizations ISO and CEN have published a set of standards for the environmental assessment of buildings and civil engineering works based on LCA (see Section 3.1). Manufacturers present the environmental information from their products in environmental product declarations (EPDs) calculated according to ISO 21930 [3] or EN 15804 [4].

The calculation defined in the sustainability assessment standards can be integrated into BIM tools. The use of BIM to design, construct and manage buildings and infrastructures is rapidly growing in Europe, as shown in the analysis from the European Commission [5]. Ahmed, O'Donoghue & McGetrick [6] identified the integration of LCA tools with BIM as an enabler for the implementation of green public procurement (GPP), together with standardization. Nevertheless, the substantial volume of data necessary to perform the LCA of a built asset complicates its utilization for most projects, as it necessitates the consideration of numerous distinct materials. Furthermore, the environmental data is presented in various formats, many of which are non-structured or incompatible with BIM tools.

The predominant digital format used to issue EPDs is pdf, which generally lacks an inherent logical data structure, thereby impeding machine interpretation of the information. The provision of EPD data in BIM-compatible formats, such as IFC, can reduce the effort required to use environmental information in digital models.

IFC (see Section 3.3) is the main format used in the BIM environment, primarily due to its role as an open, vendor-neutral, and internationally recognized standard developed by buildingSMART and ISO. It represents a universal language for construction information, ensuring seamless data exchange and interoperability between diverse software applications and disciplines throughout the entire building lifecycle. Dervishaj & Gudmundsson [7] provides a comprehensive assessment of digital approaches for the integration of LCA in circular design strategies, addressing interoperability aspects and the link with regulations and standards. The integration of LCA into BIM with plug-ins is analyzed as a promising solution. However, the use of plug-ins presents several limitations, as the data will have limited interoperability across the system. Therefore, this paper proposes the integration of LCA data into the official IFC schema.

The current schema (IFC 4.3, see Section 3.3 for more information) is not entirely machine-interpretable for environmental information, requiring significant effort to incorporate LCA data into BIM. The primary resource employed in this process is the *time* consumed by practitioners and experts in the analysis, validation, modification and transfer of the data.

To provide a BIM-compatible structure, the international standard ISO 22057:2022 [8] defines the data templates for EPD data. The research in Aragón & Alberti [9] and in Aragón, Nieto et al. [10] examined the specific gaps applicable to the computer interpretability to propose a revision of this international standard. The analysis was partially based on the results of a survey conducted with EPD and BIM experts such as the members of ISO/TC 59/SC 17/WG 3, the group in charge of the development of ISO 22057, including some questions related with IFC. Forty-five experts from seventeen countries completed the survey, representing different producers and users of environmental product information. The survey demonstrated the importance of improving the structure for LCA data in IFC, as a substantial proportion of respondents perceive that the issue remains unresolved in the current schema (see Figure 1).

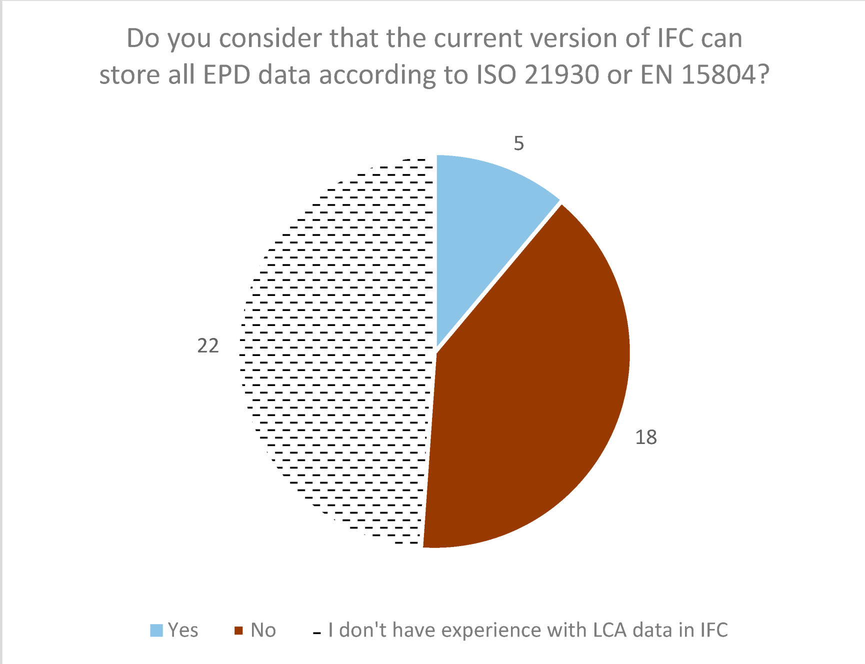

Figure 1. Responses to the question related to the possibility of storing EPD data in the current IFC schema.

It is imperative to distinguish between digital EPDs (dEPDs) and EPDs presented in a digital format (e.g., pdf). dEPDs should be understood as EPDs issued in a **machine-interpretable structured format** that can be seamlessly transferred to other tools (e.g., BIM software) with minimal or no human intervention.

Machine interpretability of the IFC schema should be improved with a revision of the current version, to allow direct transfer of environmental information from construction products info BIM. This revision should align with ISO 22057 to ensure a seamless transfer of LCA-based product information into digital models.

The overarching goal of the authors is to promote the use of life cycle assessment during the design, construction and operation of built assets, by reducing the resources required to transfer product data into BIM.

The **purpose** of this paper is to define concrete improvements to the IFC 4.3 structure with a view to making environmental information machine-interpretable, in order to bridge the gap between digital EPDs and BIM tools.

The **scientific question** that guided the study was as follows: What are the gaps that limit the machine interpretation of LCA data in IFC 4.3, and how can these gaps be bridged?

The **significance** of this study lies in its pragmatic approach, which is focused on current industry practices and standards. Furthermore, it is novel in its analysis of the gaps between EPDs and IFC, a topic which has been addressed in few scientific papers. Previous publications have described limitations of IFC with regard to the storage and transfer of EPD data. However, there is a lack of research in this area, particularly in terms of proposing concrete modifications to the IFC schema to ensure machine interpretability of LCA data. Furthermore, the integration of IFC with ISO 22057, as the main international standard for BIM-compatible data templates for EPDs of construction products, has not been thoroughly addressed with enough detail in published research. As described in the conclusions, the potential for direct application within the standardization system further substantiates the significance of this paper.

2. Materials and Methods

The research is based on a comprehensive assessment of the state of the art described in Section 3. The analysis of the current situation is based on the following sources of information:

1. Analysis of the current version of IFC, of the main EPD standards (EN 15804, ISO 21930 and ISO 22057), and the ongoing developments related to the digitalization of construction product information in the BIM standardization committees (ISO/TC 59/SC 13 and CEN/TC 442). In particular, the European project WI 0442061 defining the digital declaration of performance and conformity of construction products [11] was considered. A sample of dEPDs from programme operators (POs), available in the ILCD + EPD format in the ECO Platform portal [12], was analyzed for discrepancies with the IFC elements. The EPDs were selected to represent a range of POs and product families, and the availability in English was a requirement. Each indicator in the EPD was analyzed to determine its correspondence (or lack thereof) with an existing IFC element.
2. Gaps related to the integration of LCA data in other formats (e.g., ISO 22057 or ILCD + EPD) identified in [9,12]. The conclusions of these studies were assessed and summarized to evaluate its applicability to the IFC schema, testing the assumptions with the use case (the BIM model described in Section 4.3).
3. Gaps related to the integration of LCA data in BIM identified in previous research not identified in [9,12]. It was based on a search in major journals with combinations of the keywords BIM, EPD, EN 15804, ISO 21930, life cycle assessment, LCA, IFC, ISO 22057, DPP, digital product passport, construction products, buildings, and built assets. As the research conducted in [9,12] was recent, few additional limitations were found in these queries.

The research also considered the practical experience of the authors in the fields of LCA, EPD development and verification, modelling of buildings for sustainability assessment purposes, policies related to construction products and scientific research. This experience was very valuable to identify limitations and bottlenecks in the process of transferring LCA-based data into BIM.

The gaps identified during the research were analyzed considering the environmental parameters defined in the core EPD standards (EN 15804 and ISO 21930), EPDs published by POs, the international standards defining requirements for data templates, and the DPP for construction products defined in the Regulation (EU) 2024/3110 on construction products (new CPR) [13]. The research assigned each EPD parameter (impact category or indicator) to an IFC element, when possible, and identified the gaps (e.g., information which cannot be stored in IFC 4.3). For some of the identified limitations, a tentative solution or action is defined. The analysis is described in Section 4 and summarized in the conclusions.

Adding customized properties is a widely used strategy, useful for projects within the same organization or groups of organizations. However, it limits the interpretation in different software tools or across systems. Therefore, this paper proposes a common and globally standardized structure for LCA-based product data.

The preliminary solutions were tested in the digital model of one of the five pilots [14] from an EU-funded research project, CHRONICLE (see Section 4.3). CHRONICLE develops digital tools to improve building performance by monitoring energy consumption, comfort, and assisting with renovation and maintenance planning. These tools will help establish good building practices by considering environmental, social, technical, and financial aspects. The selection criteria for the pilot were the maturity of the BIM model (as IFC), the availability of EPD data of its constituent materials, and the replication potential. The selected building is a former commercial building located in Zaragoza (Spain) that has been refurbished and repurposed as a social housing block. It has a building typology very common in Spain, including the heating systems. The building is equipped with IoT devices, enabling researchers to access real-time data concerning energy performance. However, this information was not incorporated as part of the testing because it does not originate in EPDs. The objective of verifying the applicability of the results to a use case was to confirm, or reject, the hypothesis related to the limitations for the interoperability between LCA and BIM with current software tools. The analysis performed does not consider the accuracy of the model itself in relation to the LCA results (impact categories, such as GWP, or other environmental indicators). It focuses exclusively on the resources (mainly time) required for the validation (applicability to the actual building), modification and transfer of EPD data to the IFC model in the options under study. The primary limitations of this testing in a real case were the simplifications implemented in the modelling of the options, not considering the unique identification of the LCA calculation method used for each impact category. It is important to note that the authors do not propose to define new entities in each model (entity extensions), as this approach endangers interoperability across systems. The proposal of new entities used in the pilot intends to provide insights in order to make concrete proposals for a revision of the official IFC schema, thereby ensuring the standardization of these entities across systems.

The gaps and the proposed solutions, described in Sections 3 and 4, are summarized in the conclusions (Section 5). The methodology is represented in Figure 2.

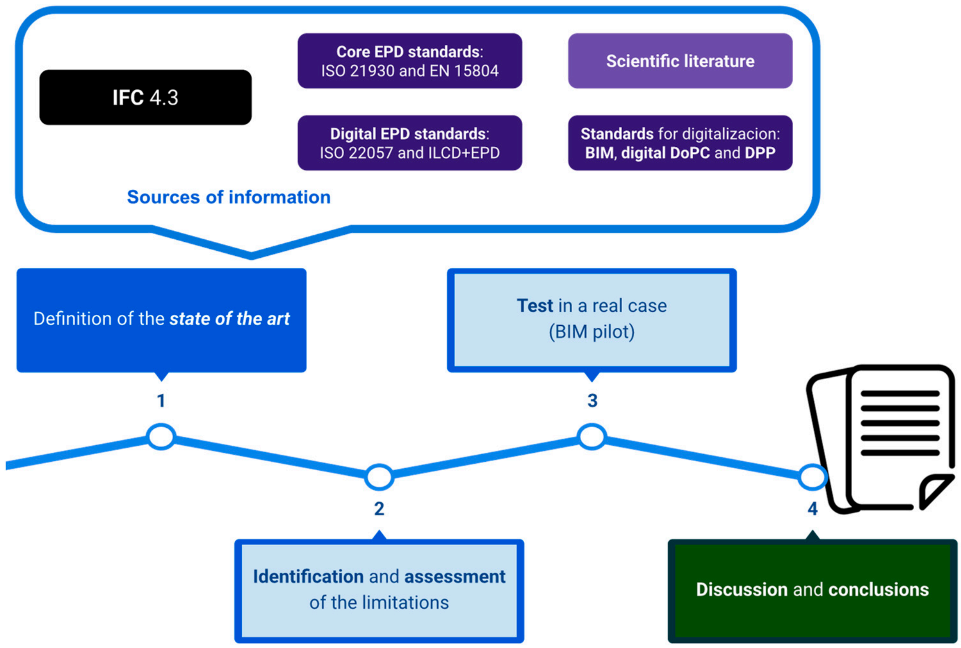

Figure 2. Methodology.

The testing with an actual building (pilot) presents several limitations related to the simplifications applied to incorporate EPD data. The incorporation of user-defined properties was applied to verify options to store LCA data, but it is not considered a suitable option unless incorporated into the official IFC schema. Moreover, further research is required to incorporate EPD data compatible with ISO 21930 and EN 15804 into the IFC schema. Some of these lines for future research are proposed in the conclusions.

3. State of the Art

This section describes the state of the art related to the digitalization of construction products' information and, in particular, LCA-based environmental data. It also addresses how environmental information from construction products is aggregated for the sustainability assessment of buildings and infrastructure. It is based on published research papers, international and European standards, and in European policy, in relation to the limitations of this current situation in relation to the digitalization of EPD data.

3.1. LCA and EPD Standards

ISO/TC 59/SC 17, at an international level, and CEN/TC 350, for Europe, describe a methodology for the environmental assessment of construction assets based on LCA. The methodology for the environmental assessment of buildings is defined in the international standard ISO 21931-1:2022 [15] and in the European standard EN 15978:2011 [16]. A revised version of the standard for buildings (EN 15978:2025) will be available in December 2025 if the CEN Formal Vote is approved in October. For civil engineering works (CEWs), the relevant standards are ISO 21931-2:2019 [17] and EN 17472:2022 [18]. The assessment at building or infrastructure level according to these standards requires data from their constituents, i.e., construction products and materials.

The main sources of environmental data for these constituents are EPDs, a tool to communicate standardized LCA results calculated according to the international standards EN ISO 14025 [19], which defines the criteria and requirements for EPDs, and EN ISO 14040 [20] and EN ISO 14044 [21], which defines the requirements for the LCA. These standards are applicable to any product and can also be used for services. EPDs require horizontal rules for each product grouping, called PCR (product category rules), defined as a group of products that can fulfill equivalent functions. To avoid confusion between the terms used in ISO 14025 and in the new CPR, this article uses the terminology proposed in Aragón & Alberti [9]. Therefore, the term *EPD category* is used in place of *product category*, but maintaining the abbreviation PCR. EN ISO 14025 is currently under revision and the DIS ballot concluded on 26 June 2025, with a positive result. The definition of *product category* remains.

For construction products and materials, the PCRs are defined in ISO 21930:2017, at a global scale, or EN 15804:2012+A2:2019, for Europe. One of the improvements of EN 15804+A2, compared to its previous version, was the alignment with the international standard in terms of modules, impact categories, and other relevant LCA criteria.

CEN and ISO standards use impact categories and other indicators to describe the environmental performance of buildings and infrastructures presented with a modular approach. The modules have been expanded into the latest version of CEN/TC 350 standards and are listed below:

- Non-physical processes before the construction (A0): Studies, tests, acquisition, etc.
- Product stage (A1–A3): Raw material extraction and sourcing, transport to the factory and manufacturing.
- Construction process stage (A4–A5): Transportation to the site and incorporation (e.g., installation) of the product into the built asset.
- Use stage (B1–B8): Use-related processes and maintenance, repair, replacement or refurbishment activities. It also includes operational energy and water consumption.
- End-of-life stage (C1–C4): It includes the removal or the product and deconstruction processes, the processing for reutilization or recycling, disposal and all the related transports.

- Benefits and loads beyond the built asset LCA boundaries (D1–D2): It includes the net flows from reuse, recycling and recovery as well as the exported utilities (e.g., energy or potable water).

Modules A0, B8, D1 and D2 were not included in ISO 21930 or EN 15804+A2, as these standards were published before the new modules were incorporated into the life cycle stages. However, they should be incorporated into the new versions of these standards and will be needed for the environmental assessment of buildings according to the future standard EN 15978:2025. The standard also subdivides some existing modules (see Section 4.2), e.g., B6 can be structured into B6.1, for the energy consumption of regulated building integrated systems, B6.2 for the energy consumption of unregulated building integrated systems, and B6.3 for user-related energy consumption.

3.2. Digital EPDs

Digitalization of EPDs is a critical element for the environmental assessment of built assets. This research is based on the conviction that digital EPDs should be structured to ensure not only machine readability, but also machine interpretability, thereby reducing the resources required to perform the LCA by automating data interpretation and transfer. These tasks currently require the time-consuming analysis of experts.

There are several digital formats available for transferring LCA data into BIM or other software tools. However, there are limitations that may hinder the use of EPDs due to the cost and resources required for human interpretation of the content (including hypothesis) or transferring the data into BIM. The lines of future research identified in [9] include the assessment of its application to particular formats, such as ISO 22057, ILCD+EPD or IFC.

The results of Aragón, Nieto et al. [10] include nineteen gaps applicable to ISO 22057 dEPDs, which have been analyzed in this research to assess their applicability to IFC.

Olanrewaju et al. [22] recommended several actions to improve the data quality of digital EPDs related to the results of this paper, in particular:

- Harmonization among LCA data or EPD issuers and users (manufacturers, LCA practitioners, EPD programme operators, etc.).
- Standardization of EPD data generation and reporting, including traceability of environmental impact data.
- Interoperability between EPD databases and BIM.

3.3. Industry Foundation Classes

The Industry Foundation Classes (IFC), defined in the IFC Specifications Database [23], is a standardized data structure that allows for the transfer of information within various systems using digital models employed in the construction sector. It facilitates a seamless exchange of data using several IFC file implementations (formats). The IFC structure encompasses various types of properties or attributes, including geometric data, physical properties, environmental-related information, and other relevant characteristics. BuildingSMART and ISO have continuously updated IFC to address the changing requirements of contemporary building and infrastructure projects.

The first official version of IFC, released in 1997 (IFC 1.0), established a framework for representing and exchanging construction and facility management data. BuildingSMART commenced a collaboration with the International Organization for Standardization (ISO), which culminated in the publication of the document ISO/PAS 16739 [24] in 2005. BuildingSMART and ISO continued their cooperation and published the first version of IFC as an international standard: ISO 16739:2013 [25]. This standard was revised in 2018, and the current edition was published in March 2024 as ISO 16739-1:2024 [26]. The latest international standard corresponds to IFC 4.3 ADD2 version according to buildingSMART naming convention and includes, among other improvements, a schema for civil engineering projects, allowing IFC to cover more typologies of construction assets. There are two versions under development: IFC 4.4, improving the structure of IFC 4.3, and IFC 5, which will change the approach of the data structure. However, the present study concentrates exclusively on IFC 4.3, disregarding the versions currently under development. This decision is based on the objective of concentrating the assessment on a finalized version, one that may incorporate feedback from industry based on actual experiences.

IFC uses the Standard for the Exchange of Product (STEP), defined in ISO 10303 set of standards, to transfer product data across different software applications and computer systems. The IFC definitions are documented using EXPRESS (defined in ISO 10303-21:2016 [27]), a conceptual schema used to specify classes for a defined domain, the data, attributes or constraints relevant for certain classes, and also the relations between classes. An XML implementation of the STEP format based on ISO 10303-28:2007 [28] can be used for IFC data representation and exchange. The IFC data formats and their internal mappings are described in Xu, Kim and Chen [29]. The IFC schema is organized into four conceptual layers, as described by buildingSMART [30] and Youngsu et al. [31]:

1. The domain layer is the highest layer, facilitating the intra-domain exchange and sharing of information, providing model details for a domain process or a type of application (e.g., structural engineering or HVAC). It encompasses schemas that comprise entity definitions, which represent specializations of products, processes or resources that are discipline-specific.
2. The interoperability layer facilitates the inter-domain exchange and sharing of construction data across different architecture or engineering disciplines, providing definitions of concepts or objects common to different domains or applications. It encompasses entity definitions that are specific to the general product, process, or resource specializations applicable across multiple disciplines.
3. The core layer provides the basic structure of the IFC object model and defines the abstract concepts that will be defined in higher layers. It incorporates the kernel and core extension schemas, including a globally unique identifier (GUID) for all the entities and other relevant information.
4. The resource layer is the lowest layer, facilitating the definition of individual schemas containing resource definitions for geometry, material, quantities, etc. These definitions will not generally include a GUID and will be used in relation with the definitions from other layers.

One of the limitations of IFC is the incomplete implementation in several domains, such as the environmental information covered in this paper. Some solutions to address this limitation will compromise machine interpretation in different systems. One example is the entity extension, a method that allows users to define new entities. As these new entities are not globally standardized, they can only be used by their authors or by software customized with these subtypes. To circumvent this limitation, it is imperative to implement a centralized or semi-centralized data dictionary in conjunction with a governance system. The buildingSMART Data Dictionary (bSDD) [32] can be considered a solution to address the management of new entities and files which can be interpreted not only by humans, but also by machines, and can display the information in different human languages. The current version of bSDD contains certain indicators based on ISO 21930:2017. Kładź & Borkowski [33] showed the impact of bSDD, in combination with an Information Delivery Specification (IDS) and data dictionaries, for the automation of information exchange and for the verification of data in construction projects.

bSDD can be used in conjunction with an information delivery specification (IDS) defining specific requirements for environmental data exchange within the BIM project.

This relation can ensure semantic interoperability. The IDS, typically at the beginning of a project, defines a machine-readable format specification, covering the necessary attributes of elements that are not part of the predefined IFC schema. The principle is based on the mapping of required attributes to IFC classes, and the description and standardization, including units of measure, data types, formats and other relevant metadata, which can be presented in either human-readable or machine-readable formats. IDS can be used to create machine interpretable requirements and, in combination with the bSDD, to validate the LCA information contained in the IFC file.

3.4. LCA and BIM

The use of BIM can increase the capacity to assess life cycle environmental-related indicators of buildings, including carbon emissions and resource consumption. Digital models can reduce the effort of calculating the embodied environmental impacts of built assets, improving the sustainability assessment during the design, construction or operational stages, as shown by Hollberg, Genova & Habert [34]. The integration of LCA in BIM is usually performed in one of the following ways:

- Data management 1: BIM data is extracted and transferred to provide materials and product quantities for LCA calculations. However, as it is based on simplified calculation procedures using spreadsheets or custom tools, it is typically used for basic forms of LCA.
- Data management 2: Use of BIM software plug-ins that allow BIM-integrated analysis and the optimization of design alternatives. Such an approach facilitates continuous analysis that directly reflects impact calculation results.
- Data management 3: Specialized LCA tools are used to support BIM data integration and database management.

IFC allows the inclusion of certain LCA data from EPDs. The element *LifecycleStage* supports the modular approach used to structure the life cycle in ISO 21390 and EN 15804. The environmental indicators are stored in the element *PSet_EnvironmentalImpactIndicators* and the functional unit, as defined in the LCA standards (ISO 14040 and ISO 14044), uses the property *FunctionalUnitReference*. A detailed description and analysis of the limitations of IFC in relation to LCA data are provided in Section 4.2.

There are significant differences in the handling of BIM and LCA data. Klumbyte et al. [35] show that APIs provide satisfactory results on embodied carbon calculations. In addition, as BIM stores multi-dimensional information, it can be effectively used to assess and compare sustainability performance of buildings in relation to their thermal performance, as shown in Spudys et al. [36]. One of the main limitations for the use of LCA in BIM found in Hussain et al. [37] was the effort and resources required for the LCI creation and the data harmonization, and the manual input necessary to transfer data from EPDs (or other sources of data) into BIM tools.

Theißen et al. [38] analyzed 7312 BIM objects and only 5.5% could be directly linked without any adaptation. Other publications stress the number of resources required for the transfer of LCA data into BIM models. Therefore, the use of machine-interpretable IFC formats will enhance the efficiency of environmental assessments of buildings and infrastructure based on digital models.

Forth, Abualdenien & Borrmann [39] provide a thorough explanation of five case studies to calculate the embodied emissions of buildings in early design phases using LCA data integrated into BIM models. It shows the significant time investment required for the interpretation of each element to incorporate any missing or incomplete information. The process of *model healing* outlined in [39] is promising. However, errors in the results or missing data still endangers the reliability for incomplete models. Therefore, the primary approach should be to ensure that IFC can store reliable information, identify mandatory data and apply this *healing* process only to tackle unsolved issues.

3.5. Digital Product Passport and Regulatory Framework in Europe

The new construction products Regulation (new CPR) [13] and the ecodesign for sustainable products Regulation (ESPR) [40], both published in 2024, require manufacturers to provide a digital product passport (DPP) when placing their products in the EU Single Market. The DPP is a digital record of product information related to a model, a batch or an individual item. A data carrier, linked to a unique product identifier physically attached to the product or the accompanying documentation, enables data sharing along the value chain.

The legal provisions of the CPR require interoperability of the DPP data with BIM, with the objective of delivering regulatory-compliant information to design or construction companies, facility managers, public authorities, and asset managers. Data must be provided in accordance with strict content requirements derived from the CPR, facilitating the comparison of performance metrics. This regulatory framework imposes constraints on the available approaches to digitalizing data.

The DPP will include information related to the environmental performance, to be defined for each product family. For construction products, a detailed set of life cycle environmental indicators aligned with EN 15804 (and the Product Environmental Footprint (PEF)) is listed in annex II of the new CPR.

All products covered by the CPR, and many of the products covered by the ESPR, are installed in built assets. Examples of products covered by the ESPR include water pumps, light sources and space heaters. To perform calculations and assessments for buildings or infrastructures, the environmental data of these products must be stored in IFC models.

The DPP concept can be aligned with other models, such as the Internet of Materials described in [41], to support the validation of claims or its application beyond the European regulatory context. At the international level, ISO and UNECE launched an initiative to align the DPP across industries and regions [42].

DPPs should be integrated into digital building logbooks (DBLs), envisioned as a centralized digital repository for all relevant information throughout a building's entire lifecycle. The European Commission has identified the potential for harmonizing this tool and has proposed a definition of DBL to facilitate its implementation and ensure the interoperability [43]. The integration of IFC into DBLs is feasible, provided that their structures and methodologies are aligned. Malinovec et al. [44] proposed a data structure for the DBLs, which can be considered in the description of the requirements for new versions of IFC.

The integration of LCA data contained in the CPR-DPP and the ESPR-DPP into the IFC schema will allow for the direct use of reliable environmental product data in current BIM software tools, thereby reducing the resources required for the sustainability assessment of buildings and infrastructure. Integration into DBLs has the potential to enhance the efficiency of these assessments, as it ensures that all asset-related information is accessible within a single digital model.

4. Results and Discussion

4.1. Gaps Related with Digital LCA Data

The gaps related to the identification of the product-related data are analyzed in Table 1.

Table 1. Gaps related to the identification of product-related data.

Gap	Name	Analysis
1	Unique identification of the EPD issuer and the manufacturing site(s)	IFC 4.3 includes the property *ManufacturerAddress* in the *Pset_ProductEnvironmentalDeclaration*. However, this property is presented as free text and does not ensure the uniqueness of the information or the machine interpretation of the data. The manufacturer's address and the location of the factory may be different. Therefore, two separate elements should be provided.
2	Unique identification of the product type	The concept *product type* is defined in the CPR (for Europe). It should not be used in other contexts to avoid confusion.
3	Unique identification of the PCR and the EPD code assigned by the PO or the manufacturer	For the PCR, IFC 4.3 includes the property *StandardNumber* in the *Pset_ProductEnvironmentalDeclaration*. However, it remains unclear whether it refers to the core EPD document (EN 15804 or ISO 21930), or to the complementary PCR.
4	Unique identification of the product family and subfamily	The unique identifier (UID) can differ depending on the market. IFC should allow the declaration of multiple families and subfamilies, identifying the relevant domain.
5	Unique identification of the model, batch and/or item	The UIDs should follow the criteria developed in CEN/CLC/JTC 24. In particular, prEN 18219 *Digital product passport—Unique identifiers* is currently under Enquiry ballot until September 2025.

The gaps related to the LCA information are analyzed in Table 2.

Table 2. Gaps related to the LCA information.

Gap	Name	Analysis
6	Unique identification of the functional unit and the reference service life (RSL)	The options for the RSL should be predefined in the relevant PCR and provided in the digital format as enumerated values. It can be based on parameters to be declared in the EPD. The RSL should also include any conversion factors required to transform the functional or declare unit into a usable quantity at building level.
7	Information modules, defined in CEN/TC 350 or ISO/TC 59/SC 17 standards, not included in IFC 4.3	The modules identified in 4.3 should be included. Note that the definitions of current modules in IFC do not always match the core EPD standards (gap 17).
8	Parametric definition of all the scenarios based on standardized models	IFC should include parameters for general properties, but the parameters specific for a product family should be defined in the relevant PCR. Therefore, this gap cannot be resolved solely by revising the IFC schema.
9	Unique identification of the constituent materials, including their percentage in mass or volume	The unique identification of materials should be globally recognized to ensure interoperability. Therefore, this gap cannot be resolved solely by revising the IFC schema. However, IFC can include a system to define constituents and their percentage in mass or volume. To optimize data management and reduce unnecessary data loading in the model, this information can be retrieved from the source EPD when needed, provided that the link is available (see gap 20).
10	Identification of any LCA databases or sources for background data	The identification of LCA sources should be globally recognized to ensure interoperability. Therefore, this gap cannot be resolved solely by revising the IFC schema. IFC can include an element to store this information but, as with gap 9 above, it will generally be more efficient to retrieve the data from the source EPD when needed.
11	Parametric description of any other LCA assumptions or decisions, such as processes excluded	The declaration of this information should be globally standardized in a revision of ISO 22057. The PCR should include the relevant criteria for this information, which should then be used to compare the assumptions with the actual building. This will help determine if the information can be transferred with modifications.

The gaps related to the results of the LCA and the product's performance data are analyzed in Table 3.

Table 3. Gaps related to results of the LCA and the product's performance data.

Gap	Name	Analysis
12	Unique identification of the test, calculation or assessment method for any property included, both performance characteristics and LCA-based indicators	The dated version of the method must be uniquely identified, using a single UID or a pair of UIDs (one for the property, e.g., GWP-total, and one for the dated version of the calculation method). However, this gap cannot be resolved solely by revising the IFC schema, as the UIDs must be common for different systems. Options to identify documents can be the DOI or, for standards, the WI code. WI 0442061 [11] will provide additional information on how to refer to the assessment method for European harmonized standards.
13	Unique identification of additional quantitative or qualitative environmental information	Additional information on EPDs includes different types of data referring, for example, to an attribute of the product (e.g., compostable), a quantifiable property (e.g., 50% recycled content) or information from the manufacturer (e.g., certified according to ISO 14001). The identification of common information should be made in the horizontal standard and, for properties applicable to the product family, in the PCR. Therefore, this gap cannot be resolved solely by revising the IFC schema. However, IFC can include elements to store this type of data. This information can also be retrieved from the source EPD, if the link is provided (see gap 20).
14	Structure for the metadata to allow machine interpretation, avoiding free text fields	This gap requires further research in order to structure metadata using, when possible, parameters allowing machine interpretation.

The gaps identified in Tables 1–3 are common to most formats used to manage dEPDs and are not always relevant for the IFC model of a built asset. However, when IFC is used to transfer product information in a manufacturer's catalogue, all the elements above apply. Therefore, unless a specific format for product data aligned with IFC is defined, the standardized schema should be able to store this data.

According to Otero et al. [45], EPDs also present limitations due to the lack of uniformity in the criteria used to calculate their LCA or the uncertainties associated with the use of different background databases, together with the human factor. However, the limitations inherent to current EPDs are not part of this study, which only covers their machine-interpretability.

Tam et al. [46] concluded that a new data structure should be developed, with a view to aligning it with the BIM and LCA fields. This structure should include improved and unified naming conventions. The study highlights the current situation, in which the transfer of data from BIM models to LCA tools is dependent on manual processes. This approach is susceptible to unexpected errors, including information loss and deviations in the BIM models. In particular, [46] concluded that more IFC attributes should be developed for a complete LCA.

4.2. Identification of Gaps Related to the Integration of EPD Data in IFC

A fundamental distinction that limits the direct integration of EPD data into IFC is that the EPD contains more detailed or additional indicators than the current IFC schema (IFC 4.3.2.0 [30]) supports. This study assessed IFC 4.3 elements used to store EPD data and tested the integration of product environmental data into a BIM model (see Section 4.3), to analyze the effort required for human interpretation, validation and transfer of data.

The primary mechanism for environmental data storage in IFC is *Pset_EnvironmentalImpactIndicators*, which defines properties for various impact indicators per a product's functional unit. Direct mapping of EPD and IFC parameters are currently used for some elements, such as:

- Depletion potential of the stratospheric ozone layer (ODP) (in EPDs) with *StratosphericOzoneLayerDestructionPerUnit* (in IFC).

- Acidification potential (AP) (in EPDs) with *AtmosphericAcidificationPerUnit* (in IFC).
- Formation potential of tropospheric ozone (POCP) (in EPDs) with *PhotochemicalOzoneFormationPerUnit* (in IFC).

However, this mapping should be assessed with caution. Typically, IFC parameter descriptions offer only generic definitions, without referring to the calculation standards. The identification of the calculation method (gap 12) is required to evaluate the result, and its absence poses a significant challenge to the automated data integration process. When the reference is not provided, it is imperative that the data is assessed by a qualified expert to ensure that the model is populated with the appropriate information.

The limited set of environmental parameters in *Pset_EnvironmentalImpactIndicators* makes it so that a full EPD data import cannot be completed without the creation of custom attributes. In particular, EPDs according to EN 15804+A2 require a detailed breakdown for GWP (GWP-total, GWP-fossil, GWP-biogenic and GWP-luluc), while the IFC schema contains only a generic parameter *ClimateChangePerUnit* that can be mapped to GWP-total. Furthermore, the IFC schema does not include indicators such as the eutrophication potential (EP-freshwater, EP-marine and EP-terrestrial), the abiotic depletion potential for fossil (ADPF) and non-fossil (ADPE) resources, and the water deprivation potential (WDP).

Ensuring unit consistency is another key aspect of successfully integrating EPD data into IFC. Currently, some of the EPD indicator units correspond to elements in *IfcMeasureValue*, meaning that values could be transferred to IFC, with some limitations:

- Mass-based units such as kg CO_2 eq, kg CFC-11 eq, kg P eq, kg N eq, kg NMVOC eq, kg Sb eq can be aligned with IFC mass units *IfcMassMeasure*. However, indicator values are provided in mass equivalents, which do not ideally correspond to *IfcMassMeasure* values. Furthermore, additional extension should be considered that would enable the direct representation of the mass of a specific substance rather than just mass itself. Since different substances have different environmental implications, IFC should differentiate mass-based units based on a substance.
- Volume-based units such as m^3 for the WDP indicator. This unit could directly correspond to *IfcVolumeMeasure*.
- User-defined units associated with environmental indicators, applying *IfcMeasureWithUnit* or the attribute *UnitsInContext* in the *IfcProject* class, are not considered a viable option, as they endanger interoperability.

Moreover, EPD contains specific units of measurement that IFC does not support natively. Specifically, units that require IFC schema extension or additional processing are listed below:

- Energy-based units, such as MJ for the ADPF indicator. Even if IFC supports description of energy required or used, which is under *IfcEnergyMeasure*, the units (J, Nm) differ from the ones provided in EPD (MJ), meaning that additional processing would be needed.
- Mole-based units, which represents mol H^+ eq, mol N eq are not defined in the IFC schema.

Table 4 contains the indicators using the default characterization method taken from the European Platform on LCA for EN 15804 [47] and the correspondence with IFC. TRACI and EN 15804 can also be used for EPDs according to ISO 21930:2017. Therefore, the characterization method used must be declared with the relevant values.

Table 4. Comparison between the core indicators in EPDs (default characterization method in EN 15804) and the related IFC parameters.

Indicator	Name	Unit	Description
EPD GWP_{total}	Global Warming Potential [1] (GWP 100)	kg CO_2 eq	Baseline model of 100 years of the IPCC.
IFC GWP_{total}	ClimateChangePerUnit	IfcMassMeasure	Quantity of greenhouse gases emitted calculated in equivalent CO_2
EPD GWP_{fossil}	GWP fossil fuels	kg CO_2 eq	Baseline model of 100 years of the IPCC.
IFC GWP_{fossil}	N/A [2]		
EPD $GWP_{biogenic}$	GWP biogenic	kg CO_2 eq	Baseline model of 100 years of the IPCC.
IFC $GWP_{biogenic}$	N/A [2]		
EPD GWP_{luluc}	GWP land use and land use change	kg CO_2 eq	Baseline model of 100 years of the IPCC.
IFC GWP_{luluc}	N/A [2]		
EPD ODP	Ozone depletion potential	kg CFC-11 eq	1999 WMO assessment of ozone depletion (World Meteorological Organization 1999).
IFC ODP	StratosphericOzoneLayer DestructionPerUnit	IfcMassMeasure	Quantity of gases destroying the stratospheric ozone layer calculated in equivalent CFC-R11.
EPD AP	Acidification potential	mol H^+ eq	Accumulated Exceedance method (combination of models).
IFC AP	AtmosphericAcidificationPerUnit	IfcMassMeasure	Quantity of gases responsible for the atmospheric acidification calculated in equivalent SO_2.
EPD $EP_{freshwater}$	Eutrophication potential, fraction of nutrients reaching freshwater end compartment	kg PO_4 eq	CARMEN model for waterborne emissions and EUTREND for airborne emissions.
IFC $EP_{freshwater}$	EutrophicationPerUnit	IfcMassMeasure	Quantity of eutrophicating compounds calculated in equivalent PO_4.
EPD EP_{marine}	Eutrophication potential, fraction of nutrients reaching marine end compartment	kg N eq	CARMEN model for waterborne emissions and EUTREND for airborne emissions.
IFC EP_{marine}	N/A [2]		
EPD $EP_{terrestrial}$	Eutrophication potential, accumulated exceedance	mol N eq	Accumulated exceedance method (combination of models).
IFC $EP_{terrestrial}$	N/A [2]		
EPD POCP	Formation potential of tropospheric ozone	kg NMVOC eq	LOTOS-EUROS
IFC POCP	PhotochemicalOzoneFormationPerUnit	IfcMassMeasure	Quantity of gases creating the photochemical ozone calculated in equivalent ethylene [3].
EPD ADPE	Abiotic depletion potential for non-fossil resources	kg Sb eq	Abiotic resource depletion (ADP ultimate reserve).

Table 4. *Cont.*

Indicator	Name	Unit	Description
IFC ADPE	N/A [2]		
EPD ADPF	Abiotic depletion potential for fossil resources	MJ	Abiotic resource depletion (ADP fossil).
IFC ADPF	N/A [2]		
EPD WDP	Water (user) deprivation potential, deprivation-weighted water consumption	m^3	AWARE 100 (Available water Remaining).
IFC WDP	N/A [2]		

[1] Considering that *ClimateChangePerUnit* refers to the total GWP, unclear in IFC 4.3. [2] Not available. [3] EN 15804+A2 refers to NMVOC, also including non-reactive VOC.

It should be noted that different versions of EN 15804 or ISO 21930 define different calculation methods and/or allow the declaration of indicators calculated according to different methodologies. Consequently, the reference to the dated calculation method used for each environmental indicator must be included in the dEPD. In addition, IFC contains properties referring to *old* standards such as ISO 21930:2007, which has been superseded by ISO 21930:2017. An example is *TotalPrimaryEnergyConsumptionPerUnit*, which is described in IFC as "Quantity of energy used as defined in ISO 21930:2007".

The report [48] proposed the inclusion of additional properties for the impact categories defined in EN 15804+A2, but it has not been implemented in IFC yet. In addition, the proposed terminology should be adjusted according to EN 15804 and ISO 21930. As an example, *GWPtotal* should be used instead of *ClimateChangeTotal*.

IFC represents individual properties and their sets with predefined property types, which reflect the data type of the corresponding property. The most widely applied and used property type is *IfcPropertySingleValue*, which defines a property with a single value. *IfcPropertyEnumeratedValue* defines a list of predefined classes, *IfcPropertyBoundedValue* defines the data range, *IfcPropertyListValue* is intended for multiple ordered values, *IfcPropertyReferenceValue* assigns a value to the property set through a link with predefined complex properties and *IfcPropertyTableValue* defines one or many ranges of values (see Table 5).

The *IFCPropertyAbstraction* and the relation with other entities are defined on buildingSMART documentation in the diagram for entity inherence of the *IfcPropertySingleValue* [49].

For each impact category defined in IFC, a specific element can be included to store the link to the calculation method, including the reference to the relevant ISO, IEC or CEN/CENELEC standard. They can be referenced with a unique identifier, such as the work item (WI) code. For example, the WI code for EN 15804:2012+A2:2019 is 00350032. The same IFC element can be used for other documents, e.g., the IPCC methodology with its dated version. Existing IFC elements can be used for this purpose, such as *IfcExternalReference* or *IfcDocumentReference*. It can be defined as a complex element, allowing the identification of documents using different codification, such as the digital object identifier (DOI) defined in ISO 26324:2025 [50].

Pset_EnvironmentalImpactIndicators can refer to the relevant lifecycle module using the element *LifeCyclePhase*. However, the enumerated values included in IFC 4.3 do not cover all the information modules defined in the EPD standards (see gap 7). Table 6 below lists the *PEnum_LifeCyclePhase* with reference to the information modules in current EN 15804 and in the future standard EN 15978, which should be published in December 2025.

Table 5. Definition of the properties in IFC.

IFC Property Type	Definition	Analogous Data Type	Example	
			Property Name	Property Value
IfcProperty SingleValue	A property which has a single (numeric or descriptive) value assigned.	Scalar, text, number	WaterCon sumption	20
IfcProperty Enumerated Value	A property which has a value assigned that is chosen from an enumeration.	List, 1-D array	StructureIn dicator	[COATED; COMPOSITE; HOMOGENEOUS
IfcProperty BoundedValue	A property which has a maximum of two (numeric or descriptive) values assigned, the first value specifying the upper bound and the second value specifying the lower bound.	List with 2 or 3 values, range	OverallHeight OverallWidth	[1200;900] [220;110]
IfcProperty ListValue	A property that has several (numeric or descriptive) values assigned which are given by an ordered list.	List, 1-D array	ApplicableSize	[3200;6400;9600]
IfcProperty ReferenceValue	A property value to be of type of a resource level entity via the *IfcObjectReferenceSelect* types (e.g., IfcTable).	Scalar, number, text, 1-D or 2-D array; dictionary	GWPtotal ADPF	{GWPtotal:[445,614,16,7.3,−12], ADPF:[4210,81,241,101,78,−116]}
IfcProperty TableValue	A property with a value range defined by a property object which has two lists of (numeric or descriptive) values assigned.	Limited 1-D or 2-D array	SoundTrans missionLoss	[[100;200;400], [20;42;46]]

Table 6. Relationship between the *LifeCyclePhase* element in IFC 4.3 and the information modules in CEN/TC 350 standards.

EN 15804:2012+A2:2019	EN 17472:2022 and EN 15978:2025 [1]	PEnum_LifeCyclePhase in IFC 4.3
Not defined in EN 15804+A2	A0 Pre-construction stage	Part of the processes included in A0 can be assigned to ACQUISITION and PROCUREMENT. However, a dedicated phase must be defined
A1 Raw material supply, including processing of secondary material input [2]	As in EN 15804+A2 [2]	Not defined
A2: Transport of raw material and secondary material to the factory [2]	As in EN 15804+A2 [2]	Not defined
A3 Manufacture of the construction products [2]	As in EN 15804+A2 [2]	MANUFACTURE or PRODUCTION. A specific element should be defined to avoid ambiguity

Table 6. *Cont.*

EN 15804:2012+A2:2019	EN 17472:2022 and EN 15978:2025 [1]	PEnum_LifeCyclePhase in IFC 4.3
A4 Transport to the construction site	A4.1 and A4.2, for transport to the construction site [3]	It can be PRODUCTIONTRANSPORT. A specific element should be defined to avoid ambiguity
A5 Installation into the construction asset	A5.1, A5.2, A5.3 and A5.4, for installation and construction onsite activities [4]	INSTALLATION
B1 Use of the asset	B1.1 and B1.2 for the use of the installed products [5]	It can be USAGE or OPERATION, but the stages may also include B6 or B7. Therefore, a specific element should be defined.
B2 Maintenance	As in EN 15804+A2	MAINTENANCE
B3 Repair	As in EN 15804+A2	REPAIR
B4 Replacement	As in EN 15804+A2	REPLACEMENT
B5 Refurbishment	As in EN 15804+A2	REFURBISHMENT
B6 Operational energy use	B6, B6.1, B6.2 and B6.3, for operational energy use [6]	Not defined
B7 Operational water use	B7, B7.1, B7.2, B7.3 B7.4, for operational water use [7]	Not defined
Not defined in EN 15804+A2	B8, B8.1, B8.2 and B8.3 building related users' activity [8]	Not defined
C1 De-construction and demolition processes	As in EN 15804+A2	DECONSTRUCTION
C2 Transport to waste processing facilities	As in EN 15804+A2	Not defined
C3 Waste processing for reuse, recovery and/or recycling	As in EN 15804+A2	Not defined
C4 Waste disposal	As in EN 15804+A2	DISPOSAL
D Potential net benefits and loads from the reuse, recycling or recovery	Divided into D1 and D2, see rows below	
Not defined in EN 15804+A2	D1.1, D1.2, D1.3 and D1.4 for Potential net benefits and loads from the reuse, recycle or recovery of secondary flows [9]	Not defined
Not defined in EN 15804+A2	D2 Potential net benefits and loads resulting from the export of utilities such as power and heat	Not defined

[1] FprEN 15978:2025 will be under ballot between August and October 2025. If approved, it should be available as EN standards in December 2025 and published by national standardization bodies before the end of June 2026. [2] Modules A1, A2 and A3 can be aggregated into a single A1–A3 module. [3] Module A4 is divided into two submodules in EN 15978:2025 to differentiate between the transport of construction products and the transport of equipment. [4] Module A5 is divided into four submodules in EN 15978:2025 to differentiate between construction and preconstruction activities, and to report the transport of construction workers. [5] Module B1 is divided into two submodules in EN 15978:2025 to differentiate between types of emissions. [6] Module B6 is divided into three submodules in EN 15978:2025 to differentiate between regulated and not regulated integrated systems, and to report user-related consumptions. [7] Module B7 is divided into four submodules in EN 15978:2025 to differentiate between systems. [8] Module B8 is structured into three submodules in EN 15978:2025 to differentiate typologies of user activities. [9] Module D1 is structured into four submodules to differentiate the reuse, recycling and energy recovery.

LifeCyclePhase values must include all CEN/TC 350 information modules. In order to store EPD data according to CEN/TC 350 standards (see gap 7), the following information modules should be added as enumerated values in *PEnum_LifeCyclePhase*: A0, A1, A2, A3, A1–A3, A4, A4.1, A4.2, A5.1, A5.2, A5.3, A5.4, B1, B1.1, B1.2, B6, B6.1, B6.2, B6.3, B7, B.7.1, B7.2, B7.3, B7.4, B8, B8.1, B8.2, C2, C3, D, D1, D1.1, D1.2, D1.3, D1.4 and D2. The following modules have some correspondence with IFC (see Table 6 above): A5 INSTALLATION, B2 MAINTENANCE, B3 REPAIR, B4 REPLACEMENT, B5 REFURBISHMENT, C1 DECONSTRUCTION and C4 DISPOSAL). However, it is recommended that some of these existing *PEnum_LifeCyclePhase* be renamed to align with the terminology of ISO 21930 and EN 15804 (gap 17). BuildingSMART identified the need to incorporate some of the modules in 2022 [48], but it should be noted that the report does not consider the modules added by CEN/TC 350 after the publication of EN 15804+A2 and, in some cases, their names do not match the terminology of the European standards.

Santos et al. [51] explored the potential of a life cycle repository for environmental and economic analysis. It identified several EPD-related elements in the structure created for the information delivery manual (IDM) and the model view definition (MVD), such as 10 properties focused on the environmental impacts of its manufacture, 22 properties focused on transportation impacts and 26 properties focused on the waste treatment of materials. Santos et al. also proposes the creation of a specific *IfcValue* for each category, to better define the environmental characteristics.

The main additional gaps related to IFC are analyzed in Table 7.

Table 7. Gaps specific to IFC.

Gap	Name	Analysis
15	*Pset_EnvironmentalImpactIndicators* calculation method	The calculation methods are not generally defined (with a dated version). The document defining the calculation method can be defined with the DOI or, for standards, with the WI code. In some cases, the reference standard is superseded (e.g., ISO 21930:2007). The reference to *old* methods should be maintained, to ensure compatibility, but new references should be added. It is a particular case of gap 12.
16	Impact categories and indicators not defined in *Pset_EnvironmentalImpactIndicators*	It is essential that all properties and indicators from the core EPD standards are included. Incorporating new indicators into a revision of the official IFC schema will require careful consideration to ensure that the necessary changes can be made in a timely manner to keep pace with market demands. Therefore, new properties should be tentatively included based on a governance system or in repositories such as bSDD.
17	Lack of alignment of life cycle stages	The element *LifeCyclePhase* should be aligned with the core EPD standards (see gap 7 and Table 6).
18	Adaptation of properties to the *concepts* in the core EPD standards, including terminology	e.g., IFC uses *ClimateChange* but the terminology of ISO 21930 and EN 15804 is GWP.
19	Limitations of *IfcMeasureValue*	There are units which are not supported natively by the current IFC schema. In addition, some units need to refer to specific elements, e.g., unit "mass" can refer to kg CO_2 eq (GWP) or kg CFC-11 eq (ODP).
20	Reference to source (original data)	Elements in IFC can be multilayered or kits, aggregating data from several products. In addition, data transfer can result in the loss of information. Therefore, the URI of the original dEPD should be included in the BIM model. This option will ensure that the primary data is available for retrieval if needed, thereby avoiding an excessive loading of the model.

Consequences of unsolved issues in the IFC schema were identified in studies such as Aragón [52] and Lai & Deng [53], including the data loss and misrepresentation due to semantic differences in software tools using different mappings between the schema of each particular software tool and the IFC structure. These gaps are not specific for LCA data, but applicable to the whole IFC structure.

Any revision of the IFC schema should consider the data template structure provided in ISO 22057, to ensure the compatibility between digital EPDs and the building model. However, the standard itself needs to be revised to improve the automatization of the interpretation of ISO 22057 digital EPD content, as shown in [10]. The structure for the digital DoPC provided in WI 0442061 [11] should also be considered.

4.3. A Case Study for the Environmental Performance Indicators in IFC

The Horizon Europe-funded research project CHRONICLE (Grant Agreement number 101069722) aims to improve energy efficiency, occupant comfort, and building sustainability by leveraging IFC-based digital twins for renovation planning, carbon assessment, building operations, and long-term data management. The project runs for 42 months, from 1 July 2022 to 31 December 2025, with 18 partners and utilizing five pilot sites in five countries.

Specifically, CHRONIICLE designed an "investment appraiser" using IFC models to calculate embodied and operational carbon in various renovation scenarios. This tool provides an analysis of the life cycle cost (LCC) of the building based on several key performance indicators (KPIs), such as material quantities and other information extracted from the IFC model. It also integrates life cycle assessment indicators and dynamically calculates a carbon bill to facilitate stakeholders' decision making on climate-conscious renovations.

The project has proposed a CEN/CENELEC Workshop Agreement (CWA) to develop a methodology for the calculation of the carbon bill of the refurbishment of buildings based on data from construction products provided in dEPDs [54]. The Workshop had its kick-off meeting on March 2025, and the draft generated was sent to a consultation period from June 26th until August 21st [55]. The goal is to publish the document before the end of 2025.

The use of these tools to analyze the carbon footprint of the European built stock requires dEPDs to be structured in an efficient manner. This ensures that the content can be directly integrated into BIM models without human intervention or requiring very limited resources for the transfer. The BIM model can be used to create a digital twin of the building, enabling proactive interventions (e.g., refurbishment or maintenance) that reduce costs and downtime, improving the environmental performance of the building, as shown in Aragón, Arquier et al. [56].

The development of integrated LCA methodologies during the research revealed certain limitations in data collection and processing workflows, and also in the environmental information included in the current IFC schema. The mapping of material and EPD data in IFC relies on material naming and labelling in the model, which is subject to human error due to differing labelling conventions, data entry errors, etc. The accuracy of the data mapping process is contingent on the accessibility of a comprehensive EPD database, as it necessitates a diverse and well-maintained dataset. In cases where the dataset is incomplete, lacking region- or manufacturer-specific data, the calculations may have a reduced accuracy, generating discrepancies during environmental impact assessments. This limitation can be addressed by directly providing relevant dEPDs to the assessment engine and by ensuring careful data mapping, a process which can be time-consuming. However, additional efforts have been made during the project activities to identify existing limitations and provide future recommendations for seamless integration of EPD data into the IFC structure.

CHRONICLE developed several BIM models for project pilots. An IFC model from the project was used to test the transfer of LCA data from EN 15804 EPDs into BIM, identifying this information's EPIs (Environmental Performance Indicators). A building located in Zaragoza (Spain) was selected to analyze the applicability of identified gaps. The pilot is a former commercial building recently refurbished (2021) as social housing, improving the energy rating from level G to level C.

The EPI representation format, standardized according to EN 15804 indicators, provides a tabular data structure that characterizes the EPI names, their units of measurement and declared values, arranged according to the LCA stages (modules A to D).

However, the possibilities for standardizing the tabular data structures in IFC are limited based on the capabilities of the current official schema. The required data structure should consist of 19 columns to represent the EPI, multiplied by all the LCA stages.

In this case, it is reasonable to define multiple options considering different IFC property types and structuring approaches. Four options for structuring LCA data are described below. These options do not consider the reference to the method used to calculate the indicator (LCA impact category) to simplify the integration and testing in the pilot IFC model. The strategy of the first two options is quite similar; they have been considered as variants of the same approach and named 1A and 1B.

Option 1A: Property set for each LCA stage (see Table 8): EPIs could be defined as separate property sets for each of the LCA stages, e.g. *Pset_EPIA1*, *Pset_EPIA2*, etc., using *IfcPropertySingleValue*.

Table 8. Structure for some impact categories attributed as separate property sets with LCA stages.

Indicators	Pset_EPIA1	...	Pset_EPIA1
GWPtotal			
GWPfossil			
GWPbiogenic			
GWPluluc			
ODP			
AP			
EPfreshwater			
EPmarine			
EPterrestrial			
POCP			
ADPE			
ADPF			
WDP			

Option 1B: Single properties with concatenated LCA stages (see Table 9): *Pset_EPI* or separate properties are created and all the stages are concatenated together with the single property names, e.g. *GWPtotalA1*, *GWPtotalA2*, etc., using *IfcPropertySingleValue*.

Table 9. Structure for impact categories attributed as separate property sets with LCA stages (tabular approach).

Indicators	Pset_EPI
GWPtotalA1	
...	
GWPtotalD	
GWPfossilA1	
...	
GWPfossilD	

Option 2: List of property values corresponds to the LCA stages: Each list is dedicated to a specific EPI, and the list values reflect the ordered format of the LCA stage, using the element *IfcPropertyListValue*.

Option 3: Using *IfcPropertyReferenceValue* and *IfcTable*: Aligned with the tabular nature of EPD data, this approach utilizes *IfcPropertyReferenceValue* and *IfcTable* for enhanced data organization.

To assess these options, their advantages, disadvantages, and potential limitations must be considered. Table 6 provides a comparative overview, highlighting how each approach impacts data structuring, integration with BIM authoring tools, and implementation. Each scenario has its own pros and cons as well as possible limitations in terms of data structure or implementation level. Table 10 summarizes the options analyzed during the study.

Table 10. Summary of approaches (options) to attribute LCA data in a revised IFC standard.

Option	IFC Property Type	Advantages	Disadvantages	Limitations
1A	IfcPropertySingleValue	Embedded in the majority of BIM authoring and IFC editing tools.	Large number of property sets and properties.	Not suitable for layer-based representation (e.g., material layers) or assembled IFC elements.
1B	IfcPropertySingleValue	Embedded in the majority of BIM authoring and IFC editing tools; suitable for layered/assembled IFC elements.	Large number of properties. Complex property names (concatenated).	Not all BIM authoring tools have the ability to create custom property sets.
2	IfcPropertyListValue	Requires up to 19 times less properties (EPIs) compared to scenarios 1 and 2.	Requires metadata about the sequence (list order).	No integration with BIM authoring tools; limited integration with IFC editing tools.
3	IfcPropertyReferenceValue IfcTable	The best scenario in terms of data structuring. Possibility to create the required number of columns and rows.	The entities are not part of a standardized IFC schema subset or implementation level.	No integration with BIM authoring and IFC editing tools.

Options 2 and 3 are more aligned with the EPD data structure. However, effective implementation is currently hindered by the limitations in BIM authoring tools. Even if a list or table structure is available, it is typically not integrated within BIM tools. The structure of option 1A provides a compromise and can be used to associate EPD information with building elements (*IfcElement*) that are unitary and do not have a layered structure, i.e., windows, columns, hollow slabs, etc. In the case of layered building structures (e.g., floors, walls, roofs, etc.), the EPD provides information on specific layers of materials. Consequently, the environmental impact indicators should also be assigned to specific layers in the building model, as *IfcProperty* for materials is used to express the individual material properties by name, description, value and unit. Option 1A cannot be applied to layer-based representations. Given these limitations and drawbacks, only option 1B can currently be applied for the integration of EPD and IFC data without additional third-party software or additional processing of data input files.

To test the proposed approach, option 2 was adopted for the pilot building, storing environmental data from EPDs accessible from manufacturers or POs. This option provides *IfcPropertySingleValue* entries for each EPD indicator–stage combination, i.e., a property named *GWPtotalA1* for global warming potential value for module A1 (see Figures 3 and 4).

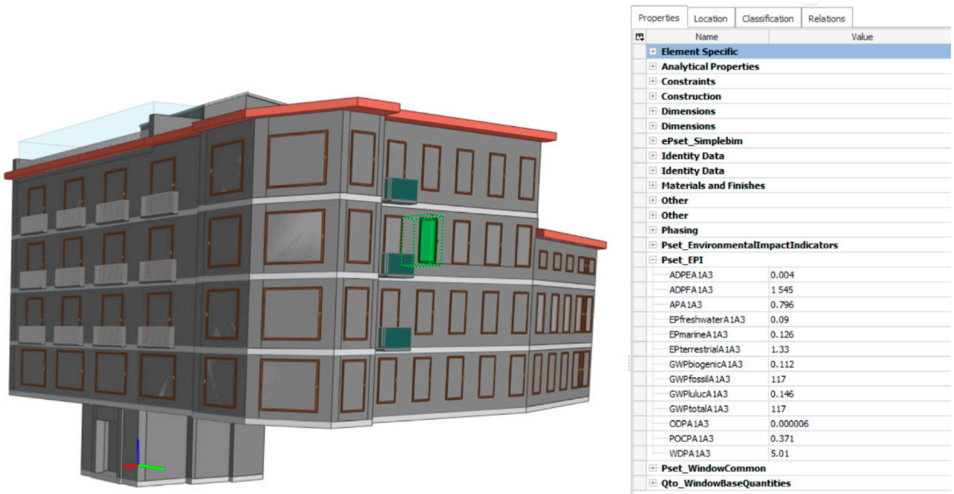

Figure 3. Integration of information modules A1–A3 for a product.

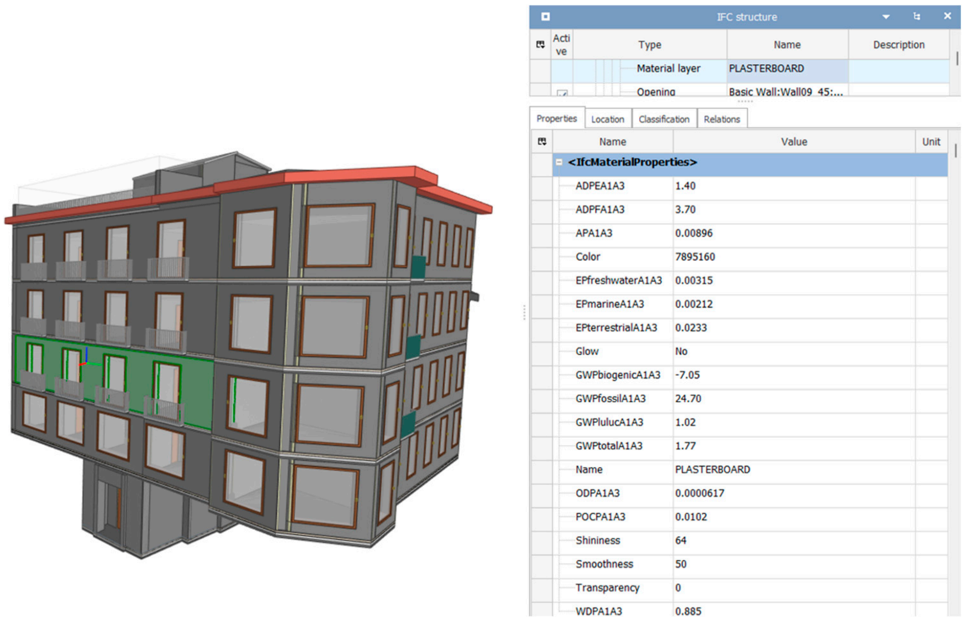

Figure 4. Integration of environmental indicators for the A1–A3 information modules for layered elements.

This approach was selected following an evaluation of available options to integrate the tabular data from EPDs into IFC. A typical construction EPD according to EN 15804+A2 comprises nineteen environmental impact categories across multiple life cycle stages. In order to perform the assessment, it is also necessary to consider other environmental indicators related to waste generation, transport, and other parameters. Option 1B (name concatenation) stores each value as an individual property with the stage appended to the name, which can be easily implemented in any BIM tool. However, incorporating a phase in the name of an indicator deviates from the consistent standard naming conventions. In summary, *GWPtotalA1* is not a formally standardized property identifier, but rather an application-specific convention. In addition, it does not include the calculation method.

However, this trade-off was considered acceptable in the pilot for practicality and for integration purposes for single projects, as it allows the embedding of EPD data directly in the IFC using standard mechanisms, such as property values. This action can be performed with most of the modelling tools without requiring specific IFC extensions. This approach may enhance EPD data integration into BIM projects. However, machine interpretation will require the integration into the official IFC schema to support EPD data integration in a structured and efficient way. Overall, option 1B combines standardization and usability by utilizing the basic structure of the IFC schema to integrate EPD data, while recognizing that more standardized solutions (i.e., IFC tables or complex attributes) would be more advantageous if they were integrated into BIM authoring tools.

The accuracy of the values will be dependent on the background data and rely on the BIM tool. The reliability of BIM authoring tools or IFC viewers was not considered during the study and should be assessed in future research.

Based on the results of the use case, some tentative lines for future development are proposed below:

- **Option 1A and 1B**: Develop BIM authoring tool plugins/add-ons with API capabilities for automatic retrieval and mapping of LCA data from EPDs to IFC. These plugins will not ensure machine interpretability across systems. Therefore, LCA data properties according to EN 15804 or ISO 21930 must be standardized for IFC elements.
- **Option 2:** Implement *IfcPropertyListValue* data type into the BIM authoring tools, IFC viewers, editors and parsers. This implementation cannot ensure machine interpretability across systems. Therefore, LCA data properties according to EN 15804 or ISO 21930 must be standardized for IFC elements.
- **Option 3:** Implement *IfcPropertyReferenceValue* and standardize LCA data properties for IFC elements.

The use case illustrates the importance of defining a data structure for EPD information within the IFC schema to ensure machine interpretation across systems.

The use case does not fully address the requirements for machine interpretability of LCA data in BIM described in this paper, as certain limitations were not considered during the modelling process. A key issue that was not addressed in the use case analysis is the unique identification of the LCA calculation method used for each impact category. The simplifications were taken to facilitate the testing of the options in the modelled structure. It is therefore recommended that future research includes a more detailed structure to allow for the inclusion of this information.

4.4. Proposed Actions

This study identifies 20 limitations for the incorporation of LCA data in IFC, enumerated in Tables 1–3 and 7. Future revisions of IFC should consider these gaps to improve the machine interpretability of EPD data, allowing its direct incorporation in BIM models. This incorporation will reduce the resources required for the environmental assessments of buildings, therefore promoting its widespread use.

The study has analyzed four options for the delivery of tabular-based EPD data using the IFC 4.3.2.0 schema in a use case (see Section 4.3). Each option has its own limitations and constraints. The use of the *IfcTable* entity, standardized within the current IFC schema, is an interesting solution, as it aligns well with the tabular structure commonly used to represent EPD data. However, it should be noted that this option does not guarantee interoperability across systems unless a revised IFC schema defines a common structure for LCA data. Current BIM authoring software does not support the transfer of EPD data across systems or organizations using different tools. The reason is that each software relies on proprietary/native data structures that have been developed over time. Switching to a single standard brings significant technical and resource-related challenges, in addition to the efforts needed to enhance IFC standards in relation to LCA data. The approaches described in 4.3 require further research to assess the impact of its implementation.

The main topics for consideration in the next versions of IFC are outlined in Table 11.

Table 11. Issues for consideration in the revision of the IFC schema.

Action	Headline	Description
1	Improve *Pset_EnvironmentalImpactIndicators*. Gaps 12, 15, 16, 18 and 19	Improve the structure of *Pset_EnvironmentalImpactIndicators* to cover all EPD indicators and impact categories. In particular, for EN 15804+A2: a. *ClimateChangePerUnit* should be structured into four elements: *GWPtotal*, *GWPfossil*, *GWPbiogenic* and *GWPluluc*. The report [48] from buildingSMART proposed this structure, but the terminology used in EPD standards should be applied (i.e., *GWP* instead of *ClimateChange*). b. A new version of POCP should be included, reflecting the change in the units. c. The impact categories not included in IFC 4.3 must be defined, including the ADPF, ADPE, WDP, PM, IRP, ETP-fw, HTP-c, HTP-nc and SQP. d. All impact categories must include an explicit reference to the LCA calculation method (see action 2). Table 4 shows the calculation method used in EN 15804+A2.
2	Consider the use of *IfcDocumentReference* to refer to the calculation method. Gap 15	All relevant properties, including impact categories and environmental indicators, should refer to the calculation method. The reference should be based, when possible, on a URI (e.g., DOI according to ISO 26324). A domain for technical standards can use the WI code to refer to the calculation method defined in a standard.
3	Consider the use of *IfcTable* to store EPD data (see Section 4.3)	The entity *IfcTable* can also be used to store LCA data with current EPD structure (indicators and information modules). A standardized definition will ensure its implementation in BIM authoring tools. The schema must apply the GUIDs defined in the relevant standards, when available, to ensure interoperability between different systems and formats.
4	Improve *IfcMeasureValue*. Gap 19	The element *IfcMeasureValue* does not currently cover all units required for EPD indicators and, in some cases, a unit conversion is needed. This element should be extended to include the required units. Elements such as *IfcMassMeasure* and *IfcVolumeMeasure* should be extended to adapt to LCA units.
5	Modules of the life cycle in *LifeCyclePhase*. Gaps 7 and 17	The enumerated values in *LifeCyclePhase* should be updated to cover CEN/TC 350 information modules, as described in Table 6. The terminology in *PEnum_LifeCyclePhase* should match the terms of the core EPD standards.
6	Inclusion of unique identifications for EPD data. Gaps 1, 3 and 20	Retrieval of product information from an external source (e.g., the database of a PO) is to be accompanied by inclusion of the main information required for data traceability in the model. This information should include the unique identification of the EPD issuer or manufacturer, the EPD code and the link to the published EPD. This identification should be based on the same criteria as the identification of the manufacturer, manufacturing site and product, described below. The inclusion of the link to the source EPD will allow the retrieval of product data.

Table 11. *Cont.*

Action	Headline	Description
7	Inclusion of unique identifications of the manufacturer and the product. Gaps 1, 2, 4 and 5	When IFC is used to transfer product data (e.g., the catalogue of a manufacturer), it should include the unique identification of the manufacturer, the manufacturing site (where relevant) and the product. Regulations can specify mandatory identifications (for example, the *product type* for certain products in Europe). The product can be identified at the level "model", "batch" or "item". This identification should be based on the future standard EN 18219, which is currently being developed in CEN/CLC/JTC 24/WG 2 "Unique identifiers". Current identification systems such as the GTIN [57] can be used.
8	Consider the relations between the scenarios in the EPD and the information of the IFC model, to verify its applicability to the actual building. Gaps 6, 8, 11 and 18	The incorporation of product EPD data requires the compatibility of the LCA assumptions and boundaries with the actual built asset under consideration. To automate the transfer and minimize human intervention, the product information must be defined with compatible parameters in the digital EPD and in the IFC model. To ensure machine interpretability, it is essential to uniquely identify LCA information, such as the RSL, the scenarios, and the processes excluded in the EPD (where relevant at building level). These parameters should be defined, when possible, in the PCRs. Automation should incorporate the automatic selection of the scenario (in the EPD) most suitable for the actual building, applying the relevant parameters, where relevant, and identifying any divergence.
9	Mapping IFC elements and the definition of scenarios and hypothesis	The relations between the information available in the model and the scenarios in the EPD are very important to determine whether the data can be directly transferred. For instance, an insulation material can be incorporated into the EPD in various scenarios, such as installation in the roof or in external walls. BIM should be able to extract the necessary data for the project based on the information in the model. This action will require extensive additional research to ensure a standardized mapping.
10	Provide guidelines on metadata. Gap 14	Metadata can be incorporated into digital EPDs to improve its direct incorporation in IFC. IFC can provide requirements and criteria for such metadata, to ensure that dEPDs can be transferred to BIM. It will require the implementation of this metadata in dEPD standards, such as ISO 22057.
11	Define a governance system for the management of properties	A governance system for the properties (and the generation of the related unique identifiers) should be implemented to ensure a common understanding in different domains. Governance must be common to other formats and, therefore, this issue cannot be resolved solely by revising the IFC schema.

Interoperability should not be equated with the automatic transfer of data between systems (or formats). The relevant data should be filtered based on the level of detail required at asset level, to avoid excessive computation loads. Ensuring the maintainability and quality of the model is contingent upon selecting the relevant data in an efficient manner. Therefore, each addition to the IFC schema should be carefully considered and the mapping between dEPDs and BIM should be based on efficiency.

The IFC standard itself is evolving as it expands its application across a broader range of domains within the built environment, such as infrastructure. Although the IFC schema has certain shortcomings, it is the most widely recognized and implemented open standard in the construction industry. Therefore, it is essential to ensure that EPD data is included in IFC in order to improve the sustainability assessment of built assets based on BIM tools.

4.5. Advantages of the Implementation in the Official Schema

As previously outlined, the *PropertySets* (Pset) defined in the latest international standard for IFC, ISO 16739-1:2024, does not fully represent ISO 21930 or EN 15804 environmental indicators. The limited set of environmental parameters and units of measurement in IFC means that a full EPD data import is not possible without endangering machine interpretation. While the EPD data integration into IFC is technically feasible, it is not seamless due to the necessity for meticulous mapping for the alignment of values and the extension of the IFC schema for non-aligned data.

The application of user-defined properties modelled by each organization is a short-term solution that requires decisions from practitioners on how to map each property. Therefore, these properties will not be interoperable across systems. This situation will generate challenges during implementation in software solutions, reducing interoperability and creating a vendor lock-in effect. As a result, users will be dependent on particular vendors.

Therefore, to facilitate seamless integration of EPD data into BIM and reduce burdens on industry, the identified gaps must be addressed through international standardization of the official IFC schema. This can be achieved by expanding IFC 4.3 to encompass EPD indicators and corresponding values, and also by establishing conventions for linking to EPD documents. The inclusion as *Psets* will have other advantages, such as consistent interpretation across systems, allowing for interoperability and improving data exchange; validation and quality control of the properties, reducing errors; and providing forward compatibility (future-proofing), ensuring that the data remains readable and usable in the long term. The properties defined should also be incorporated into the bSDD.

Any improvement in interoperability along the construction value chain will positively affect industry and society, especially for countries with lower implementation of digital technologies, facilitating direct implementation of sustainability assessment software with reduced costs.

4.6. Lines for Future Research

To incorporate product environmental data seamlessly into BIM models, additional research is required to uniquely identify the elements listed above (e.g., impact categories with the relevant calculation method) across separate platforms. The same GUID should be used in digital EPDs (using ISO 22057 or other data structure) and in IFC. Some of these GUIDs can be incorporated into international or regional standards, but others will require *faster* management to respond to market needs. Future research should explore options to generate a unique identification of the calculation method used for each LCA impact category or environmental indicator, to ensure that it is considered in the calculation at asset level once integrated on the digital model. Other lines for future research are:

I. The parametrization of scenarios and other LCA information contained in supporting documents, such as the PCRs. It is linked with action 9 (Table 11), to map this information with the IFC model.
II. The development of interconnected data dictionaries to ensure interoperability between different LCA and BIM formats, and across systems.
III. The relation with other data structures or ontologies used for digital models of built assets, such as CityGML or ifcOWL.
IV. Integration of the concepts described in this paper (unique identification of products, performance and environmental characteristics and assessment methods, parametrization of the elements within a data template structure, etc., applied to environmen-

tal information) into the DPP and the Internet of Materials concept described in Section 3.5.

V. A governance system should be implemented to improve interoperability across systems (see action 11). Future research should explore different options for this governance, assessing the feasibility of a central authority, the definition of a hierarchy of issuance organizations, or other distributed approaches.

VI. Definition of metadata to support the transfer of EPD data (see action 10).

5. Conclusions

This study identifies limitations related to machine interpretability for the direct transfer of LCA data into IFC. The research is grounded in literature (scientific papers and technical standards) related to LCA, EPDs, digitalization of product data and BIM. The limitations were analyzed using a pilot from a research project (see Section 4.3).

The twenty identified limitations (gaps) are presented in Tables 1–3 and 7. The BIM model of a building pilot was used to assess the identified gaps. The assessment revealed several areas for improvement in the current version of IFC, which define the issues to consider in the next versions. Based on the required modifications, this paper presents eleven actions in Table 11.

Compared to previous research, this study provides a structured enumeration of gaps and proposals to bridge them, allowing for a systematic inclusion of the solutions in a revision of IFC 4.3. The results identify the standards to be revised in addition to the IFC schema (ISO 16739-1:2024), including ISO 21930, EN 15804 and EN ISO 22057. It also provides the relation with new initiatives such as the DPP (see Section 3.5).

This research concludes that the revision of the IFC schema alone cannot achieve the desired outcomes (automatic incorporation of LCA/EPD data into IFC). To achieve this goal, it is necessary to align the IFC structure and the format of the digital EPD. Therefore, the improvement of the IFC schema should be made in parallel with the revision of the international standard ISO 22057. This will require cooperation between the following groups: ISO/TC 59/SC 17/WG 3 (responsible for ISO 22057) and ISO/TC 59/SC 13/JWG 12 (responsible for ISO 16739-1). ISO/TC 59/SC 17/WG 1 should participate in the creation of any data model for the environmental information at building level, and ISO/TC 59/SC 17/WG 5 for civil engineering works.

The findings of this study demonstrate the importance of promoting the integration of IFC entities and IFC schema capabilities related to environmental information within BIM authoring software. The IFC schema has the potential to adequately convey LCA data, provided that its structure is enhanced to address the identified gaps. The incorporation into the official IFC schema will ensure its implementation into the BIM software available on the market. The implications for industry will be significant if enhanced interoperability enables designers and contractors to directly utilize environmental product data from manufacturers.

The availability of machine-interpretable EPD data will reduce the resources required to perform the LCA of built assets. Integrating EPD data into BIM will enable building managers to incorporate real-time data from sensors and IoT into digital twins containing LCA data obtained from IFC models. This integration will improve asset management of buildings and civil engineering works, allowing new possibilities. Examples are assessment of alternatives for predictive maintenance, using AI, during the operation of a building, or the application of generative design during the earlier stages of the project. LCA based on BIM or digital twins will also be instrumental in identifying opportunities for improving energy performance during the operational stage or to improve the recyclability of materials at the end of life.

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Abbreviations

The following abbreviations are used in this manuscript:

ADPF	Abiotic depletion potential for fossil resources
ADPE	Abiotic depletion potential for non-fossil resources
AI	Artificial intelligence
AP	Acidification potential
BIM	Building information modelling
bSDD	buildingSMART data dictionary
CEN	European committee for standardization
CENELEC	European electrotechnical committee for standardization
CEW	Civil engineering works
CPR	Construction products Regulation
DBL	Digital building logbook
DOI	Digital object identifier
DPP	Digital product passport
EP	Eutrophication potential
EPD	Environmental product declaration
EPI	Environmental performance indicator
ESPR	Ecodesign for sustainable products Regulation
ETP-fw	Ecotoxicity—freshwater
HTP-c	Human toxicity—carcinogenic
HTP-nc	Human toxicity—non carcinogenic
e.g.,	For example (in Latin, exempli gratia)
GUID	Globally unique identifier
GWP	Global warming potential
IDS	Information delivery specification
IFC	Industry foundation classes
ILCD	International reference life cycle data system
ISO	International organization for standardization
i.e.,	That is (from Latin, id est)
LCA	Life cycle assessment
MVD	Model view definition

ODP	Ozone depletion potential
PCR	Product category rules
PO	Programme operator
POCP	Photochemical ozone creation potential
RSL	Reference service life
SQP	Potential soil quality index
UID	Unique identifier
UNECE	United Nations economic commission for Europe
WDP	Water deprivation potential
WI	Work item

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