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A Methodology for Integrating Life Cycle Assessment Data within the IFC Schema through openBIM Workflows.

Master Thesis

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Abstract

The construction industry is faced with a critical challenge of reducing its environmental impacts if climate neutrality by 2050 is to be achieved. This thesis examines the potential for integration of Whole Building Life Cycle Assessment (WBLCA) data into the IFC schema and related openBIM tools as a key instrument in this goal. Several obstacles in the current WBLCA workflow are identified, such as fragmented communication, complexity of LCA processes, and the intensive workload required to manage and process Environmental Product Declarations (EPDs) data.

Central to the thesis is the investigation of how the IFC schema and openBIM workflows can be utilised to encapsulate building LCA data efficiently in the current day. This investigation is structured around three main objectives: mapping the LCA information requirements for a WBLCA, developing a methodology for integrating LCA data into the IFC schema using openBIM tools, and evaluating this methodology through practical implementation.

The Constructive Research Approach, which emphasises the creation of solutions to practical problems, is the backbone of the thesis. Comparative analysis is utilised iteratively to address, and propose solutions to, each of the three main objectives. Potential solutions are assessed in terms of their alignment with evaluation criteria, which centre around reliable, open and machine-interpretable data, simplification of solutions whenever possible and emphasis on the experience of the end-user.

The thesis presents a comprehensive analysis of LCA data sources, formulating information requirements for both the building and product levels, with a focus on compliance with Danish regulations and broader European LCA standards. It explores data dictionaries (DD), product data templates (PDTs), and information delivery specifications (IDS) as methods for communicating these requirements. The research suggests a novel data model that integrates environmental PDTs, according to EN ISO 22057, into IFC, by using CODview2 MVD defined in EN 17549-2. This model is then evaluated through an implementation into the IFC STEP format, through a custom script based on the IfcOpenShell library.

The outlined method proves that integration of WBLCA data into IFC is feasible today, but further improved support of federated models, integration with existing systems, and upcoming standards would ensure that the solution is viable for large-scale and long-term adoption. Further work in this area could explore how such solutions could be enhanced with automatic compliance checking, continuous integration and be part of repository based systems like Digital Building Logbooks.

Contents

1 Introduction

As 2023 was emerging as the hottest year on record, the EU Commissioner for Climate Action celebrated the unprecedented inclusion of the phrase ”transition away from fossil fuels” into the final agreement text of UN’s 28th Climate Change Conference[1]. The lack of urgency among world leaders stands in stark contrast with the tens of thousands people killed or displaced by catastrophic weather events just this past year[2]. The direct deaths caused by extreme weather are, however, only a fraction compared with the millions of lives lost due to the less overt consequences of climate change. Excess deaths from air pollution related to burning fossil fuels alone, are estimated at over 5 million a year[3]. Even more striking, up to 1 billion lives, mainly those of poorer humans, could be lost over the next century through anthropogenic global warming if it reaches two degrees Celsius [4].

Unfortunately, even though the stark impact of climate change is undeniable, the trajectory continues to move in the wrong direction. Apart from temperature, 2023 broke a number of other climate records, including reaching the highest sea levels and warmest ocean temperatures, the lowest Antarctic sea ice extent, and the highest levels of greenhouse gas emissions[5].

The building and construction industry has long been recognised as one of, if not the, sector contributing the most to this trend. Despite the fact that emission intensity per square metre of new buildings is falling, the sector is still responsible for 37% of global greenhouse gas (GHG) emissions and 40% of global energy consumption [6]. The primary cause can be found in the historically high fossil fuel subsidies, following the energy price volatility brought on by the war in Ukraine[**subsidies**]. But even disregarding current events, growth of new building mass is outpacing any efforts and investments in energy efficiency, and leaves the industry off track from UN’s 2050 decarbonisation goal [7].

There is however hope, with studies showing that alternative materials and techniques can reduce up to 90% of CO2 emissions at different stages of the building life cycle. [8] The basis for these reductions is however strict climate policy including restrictions on total emissions.[9] Within the European Union, the 2020 European Green Deal outlines a number of policy initiatives with the overarching goal of reaching climate neutrality by 2050. (This goal also concerns the construction industry, including the operational, and embedded emissions of buildings.) A pivotal regulatory tool needed to meet the European Green Deal’s objective, is the EU taxonomy for sustainable activities (EU taxonomy for short). It is a classification system, that establishes clear definitions of environmental sustainability to prevent greenwashing and guide investments. It became legally binding in 2021, with provisions for circularity and biodiversity coming into effect in 2024.

The EU Taxonomy sets environmental objectives, called technical screening criteria, for a number of sectors with an especially high impact, including buildings, infrastructure, energy supply and manufacturing. These objectives address the mitigation of and adaption to climate change, the protection of aquatic resources and biodiversity, prevention of pollution and transition to a circular economy. Of these, climate change mitigation and circular economy objectives most directly influence the building design process, for example through Global Warming Potential (GWP) reporting included as part of the technical screening criteria for sustainable buildings. GWP reporting according to the Taxonomy is guided by the European framework for sustainable buildings — Level(s). Level(s) is a voluntary sustainability assessment and reporting framework for buildings developed by the EU Commission. Level(s) tries to be holistic in its approach and thus, apart from measuring GWP impacts, it includes indicators on water and material resources, health, comfort, adaption to climate change and life cycle costs.

In the Danish context, new building regulations were set at the start of 2023, requiring an overall climate impact assessment for all buildings. BR18 §297 requires a computation of the environmental impact, and § 298 contains a limit value of this impact for buildings with heated area over 1.000m^2[10]. These new regulations accelerated the interest and innovation in this field throughout the Danish building industry, leading to the creation of a host of new tools aiding the process.

1.1 Life Cycle Assessment

The methodology used for quantifying the environmental impacts of buildings used in all those policies is Life Cycle Assessment (LCA). LCA studies focus not only on GHG emissions, but a wide range of environmental indicators, and evaluates them throughout their entire life cycle, from raw material extraction to end-of-life. It includes assessment of the consumption of resources like energy, water, scarce materials, and pollution, and quantifies the impacts on not only the environment, but also human health. The holistic and comprehensive approach of LCA is critical to avoid the “shifting of burdens” from one environmental problem to another [11]. At its core, it is internationally standardised through the ISO 14000 standard series, which provides guidelines for conducting the assessment consistently and transparently. While an LCA can have a number of different goals, ranging from accounting (reporting) to policy development, a common goal is aiding sustainable design by identifying environmental hot spots and potential areas of improvement throughout the product’s life cycle.

Although Life Cycle Assessment, was created with focus on products and processes, it is today widely used in the context of buildings, where it is known as a “building LCA”. Mandatory reporting of building LCAs has been identified as a crucial strategy for reaching EU’s target of carbon neutrality by 2050 [9], especially in the procurement process[12]. The term ”building LCA”, sometimes referred to as Whole Building Life Cycle Assessment (WBLCA) in the literature, is used to distinguish the detailed assessment of a product’s inputs and outputs of all upstream and downstream processes (flows) from the aggregation of these products in a building system. A building, by and large, is a collection of products, and as such, a WBLCA consists largely of summing the impacts of these products and adding them to the emissions released during the operational phase af the building. These LCAs of products used in the context of building LCAs, are typically communicated through Environmental Product Declarations (EPD).

1.2 Building Information Modelling and Industry Foundation Classes

Building Information Modelling (BIM) is a process that involves creating and managing digital representations of physical and functional characteristics of our built environment. It involves much more than 3D modelling; in fact, geometry is optional and most data is non-geometric. It’s a comprehensive approach that incorporates all facets of a building’s lifecycle, from design and construction to use and upkeep. A BIM model can contain information about:

- **Products**, like walls, doors, and windows
- **Processes**, like construction or maintenance tasks, and procedures

- **Resources**, like labour, materials, and equipment
- **Controls**, like permits, orders, costs, or calendar availability
- **Actors**, like occupants, clients, architects, and liable parties
- **Groups**, like systems, inventories, or zones

These objects themselves can have associated relationships and data like classification systems, physical materials, associated documents, simulation results, and construction types[13].

BIM allows stakeholders from various disciplines to collaborate more effectively throughout the entire life cycle of a construction. Contractors can use BIM to generate comprehensive construction schedules, identify potential conflicts before they occur, optimise construction sequences, and improve overall project efficiency. Additionally, BIM can be integrated with construction management software to track progress, manage resources, and minimise delays. Then, during the building's use phase, facility managers can use BIM to streamline operations, plan maintenance activities, track assets, and optimise energy usage. As the building evolves, BIM models can be continuously updated to reflect changes, renovations, or upgrades.

Industry Foundation Classes (IFC), are the most well-established and comprehensive language for BIM. It is an open, international standard (ISO 16739-1:2020) and promotes vendor-neutral exchange of building data throughout its life cycle. [14] It describes both geometric and semantic information about buildings and other built structures. IFC defines a comprehensive data model that covers a wide range of building elements, systems, and attributes. IFC has been developed and managed by buildingSMART, an international industry-led organisation, since 1995. Apart from IFC, buildingSMART manages the development of a number of tools and standards, that together form the basis for the openBIM workflow. At its core, openBIM is a vendor-neutral collaborative process, emphasising open standards and data formats.

Historically, IFC was thought of as an exchange format to be used between programs, but not edited directly, akin to PDF. The process of importing and exporting data however, necessarily involves data loss. To avoid this data loss, design teams will naturally create workflows that avoid the round-tripping of data, leading to an indirect vendor-lock where the price is data and model quality. Today however, a new movement pushes for using IFC as a native format, and editing it in place, called NativeIFC [15]. FreeCAD and BlenderBIM are the most prominent examples of graphical softwares that support NativeIFC.

The move towards openBIM and nativeIFC workflows represents a significant step towards overcoming the fragmentation and inefficiencies that have historically characterised the building industry.

1.3 Scope and Focus of the Project

Today, performing a WBLCA is an intricate and intricate and labour-intensive due to manual procedures, such as extracting data from 3D, or even 2D, models, mapping materials to appropriate EPDs and coordinating across various disciplines. This manual approach presents several bottlenecks, which make iterative approaches too time-consuming to be practical. Meanwhile, proposed automatic workflows often lack adherence to standards, compromise data quality, or require transferring data from one system to another, resulting in additional workload and time spent on information mapping or migration.

Another issue with current workflows is the difficulty of storing and communicating information from the building LCA in the long term. A lifetime of a building can be anything between a few decades to hundreds of years, but we typically can't open or use this information just a couple of years down the line.

There is considerable potential to streamline workflows for both humans and data so a WBLCA process can;

- require less manual, tedious work leading to strain, dissatisfaction and is error-prone
- be utilised earlier in the building design process when it can have a most significant impact
- facilitate an iterative approach, allowing for ongoing improvements and adapt to the continuously changing design
- allow using BIM as the primary communication tool between disciplines, reducing reliance on emails and other forms of communication
- adhere to the latest standards and requirements for data quality
- maintain high data and model quality ensuring self-documentation, thereby minimising the need for extensive documentation at the end of the process
- doesn't compromise on the scientific rigour of the LCA methodology and the expertise required for an interpretation of results

To achieve these goals, integrating the LCA process with BIM, is necessary[16]. This integration must also prioritise open standards, such as IFC, and vendor-neutral, collaborative processes like openBIM and NativeIFC, to ensure interoperability and accessibility for decades to come.

Despite the fact that all three facets of sustainability; the environmental, social and economic are important for a holistic approach, this research concentrates on the environmental aspect of building sustainability. Geographically, the focus is on the Danish context and Europe more broadly.

The aim is to develop a comprehensive framework that is capable of capturing LCA data in its most advanced form, as well as a smaller subset of it. An effective and flexible workflow shouldn't necessitate changing the data- or modelling framework in the middle of the project. Therefore, the goal is that the same data model can be used for earlier and less defined stages as well as late ones. Features like flexible product requirement definitions and predefined component libraries should empower designers and engineers to actively define the uncertainty of early stage projects as part of the schema. Ultimately, however, the emphasis in case studies and implementation tends to be placed more on the advanced stages of project development.

1.4 Objectives and Overview of the Structure

A key challenge outlined in this introduction is the effective integration of LCA data into the BIM process, which is crucial for enhancing sustainability and achieving goals such as climate neutrality by 2050. Thus, this research pivots around the critical question:

> *How can the IFC schema and openBIM workflows be utilised to encapsulate building LCA data effectively today?*

The specific objectives of this research include: (1) identifying and mapping the LCA information requirements needed to perform a WBLCA; (2) developing a structured methodology for integrating LCA data into BIM workflows and IFC specifically; and (3) evaluating the effectiveness of this methodology through a proposed implementation.

The thesis is structured as follows; Chapter 2 provides a comprehensive background on sustainable building design, LCA, and BIM, setting the stage for the research. It also includes a literature review of related research centred around the integration of LCA and BIM. Chapter 3 details the methodology used throughout the thesis and defines the evaluation criteria used to analyse and select potential solutions.

Chapter 4 presents a comparative analysis of the sources of LCA information requirements and related challenges. It then goes on to compare different information requirement specification methods and recommends the most suitable ones. Subsequently, strategies for storing and sharing environmental product data are analysed. The analysis chapter concludes by proposing a comprehensive data model for integrating LCA data into an openBIM workflow.

Chapter 5 discusses the implementation of both product and building level data as STP-IFC files using a custom script based on the IfcOpenShell library and analyses various detailed methods for implementation.

Finally, in Chapter 6, the dissertation concludes with a discussion of the proposed solution, alternative approaches and recommendations for future research.

2 Background

2.1 Regulatory and Theoretical Foundations

2.1.1 Life Cycle Assessment Fundamentals

In the beginning of the 1960s questions about a product's environmental impact arose. How much does it pollute to manufacture product A? What about its transportation or disposal? How do we consider these topics in an environmentally degrading world?

Initially, the studies, which are now accepted as the earliest LCA studies, were limited to the manufacturing of products and their energy usage. Later expanded to also include requirements for resources, emissions, and waste. Finding alternatives for packaging was the main focus. In the 1980s the interest in LCA grew greatly, which led to the introduction of standards for airborne and waterborne emissions. The interpretation of LCA followed a diverse approach to the terminology and its system. International scientific discussions were deficient, which led to a rather chaotic procedure with no common theoretical backbone. This prevented LCA from becoming applied as an analytical system.

The 1990s provided extraordinary changes in both science and activities around the world. An example of that could be the amount of SETAC (Society of Environmental Toxicology and Chemistry) workshops, different organisation summits, and the amount of LCA manuals and handbooks that have been manufactured. While ISO had been participating in LCA since 1994, their purpose was mainly the standardisation of methods and processes. This period also represents a time when LCA became a critical part of legislation and policy documents. On top of that, multiple methods, which are still widely utilised today were developed at that time. The CML 1992 environmental theme approach is an example of that.[17]

The beginning of 2000's brought the development of the two primary ISO standards, that form the basis of the Life Cycle Assessment (LCA) methodology today, namely ISO 14040 and ISO 14044.

The ISO 14040:2006 standard outlines the principles and framework for conducting an LCA. It defines four phases of the LCA process; defining the goal and scope, conducting life cycle inventory analysis (LCI), performing life cycle impact assessment (LCIA), and interpreting results (see Figure 2.1). ISO 14040 differentiates between life cycle assessment (LCA) studies and life cycle inventory (LCI) studies. LCI studies differ from LCA by excluding the LCIA phase. While ISO 14040 provides a comprehensive overview of the LCA process, it does not delve into the detailed methodology for conducting the analysis. Additionally, while the intended application of LCA or LCI results is considered during the definition of the goal and scope, the actual application itself falls outside the scope of this standard. [18]

ISO 14044 provides detailed requirements and guidelines for conducting an LCA. It builds upon the framework defined by ISO 14040, and details how to implement each phase of an LCA study. The focus of ISO 14044 is on the practical implementation of LCA studies. It provides detailed guidance on how to conduct an LCI, LCIA, and how to interpret and report the results of the assessment. The standard specifies the requirements for LCI, LCIA, interpretation, and reporting. Furthermore, it also lays out the requirements for comparative studies and provides guidelines for conducting critical reviews of LCAs.

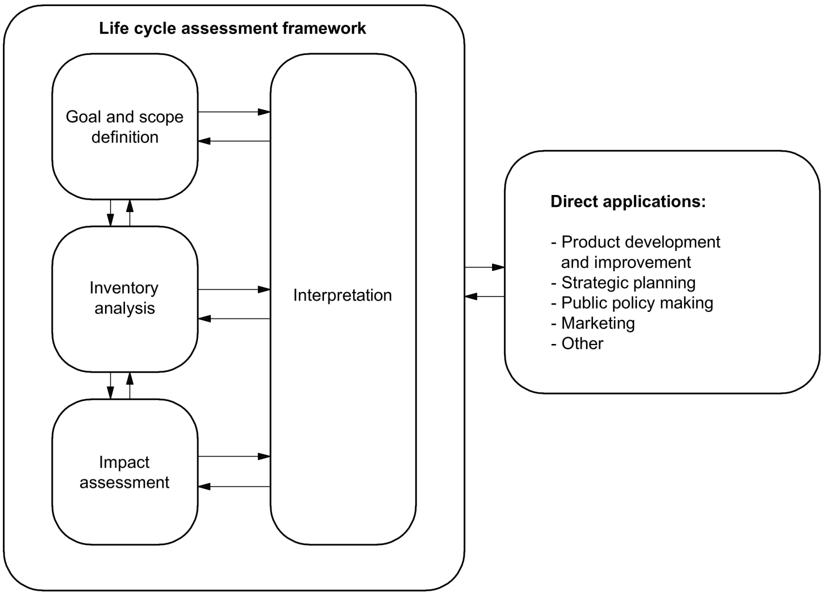


Figure 2.1: Stages of an LCA. Source: ISO 14040

Together these two standards provide a framework for conducting comprehensive and scientifically rigorous assessments, and form the basis for all other more specialised applications of the LCA methodology. This framework leaves, however, many aspects of it up to subjective interpretation, which can lead to differences in consistency, reliability, and comparability of results. To help guide LCA practitioners in the choices presented by ISO 14040 and ISO 14044, the European Commission's science and knowledge service, Joint Research Centre (JRC), has been developing the International Reference Life Cycle Data System (ILCD)[11] since 2005.

ILCD

The ILCD consists of a series of technical documents designed to offer guidance on best practices in Life Cycle Assessment (LCA) within both business and government contexts. The most important of these guides the is ILCD Handbook, which covers all aspects of conducting an LCA. The ILCD handbook is complemented by templates, tools, and supplementary materials. Acting as a foundational document, the ILCD Handbook serves as a basis for creating sector-specific and product-group-specific guidance documents, criteria, and sustainability tools.

JRC later developed an XML-based format, under the same name, which aligns with the guidelines outlined in the ILCD Handbook[19]. It was originally developed for the purposes of the European Reference Life Cycle Database (ELCD), which was discontinued in 2018. Since its development however, the ILCD format became one of the two most well-established exchange formats for LCA and LCI data, ecoSpold being the other one. The ILCD format is structured like a relational database with information being separated into several XML files, known as data sets, and entities referring to each other with unique IDs. Each data set contain thematic information about one part of the whole LCA or LCI, such as processes, LCIA methods, flows, unit groups and others (Figure 2.2.

2.1.2 Data Quality in LCA

As outlined in the ILCD Handbook[20], data quality in LCA is characterised by three key concepts: accuracy, precision/uncertainty, and completeness.

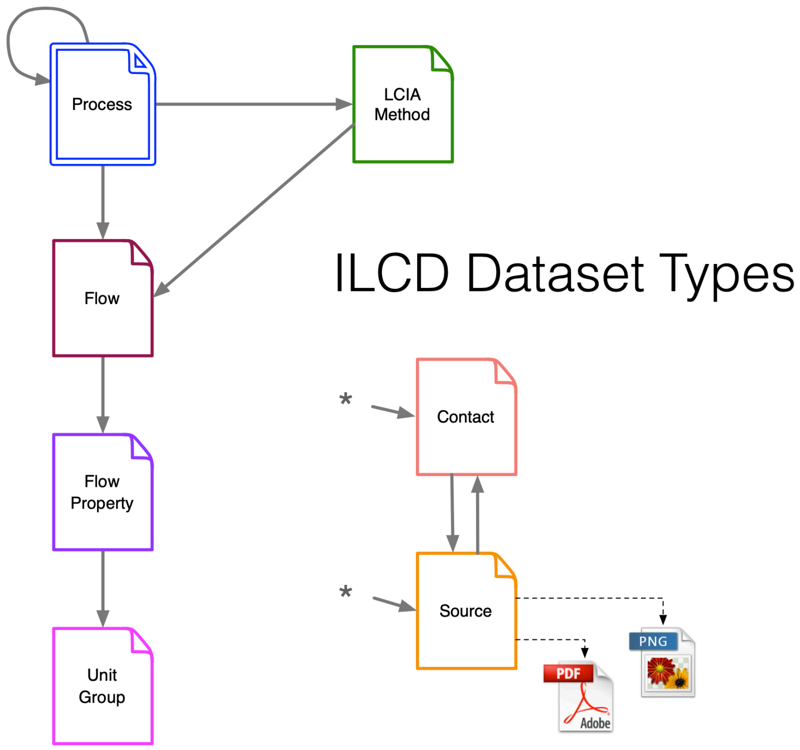


Figure 2.2: Types of datasets in the ILCD format. Source: Oliver Kusche - ”ILCD+EPD Data Format Primer”

Accuracy
In the realm of LCA, ’accuracy’ refers to the degree to which a measured or calculated value reflects the true value, also taking into account the impact of the methodologies used and their underlying assumptions. Accuracy in an LCA framework is detailed through several sub-dimensions of data quality, including:

- Representativeness, which further breaks down into:
  - Technological Representativeness: How well the data reflects the specific technologies used.
  - Geographical Representativeness: The extent to which the data is relevant to the geographical context of the assessment.
  - Time-related Representativeness: The degree of alignment between the data’s temporal context and the period of interest in the LCA.
- Methodological Appropriateness and Consistency: This aspect evaluates whether the methodologies applied are suitable for the study’s context and whether they are applied consistently throughout the assessment.

Precision and Uncertainty
ISO 14044:2006 defines precision as the “measure of the variability of the data values for each data expressed (e.g. variance)”. Precision in science and engineering refers to reproducibility, indicating consistent results among different experts [20]. The ISO definition links precision to stochastic uncertainty (i.e. variance), encompassing both measurement and choice errors. Accuracy, as a combination of representativeness and methodological consistency, is hence complementary, but distinct, to the ISO definition. Problems with

accuracy, like a lack of data representativeness, will therefore be an issue of bias and not stochastic uncertainty (see Figure 2.3).

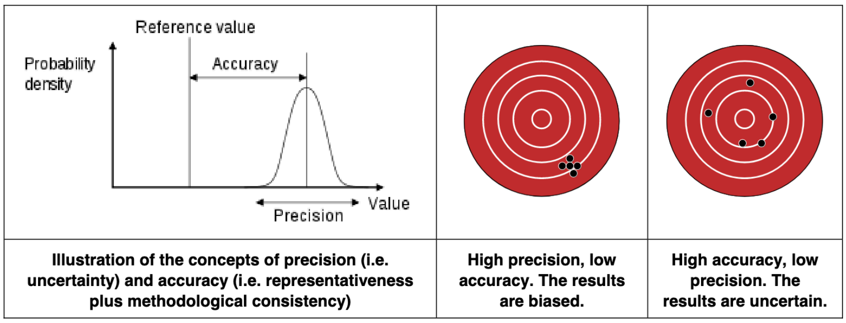


Figure 2.3: Accuracy vs. precision in LCA. Source: ILCD Handbook, p. 326.

Completeness
“Completeness” refers to the level of comprehensiveness in the accounting of inventory flows with the purpose of creating a complete coverage of all relevant impact categories.

2.1.3 LCA of Products

Product Category Rules and Environmental Product Declarations
A frequent objective of an LCA is the development of a so-called type III environmental declaration — Environmental Product Declaration (EPD), defined by ISO 14025:2006. EPD differs thus from type I independent eco-labels and type II self-declared eco-labels. The goal of and EPD according to ISO 14025 is enabling the comparison of products fulfilling the same function [21]. As such, a fair base for this comparison is needed. The definition of assumptions and scope of information included is however part of the LCA methodology, and is determined independently for each study. As such, two LCA studies of products fulfilling the same function, may not be comparable. Product Category Rules (PCRs) provide common definitions for the LCA of products among the same category, making comparisons between them equitable. A PCR document includes, among many others, descriptions of the product category itself, which stages and processes of a product’s life cycle should be included (system boundaries), the amount and functions covered by the product (functional unit), impact categories, definition of use-phase, and units. EPDs used in the construction sector are harmonised primarily by the PCR standard EN 15804. Today, this standard is split into two versions; the original, 2012 EN 15804+A1, and an updated version, EN 15804+A2, published in 2019.

The updated version aligns more closely with the European Commission’s Product Environmental Footprint (PEF) method and introduces a number of new impact indicators. Key changes include that EPDs must now cover all life-cycle stages, including end-of-life (EOL) recycling, resulting in increased complexity and workload for stakeholders. The loads and benefits of end-of-life (EOL) recycling must also be computed, which makes the LCA more complete but also more complex. Furthermore, declarations about the mass of biogenic carbon from the manufactured goods and their packaging must be stated separately.

On the global level, EPDs of construction products can also be created according to ISO 21930:2007[22]. It is virtually unused in Europe due to the popularity of the EN 15804 standard. ISO 21930 clarifies however the difference between a PCR and the LCIA method used to perform the LCA, since it allows the usage of EN 15804 as an LCIA method (Figure 2.4) together with ISO 21930 as a PCR. The American TRACI or the international default LCIA methods can also be used.

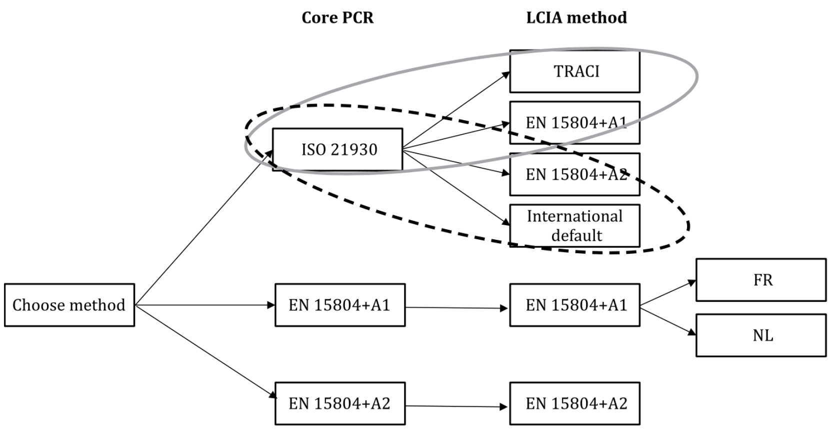


Figure 2.4: Different methodological frameworks of EPDs. Source: EN ISO 22057:2022.

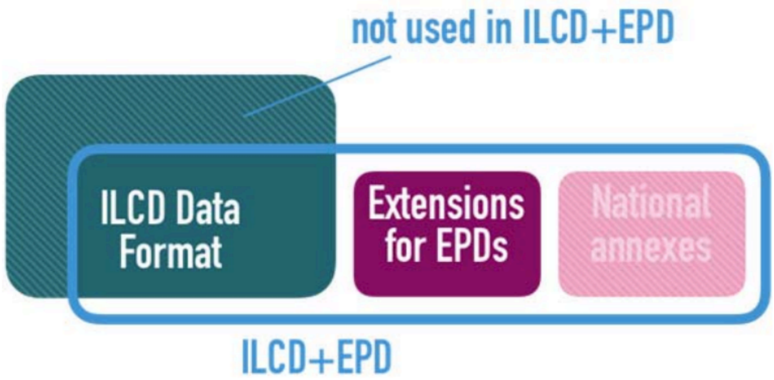
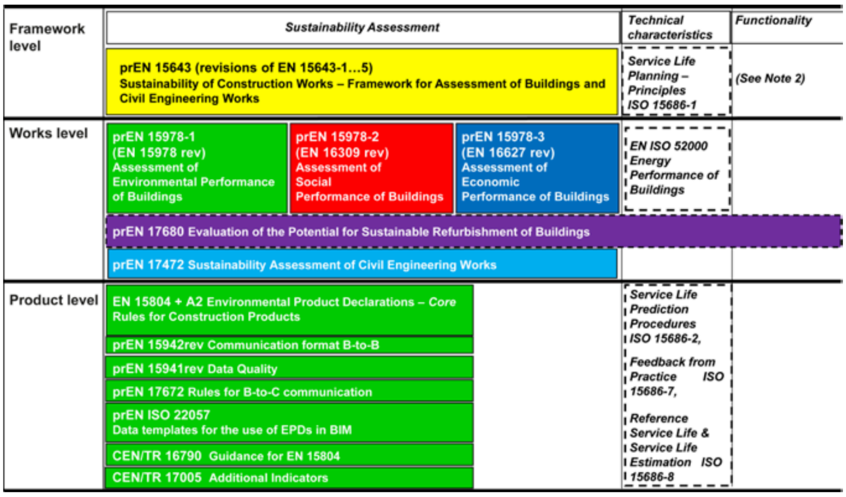


Figure 2.5: Scheme-ILCD+EPD data forma. Source: InData

Various Types and Formats of Product LCA Data
Product LCA data can come in be structured in a number of ways. Most important is the distinction between generic product data and product-specific data like EPDs. Generic data, provided by platforms like ÖKOBAUDAT, still follows the EN 15804 PCR, but are modelled based on literature and expert knowledge instead of specific products [23]. Product-specific data can then further be separated into single-company and single-product EPDs (the most common), industry-average EPDs, EPDs containing multiple products and EPD of product not yet on the market.

These different types of data can be expressed in various formats. The format most used to describe EPDs to this day, is PDF. However, when it comes to machine-readable EPDs, one of the most important formats in Europe is the ILCD-based, ILCD+EPD. It is developed by the International Open Data Network for Sustainable Construction (InData), an informal, non-profit work group, with the goal of establishing an open web based international data network structure for EPD and LCA data. Figure 2.5 shows the relation of the ILCD+EPD format with the broader ILCD format. ILCD+EPD introduced a number of extensions specific to EPDs and limited the amount of information from ILCD, specifically the LCIA method data set. ILCD+EPD is also the chosen format of ECO Portal, a central data base for European EPDs.

Other notable digital EPD formats are the JSON-based openEPD mainly used in the US,



NOTE 1 The coloured boxes represent the current work programme of CEN/TC 350.

NOTE 2 Functional requirements are part of client's brief and building regulations.

Figure 2.6: European sustainability standards relating to buildings. Source: EN 15643:2021.

and the new standard EN ISO 22057, which defines EPDs as data templates for the purpose of integrating them in BIM models.

EPDs can also be extended with other types of information, as exemplified by the French FDES and PEP. FDES (Fiche de Déclaration Environnementale et Sanitaire) translates to Environmental and Health Declaration Sheet. It is a standardised document in France that, apart from the regular environmental information of an EPD, provides information about the health impacts of construction products. PEP (Profil Environnemental Produit) is a different type of document, which translates to Environmental Product Profile. Similar to FDES, PEP provides environmental information about products, but it goes beyond construction products and encompasses a broader range of goods and services. PEP aims to provide transparency and facilitate sustainable consumption choices by being directed at final consumers and informing them about the environmental performance of products.

2.1.4 LCA of Buildings

EN 15643, "Framework for assessment of buildings and civil engineering works" is the highest level, conceptual standard that serves as the foundation for assessing the sustainability of buildings. It provides a framework for the assessment of buildings in terms of environmental, social and economic sustainability. Figure 2.6 shows the different levels of sustainability standards including the framework level, building level and product level.

EN 15978 specifically focuses on evaluating the environmental performance of buildings and is the foundation of all WBLCA and building carbon footprint assessments. The upcoming new version of EN 15978, prEN 15978-1, updates it with the EN 15804+A2:2019 PCR, and data quality requirements defined in FprEN 15941:2023.

FprEN 15941:2023 (EN 15941:2024), "Sustainability of construction works — Data quality for environmental assessment of products and construction work — Selection and use of data" addresses the assessment of LCA data quality both on the product and building level. It provides detailed and concrete guidance on selection and assessment of product level LCA data (EPD and generic data) when used in the context of a building

LCA. It defines data quality requirements in terms of representativeness, precision and completeness, as well as provides strategies to quantify the evaluation of data quality in a building LCA. Additionally, it outlines examples of how to document and report data quality comprehensively.

2.1.5 Danish Regulatory Context

In 2023, Denmark introduced new regulations concerning energy consumption and climate impact, detailed in sections §297 - §298. These regulations mandate the completion of an LCA for all buildings to ensure they meet specific environmental standards throughout their lifecycle.

A significant aspect of these regulations is the establishment of Global Warming Potential (GWP) (measured in kg CO2-eq) thresholds for buildings over 1000 m2. For a standard 50-year consideration period, the limit is set at 12 kg CO2-eq/m^2/year. Moreover, for buildings classified under the low emission class, a more stringent requirement is in place, with the threshold being 8 kg CO2-eq/m^2/year. This benchmark aims to encourage more sustainable construction practices and materials that have a lower impact on the environment over the building's lifetime.

Tabel 6 — Required Building Elements to be Included in the LCA
To accurately calculate a building's climate impact, it's essential to account for the emissions from the materials used in each part of the structure. Ideally, a building's LCA should encompass as many components as possible to provide a true reflection of its environmental footprint. But given the complexity of buildings, this could easily become an unfeasible task.

Annex 2 of Danish building regulations §298, referred to as Table 6, defines which parts of a building must be included in a building LCA to be compliant, and which can be omitted. It serves to ensure uniformity in building LCA by defining a consistent scope of inclusion for all buildings. Table 6 distinguishes between the different parts of a building and the materials used in each of those parts. This approach aims to strike a balance between resource use and the precision of the building LCA. This ensures that the evaluation reflects the true climate impact of a building as closely as possible, but is feasible to execute on a large scale.

Tabel 7 — Generic Material Data
According to BR18, the environmental impact of each material used in a building's construction must be evaluated using either specific product data (EPDs), or generic data defined in BR18, Annex 2, Table 7. The Table 7 dataset provides generic environmental data derived from the ÖKOBAUDAT database, using average values for common material groups.

According to § 298, subsection 6, no generic data other than that provided in BR18, Annex 2, Table 7, may be used. Environmental data specific to products, necessary for a more detailed analysis, must be sourced from third party verified EPDs. This requirement ensures that LCA results are based on reliable and standardised data, contributing to the accuracy and integrity of the building's environmental assessment.

2.2 Technical Norms and Standards in BIM

Over the past few decades, BIM has witnessed a significant evolution in the amount of information contained within its models. Initially, BIM's models focused primarily on representing the geometric aspects of buildings, such as their shape, size, and spatial relationships. These early models lacked detailed information regarding components and systems. Later information about materials, dimensions, manufacturer details, and installation requirements were added. With a growing emphasis on sustainability and energy efficiency, the modern BIM model can now incorporate data about energy consumption, thermal properties, daylight analysis, indoor air quality and much more. Today, BIM is not only being used on new projects, but can also be used to describe existing structures, and encompass information on how a building can be adapted, renovated, or its parts reused. Thus, BIM has evolved beyond just a design and construction tool to encompass the entire life cycle of a building.

The Industry Foundation Classes (IFC) have their historical roots in the Architecture, Engineering, and Construction (AEC) industry's efforts to standardise data exchange and interoperability. IFC was developed as an open standard by the International Alliance for Interoperability (IAI), now known as buildingSMART International. The development of IFC began in the early 1990s, driven by the recognition that the lack of interoperability between different software tools and systems was hindering collaboration and efficiency in the AEC industry. The first version of the IFC standard, IFC 1.0, was released in 1996. Since then, IFC has undergone several revisions and updates to accommodate advances in technology, changes in industry practices, and evolving requirements. ISO 16739-1:2018 provides the international standard for IFC, ensuring consistent data exchange[24].

In recent years, buildingSMART has been developing a set of high level process maps, that combine the different solutions and standards they offer, under the name openBIM workflows. openBIM workflows are based on the methodology of the vendor-neutral collaborative framework, openBIM. They centre around four main use-cases; Define requirements for IFC, Author IFC, Extend IFC and Validate IFC. These use-cases are realised through the integration of following tools or standards as defined by buildingSMART[25]:

1. **UCM** – Use Case Management, enables the capture, specification, and exchange of best practices and makes them accessible to the entire built asset industry
2. **IFC** – Industry Foundation Classes, a standardised, digital description of the built asset industry
3. **IDS** – Information Delivery Specifications, a computer-interpretable document that defines the Exchange Requirements of model-based exchange.
4. **bSDD** – buildingSMART Data Dictionary, an online service that hosts classifications and their properties, allowed values, units, and translations.
5. **Validation Service** – provides a judgment of conformity of a given file, to the IFC specification (new free online service, still in beta)
6. **openCDE** – open common data environment that allows for great interoperability within the AEC software ecosystem.
7. **BCF** – BIM collaboration format, allows different BIM applications to communicate model-based issues with each other by leveraging IFC data that have been previously shared among project collaborators.

2.2.1 Data Dictionaries

Although the buildingSMART Data Dictionary (bSDD) has become ubiquitous with the concept of Data Dictionaries in the openBIM community, it is only one possible realisation of this concept.

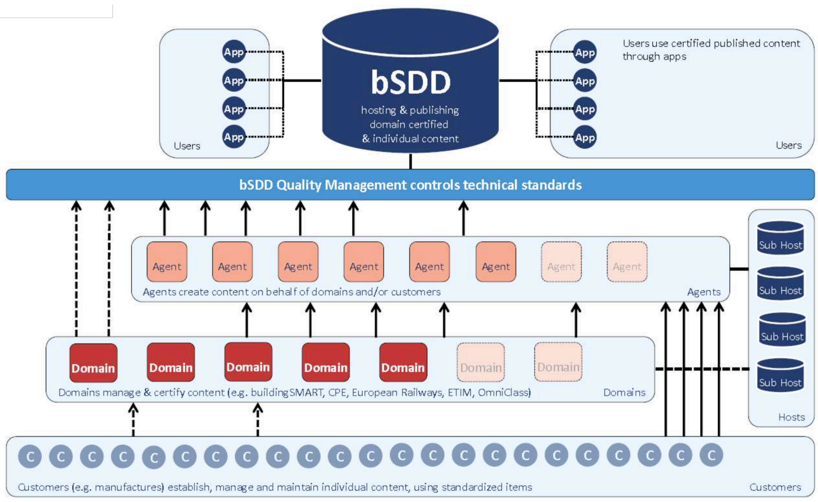


Figure 2.7: Operating model of bSDD. Source: buildingSMART Technical Roadmap.

Data dictionaries are critical components in the domain of data management and BIM, serving as a single source of truth (SSOT) for the definitions, classifications, and specifications of data. An SSOT ensures that everyone in an organisation or project has a common understanding and access to the same data, thereby reducing errors and misunderstandings. The foundation of any reliable data dictionary is its ability to provide trusted definitions. These are not mere amalgamations of names and text descriptions but are built on a framework that ensures clarity, consistency, and compliance with international standards. The significance of standardised definitions cannot be overstated, as they are crucial for interoperability, data quality, and the efficient exchange of information across different systems and stakeholders.

Standards and Frameworks

The framework for effective data dictionaries is defined by key standard ISO 12006-3, which establish a data model and an API framework to facilitate communication between different data dictionaries. This is instrumental in achieving interoperability among varied data management systems. Meanwhile, ISO EN 23386:2020 — “Building information modelling and other digital processes used in construction Methodology to describe, author and maintain properties in interconnected data dictionaries” provides a comprehensive methodology for the definition and management of properties and groups of properties within data dictionaries. It encompasses the process of property definition, ensuring quality, trust, and a systematic approach to the authoring and maintenance of dictionary content. Additionally, it offers guidelines on how to interconnect different dictionaries, facilitating a cohesive ecosystem of data management tools.

Implementations and Solutions

BuildingSMART Data Dictionary (bSDD): bSDD stands as a specific implementation of a data dictionary governed by the buildingSMART organisation, adhering to the principles laid out by the aforementioned standards. It provides a structured platform for managing property sets and ensuring that data across the construction and operation of buildings and infrastructure is consistent and interoperable.

The BuildingSMART Data Dictionary (bSDD) consolidates data from numerous stakeholders, each tasked with ensuring their contributions remain current and reliable. To uphold stringent quality standards, data must undergo a thorough vetting process before publication. It is imperative to maintain a clear demarcation between datasets owned by different stakeholders, ensuring that only the rightful owners or their designated representatives have the authority to modify their respective datasets.

As illustrated in Figure 2.7, the operational model mandates that data from various owners be segregated into distinct domains. This separation facilitates the accurate differentiation between similarly named entities that possess unique semantic meanings. Furthermore, translations are meticulously associated with their original semantic concepts to preserve clarity and consistency.

Define by CoBuilder: Representing a commercial and proprietary solution, Define by CoBuilder offers an expert committee approach to data dictionary management, similar to bSDD. One of the challenges with proprietary data dictionaries (more so than open source dictionaries) is ensuring longevity and reliability. This challenge could be addressed by incorporating redundancy mechanisms, such as multiple URIs linking to a single product, ensuring that data remains accessible even if one link fails.

LeksiCON by Molio: In the Danish context, LeksiCON represents a national initiative to host a Danish dictionary, leveraging CoBuilder's solution. The dictionary created by Molio, known as "Danish Context" ("dansk kontekst"), currently features 42 building parts in data templates specific to the Danish context. These templates encompass unique standardised properties across four purposes: Molio Building Part Specification R5, Classification and Identification (CCS/CCI/BIM7AA/BIMTypeCode), Operation, and an upcoming EPD according to DS/EN ISO 22057. The development of data templates and properties is ongoing, evolving to meet the demands of the industry.

All the current solutions like CoBuilder and bSDD represent centralised data dictionaries, where a single entity manages the dictionary. However, the concept of a decentralised data dictionary, where different countries or regions manage their own segments within a global framework, presents an intriguing possibility for enhancing the longevity and resilience of data. Such a structure could prevent the loss of data due to the failure of a single dictionary and ensure a more robust and adaptable data management ecosystem.

2.2.2 Common Data Environment

The Common Data Environment (CDE) is a web-based platform for project management, enabling efficient collaboration across various stakeholders and software applications by centralising data storage and structuring. While CDEs offer significant advantages in project management, including reduced setup costs and improved efficiency, they also present challenges, particularly the labour-intensive and error-prone process of manually uploading and categorising project documents and models.

To overcome these challenges, advancements like openCDE have been introduced, shifting from a file-based to a database-driven exchange process. This innovation eliminates the need for manual data handling, allowing for the transfer of only changes, thereby optimising data volume and transfer times. The implementation of such technology, as seen in platforms like BIMcollab, facilitates more streamlined and error-free project collaboration, marking a significant improvement in the management and efficiency of CDEs.

2.3 Literature Review

2.3.1 Guidance on Performing Whole Building LCAs

Saavedra-Rubio and colleagues [26] present a comprehensive framework for data collection in the Life Cycle Inventory (LCI) phase, specifically focusing on building technology-related LCI blocks. The study offers stepwise guidance to streamline data collection processes, which are crucial for conducting life cycle assessments (LCAs) of building technologies. By emphasising the importance of accurate and reliable data, the authors address challenges associated with data collection in LCA, such as data availability, quality, and consistency. The framework outlined in the study provides practical strategies and methodologies for collecting data at different stages of the life cycle, from raw material extraction to end-of-life disposal. Through a systematic approach, Saavedra-Rubio et al. aim to enhance the accuracy and robustness of LCA studies in the built environment, ultimately contributing to more informed decision-making and sustainable building practices.

Bari and colleagues present a step-by-step approach to implementing BIM in conjunction with LCA, referred to as BIM-LCA [27]. The study highlights the integration of BIM and LCA as a promising strategy for assessing the environmental impacts of buildings throughout their life cycle. By leveraging the data-rich BIM models, the authors propose a structured methodology for conducting LCA analyses, which involves mapping building elements to corresponding environmental impact categories. Through case studies and practical examples, Bari et al. demonstrate the feasibility and benefits of BIM-LCA integration in informing sustainable design decisions and optimising building performance. The study underscores the potential of BIM as a powerful tool for facilitating LCA workflows, promoting interdisciplinary collaboration, and advancing sustainability goals in the construction industry.

Both studies focus on enhancing sustainability assessment methodologies in the built environment, albeit from different perspectives. While Saavedra-Rubio et al. primarily address data collection challenges in LCA, Bari et al. suggest a methodology for integrating BIM and LCA to streamline sustainability assessments. Despite their distinct approaches, both studies underscore the importance of comprehensive and systematic methodologies for conducting LCA analyses of building technologies. By providing practical guidance and frameworks, these studies contribute to advancing sustainability practices in the construction industry and promoting the adoption of environmentally responsible building designs and technologies.

2.3.2 Best Practice in Integrated LCA-BIM Approaches

The integration of BIM and LCA stands at the forefront of evolving sustainable construction practices. This synthesis of recent research explores the fusion of BIM and LCA, highlighting strategies, comparisons, and applications aimed at reinforcing sustainability within the construction field.

Wastiels and Decuypere's [28] comprehensive analysis of various BIM and LCA integration methodologies provides a critical examination of their effectiveness and practicality. Their work illuminates the strengths and limitations of each approach, offering valuable guidance for practitioners in selecting the most fitting integration techniques for their projects.

Focusing on the crucial phase of data gathering during the LCI, Saavedra-Rubio et al. [26] introduce a meticulously structured approach for compiling building technology-related LCI blocks. This method significantly improves the integrity and precision of LCA studies, paving the way for more accurate environmental impact assessments in construction projects.

Bari et al. [27] present a detailed, actionable roadmap for the practical implementation of BIM-LCA integration in construction endeavours. Their step-by-step guide facilitates a seamless melding of LCA processes into BIM workflows, empowering stakeholders to make decisions that are both informed and aligned with sustainability objectives.

Klumbyte et al. [29] discuss principles and best practices for leveraging BIM to enhance whole building LCA. Their insights highlight the indispensable role of integrating BIM and

LCA in elevating the accuracy and efficiency of environmental assessments, crucial for informed decision-making in building design and construction.

The collective insights from the literature underscore the pivotal role of BIM-LCA integration in advancing sustainable construction. By outlining effective strategies, offering methodological guidance, and suggesting practical steps for implementation, these studies contribute significantly to the advancement of sustainability efforts in the construction industry, marking a path toward more environmentally responsible building practices.

2.3.3 Specific Workflows

Primary Literature

The project "Ökobilanzierung und BIM im Nachhaltigen Bauen" (Life Cycle Assessment and BIM in Sustainable Construction)[30][31][31] provides a comprehensive examination of the integration of LCA and BIM within the German context, with ÖKOBAUDAT, the German LCA database at its centre. It encompasses multiple papers and reports, representing the thorough investigation into the subject. The project evaluates various approaches for linking ÖKOBAUDAT's LCA data into IFC. Although a number of comprehensive methods were evaluated, including defining exchange requirements (ERs) for over 900 properties, the final recommended solution is to only reference the Universally Unique Identifier (UUID) of EPDs within the IFC model. The project includes the development of a use case implemented in UCM (Unified Collaboration Model), demonstrating the practical application of the proposed integration framework.

The paper "The BIM2LCA Approach: An Industry Foundation Classes (IFC)-Based Interface to Integrate Life Cycle Assessment in Integral Planning" [32] outlines a detailed project aimed at seamlessly integrating LCA into BIM processes. It utilises the IFC standard and its serialisation in XML, IFCXML, to ensure compatibility with existing BIM workflows. The authors introduce a custom LCA XSD schema to enrich the IFCXML data with LCA-specific information, addressing challenges related to data format compatibility and semantic mapping. The approach is designed to work across different stages of building planning and development. Through a case study, the paper demonstrates the feasibility of this approach and discusses the potential adjustments required in IFC, LCA, and planning practices to make comprehensive, informed decisions based on environmental impact data. As such, BIM2LCA represents an approach to LCA-BIM integration that extends the capabilities of IFC with a whole separate, custom schema on top, instead of direct integration into IFC.

The project, entitled "Industry Report on Environmental Impact Indicators" is a proposed approach from the buildingSMART Sustainability Group. As such, it represents industry-driven insights and practical solutions rather than theoretical research findings. This report includes the implementation of LCA and EPD modules within bSDD, and introduces a novel approach to integrating this data in IFC, utilising existing concepts like IfcTasks and IfcResources. By leveraging these existing concepts, the proposed approach is practical and doesn't require the extension of IFC (apart from custom property sets). It addresses however only a part of the product level data needed to perform a WBLCA and may not be directly implementable in most BIM software.

Secondary Literature

The following two papers explore the integration of LCA methodologies with BIM. The paper titled "BIM-Based LCSA Application in Early Design Stages Using IFC" [33] focuses on the application of BIM-based Life Cycle Sustainability Assessment (LCSA) in the early design stages utilising Industry Foundation Classes (IFC). The study emphasises the integration of various assessment aspects, including LCA, Life Cycle Costing (LCC), and

Social Life Cycle Assessment (S-LCA), with BIM through IFC. By leveraging BIM as a platform, the authors aim to facilitate a more comprehensive sustainability evaluation during the initial phases of construction projects. This approach not only enhances the decision-making process but also enables stakeholders to identify and address sustainability issues early on, potentially reducing environmental and social impacts throughout the life cycle of the building.

The paper “Using Open BIM and IFC to Enable a Comprehensive Consideration of Building Services within a Whole-Building LCA” [34] discusses the use of Open BIM and IFC for enabling a holistic consideration of building services within a whole-building LCA framework. The authors highlight the importance of integrating building services, such as HVAC systems and electrical installations, into the LCA process to achieve a more accurate assessment of a building’s environmental impact. By leveraging Open BIM principles and IFC data exchange standards, the study proposes a methodology for seamlessly incorporating building services data into the LCA workflow. This integration allows for a more comprehensive evaluation of environmental performance, contributing to the development of sustainable building practices.

Both papers underscore the importance of integrating sustainability assessment methodologies with BIM processes to facilitate more informed and sustainable decision-making in the construction industry. They demonstrate the potential of utilising standardised data formats like IFC to streamline data exchange and collaboration among stakeholders, ultimately advancing the integration of sustainability considerations into the building design and construction process.

2.4 Current Workflow and its Challenges

One of the current challenges in today’s workflow is the often fragmented communication and information flow. Different parties involved in the design process do not necessarily have deep knowledge about each other’s areas, or the requirements they each have for the building, creating so-called technical silos. Information is communicated differently from discipline to discipline, using different software, formats, and customs. Apart from poor information flow between disciplines, there occurs an even greater breakdown between project phases. Architects and engineers working in the design phase may not consider the fact that the project information has to live on and be useful for other parties further down the line. The data needs of professionals working in the construction and operation phases frequently get forgotten, as they don’t work in the same proprietary ecosystems as individuals creating the BIM model.

LCA is a new ’task’ in the design process and relies heavily on compiling information from all other disciplines, finding solutions that satisfy all requirements, communicating the proposed solution back to all parties, and getting their approvals. This process is made more difficult by a lack of a unified requirement and information model. Even if the information is in a unified, open standard like IFC, having separate discipline models can pose a challenge in a task that heavily relies on combining information (although separate discipline models also have their advantages in other areas).

LCAs are most influential on the design in the early stages, where discipline-specific expertise and requirements aren’t available. This leads to either LCAs only being performed too late in the design process to have meaningful impact on the design. Or early-stage LCAs not being utilised to their full potential because of chosen solutions being unfeasible and having to be changed late in the process to something suboptimal.

EPD data isn’t prepared to be easily searchable, usable, or integrated into a model, which results in a considerable workload for the architect or LCA specialist in searching and data processing the information for it to be useful. These circumstances create a bottleneck in iterative changes, communicating the information to others, and saving it for the future. Finally, there is no automatic way of properly documenting the chosen products, which can lead to added workload at the end of the process in documenting the LCA.

Altogether, there are significant differences in regulations between countries, even though international components are used frequently in building LCAs. There is a lack of harmonised regulations for building LCAs on the EU level. EN 15978 can provide some common structure, but individual countries can still define key factors, like the system boundaries, required building components, definition of floor area metrics, reference study period and impact categories. This leads to the results of building LCAs for otherwise similar buildings, being profoundly different and thus incomparable.

The lack of methodological and data transparency in available tools can become problematic for governing agencies, comparisons, and long term documentation. In Denmark, there are no clear requirements to hand-in formats, contents of an LCA report or documentation. This makes effective and efficient validation and compliance checking virtually unfeasible. Too little information is included for a proper check and even if the information was there, it would be impossible for a human to check the validity of all the information.

Insufficient information is provided for a thorough verification, and even if the requisite details were available, it would be impossible to assess the validity of the provided information.

On top of that, a lack of emphasis on considering reporting on data quality, both on the product and building level, which might however change with the introduction of Fpr EN 15941.

Finally, solutions trying to automate the process, often focus on mapping specific product EPDs to materials in a BIM model at an early stage, which can cause premature optimisation and issues relating to accuracy vs precision as described earlier.

These challenges can be summarised as follows:

1. Fragmented communication and information flow: There's a significant challenge in the siloed approach to communication and information sharing across different disciplines and project phases. This fragmentation leads to inefficiencies and difficulties in ensuring that all necessary information is accurately conveyed and utilised throughout the life of a project.
2. Challenges in integrating and utilising LCAs effectively: Conducting LCAs is complex due to the lack of unified information and requirements, the separation of discipline-specific models, and the difficulty in obtaining and processing EPD data. This complexity is compounded by the timing of LCAs, which are most impactful early in the design process when detailed information may not yet be available, leading to risk for suboptimal design changes later on.
3. Regulatory and methodological inconsistencies: The absence of harmonised building LCA regulations at the EU level results in inconsistencies that complicate the comparison of LCA results for similar buildings. This, along with unclear documentation and reporting requirements, makes verification and compliance checking challenging, impacting governance and long term usability of data.

3 Methodology

3.0.1 Comparative Analysis

This project is anchored in Comparative Analysis, a method characterised by its systematic approach to uncovering patterns, alongside comparing and contrasting differences and similarities across various data points, theoretical concepts, or methodologies. This method is pivotal in crafting a robust evaluative framework, essential for pinpointing the crucial information requirements that underpin the development of an effective data model tailored for the storage and sharing of product data.

In this chapter, the methodology underpinning the thesis is outlined, detailing the structured approach adopted to achieve the research objectives. The aim is to provide a comprehensive understanding and evaluation of the sources of LCA information requirements, the methodologies for storing this information, and the strategies for implementing product data sharing. The structure of this thesis is methodically organised into several critical components, to ensure clarity and coherence in the presentation of the research process. The structure is organised around the following key segments:

1. Establishing Evaluation Criteria: As an initial step, criteria for evaluation are determined to guide the subsequent analysis and selection processes.
2. Identification of Primary LCA Information Sources: This involves selecting the most relevant sources of LCA information based on their significance within the field.
3. Assessment of Each Source: Every identified source is evaluated against the pre-established criteria to ensure its relevance and utility.
4. Compilation of Information Requirements: A comparative analysis of the sources is conducted to compile a comprehensive list of information requirements.
5. Review of Information Storage Methods: This step involves examining various methods for storing the identified information requirements.
6. Description of Storage Methods: Each storage method is described in detail, including a brief history and its intended use, to provide context.
7. Comparative Analysis of Storage Methods: A critical comparison of the storage methods is performed to assess their efficacy in meeting the information requirements.
8. Analysis of Data Sharing Strategies: Different strategies for storing and sharing product data are analysed and compared to identify the most effective approach.
9. Presentation of the Final Data Model: A conclusive data model is presented, encapsulating the findings and recommendations derived from the comparative analyses.
10. Implementation and Critical Review: The data model is implemented, followed by a critical analysis of the implementation choices, including a discussion on the implications and potential improvements.

This comprehensive organisational scheme ensures a systematic exploration of the topic, facilitating a detailed examination of each aspect of LCA information management, from sourcing to sharing. Further methods and approaches employed throughout the project are described in the following sections.

3.1 Constructive Research Approach

The “Constructive Research Approach” as described by K. Lukka [35] is an approach to academic research, that emphasises the creation of solutions to practical problems. This method is distinguished from purely theoretical or empirical research by its focus on developing innovative, practical interventions that can be applied in real-world contexts.

The core principles of the Constructive Research Approach include:

- Problem Relevance: The research must address a real-life issue that is significant and relevant to practitioners in the field. This ensures that the outcomes of the research have practical applicability and can contribute to solving actual challenges faced by professionals.
- Innovation: The approach encourages the creation of new solutions, models, frameworks, or systems that offer a novel way of addressing the problem at hand. These innovations should not only be new but also better than existing solutions, contributing to the advancement of the field.
- Research Rigour: Even though the approach is solution-oriented and practical, it requires rigorous scientific methods in the development and evaluation of the proposed solutions. This includes the use of appropriate theories, methodologies, and analytical techniques to ensure that the research findings are credible and valid.
- Applicability: The solutions developed through this approach are intended to be directly applicable in real-world settings. This means that the research should not only propose theoretical models but also demonstrate how these can be implemented in practice, including potential implications and benefits for the target field.
- Theoretical Contribution: While the primary focus is on solving practical problems, the Constructive Research Approach also emphasises the importance of contributing to the existing body of knowledge. This involves linking the practical findings back to theory, either by providing insights that can enhance understanding of a phenomenon or by challenging and extending existing theoretical frameworks.

In essence, the Constructive Research Approach bridges the gap between theory and practice by focusing on the development of actionable solutions to real problems, while still adhering to the principles of academic rigour and contributing to theoretical knowledge. It is particularly valued in applied disciplines where the impact of research on professional practice is a key measure of success.

3.2 Evaluation Criteria

The evaluation of solutions within this project adheres to a multifaceted approach, grounded in principles that ensure not only technical robustness but also ethical integrity, user-centricity, and long-term sustainability. This section delineates the criteria that will guide the analysis and selection of solutions.

3.2.1 Dependence on High-Quality, Reliable Data

The foundation of any solution’s credibility lies in the quality and reliability of the data it uses. The hierarchy of preferred data sources is as follows:

1. National standards, reflecting the most direct applicability and compliance with local regulations and norms. (Danish building regulations)
2. EU/CEN (European Committee for Standardization) standards, which provide a broader, regional consensus on best practices.

3. ISO (International Organization for Standardization) standards, offering a global perspective and widespread acceptance.
4. EU guidelines and voluntary frameworks (e.g., Level(s), EeBGuide, EU taxonomy), along with BuildingSmart services (IDS, BSDD, BCF), which are instrumental in promoting sustainability and interoperability in building projects.
5. Legislation and schemas from other EU countries (e.g., Germany's BBSR/ökobau, Sweden's SBE, Norway's Digi), offering insights into successful practices elsewhere in the EU.
6. Consensus-based and compliant programs/methods (e.g., OneClickLCA BR18/EN15978, LCAbyg), which ensure alignment with recognised standards.
7. Legislation and schemas from non-EU countries, such as openEPD, which can provide valuable alternative perspectives and solutions.
8. Custom, privately-created, provided they offer unique advantages and comply with the principles of openness and interoperability.(e.g., EPDx, LCAx)
9. Custom, proprietary solutions

This prioritisation underscores a preference for solutions grounded in widely accepted standards and frameworks, ensuring their reliability, relevance, and compliance.

3.2.2 Adherence to Open Standards and Free Software Principles

In light of the EU's Interoperable Europe Act adopted on February 6, 2024, the project emphasises the use of software and systems that champion interoperability and open standards. This act advocates for the seamless exchange of information and technology across public bodies, aiming to dismantle information silos and encourage the reuse of data.

Key to this framework is the commitment to open systems and software that eliminate barriers to information access, such as proprietary data formats and exclusive APIs. The criteria for open standards, as defined by the Free Software Foundation Europe (FSFE), include:

1. Adoption and maintenance by a non-profit organisation with open and inclusive decision-making processes.
2. Public availability of the standard specification at minimal or no cost, along with the freedom to distribute and use.
3. Unrestricted availability of intellectual property on a royalty-free basis.
4. No constraints on the re-use of the standard.

These criteria ensure that selected solutions promote interoperability, innovation, and competition, adhering to the principles of open access and technological neutrality.

3.2.3 Enables Safe, Long-Term Data Storage

Given that the lifespan of buildings significantly surpasses that of many digital solutions, it is imperative that selected solutions offer reliable long-term data storage capabilities. This aspect is crucial for ensuring that data remains accessible and usable over the decades to come, supporting the ongoing maintenance, renovation, and historical analysis of building projects.

3.2.4 Machine-interpretable

The project adopts the SMART ISO standards framework, which outlines five levels of digitisation. SMART ISO standards [36] refer to a specific approach to creating and implementing international standards that are designed to be more easily understood, applied by machines, and transferred across different systems and platforms. The SMART acronym stands for Standards, Machine-Applicable, Readable, and Transferable, indicating a set of qualities that make these standards more adaptable and useful in the digital age. Table 3.1 presents 5 levels of digitisation as defined by ISO.

Level 0	Paper format: not suitable for direct machine processing or use.
Level 1	Digital document: the document can be managed and displayed by machine (WORD, PDF).
Level 2	Machine-readable document: the structure of the document can be captured by machine and certain granular content can be read (chapters, graphics, terms, etc.). Separation of content and presentation has been made.
Level 3	Machine-readable content: all essential granular information units can be uniquely identified, the relationships between them recorded and made available for further processing or partial execution.
Level 4	Machine-interpretable content: the information in a standard is linked to execution and application information so that it can be directly executed or interpreted by machines and combined with other information sources so that complex actions and decision processes can be automated.

Table 3.1: Levels of digitisation — SMART standards concept. Source: ISO/QI Digital[37].

At Level 0 are paper documents that cannot be read by machines and are unsuitable for digital processes. Level 1 advances to basic digital documents, like those in Word or PDF formats, which can be displayed and managed on a computer but lack structured data for machines to process. Level 2 introduces machine readability, allowing computers to identify and process the document's structure and some content elements, though it's not fully automated. With Level 3, the content becomes fully machine-readable, with granular data organised for more sophisticated processing and some level of automation. Finally, Level 4 represents the pinnacle of digitisation, where the content is not just readable but also interpretable by machines, enabling complex actions and validation to be automated without human input.

For data to be deemed reliable, it must be subjected to a rigorous validation process. [38] EN 17412-1 defines validation as the process of providing objective evidence to confirm that specific requirements have been met. In the context of this project, attaining the highest level of digitisation is imperative. This is because, although the majority of methods analysed are categorised as machine-readable, not all of them support the automatic validation of requirements for the models they deliver, often necessitating manual intervention or relying on rudimentary Natural Language Processing (NLP) techniques. Consequently, a distinct differentiation has been established between methods that are merely machine-readable and those that are fully machine-interpretable, underscoring the importance of advanced data processing capabilities for effective solution evaluation.

3.2.5 Commitment to Ontological Parsimony

The principle of ontological parsimony, often encapsulated in Occam's Razor, is a methodological principle that suggests that in the case of two competing ideas, trying to explain the same phenomenon, the simpler one is preferential. This principle originates from the philosophical work of William of Ockham, a Franciscan friar and scholastic philosopher of the 14th century. Although Occam's Razor is frequently mentioned in the context of scientific and philosophical discourse, its essence is applicable across various domains, including information modelling and data architecture. In the realm of ontology within computer science and information systems, which deals with the nature and organisation of data, ontological parsimony advises against creating additional classes, properties, or entities when existing ones suffice. By minimising the number of constructs and maintaining simplicity, ontological parsimony aims to ensure that the system or model is no more complex than it needs to be, thus enhancing understandability, maintainability, and interoperability.

Following the principle of ontological parsimony, the project favours solutions that maintain simplicity in their data models and workflows. This approach avoids unnecessary complexity, ensuring that solutions are as streamlined and efficient as possible. By avoiding the creation of superfluous classes, properties, or entities, the project ensures that solutions remain focused, understandable, and maintainable. This also applies to introducing new schemas or steps to the workflow, when they can be omitted.

3.2.6 Agnostic to specific technology implementations

The European Interoperability Framework discourages over-restrictive obligations to use specific digital technologies or proprietary solutions, aiming to foster an environment of technological neutrality. This approach ensures that public administrations and their stakeholders are not locked into using specific products or services, thereby promoting a competitive market and innovation. The framework emphasises the importance of interoperability — the ability for diverse systems and organisations to work together — while allowing for the flexibility in choosing the most suitable technological solutions that meet the required standards and operational needs.

In line with this principle, the evaluation of solutions within this project will remain agnostic to the specific technologies implemented, focusing instead on whether the solution meets the established criteria for interoperability, data quality, open standards, and long-term viability. This approach facilitates a broader acceptance and adaptability of solutions, enabling the seamless exchange and utilisation of information across various platforms and systems without hindering the integration due to technological biases.

3.2.7 Emphasis on User-centric Solutions

A critical criterion for evaluating solutions is their focus on being user-centric and user-friendly, ensuring simplicity and automation for the end user. Solutions must be intuitive, minimising the learning curve and enhancing user satisfaction through ease of use.

Key features of user-friendly solutions include:

- Intuitive Navigation: Clear and logical interfaces that users can navigate effortlessly. (where applicable)
- Automation: Reduction of manual tasks through automation, enhancing efficiency.
- Customisability: Options for users to tailor the solution to their needs.
- Accessibility: Design that is accessible to all users.

Prioritising user-centric design ensures solutions are not only technically robust but also enjoyable and practical for end users, fostering wider adoption and effective use.

3.2.8 Conclusion

The criteria for evaluating solutions in this project are comprehensive and designed to ensure that the selected solutions are not only technically sound but also ethically responsible, user-friendly, and sustainable over the long term. This project aims to identify and implement solutions that will serve the needs of its stakeholders today and in the future. It does this by prioritising high-quality, reliable data sourced from recognised standards and frameworks, adhering to open standards and free software principles, ensuring data is machine-interpretable, and maintaining a focus on simplicity, and technology agnosticism.

Through this meticulous evaluation process, the project aspires to set a benchmark for future initiatives, promoting the adoption of best practices that align with the principles of interoperability, sustainability, and user-centred design. By doing so, it contributes to the broader goal of creating more resilient, efficient, and inclusive digital ecosystems.

4 Analysis

4.1 Quantifying LCA Information Requirements

4.1.1 Comparative Analysis of Various Sources for LCA Information Requirements

This chapter presents a comparative analysis of various sources relevant to LCA information requirements, focusing on both building and product levels. The evaluation encompasses a diverse range of standards, frameworks, and tools, summarised as follows:

Building level sources:

- BR18: § 297 — § 298 of the Danish building regulations concerning the climate impact of buildings.
- EN 15798: A core European standard for building level LCA providing guidelines for the assessment of sustainability of construction works.
- Level(s) - 1.2 — Level 3: Most detailed level of the LCA part of the EU framework designed for the assessment of the sustainability performance of buildings.
- LCAbyg: The most widespread and established tool for the environmental assessment of buildings in Denmark.
- EeBGuide: A comprehensive guidance document for the product- and building LCAs based on EN 15798.
- LCAx: A schema developed for standardising the exchange of building-level LCA data.
- LCAcollect: A platform facilitating the collection and management of building LCA data developed for the Danish AEC industry.
- OneClickLCA – BR18/EN15878: The version of OneClickLCA platform compliant with BR18 and EN 15978 standards.

Product level sources:

- ILCD+EPD: A format supporting the creation and management of EPDs within the ILCD framework.
- BBSR/ökobaudat: An established German database for generic environmental data, widely used in Denmark.
- EPDx: A custom schema/open data format for the generation and exchange of product-level EPD information.
- ISO 22057: International standard proposing a new schema for the digitisation of EPDs aligning with Product Data Template (PDT) principles.
- openEPD: A US-based JSON schema offering a flexible and open format for EPD data.
- EN 15804+A2: A central European standard specifying the core product category rules (PCR) for construction products (EPDs).

- openLCA schema: An open-source framework designed for LCA data. Not specific to the building context.
- EN 15942 (EPD communication format B2B): Standard defining properties necessary in the business-to-business communication of EPD information.

Each source is analysed for its contribution to the standardisation and accessibility of LCA data, according to principles outlined in Section 3. This concise overview lays the groundwork for a detailed comparison table and spreadsheet presented later, highlighting the nuances and applications of each standard, and its contribution to defining combined LCA information requirements.

Overview and Comparison of Sources.

Name	Scope	Status	Specificity	Application
BR18	Building LCA	Legislation	Very vague	Denmark
EN15978	Building LCA	Standard	Vague	EU
Level(s)- 1.2 — Lvl 3	Building LCA	Official framework	Specific	EU
LCAbyg	Building LCA	Software	Specific	Denmark
EeB Guide	Building LCA	Guide	Specific	EU
LCAx	Building LCA	Custom schema /Format	Specific	Denmark
LCAcollect	Building LCA	Software	Moderately Specific	Denmark
One Click LCA BR18/EN15878	Building LCA	Software	Specific	Denmark
ILCD+EPD	Product LCA	Official schema /Format	Highly Specific	EU
BBSR/ÖKOBAUDAT	Product LCA (generic data)	Database	Highly Specific	Germany/EU
EPDx	Product LCA	Custom schema /Format	Specific	Denmark
ISO22057	Product LCA	Standard/Schema	Highly Specific	EU
openEPD	Product LCA	Schema/Format	Specific	US/Global
openLCA schema	Process LCA	Schema/Format	Specific	Global
EN15942	Communication of EPDs B2B	Standard	Moderately Specific	EU
EN15804+A2	Product LCA	Standard	Moderately Specific	EU

Table 4.1: Comparison on various sources of LCA information requirements (IRs).

Table 4.1 provides a comprehensive overview of various sources of Life Cycle Assessment (LCA) information specifically tailored towards building and product LCAs. It categorises each source by its name, scope, status (such as legislation, standard, software, custom schema, official schema, database, or schema), specificity (ranging from very vague to highly specific), and its primary geographic area of application (Denmark, EU, Germany/EU, US/Global, or Global). This assortment covers a broad spectrum, from legislative measures like BR18 to standards such as EN15978 and ISO 22057, software tools (e.g., LCAbyg, One Click LCA), databases like BBSR/ÖKOBAUDAT, and schemas (e.g., ILCD+EPD, open EPD, LCAx and EPDx). Specificity levels help distinguish between the general guidance provided by some sources and the detailed, highly specific frameworks and data sets offered by others, indicating their suitability for different types of LCA analysis.

BR18 and EN15978 were categorised as "very vague" and "vague" respectively. Given that BR18 is legislation, it is expected to be concise and direct. However, it falls short in directing users to specific requirements or providing detailed guidelines. It merely references EN15978 without defining the type, quantity, or format of data required. EN15978, on the other hand, offers more detailed guidance, specifying various sections and the information needed. Yet, it mostly does so descriptively rather than defining clear, actionable data fields. Consequently, converting the guidance from EN15978 into specific data fields is a considerable task, requiring a fair amount of subjective judgement.

Sources tagged as "specific" detail specific data fields or properties. In contrast, those marked as "highly specific" not only enumerate these fields but also provide a thorough description of each, including the origin of the requirement if relevant, data types, and other pertinent metadata. This granular level of detail signifies the source's depth and the reliability of its data.

ISO22057 and ILCD+EPD stand out as highly specific and reliable sources based on standards. Both define specific data fields with UUIDs/GUIDs, descriptions, data types and sources. While the ILCD+EPD format is not a standard in it and of itself, it is indirectly tied to standards through ILCD. Similarly, ÖKOBAUDAT is identified as both reliable and highly specific, with clearly defined requirements for its data properties. While ÖKOBAUDAT's database provides data in the ILCD+EPD format, it's worth noting that its minimum data requirements are somewhat a simplified version of those in ILCD+EPD, albeit with a few minor variations.

In the realm of building LCA, there's a noticeable absence of a highly detailed schema that not only specifies particular information but also adheres to established standards. The Level(s) framework and EeBGuide offer some resolution by providing data fields in their spreadsheets and accompanying them with detailed guides, with EeBGuide offering more in-depth explanations. However, they leave the level of detail, data type, and format for the user to determine. Software tools like LCAbyg, LCAcollect, and OneClickLCA do specify concrete data fields, as expected from software solutions. However, they fall short in leaving the interpretation of these fields up to the user, clarifying the source of their requirements, and often rely on vague, open-ended text fields. While both ISO 22057 and ILCD+EPD also include free-form text fields, these are limited in number and are only used when no suitable structured data fields are available, especially in the case of ISO 22057. This approach minimises ambiguity and encourages the use of structured data wherever possible.

Comparison of ILCD+EPD, openEPD and ISO22057

ILCD+EPD, openEPD, and ISO 22057 are three EPD schemas that provide a similarly high level of detail. Their nuanced advantages and disadvantages are explored below.

The introduction of the ILCD+EPD format marked a significant, early step in digitising EPDs using XML to enhance the accessibility of data for computational processes. It's considered machine-readable[39] (Level 3 on the digitisation scale) Initially tailored for the German government's requirements, this format has played a pivotal role in promoting sustainable construction practices across Europe. Unlike the broader scope of data presented in the European Commission's ILCD, the ILCD+EPD format focuses on delineating the environmental impacts of products. Since 2022, it has become mandatory for all new EPDs in Europe to be published in this digital format.

In parallel, Building Transparency in the United States developed OpenEPD, developed using the JSON format which is also considered machine-readable (Level 3). This format was meant to be an advancement over ILCD+EPD, by offering an "enforces a key set of guarantees for interoperable data processing"[39], including ensuring data uniqueness across organisations, precise references to Product Category Rules (PCR), and version control. Furthermore, OpenEPD broadens its evaluative criteria to include technical performance alongside environmental impact, offering a more comprehensive view of a product's sustainability profile. However, this approach has encountered challenges in aligning with certain European standards like Smart CE marking.

Despite the progress facilitated by ILCD+EPD and OpenEPD in digitising EPD processes, limitations persist, particularly in the application of these datasets as construction objects in the context of BIM. This gap prompted the development of ISO 22057, which aspires to standardise EPD digitisation and ensure future EPDs are fully "machine-interpretable" (Level 4 on the digitisation scale).

4.1.2 Harmonising LCA Methodologies: A Comparative Analysis

The examination of LCA methodologies across various national and international standards reveals considerable differences in the calculation of buildings' emissions and environmental impacts. These differences arise from the diverse indicators, methodologies, and definitions employed in WBLCAs.

One study, entitled "Comparison of the Environmental Assessment of an Identical Office Building with National Methods"[40], analyses the same office building with various national assessment methods. It highlights the disparities in greenhouse gas emissions per kilogram of building material, attributing variations to factors like transportation, construction activities, and operational energy demand. It concludes by underscoring the need for harmonisation in building assessments to ensure consistency across studies.

The paper "Adopting The EU Sustainable Performance Scheme Level(s) In The Danish Building Sector"[41] explores the adoption of the EU Level(s) indicators in the Danish context. It focuses on how Level(s) LCA requirements compare with those of LCAbyg, highlighting the potential for alignment and integration. The study suggests that while LCAbyg can comply with Level(s) criteria, enhancing the integration between the EU guidelines and local calculation tools could improve LCA's applicability in the building sector.

Further, a comparison between the Level(s) methodology and the European (EN 15978) and Norwegian (NS 3720) standards for building LCA [42] identifies methodological discrepancies, particularly in the scope of building elements, life cycle stages, and data reliability. This comparison advocates for the adoption of Level(s) for its detailed guidelines, proposing adjustments to NS 3720 to better align with European norms.

A study within the Danish context, entitled "Influence of BIM's Level of Detail on the Environmental Impact of Buildings: Danish Context"[43] emphasises the significance of detailed BIM models for accurate environmental impact assessments. It points out that oversimplified BIM models may significantly underestimate results for environmental indicators like Global Warming Potential (GWP), especially in materials with high environmental impact but low mass or volume, such as aluminium, mineral wool, and bitumen. This finding highlights the critical role of detailed modelling in making informed sustainability decisions in early design phases.

Lastly, Soust-Verdaguer et al.[44] delve into the impact of employing systematic decomposition structures in organising building LCA information, focusing on a comparative analysis of national standards and guidelines. They define systematic building decomposition as the groupings into which a building can be subdivided when reporting the results of a building LCA. This includes the type of classification used to categorise building elements in the first place. These groupings can represent systems, parts, components, elements, or materials. The study highlights the variation across national approaches and the necessity for a unified methodology to enhance LCA reliability and comparability globally, emphasising the critical role of systematic decomposition in achieving these objectives.

The BR18 Table 6 can be seen as an example of such a building decomposition, since it defines how building elements are checked for compliance and potentially affecting the presentation of results. In the Danish context, another influential factor acting as a building decomposition is LCAbyg. LCAbyg's internal structure dividing the building into elements, constructions, products, and stage is indirectly the defining factor when it's used to calculate and present LCA results. The EN15978 proposes yet another composition utilising building parts, element, component, and product levels. Table 4.2 compares these systems to each other based on four broad categories; Building, Aggregation Layer, Component and Material. Suitable IFC classes were suggested for each aggregation level based on the information that level typically defines.

	Building	Aggregation layer	Component		Material	
Description	Highest spatial hierarchy element. Contains aggregated results.	Aggregated building parts, e.g. glazing, outer walls, foundation, frame (beams and columns), façade, energy system. Contains aggregated results.	Component, element, or product. E.g. wall, masonry wall, insulation. Can represent an EPD directly. Contains e.g. quantity, classification, aggregated results or EPD LCIA results, U-value, combined lifetime, disassembly information.		Primary material or material set. Represents an EPD, if component doesn't. E.g. insulation, brick, gypsum board, sand. Contains e.g. declared unit, EPD LCIA results, layer scaling factor, UUID, scenarios, other material properties.	
IFC	IfcBuilding	IfcGroup (IfcBuiltSystem, IfcZone), IfcElementAssembly, IfcSpatialZone, IfcDistributionSystem, IfcDistributionElement	IfcElementType	IfcElementAssembly, IfcBuildingElementPart, IfcElementComponent	IfcMaterialLayer, IfcMaterialLayerSet, IfcMaterialProfile, IfcMaterialProfileSet, IfcMaterialConstituent, IfcMaterialConstituentSet	IfcMaterial
EN 15978 Proposed structure	Building	Building part, Element level	Element level, Component level	Product level/Sub-component level	Product level/Sub-component level	
BR18	–	Kategori, Type	Type, Bygningsdel	Bygningsdel	Materiale	
LCAByg	Building	Element category, Element	Construction, Product		Stage	

Table 4.2: Comparison of Different Semantic Building Breakdown Categories

A 2023 report produced by Rambøll, entitled "Comparing differences in building life cycle assessment methodologies"[45], summarises the findings of previously discussed papers in a detailed analysis of the differences in LCA adoption across different European countries. Notably, all of the analysed adaptions are based on the EN 15978 standard guidelines. The standard's open-interpretation and minimal scope definition leads to significant result variations. The most important differences outlined by the report are:

- **System Boundary**: The system boundary defines the life cycle phases (modules) included in the assessment. Differences range from countries only requiring a cradle-to-gate LCA (A1-A3) to requiring all stages from A1 to module D. This figure is presented in Appendix A.1.1.
- **Building Element Groups**: The document points out that the disparities in minimum building elements required by each LCA methodology, is one of the factors most significantly affecting assessment results. Comparison can be seen in Appendix A.1.2.
- **Floor Area Definitions and Metrics**: LCAs often report results per unit of floor area, using different definitions of gross floor area (GFA) across countries. This variation impacts the calculation of a building's carbon footprint and its comparability with other buildings and benchmarks. The document categories GFA definitions into two groups based on whether they include the external wall thickness.
- **Reference Study Periods (RSPs)**: RSPs define the temporal boundary for an LCA, impacting the assessment of the building's impact during its use, including replacement cycles. The report highlights the variation in RSPs, which can range from 50 to 100 years depending on the building type.
- **Impact Categories**: The document compares the impact categories proposed by EN 15978:2011 with those used in the LCA methods, adding categories like "total use of energy" and "waste processing" defined by the Voluntary Sustainability Class and BREEAM.

The difference in floor area definition can for example be observed when comparing the BR18 definition, which employs a reference area (floor area), essentially considered a gross area, to the Level(s) framework. Level(s) defines a useful area, which varies for residential buildings and offices, and excluding external walls.

These differences are illustrated in the Rambøll report by a comparing two hypothetical timber-framed office buildings, one located in Denmark and the other one in Sweden. Using Denmark's BR18 and Sweden's "klimatdeklaration" for evaluation, it reveals significant discrepancies in the calculated Global Warming Potential (GWP) indicator, primarily due to variations in system boundaries and included building elements. The Danish assessment, covering a broader range of construction and operation stages, shows a higher GWP, even excluding operational energy use. With operational energy considered, the Danish building's GWP nearly triples that of the Swedish counterpart.

In the Danish context, the "Building Element Group" outlined by the report, is defined by the BR18 Table 6. The fact that it was, together with system boundaries, the most deciding factor leading to result variations, highlights the importance of harmonising these definitions on an international level. Correctly accessing and verifying compliance with these requirements is also crucial. A verification system should be developed to ensure that the submitted LCA models indeed include all the necessary building components.

Together, these studies articulate the critical need for harmonising LCA methodologies to ensure accurate, consistent environmental impact assessments across the building sector.

4.1.3 Conclusion

The conclusion of this analysis yields a comprehensive spreadsheet, referenced in Appendix B.1, that meticulously analyses the information requirements outlined by the sources. This spreadsheet features a main table, located in the “LCA_IRs” tab, which outlines each distinct piece of LCA information mandated by each source, and correlates it with equivalent requirements across all other sources. This process creates a detailed representation of typical LCA information requirements and assesses the scope of each source. The objective of this comparison is to establish a concrete list of properties through consensus among the pertinent sources.

Building LCA

In the realm of building LCA, the absence of an official, specific list of properties required at the EU/CEN level necessitates the aggregation of information from various standards and the existing implementations of them deemed compliant. Many details are not directly specified in standards, but are either implicitly necessary or have proven to be relevant through practical experience. Each Information Requirement (IR)/property should, as far as possible, trace back to a standard, primarily deriving from the EN 15978.

Two levels of detail emerge from the presenting sources with the building LCA level: a simpler level represented by sources like BR18, LCAbyg, and LCAcollect that align with the Danish building regulations’ limited requirements, and a more comprehensive level represented by sources like EN 15798, EeBGuide, to some extent Level(s) and OneClickLCA. This dichotomy leads to the creation of two different sets of IRs; a Minimum Viable Product (MVP) suited to the Danish BR18 requirements, and a more comprehensive EU-level LCA based on EN 15798 and its interpretations. These sets of IRs are presented in columns “MVP acc. to BR18” and “Full LCA” in the spreadsheet.

Building LCA information, based on the themes identified across the analysed sources, can be categorized into:

- Metadata
- Building level information
- Product level information
- Results
- Qualitative analysis (Critical review)

The critical review, a fundamental aspect of an LCA report as per the ILCD handbook, presents challenges in quantification and would require significant restructuring to be quantified effectively. Sections of the current report structure should be excluded from the model until they can be meaningfully quantified and defined as properties, avoiding the inclusion of lengthy text or multiple images in free-form fields. Although such data may be technically be considered “digitised”, it lacks computer interpretability. The shift towards quantifying data necessitates a reevaluation of the nature of information stored and its format.

Free-form text fields in software and other building LCA specific frameworks reflect the fact that main standards regarding building LCA, like EN15804, were written over a decade ago. These standards were written for the purpose of written reports in PDF format and not for BIM or machine-interpretable data. To effectively leverage the advantages of machine-interpretable automatic verification, complex analysis, and data filtering, it is insufficient to merely convert human-interpretable information into a digital format. All data requirements, also those that are most often implicit or obvious for a human and not even mentioned in the standards, must be fundamentally redesigned into structured properties with appropriate data types. For example, information that was previously defined as qualitative descriptions could be redefined as lists, enumerations or new metrics quantifying the qualitative information could be developed. An example of such a metric is the Pedigree matrix, which quantifies the uncertainty of inventory data in LCA. The upcoming standard prEN 15941:2024 — “Sustainability of construction works — Data quality for environmental assessment of products and construction work — Selection and use of data” goes in this direction and proposes a number of methods, assessment scales and tables to quantify the quality of environmental data.

However, focusing on the quantifiable aspects and properties requiring only brief descriptions remains the immediate priority, setting a foundation for later addressing the more complex qualitative aspects of building LCA information.

EPDs

Currently, the ILCD+EPD and ISO 22057 standards are the most comprehensive and recognised frameworks for storing LCA information about products. However, these would be overly complex for initial stages of LCA if they were to be considered as part of the present workflow, where architects or LCA specialists are responsible for inputting data. This process, prone to human error, can easily be automated, allowing these data schemas can be used effectively even for generic data. Early-stage unknowns could be addressed by leaving fields blank or setting requirements as ranges from different disciplines.

A key issue in building LCA documentation is the under-emphasised importance of documenting sources (EPDs). Without this, the documentation becomes an aggregated number lacking meaningful context or intermediate calculations.

Historically, EPDs, especially those conforming to the older EN 15804+A1:2013 standard, have focused narrowly on indicators like Global Warming Potential (GWP) and have limited their scope to a few indicator modules (e.g., A1 to A3). While this simplifies implementation, our growing environmental data requirements demand schemas that can encapsulate all relevant indicators throughout a product’s entire lifecycle. This ensures a holistic view of the environmental footprint and prevents the overemphasis on a single indicator or lifecycle phase, which could lead to significant impacts being overlooked. The focus on GWP and cradle-to-gate emissions has been predominant, but there’s a shifting attitude towards a more inclusive view of environmental impacts. Albeit legislation, such as the Danish building regulations (BR18) and the EU taxonomy for sustainable activities, is still lagging in this regard.

To address these challenges, a comprehensive schema that not only meets current legislative requirements but anticipates near-future needs is essential. While ILCD+EPD supports a wide range of requirements and is aligned with many of today’s EPD standards, its complexity and specialised terminology can be barriers for newcomers. It remains crucial but should be complemented by formats that integrate more seamlessly with the schemas and structures used by manufacturers, such as the Product Data Template (PDT).

ISO 22057 emerges as a modern, promising schema that focuses on integrating EPDs into Building Information Modelling (BIM), offering a “machine-interpretable” format, which ranks at Level 4 on the digitisation scale. This makes it the preferred choice for product-

○ – No
◑ – Partial
● – Yes
* – under development

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			Fields					Value constraints				Content			Geom.		Metadata		
	Standardised	Applicability	Info. type	Data type	Unit of meas.	Description	References	Equality	Range	Enumeration	Patterns	Existence	Documents	Structure	Representation	Detailedness	Purpose	Actors	Process map
Spreadsheet	○	◑	◑	◑	◑	◑	◑	◑	○	○	○	○	○	○	○	○	◑	○	○
PDT*	●	◑	◑	●	●	◑	●	○	◑	●	○	◑	○	○	○	○	◑	○	○
Data Dict.	●	○	●	●	◑	●	●	●	◑	●	◑	○	○	○	○	○	○	○	○
IDS*	●	●	●	●	●	◑	◑	●	●	●	●	●	○	◑	○	○	●	◑	○
mvdXML	●	●	●	●	●	◑	○	●	●	◑	◑	◑	○	●	●	○	○	◑	○
idmXML	●	◑	◑	◑	◑	●							●		◑	◑	●	●	●
LOIN*	●	◑	◑	●	●	◑	◑	○	○	●	○	○	●	◑	◑	●	●	●	○
IFC P.T.	●	◑	◑	●	●	◑	○	○	○	●	○	○	○	○	○	○	○	○	○
LD+SHACL	○	●	●	●	●	◑	●	●	●	●	●	◑	◑	●	●	○	◑	◑	○

Figure 4.1: Information requirement support in the described methods. Source: Tomczak et al.[38]

level information moving forward, bridging the gap between detailed environmental data and the practical needs of the construction industry for sustainable building practices.

4.2 Comparison of Different IR Specification Methods

The paper "A Review of Methods to Specify Information Requirements in Digital Construction Projects" by Tomczak et al. [38] examines various methods for specifying information requirements (IR) in the context of digital construction projects. It covers standardised methods such as Data Dictionaries (ISO12006), Information Delivery Manual (IDM), IFC Property templates, Information Delivery Specification (IDS), Level of Information Need, Model View Definition (mvdXML), and Product Data Templates (PDT), alongside non-standardised methods like Linked Data with SHACL. The analysis, based on document study and expert discussions, evaluates these methods against criteria including value constraints, field properties, geometry representation, content, and metadata. Figure 4.1 shows the comparison of the specification methods presented by Tomczak et al.[38]. Figure 4.2 presents the categorisation of them according to their expressiveness, semantic dependency, technological agnosticy and governance. The conclusion highlights that no single method fully addresses all aspects, suggesting a purpose-based selection for information managers and standardisation bodies.

Methods analysed by Tomczak et al. are explored in more detail below, split into standardised and non-standardised methods.

4.2.1 Standardised Methods

Product Data Templates (PDT): Data templates are digital frameworks that describe a product's various attributes—such as technical, environmental, and operational features—in a logically connected way, enabling software to interpret product information and reducing the need for manual processing. EN 23387 — "Data templates for construction objects used in the life cycle of built assets" defines data templates as "a data structure used to describe the characteristics of construction objects". PDTs have been widely used for years to communicate technical specifications and performance characteristics. However, with the introduction of ISO EN 22057, they are now finding new applications in fields such as LCA, expanding their possibilities and utility. A "filled out" version of a PDT,

<table>
<tr><td rowspan="2">Expressiveness</td><td>Free</td><td>Partially limited</td><td>Very constrained</td><td>Strict</td></tr>
<tr><td>DOC, IDM, MVD[a], Other[a]</td><td>XLS, PDT, LD+SHACL, LOIN</td><td>IDS, DD</td><td>MVD[a], IPT, Other[a]</td></tr>
<tr><td rowspan="3">Semantic dependency</td><td rowspan="2">Implicit</td><td colspan="2">Schema dependent</td><td rowspan="2">Self-contained</td></tr>
<tr><td>Indefinite</td><td>Explicit</td></tr>
<tr><td>DOC, XLS, MVD[a]</td><td>IDM, LOIN, DD, PDT</td><td>IDS, IPT</td><td>MVD[a], LD+SHACL</td></tr>
<tr><td rowspan="3">Technology agnosticity</td><td colspan="3">Agnostic</td><td rowspan="2">Impose technology</td></tr>
<tr><td>Plain text</td><td>Tabular</td><td>XML schema (XSD)</td></tr>
<tr><td>DOC</td><td>XLS, DD, PDT</td><td>IDM, IDS, MVD, IPT, LOIN</td><td>LD+SHACL, Other</td></tr>
<tr><td rowspan="2">Governance</td><td>Custom</td><td colspan="2">buildingSMART</td><td>ISO/CEN</td></tr>
<tr><td>DOC, XLS, LD+SHACL, Other</td><td>MVD</td><td>IDS, IPT, DD</td><td>LOIN, IDM, PDT</td></tr>
</table>

[a] plural assignment, dependent on the implementation.

Figure 4.2: Grouping of information requirement methods. Source: Tomczak et al.[38]

with product specific values, is called a Product Data Sheet.

Model View Definition (mvdXML): This method focuses on specifying and exchanging a subset of BIM data using a standardised XML schema. Originally designed for software certification, MVD's complexity and flexibility come from its ability to both define concepts within the IFC schema and constrain them (in effect creating sub-sets of IFC). While MVD facilitates the creation of self-contained and conceptually rich definitions, it's no longer endorsed by buildingSMART as a method for defining information requirement (IR), and has been superseded by the Information Delivery Specification (IDS) in this regard.

Information Delivery Manual (IDM): An IDM outlines the process and data requirements for specific operations within the construction and facility management industries. It identifies the information that needs to be delivered, by whom, when, and to whom, optimising the information exchange process and ensuring that the right information is available at the right time.

Level of Information Need (LOIN): specifies the required depth of geometric and alphanumeric information for a project, determined by its use cases. It ensures information is neither excessive nor lacking, and it mandates the information to be exchangeable and understandable for both humans and machines. The development of the third part in the LOIN standard series — EN 17412-3 — aims to provide a data schema for specifying information requirements in digital construction projects, linking data handovers to exact processes and workflows.

Data Dictionaries (ISO12006-3 and ISO 23386): This approach involves the use of standardised data dictionaries, to create a SSOT for terms and relationships in the building industry, as introduced previously in Chapter 2. These frameworks provide a structured approach to defining terminology and relationships, and could thus be used in an information requirement exchange.

IFC Property Templates: IFC Property Templates are the most direct and integrated method for providing user-defined IFC information, by providing a structured format for defining properties, property sets and their corresponding data types. These definitions can then be shared as independent IFC files.

Information Delivery Specification (IDS): IDS represents a forward-looking schema developed by buildingSMART, aspiring to standardise the specification of information requirements. Although not yet formalised as a standard, IDS aims to encompass a wide range of data sources, including IFC, domain extensions, and additional classifications and properties (be they part of national agreements or company-specific). Properties can embed external references to definitions stored in data dictionaries or alternative repositories. IDS is the preferred format for defining information requirements and verifying model compliance in most cases.

4.2.2 Non-Standardised Methods

Linked Data with SHACL: This approach uses Semantic Web technologies to link and validate data across different sources. SHACL (Shapes Constraint Language) is employed to ensure that the linked data adheres to specified constraints, improving data quality and interoperability.

Non-standardised textual or spreadsheet documents (DOC & XLS): Many projects still rely on traditional documents and spreadsheets to specify information requirements. While flexible, this approach can lead to inconsistencies and inefficiencies due to the lack of standardisation.

Proprietary Solutions: Some projects use proprietary software solutions, like Solibri to manage and specify information requirements. While these can offer powerful features, they may also introduce issues with interoperability and data exchange with other systems.

Other (e.g., dedicated visual programming scripts): Innovative methods such as visual programming scripts were also explored for specifying information requirements. These allow for more customise and automated approaches but require specific technical expertise.

The paper by Tomczak et al. highlights the diversity of methods available for specifying information requirements in digital construction projects. It also underscores the importance of choosing the appropriate method based on the specific needs and context of the project. The comparison between standardised and non-standardised methods illuminates the trade-offs between interoperability, flexibility, and ease of use, guiding practitioners in making informed decisions for their projects.

4.3 Strategies for storing and sharing product data

4.3.1 Current State

Efforts to incorporate LCA data into IFC have begun with the development of the PSet_EnvironmentalImpactIndicators and PSet_EnvironmentalImpactValues property sets. However, these efforts are still in their emergent stages and face significant challenges that limit their practical utility at present.

The PSet_EnvironmentalImpactIndicators property set is designed to capture environmental impact categories or indicators that are linked to a specific “functional unit”, a concept derived from the ISO 14040 standards. These indicators can apply to the entire lifecycle of a building element or to specific phases within that lifecycle, as defined by the LifeCyclePhase property. The indicators’ values are calculated on a yearly basis, reflecting the expected period of use. The initial properties within this set are intended to define the characteristics of the functional unit, and there is international consensus on these first five properties. However, the latter properties, which directly relate to the environmental indicators, have yet to achieve full international agreement.

The PSet_EnvironmentalImpactValues property set complements the indicators by recording the actual environmental impact values of a building element. These values are derived by multiplying the per-unit indicator value by the quantity of the element, as outlined by buildingSMART International Limited in 2019. Nonetheless, a significant limitation arises due to the inability to disaggregate these results into multiple lifecycle phases for a single entity in the IFC model. There are also challenges in storing input data for EPDs or aggregating final results for an entire building.

These property sets are primarily intended to address various lifecycle assessment impact categories and units, incorporating information about lifecycle phases and expected service life. However, the implementation faces critical issues, particularly in representing multiple lifecycle phases or modules for a single element. The current IFC data model only allows for the integration of environmental impacts from a singular phase or module through the LifeCyclePhase property. This restriction hampers the ability to fully represent the "cradle to grave" approach required for comprehensive environmental impact assessments.

Another limitation is the unavailability of these property sets at the material level, which further restricts their applicability. Additionally, the range and types of LCA impact categories supported in the IFC 4 format are limited and not fully aligned with the EN 15804 standards, leading to uncertainties regarding the source and applicability of the included indicators.

In summary, while the development of PSet_EnvironmentalImpactIndicators and PSet_EnvironmentalImpactValues represents a step forward in integrating LCA data into BIM processes, significant challenges remain. These include the need for a more comprehensive approach to represent multiple lifecycle phases, broader consensus on environmental indicators, and enhancements to the IFC data model to fully support "cradle to grave" LCA in the construction sector. This necessitates the extension of the current IFC capabilities to represent LCA data effectively.

4.3.2 Extending IFC

Extending the IFC framework is an essential process for enhancing its utility and adaptability in the construction and architectural domains. This extension can be generally achieved through three primary methods: Classification, Property Sets, and linkage with object type libraries. Each of these methods provides a systematic approach to enrich the IFC schema, allowing for a more detailed and comprehensive representation of building data.

Classification Classification serves as a foundational method for extending IFC. It enables the categorisation of elements and objects within the IFC model, facilitating easier identification, sorting, and retrieval of information. This method is crucial for organising data in a structured manner, making it more accessible and interpretable for users and software applications.

Property Sets and IFC Property Set Templates Property Sets and their corresponding templates offer a flexible way to add detailed information to IFC entities. These must adhere to the "Property Set Definition" schema, ensuring a standardised approach to extending the IFC model. The buildingSMART Data Dictionary (bsDD) plays a vital role in managing terminology and properties, providing a common language for property definition across the industry. This method distinguishes between static attributes, which are predefined within the schema, and dynamically created properties. The latter can be freely added to the instance model as needed, through subclasses of IfcProperty, enhancing the model's adaptability and specificity.

Linkage with the buildingSMART Data Dictionary and Object Type Libraries (OTLs) Integrating IFC entities with the buildingSMART Data Dictionary (bsDD) and other Object Type Libraries (OTLs) is crucial for ensuring interoperability and consistency across different software tools and projects. There are two main approaches to this linkage:

- **Classification Approach**: This method involves using the identification attribute of an IFC entity to refer to the URL of the corresponding OTL concept. This direct linkage enriches the IFC model with a wealth of standardised information and definitions, facilitating better communication and data exchange among stakeholders.
- **Linked Data Approach**: Utilising Semantic Web Technology, such as OWL, this approach applies a linkage scheme between the ontology (OTLs) and the IFC schema. The bSI's publication of the ifcOWL standard is a testament to the potential of this method in achieving a deeper, semantic integration of data within the IFC framework.

Importance of Limiting New IFC Types While extending the IFC model is crucial for addressing the evolving needs of the construction industry, it is equally important to limit the introduction of new IFC types (entities). Excessive expansion of the schema can place an additional burden on developers and may impede the swift adoption of new IFC extensions by software vendors. Therefore, any extension project should carefully consider the balance between innovation and practicality, ensuring that enhancements to the IFC model serve to facilitate its broader acceptance and use.

4.3.3 Product Catalogues in the IFC Format

Product Catalogues within the IFC format are functioning similarly, and, typically serve the same purpose as, Object Type Libraries. These catalogues are integral to the digital exchange of construction object data, serving a multitude of purposes. The primary purposes of these digital exchanges is to provide a detailed digital description of construction objects. This includes sharing technical specifications, geometrical data, images, and mounting instructions within a digital structure. Such detailed descriptions are essential for design, specification, and quotation processes, ultimately contributing to the development of Asset Information Models.

In the procurement and purchasing phase, digital product catalogues facilitate easier and more automated searches due to their standardised property structures. This not only streamlines the querying of construction object properties across digital marketplaces but also enhances the reliability of product purchases.

For construction site management, having access to accurate digital descriptions enables quality control of products during installation, ensuring they match the designed specifications. Similarly, during the handover to facilities management, the easy importation of construction object data into Asset Information Models enriches these models with vital information on spare parts, maintenance, and installation procedures.

Safety and risk management benefit from the exchange of documents proving conformity to standards and regulations, aiding in quality control, scheduling, cost control, and installation procedures. This is particularly important for Health, Safety, and Environment Coordinators on construction sites.

Digital product declarations, including Declarations of Performance (DoP), Declarations of Conformity (DoC), and also EPDs, improve the communication and interpretation of essential documentation, thereby facilitating compliance with regulations and environmental standards.

Online platforms for construction objects, offered by manufacturers, provide accessible product catalogues. These digital formats ensure interoperability and a unified data structure, which helps avoid data redundancy.

The interest in storing product data in the IFC format has been notable for years. A 2012 project by buildingSMART, titled "Product Libraries in IFC format" explored the development of product libraries within this framework. The discussion underscored the critical roles of product data, product libraries, templates, and data dictionaries in delineating which information is compulsory or optional for particular product types. It emphasised the necessity of establishing a universally comprehensible system for property information, transcending language barriers and classification systems to ensure clarity and consistency across the board.

Key components identified for an effective IFC Product Library included Implementation Agreements or MVDs, Product Templates for exchange requirements (where MVDXML was initially considered, and now PDTs are preferred), and the buildingSMART Data Dictionary (bSDD).

Construction Object Data View

prEN 17549-1 and IFC4.COD.1 The standard prEN 17549-1:2022 — "Building information modelling — Information structure based on EN ISO 16739-1:2020 for exchanging data templates and data sheets for construction objects — Part 1" is currently in a draft/withdrawn status. However, all the essential information that it encompasses is accessible through the published documentation available at buildingSMART's ProductData GitHub repository.

This standard presented an MVD framework to exchange both empty and filled product data templates, thereby bridging the gap between product data sources, such as manufacturers' catalogues, and the construction models used by designers and owners. This framework is built upon the IFC Project Library structure and demonstrates how it aligns with standards EN ISO 23386 and EN ISO 23387, establishing a coherent and structured approach for managing and exchanging construction product information.

EN 17549-2 and CODview2 This document introduces an MVD, dubbed Construction Object Data View 2, or more succinctly, CODview2, designed to establish a detailed framework for storing and exchanging construction objects. The focus of this second part of the standard is on detailing how complex product requirements can be defined within the IFC schema and the ways in which it facilitates the representation of various configurations of customizable products.

CODview2 continues the effort to develop a standard format for product exchange within the IFC framework. This effort has previously been documented under names such as "Product Library View LV 0.1" or "IFC Project Library (MVD)." These terms have been used in some research contexts[46]. It's important to note that the technical specifics across all these versions of MVDs, including the COD.1 version, are the same.

At the heart of CODview2 lies the definition of objects and their properties according to semantic definitions found in data dictionaries. This involves expressing requirements through declarative expressions and integrating them within construction workflows as defined by IFC. The key features of CODview2 include:

- enhancing access to dynamic, construction-specific semantics by leveraging the relationship between IFC and EN ISO 12006-3:2022. This aims to provide better support for data dictionaries.
- supporting concurrent engineering practices through the expression of requirements and constraints, which aims to improve collaboration and decision-making processes.
- facilitating the agile integration of construction-specific semantics to boost interoperability and enhance the user experience in construction sector software applications.

Moreover, CODview2 acknowledges the importance of data preservation and contractual integrity in construction projects. It suggests that, if necessary, making a copy of the definitions referenced in the CODview2 dataset using the data schema defined in EN ISO 12006-3:2022 can be beneficial. This approach is particularly useful when the exchanged data are part of a contract, allowing this copy to be included in the data exchange. Similarly, to mitigate the risk associated with the long-term availability of online data dictionaries, maintaining a backup of these copied definitions ensures the durability and accessibility of crucial data semantics.

CODview2 represents a significant step forward in the effort to create a standardised product exchange format within the IFC framework, building on the groundwork laid by earlier versions and aiming to improve the efficiency and collaboration in construction data management.

Other Parallel Initiatives

Apart from CODview2 defined in EN 17549-2, several concurrent standards aiming to define new schemas are underway:

- prEN ISO 22014: This standard, titled “Library Objects for Architecture, Engineering, Construction, and Operation”, aims to establish a unified framework for library objects used across the AECO industry, facilitating easier sharing and integration of digital resources.
- LOIN Data Schema (prEN17412-3): Under development as “Building Information Modelling — Level of Information Need — Part 3: Data Schema” seeks to define a comprehensive data schema that outlines the level of information required at various stages of a building’s lifecycle.
- The ISO 16757 Standard Series based on the German standard VDI 3805:
  - ISO 16757-4: “Part 4: Dictionary Structures for Product Catalogue” which focuses on the organisation of dictionary structures for product catalogues.
  - ISO 16757-5: “Part 5: Product Catalogue Exchange Format” aimed at defining a standardised format for the exchange of product catalogues within the industry.

These upcoming standards, coupled with the observation that prEN 17549-1 was initially published, subsequently withdrawn, and has since remained in draft status, implies a significant, coordinated effort aimed at harmonising and aligning these emerging schemas. The outcome of these endeavours remains to be seen, underscoring a period of anticipation and potential transformation within the field.

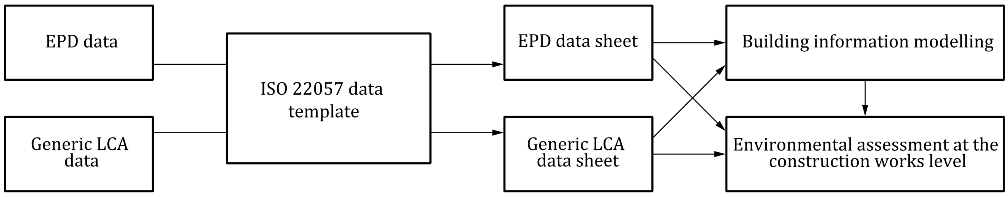

Figure 4.3: Relationship between data, data templates, data sheets, BIM and environmental assessment at the construction works level. Source: EN ISO 22057 [47]

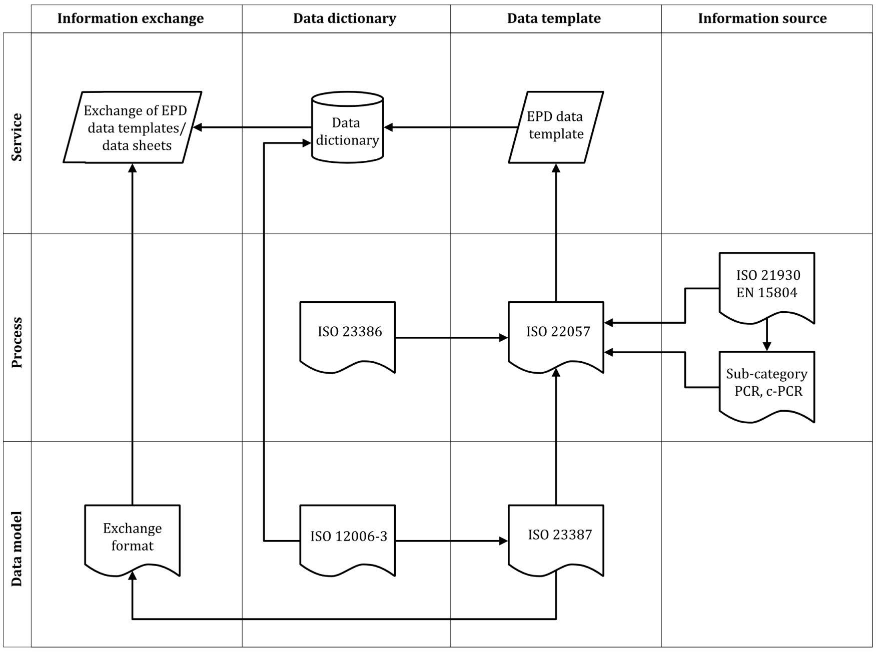

Figure 4.4: Relationship between BIM standards and sustainability standards. Source: EN ISO 22057 [47]

4.3.4 EN ISO 22057 - EPDs as PDTs

The previously introduced new standard, EN ISO 22057:2022, provides a format for the provision of EPD and generic LCA data for use in building level LCA and BIM. It outlines principles and requirements for integrating environmental and technical data from EPDs into BIM to enhance the assessment of a construction work's environmental performance across its lifecycle. The standard emphasises the importance of machine-interpretable EPD data, facilitating their integration into BIM processes, and it provides guidelines for structuring EPD information using data templates to make it machine-readable. Additionally, it applies to generic LCA data, ensuring comprehensive environmental performance assessment at the construction works level.

Figure 4.3 shows how the ISO 22057 data template can be used to digitise both product specific (EPD) and generic data, which in turn can be used to aid environmental assessment calculations at the building level.

Figure 4.4 illustrates the integration of ISO 22057 within the broader context of data dictionary and PDT standards. Product Category Rules (PCRs), primarily dictated by ISO 21930 and EN 15804, direct the content structure of the data templates, which are defined in accordance with ISO 22057. ISO 23386 defines how ISO 22057 should be represented in a data dictionary, while 23387 provides the meta definitions of the types of attributes and data model elements that can be defined in a data template in the first place.

The data template in ISO 22057, draws upon the ILCD+EPD format developed by InData, but introduces a more comprehensive approach to several key aspects. These include the localisation of companies or plants, the provision of detailed technical specification information based on harmonised standards, and the treatment of various scenarios through parameterised datasets. This enables adjustments to transport or end-of-life data within the EPD to better reflect current practices for the specific building project under study. [39]

When implementing PDTs, it's important to note that EPDs compliant with the EN15804 standard must be delivered in ILCD+EPD format, so Product Data Sheets (PDS) created with ISO 22057 today, should also reference the ILCD+EPD version. Some argue this is only a transition phase until full adoption of PDTs, but environmental data should always be 3rd-party verified. Thus, it might be acceptable to use both ILCD+EPD and EPDs in the ISO22057 format simultaneously; one serves LCA scientific and technical needs, while the other enables to broad industry implementation.

A significant benefit of ISO 22057 lies in its integration within systems already familiar to manufacturers, who will predominantly be responsible for maintaining and publishing Environmental Product Declarations (EPDs) moving forward. The task of digitising EPDs should not fall on architects or Life Cycle Assessment (LCA) practitioners. Additionally, the implementation of EPDs as Product Data Templates (PDTs) presents opportunities for integration with existing systems such as SMART CE, ETIM, and GTIN/GS1. ISO 22057 provides a detailed mapping of concepts from SMART CE, outlining precisely how an EPD should be structured within the SMART CE XML format.

4.4 Proposed Data Model

Concluding the preceding sections, EPDs can be incorporated directly into the IFC model or stored separately and referenced, with options for both local and online storage and access. The trend, as highlighted by the bSI Product Room Closing Plenary Summit 2022, is moving towards online access via APIs. This approach eliminates the need for exchanging files and facilitates real-time data updates. Deciding on the format for storing EPDs, whether within the IFC framework or as external documents, is a strategic choice. Options include IFC-specific formats such as COD, IFC Project Library, or mvdXML/ifcXML, and more general formats like XML/JSON. Each option has implications for interoperability and user-friendliness.

In general a solution that combines the following technologies would be advantageous:

- Utilising Data Dictionaries for universal definitions,
- Employing Product Data Templates for specifying construction product properties, using ISO 22057 for environmental data properties,
- Implementing IDS for specifying information requirements and verification, all linked back to the IFC model.

However, with these solutions selected, a wide range of implementation variations exists, as depicted in Figure 4.5.

Key decisions involve:

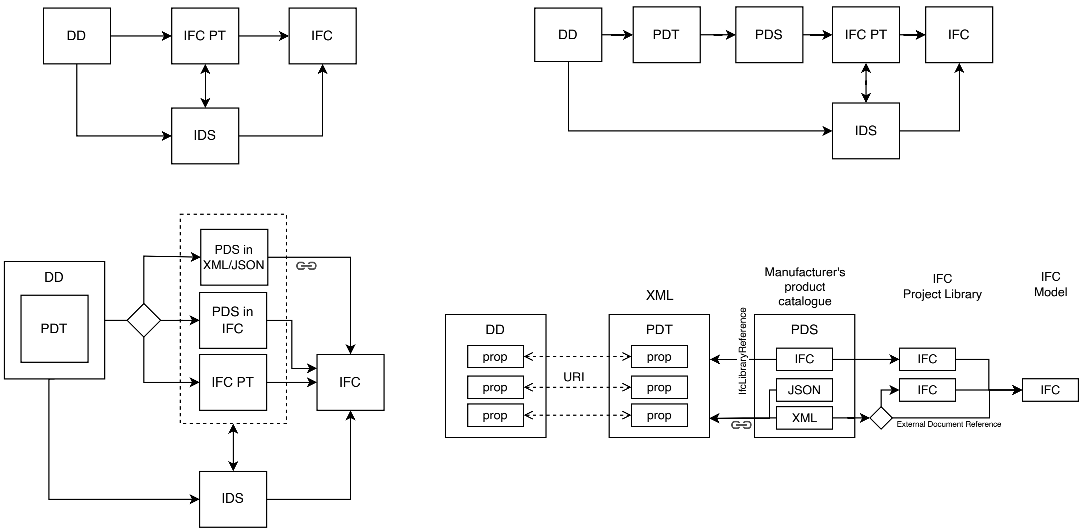

Figure 4.5: Various data architectures of integrating LCA information through DD, PDT, PDS and IFC PT.

- Whether the PDT should be integrated into the Data Dictionary or defined and hosted separately online, often specific to a manufacturer, industry, or on an aggregation website hosting numerous PDTs (manufacturer product catalogue).
- The format of the PDS created based on the PDT (IFC, XML/JSON, or represented with IFC Product Templates).
  - If a non-IFC format like XML or JSON is selected (or is the only option available), consideration should be given to whether the PDS should be converted to IFC or linked as an external document reference.

These methods offer a range of possibilities for managing product data, from close integration within the IFC model to a more loosely coupled approach via web-based references. The choice among these options impacts the model's accessibility, ease of data management, and the level of detail and timeliness of the information it contains.

Figure 4.6 illustrates the final, detailed development of the data model. A larger version of this figure can be found in Annex A.2. It showcases the dictionaries that need to be established in a Data Dictionary to comprehensively represent building LCA context information, subdivided into four levels: Global DD, European DD, National DD, and Company or Project DD. Each dictionary is linked to the official standards defining its contents. The decision to implement PDTs for EPDs as part of the Data Dictionary is based on the initiative already partially undertaken by the buildinSMART Sustainability Group with the "LCA Indicators and Modules" dictionary. A Manufacturer Product Catalogue is included, following the methodology described by Kremer et al.[46]. This section outlines various formats for information storage. The Danish context is represented by not only Danish data dictionaries but also potential generic construction objects and materials as per Table 7. An IDS tailored to the Danish LCA context is used both to define requirements and to verify the model upon completion. Finally, the model is verified using the bSI validation service, with results communicated using BCF (BIM Collaboration Format), either externally or back to the model for any necessary adjustments.

Although all formats presented in the "Manufacturer Product Catalogue" section could be implemented in some way, CODview2 emerges as the most modern solution that inte-

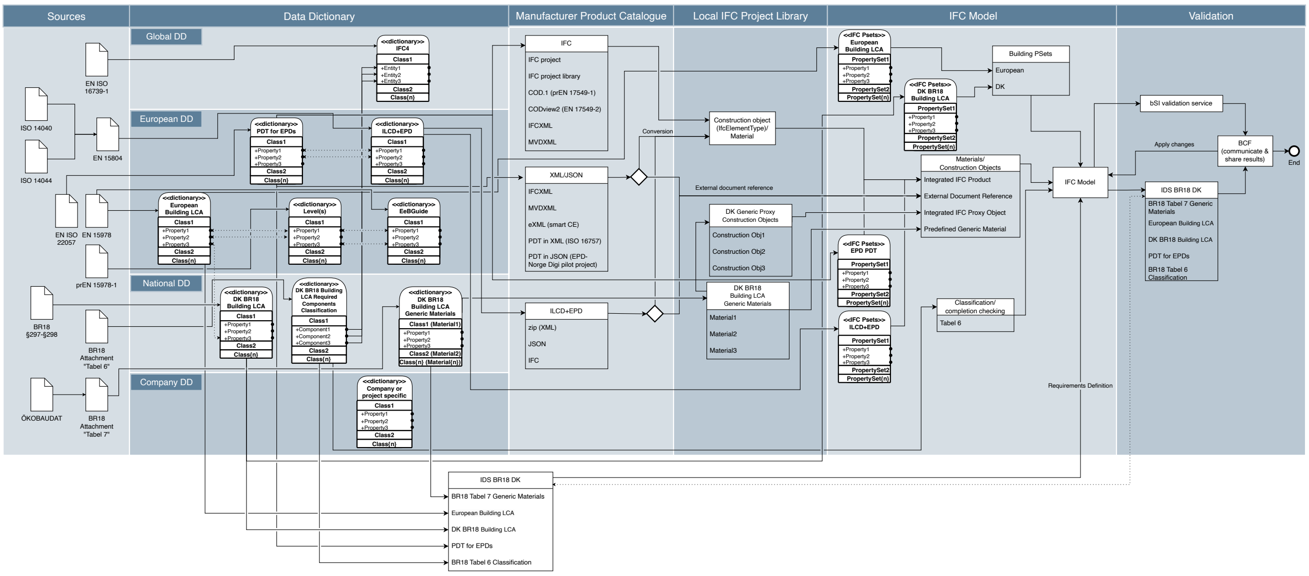

Figure 4.6: Data flow diagram of LCA information in a BIM context

grates closely with IFC while still allowing compatibility with other methods. Therefore, the previously chosen methods are expanded with the inclusion of CODview2 for storing product catalogues directly in the IFC format. The following section will explore how CODview2 can be utilised to represent PDTs, including environmental data defined in ISO 22057, marking a novel contribution to this field.

5 Implementation and Findings

5.1 A Note on Graphical Notation

Historically, the IFC schema was described using the EXPRESS data definition language, as delineated in ISO 10303-11:1994. Within this standard, Annex D introduces EXPRESS-G, a formal graphical notation that represents a subset of the EXPRESS language. At the time of its inception, EXPRESS-G emphasised features like various levels of data abstraction, the minimal use of computer graphics—including solely non-graphic symbols—and the capability of diagrams to extend across multiple pages. An illustration of an entity-level diagram in EXPRESS-G is depicted in Figure 5.1.

Documentation for IFC2x3 [48], still showcases EXPRESS-G diagrams for each concept utilising the page layout. Because of this historical context, IFC4 and IFC4x3 versions still employ EXPRESS-G diagrams to visualise IFC concepts. Nonetheless, there has been a trend towards simplifying the notation over the years in various, sometimes arbitrary, manners, resulting in a coexistence of different styles of simplification and graphical notations within the IFC documentation. A classic EXPRESS-G notation and a common simplified notation can be seen on Figures 5.5a and 5.5b respectively.

Although EXPRESS is a domain-specific language tailored for IFC, the use of EXPRESS-G notation for representing a new, proposed schema extension presents several challenges. Firstly, EXPRESS-G symbols for data types have fallen out of use, complicating the representation of data types associated with attributes or properties. Furthermore, the notation is inefficient in terms of space for representing attributes and necessitates depicting all IFC properties as separate entities, which could become unwieldy within an extensive property set definition. Additionally, EXPRESS-G is a domain-specific notation unknown in the software industry, which plays a crucial role in implementing new schema parts.

Although EXPRESS is a domain-specific language tailored for IFC, the use of EXPRESS-G notation for representing new schema extensions today, poses a number of challenges. Firstly, EXPRESS-G symbols for data types have fallen out of use, which complicates the representation of data types associated with attributes or properties. The notation is inefficient in terms of space, especially when representing attributes. All IFC properties have to be represented as separate entities, which would lead to an excessively complicated diagram in the case of an extensive property set definition. Because EXPRESS-G is a domain-specific notation, it is unknown to the software industry, which would unavoidably be involved in the implementation of any schema extensions or tools related to it.

Although EXPRESS is a domain-specific language tailored for IFC, the use of EXPRESS-G notation for representing new schema extensions today, comes with several challenges. EXPRESS-G symbols for data types have fallen out of use, which complicates the representation of data types associated with attributes or properties. The notation is inefficient in terms of space for representing attributes. It also necessitates depicting all IFC properties as separate entities, which could become unmanageable within an extensive property set definition. EXPRESS-G is also a domain-specific notation unknown in the software industry, which plays a crucial role in implementing any schema extensions.

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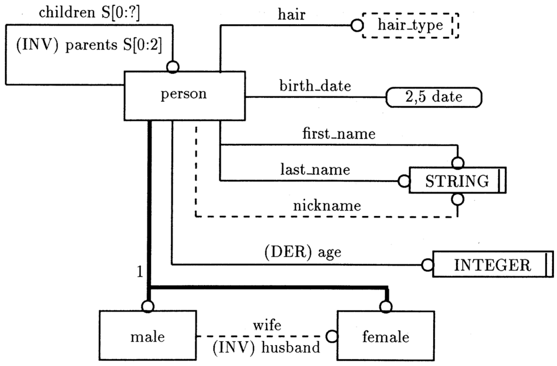


Figure 5.1: EXPRESS-G - Complete entity level diagram. Source: ISO 10303-11, Figure D.1.

Given these considerations, the Unified Modelling Language (UML) will be adopted for the representation of all subsequent diagrams. UML is a general-purpose modelling language used for software-software-intensive systems. UML is selected for its widespread recognition within the software development community and its efficiency in representing complex data models, thereby facilitating a clearer and more accessible depiction of IFC schema components.

Unlike domain-specific languages like EXPRESS(-G), UML is applied across a wide range of domains due to its general-purpose nature. Although it was designed to tailor predominantly to object-oriented programming, it also includes a profile mechanism enabling tailored constraints and customizations for specific domains and platforms, primarily through stereotypes. Perhaps the most notable example of customising UML for a specific domain is SysML, which is tailored for systems engineering.

UML consists of many types of diagrams for different purposes, one of the most popular ones being a class diagram, which shows a system's classes, attributes, and operations (methods). In a UML class diagram, primitives are connected with one of six types of relationships (visualised on Figure 5.2):

- **Dependency**: A dependency is a relationship where a change in one element (the supplier) may affect another element (the client). In the image, a "Reader" uses a "Library Card", indicating that the reader depends on the library card but not vice versa.
- **Association**: Represents a relationship between two unrelated classes and establishes a connection between them. For instance, a *Writer* writes a *Book*.
- **Aggregation (Shared aggregation)**: A variant of the association relationship that represents a whole-part relationship, where each part can still exist independently. An example is a *Team* has *Players*.
- **Composition (Composite aggregation)**: A strong form of aggregation, indicating that the part cannot exist without the whole. The "House" consists of "Rooms", indicating that rooms are integral to the house and cannot exist on their own.
- **Inheritance/Generalisation**: A hierarchical relationship where the child element inherits all features of the parent element. An "Apple" is a type of "Fruit", meaning it inherits the properties of fruits while possibly adding more features.
- **Realisation/Implementation**: A relationship between interfaces and implement-

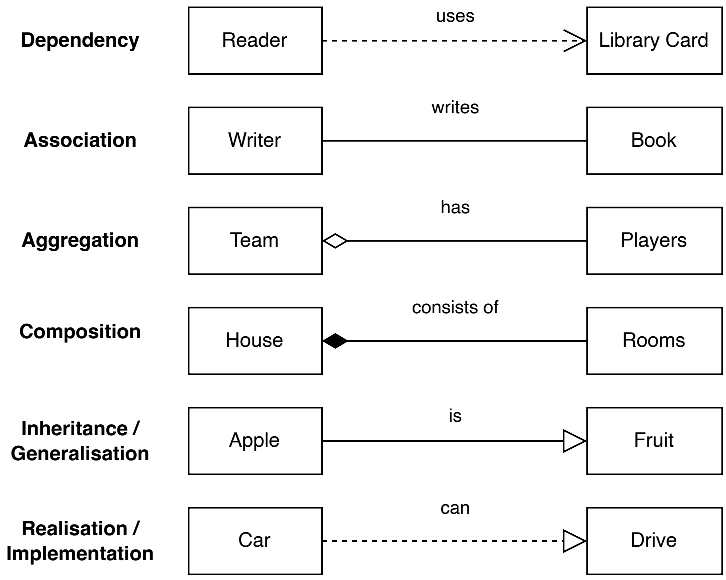


Figure 5.2: Types of UML Relationships

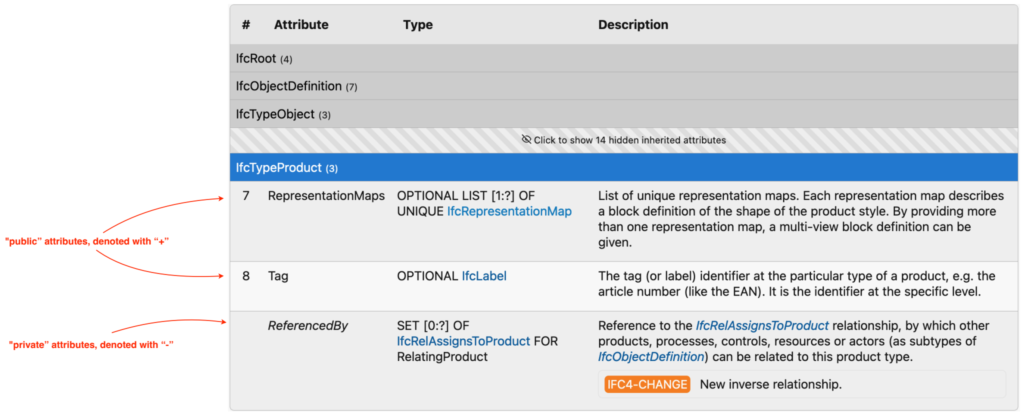
ing classes (classifiers). The interface prescribes a contract, and the implementing class provides the actual implementation. A classifier implementing an interface supports the set of features owned by the interface and complies with the constraints owned by the interface. In Figure 5.2, “Car” can “Drive”, indicating that the car class implements the driving functionality.

Attributes in UML are fundamental components of classes and define the properties [1] of a class. They are represented using a standard syntax “+ AttributeName: DataType”, where the “+” symbol denotes the access scope (in this case, public), “AttributeName” is the name of the attribute, and “DataType” is the type of data that the attribute holds (see Figure 5.4). For instance, “+ EmployeeName: String” would denote a public attribute named “EmployeeName” of type String. Access scope of class attributes is a concept used in some programming languages like Java. The “-” symbol then denotes a private attribute, that is, an attribute only accessible from inside a class. The concept of scope is not present in EXPRESS, but the “-” symbol will be used to denote attributes which are not actively declared for an entity, but are defined through other relationships or entities. In the IFC4x3 documentation, attributes which have a numbering next to it will be considered *public* while the rest will be considered *private* (see Figure 5.3).

Stereotypes provide a mechanism to extend UML models, adding more domain-specific metadata to UML constructs. They allow users to define new types of model elements or to refine existing ones to better suit the needs of a particular application or domain. Stereotypes are denoted by enclosing the name of the stereotype in guillemets (« ») above the UML element it modifies (see Figure 5.5c).

To further refine the semantics of attributes, UML allows for the use of stereotypes for attributes. The syntax for defining an attribute stereotype used in this context is “+ «SpecialAttributeType» AttributeName: DataType”. This indicates that the attribute not only has a name and type, but also a special characteristic, defined by “SpecialAttributeType”.

[1] Note: properties in context of UML are different from IfcProperties. Here ’properties’ denote feature of a classifier, and an “attribute” is one of three types of a property (the other two are “member end of association” and “part”)



#	Attribute	Type	Description
IfcRoot (4)			
IfcObjectDefinition (7)			
IfcTypeObject (3)			
Click to show 14 hidden inherited attributes			
IfcTypeProduct (3)			
7	RepresentationMaps	OPTIONAL LIST [1:?] OF UNIQUE IfcRepresentationMap	List of unique representation maps. Each representation map describes a block definition of the shape of the product style. By providing more than one representation map, a multi-view block definition can be given.
8	Tag	OPTIONAL IfcLabel	The tag (or label) identifier at the particular type of a product, e.g. the article number (like the EAN). It is the identifier at the specific level.
	ReferencedBy	SET [0:?] OF IfcRelAssignsToProduct FOR RelatingProduct	Reference to the *IfcRelAssignsToProduct* relationship, by which other products, processes, controls, resources or actors (as subtypes of *IfcObjectDefinition*) can be related to this product type. IFC4-CHANGE New inverse relationship.

Figure 5.3: Notation of public vs. private attributes in context of IFC.

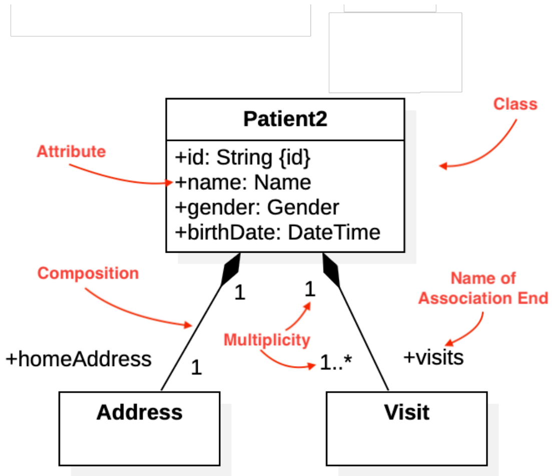


Figure 5.4: Illustration of Class Attributes and Multiplicity in UML. Source: uml-diagrams.org

For example, "+ «constant» maxSpeed: Integer" could represent a constant attribute "maxSpeed" of type Integer.

Attributes can also be externalised using notation for associations. When a relationship between two classes is defined, attributes may be shown on the relationship itself to specify a property that references another class. These attributes are shown on the association end, either with a "+"/ "-" before them or no prefix (see "Name of Association End" on Figure 5.4). Note that the association end is owned by the classifier on the opposite side of the association.

Multiplicity is another critical aspect of UML relationships. It defines the number of instances of one class that can be associated with a single instance of another class. Multiplicity is specified at each end of an association, denoted by numbers like "1", "", "1..", or a specific range such as "0..5" (see Figure 5.4). For example, if a "Library" can have any number of "Books", the multiplicity would be represented as "1" or "1..1" near the Library and "*" or "1..*" near the Books, indicating a one-to-many relationship. For clarity, multiplicity will always be shown as a range in this context. In EXPRESS-G multiplicity is denoted as e.g. "[1:?]" (corresponding to "1..*" in UML).

The approach to representing IFC graphically in a UML notation was largely based on the first part “Part 1: Introduction to the IFC Harmonised Schema Extensions” of the “UML Model Report” [49] series, which is a series of candidate standards from buildingSMART. It was developed by the Infrastructure Room, but the UML representation is intended for common domain use. Main domain-specific features of the implementation include representing IfcProperties as attributes of PropertySets, denoting the superclass (parent class) of an entity italicised in the top-right corner of the class object and using domain specific stereotypes.

Table 5.1: Summary table of UML stereotypes used to represent IFC concepts

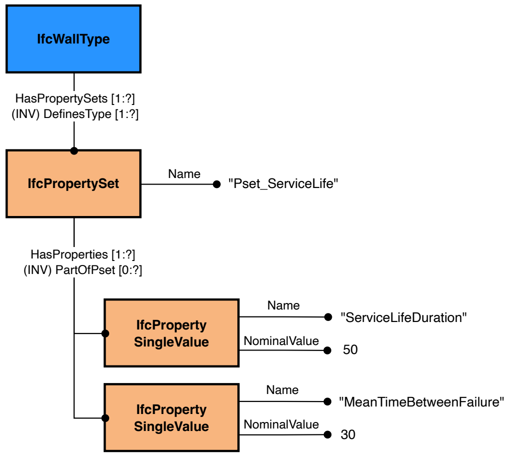
Element	Stereotype	Example Naming Convention
	Class stereotypes	
IFC Entity[1]	NONE	IfcNewEntity
IFC Predefined Type[1]	«PredefinedType»	IfcNewEntityTypeEnum.NEW
IFC Select[1]	«Select»	IfcSomeSelect
IFC Enumeration[1]	«enumeration»	IfcNewEnum
IFC Property Set Enumeration[1]	«PEnumType»	PEnum_NewThing
IFC Data Type[1]	«Datatype»	IfcMeasure
IFC Property Set[1]	«PropertySet»	LCAPset_NewEntityCommon
IFC Quantity Set[1]	«QuantitySet»	Qto_BaseQuantities
IFC Complex Property[2]	«ComplexProperty»	LCACP_NewComplexProperty
Relationship[2]	«Relationship»	
IFC Data Structure[2]	«DataStructure»	
	Attribute stereotypes	
IfcPropertySingleValue[2]	NONE	
IfcPropertyEnumeratedValue[2]	«IfcPropertyEnumeratedValue»	
IfcPropertyReferenceValue[2]	«IfcPropertyReferenceValue»	
IfcComplexProperty[2]	«IfcComplexProperty»	

[1] Defined in the ’UML Model Report’.
[2] Defined in this document.

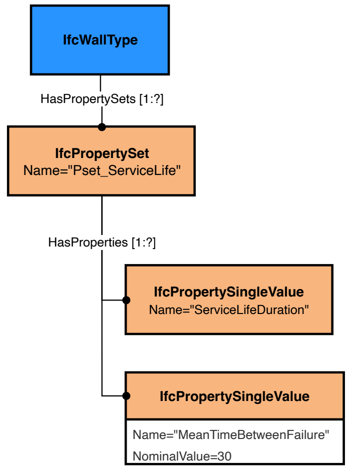
Table 5.1 shows the stereotypes used in the diagrams to visualise IFC concepts. Apart from stereotypes defined in the “UML Model Report”, additional ones were defined for the purposes of this document. This includes attribute stereotypes defining the subtype of IfcProperty. Complex property is included both in as a class and attribute stereotype. The “UML Model Report” specified that “Ifc” prefix should be avoided for stereotypes, but this was employed in the case of attribute stereotypes for clarity.

Adjustments have been made to the methodology outlined in the “UML Model Report” to better align with the goals and context of this work. Notably, the colour scheme proposed in the report was not adopted; instead, the same colours as those found in the IFC documentation and earlier diagrams were used for consistency and clarity. The idea of coloured borders to indicate the status of an entity, such as “Implemented”, “Proposed”, or “Deprecated”, was considered unnecessary for this application. Similarly, the use of stereotypes on relationships or attributes to denote status, like «Modified» or «Deprecated», was also omitted.

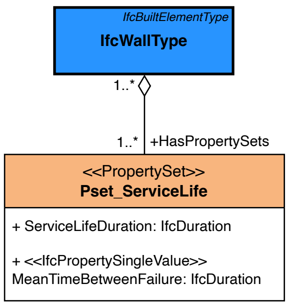
A deviation from the report’s recommendation regarding the representation of PropertySets was made. Whereas the report suggested implementing PropertySets as UML Interfaces, connected by a UML realisation relationship, this approach was revised in favour of a shared aggregation relationship. This change stems from the recognition that a realisation implies a necessity for the class to embody all features of an interface. Prop-



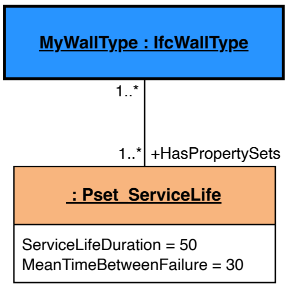
(a) Classic EXPRESS-G notation



(b) Simplified EXPRESS-G notation with two property variants



(c) UML Class Diagram with two property variants



(d) UML Object Diagram - used to illustrate examples

Figure 5.5: Different graphical notations of IFC

erties, according to the IFC schema, are inherently optional — although specific MVDs or agreements might mandate certain properties.

Furthermore, the treatment of relationships underwent modification. While the report described relationships simply as associations, this work represents them as independent classes. This adjustment was made to enhance clarity and ensure alignment with the IFC schema.

Figure 5.5c depicts all the described features of the employed UML class diagram notation and contrasting it with the same information conveyed using EXPRESS-G. Figure 5.5d shows a different type of UML diagram, namely a UML Object Diagram, which is used to illustrate concrete instances of previously defined classes. Here it will be used to showcase example implementations of the proposed schema. Figure 5.5d demonstrates an instance of IfcWallType, labelled MyWallType, with its properties encapsulated within Pset_ServiceLife. The two properties have concrete values of “50” and “30” respectively.

5.2 Verification of Mandatory Building Components in Models as per BR18 Table 6

Section 4.1.2 established a need for a verification system to guarantee that the LCA/BIM model encompasses all essential building components as specified in BR18 Table 6. For a model to accurately represent every required building element, it's crucial to conduct a methodical comparison between the model's specified IFC classes and the components stipulated by BR18 Table 6. This process can vary in approach, ranging from entirely manual to highly automated methods.

A significant amount of research has been dedicated to developing automated mapping systems in the BIM and LCA fields. These automated mapping systems are often explored as a solution to mapping EPDs to model elements or materials [50]. However, the application of automated mapping in regulatory contexts poses risks if inaccuracies in the model lead to non-compliance. The variability in modelling practices—such as modelling elements in wrong classes or the prevalent misuse of the IfcBuildingElementProxy class for undetermined objects—further complicates the accuracy of automated systems. Many proprietary software applications exacerbate this issue by incorrectly mapping a significant number of elements into IfcBuildingElementProxy elements instead of the appropriate IFC class. Consequently, reliance on automation for verifying the inclusion of mandatory building components is currently impractical and unreliable.

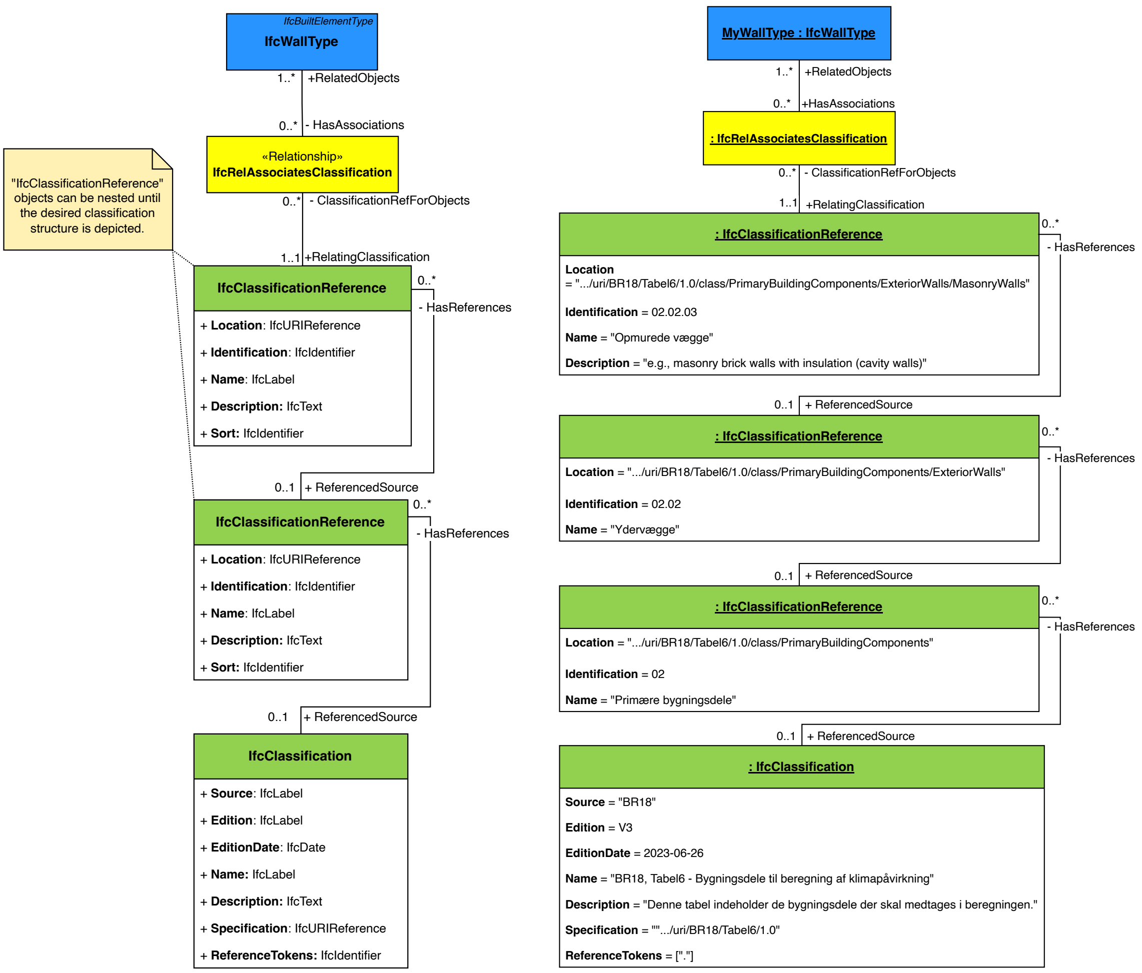
This challenge necessitates a manual or semi-manual approach to align model elements with the categories defined in Table 6. A critical step in any solution is formalising Table 6 as a robust classification system. Implementing classification within IFC can be achieved through:

- A local, file-based classification in the IFC or XML format [51].
- Reference to an online-defined classification system, as facilitated by the introduction of data dictionaries like bSDD.

Centralising classification in resources such as bSDD ensures accessibility, accuracy, and the ease of integration into IFC or XML formats. Consequently, it is advisable to define Table 6 within a data dictionary, linking it to other dictionaries vital for conducting a building LCA in the Danish context. Ideally, these dictionaries should be hosted and maintained by the Danish Housing and Building Agency (Social- og Boligstyrelsen) or a designated authority.

The spreadsheet documented in Appendix B.2 outlines the elements required by Table 6, providing an English translation of the table and suggesting numerical categories for a classification system. It also proposes mappings of all necessary building elements from BR18 Table 6 to the corresponding IFC classes. While this mapping should not be seen as a mandatory assignment to specific IFC classes, it serves as guidance for BIM practitioners during modelling. Additionally, it could be utilised in BIM software to recommend mappings based on the selected IFC class, aiding users in adhering to regulatory requirements.

Figure 5.6a shows how a building element, e.g. IfcWallType can be associated with a classification schema. Elements in IFC are linked to IfcClassificationReference objects using the IfcRelAssociatesClassification relationship. IfcClassificationReference objects can be nested indefinitely to point to a specific entry of a nested classification system. At the end of the nesting, an IfcClassifcation object, which provides general and meta information about the classification system, should be referenced. The same approach



(a) Class diagram

(b) Example object diagram

Figure 5.6: Association of classification in IFC. Schematic class diagram and an example based on BR18 Table 6 — “Masonry Walls”

can be used both in the case of a file-based classification system defined in a separate IFC file, and in when it's defined as part of a data dictionary.

Figure 5.6b presents a concrete example of how an IfcWallType could be classified as a masonry wall ("Opmurede vægge") in the BR18 Table 6 classification system, if it was defined in a data dictionary.

5.3 Data Dictionaries and IDS

To enhance the precision and uniformity of building LCAs across the European Union, the establishment of several data dictionaries (DDs) is proposed. Central to this initiative is the "EU Building LCA" a comprehensive dictionary designed to standardise LCA methodologies and practices in line with European standards such as EN15978, incorporating specific references to the origins of property definitions. A National DK BR18 building LCA dictionary is introduced to include national annexes, closely related to the definition of separate dictionaries for Tables 6 and 7. Table 7 could potentially be linked with a ÖKOBAUDAT dictionary, and the life span table definition referenced in BR18.

The LCA product level information is addressed through an existing dictionary in bSDD titled "LCA Indicators and Modules"[52], created by the buildingSMART Sustainability Strategic Group. This dictionary defines properties adhering to the ISO 22057 standard, although it is still a work in progress, as not all properties have been defined yet. This implementation also employs a custom structuring of properties into groups of properties and doesn't follow the groupings defined in the standard. Other, schemas such as ILCD+EPD could also be incorporated into the data dictionary framework. These would share numerous attributes with the "LCA Indicators and Modules" dictionary, thus creating a broader, interconnected data network.

Figure 5.7 illustrates the proposed hierarchical organisation of data dictionaries to support building LCA, operating at both EU and national levels. The "EU Building LCA" serves as the core dictionary, supplemented by country-specific or use case-specific datasets like "DGNB LCA", "DK Building LCA", and "FR Building LCA". These subsets of the central EU dictionary include unique elements for respective national or organisational needs, termed "National annexes" in the diagram. To maintain consistency and reduce redundancy, shared data should be directly referenced across dictionaries rather than being redefined.

These annexes serve to incorporate national regulations and specifications that are essential for compliance with local standards and practices. Further granularity within the national context is indicated by the inclusion of "Table 6" and "Table 7 (materials)", which represent national data that is semantically distinct from the main LCA dictionary.

Figure 5.8 expands upon Figure 5.7 by including product-level dictionaries. The "EU EPD" dictionary is conceptualised as a comprehensive collection of dictionaries related to EPDs within the European context. In practice, this would aggregate various dictionaries for different schemas and applications, such as the ISO22057 "LCA Indicators and Modules" dictionary and ILCD+EPD. The EU EPD would also contribute to a broader dictionary encompassing general LCA properties, as defined, for example, through ILCD.

An Information Delivery Specification (IDS) that outlines the model information requirements and serves as a verification tool should be clearly defined. There are several approaches to defining such an IDS:

- Creating a single IDS that encompasses all data required by the BR18 and separate IDSs for other use cases like DGNB, resulting in, for instance, a "DK DGNB IDS".

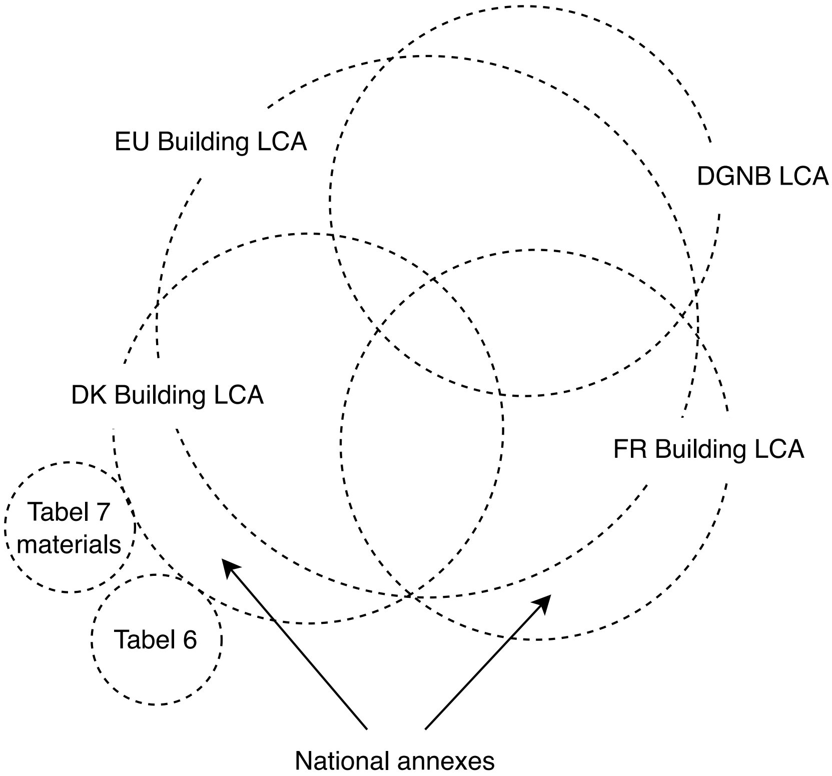


Figure 5.7: Proposed architecture of building level LCA information defined in data dictionaries.

- Creating a single IDS for the Danish context with only BR18 requirements defined as mandatory.
- Creating a comprehensive IDS for all LCA data relevant to the Danish building context, including upstream EU level definitions, specifying the required properties and designating the rest as optional, which could be changed to required on a per-project basis.
- Defining separate IDSs for the individual components of required data, such as building LCA data, EPD data, and tables 6 and 7.

Ideally, an IDS would be an officially shared definition published by regulatory authorities. Allowing users to specify required and optional parts, in such case, could be risky. Creating large, all-encompassing definitions that are not applicable in most situations, where everything beyond the bare minimum is optional, could diminish the significance of the additional data. However, redefining the IDS for each new context is also not optimal. Users dealing with multiple IDSs that define just the BR18 requirements might find it confusing.

A potentially optimal solution is a modular approach, where smaller, distinct IDS definitions are developed for specific parts but are incorporated within a larger, unified definition. This approach allows for the exchange of individual parts for other definitions, as long as they include the minimal requirements. For example, the “DK BR18 LCA” IDS could include a sub-IDS defining the Danish minimum EPD data requirements, which could be replaced with the EU EPD ISO 22057 IDS, provided it encompasses all properties defined in the Danish sub-IDS. In this manner, a different use case, such as the DK DGNB IDS, could reuse the sub-IDS definitions and add its own requirements on top if necessary. This

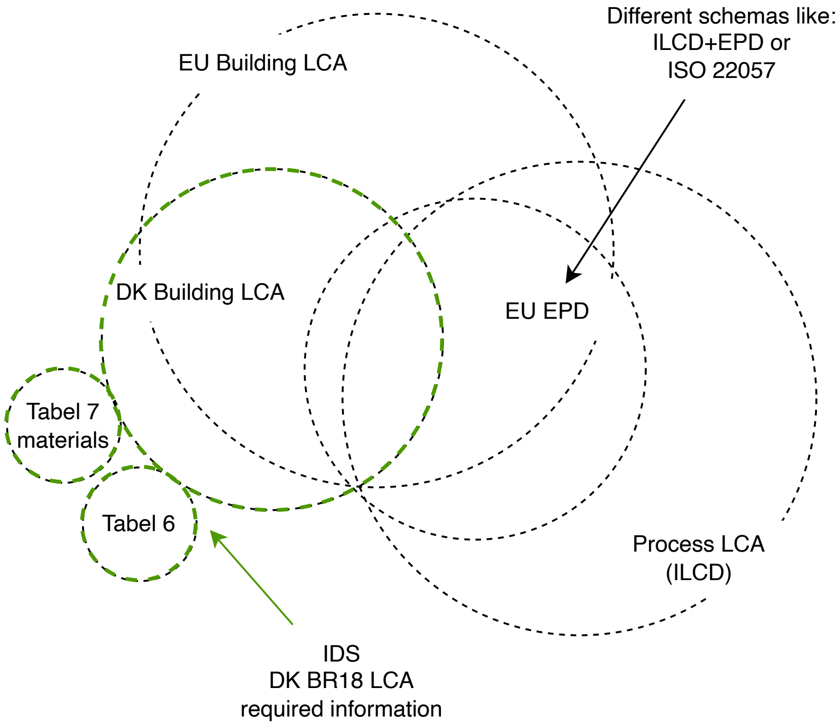


Figure 5.8: Proposed architecture of building and product level LCA information defined in data dictionaries and the contents of a proposed Danish IDS.

interchangeability would be feasible only if the bSDD manages the equivalency property mapping between the Danish data dictionary and others.

Figure 5.8 illustrates the proposed scope of the unified IDS definition for the regulatory use case. The "DK Building LCA" section includes both the building level data and EPD level data, which, in reality, would be defined as separate sub-IDSs.

5.4 Product Level Information — implementing EN ISO 22057 in IFC

Product level information consists of an integration of the EN ISO 22057 standard and its Annex A Excel workbook into the IFC schema. In general, the IFC implementation adheres as closely to the standard as possible, preserving property names, descriptions, units, and other salient details unchanged. Minor, IFC-specific implementation choices include:

- Converting property names into PascalCase to align with the IFC naming conventions.
- Prefacing property sets with "LCAPset_" to differentiate custom property sets from official IfcPropertySets beginning with "Pset_" while indicating their nature as property sets.
- Mapping "Data type" fields to the appropriate IfcValue type. In case of enumerations, setting the property type to "IfcPropertyEnumeration" and assigning the data type to individual enumeration values as indicated in the standard.

More substantial modifications, or implementation choices, are described in the following

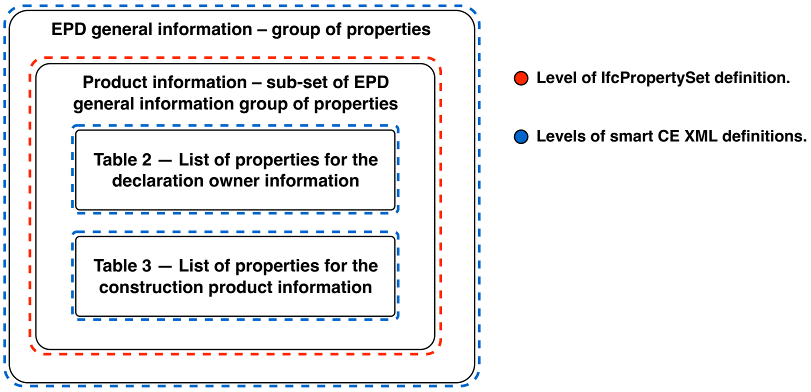


Figure 5.9: EN ISO 22057 nested structure adjusted for IFC and smart CE XML.

sections.

5.4.1 Omitting Enumerations with Boolean Values

In the EN ISO 22057 standard, several enumerations are defined with only “yes” and “no” values. This pertains to properties like “cut off rules comply with core PCR”, “allocation complies with standard PCR”, “use of upstream data which does not respect the allocation principles of the core PCR” and “generic LCA data” defined in Table 9 and 10 of the standard. Generally, using enumerations to represent binary states is redundant when a boolean data type, like IfcBoolean, is available. IfcBoolean intrinsically supports binary options (as TRUE/FALSE), rendering additional enumeration constructs unnecessary. Simplification of using IfcBoolean directly contributes to a more streamlined and interpretable data model, by (1) reducing complexity and (2) enhancing semantic clarity. This approach aligns with the principle of ontological parsimony introduced in Chapter 3.2.

5.4.2 Flattening the Nested Structure

The data template structure outlined in EN ISO 22057 features a hierarchical, multi-level nesting for most properties. It comprises various property groups, including “EPD General Information”, “EPD Methodological Framework”, “Scenarios”, “Environmental Indicators Derived from LCA”, and “Additional Environmental Information” for supplementary details. Each property group is further divided into subsets, each a property group in its own right. For instance, the “EPD General Information” group includes subsets such as “Product Information”, “Content Declaration”, “EPD Type”, “Programme Operator”, and “Technical Data”. Moreover, some property groups have additional layers of subdivision, like “Product Information”, which is segmented into “Declaration Owner” and “Construction Product” groups. This nested structure is depicted in Figure 5.9.

Annex D of the standard, titled “EPD in Smart CE Marking Declarations”, outlines the methodology for integrating the 22057 data template with the existing XML structure used in smart CE marking declarations. This XML framework typically supports a single level of nesting, where the “Property Level 2” XML element denotes individual properties and “Property Level 1” groups these properties. EN ISO 22057 proposes additional tags such as <EPDGeneralInformation>, effectively creating a two-tiered nesting structure. As highlighted in blue in Figure 5.9, “Property Level 1” elements represent the innermost groupings, whereas the additional tags correspond to the broader categories.

IFC generally allows for only a single level of property nesting, namely property sets. To balance the trade-off between restricting the number of properties in a single property set and minimizing the overall number of property sets, the decision was made to represent the intermediate grouping of properties using IFC property sets. The grouping marked with red on Figure 5.9 would thus become an IfcPropertySet with the name "LCAPset_ProductInformation".

5.4.3 Implementing Information Modules and Scenarios

Depicting the simplest form of EPD results, restricted to a singular indicator such as Global Warming Potential (GWP) across a limited set of modules—A1 to A3, often seen in EPDs aligned with the older EN 15804+A1:2013 standard, would be relatively straightforward. A single property, e.g., "GWP_A1toA3", which could be repeated for any other modules if needed, would suffice. However, as established in the analysis chapter, a comprehensive schema that accommodates a wider range of indicators and modules is needed, which as a result significantly increases data model complexity.

EN ISO 22057 specifies the implementation of life phases through an "information module" property, highlighted in Table 9 within the EPD methodological framework group of properties. This property is critical, linking all subsequent environmental indicators, waste categories, and output flows to specific modules, through a dependency relationship. The complexity deepens with the introduction of scenarios, which allow manufacturers to declare different values across alternative scenarios, further complicating the data model.

Encapsulating this complexity in the IFC framework can be done in a number of ways. Key approaches have been outlined and discussed below.

Option A — Dependent Properties
As mentioned, information modules are employed through dependent properties, which has also been reflected in the bSDD implementation of the standard through the "Connected properties" field. Although it is possible to create property dependencies in IFC through the IfcPropertyDependencyRelationship, this approach would still require repeating properties for each information module, since instantiating multiple property sets with identical names for a single entity is prohibited. Properties would need to be either consolidated into one property set or allocated across several sets, each distinguished by suffixes denoting the information module (e.g., "_A1", "_A1toA3"). To maintain a clear approach and ensure the model information directly reflects the data dictionary, these definitions would also need to be defined in e.g. bSDD, leading to accumulation of redundant information.

The inclusion of different indicator values for varying scenarios further complicates the model, escalating the quantity of required properties.

Incorporating varying indicator values for different scenarios would add another layer of complexity, increasing the total number of properties. Moreover, since IfcPropertyDependencyRelationships are generally not displayed in software, identifying the dependencies of a property set would be challenging for users, and would necessitate the use of suffixes in property set names anyhow.

Option B — Modules and Scenarios as Integrated Properties
Option B adapts the modular and scenario-based structuring from EN ISO 22057's Annex D, specifically the smart CE XML implementation, into the IFC framework. It utilises "module" and "scenario" properties as core elements in indicator property sets, systematically representing data for specific lifecycle stages and scenarios. This method requires adding suffixes to property set names to distinguish between modules and scenarios, ensuring clarity and coherence in the data model.

A variant of Option A follows the implementation of modules and scenarios outlined in EN

ISO 22057's Annex D — EPD in smart CE marking declarations, specifically in section "D.3.4 Scenarios". Smart CE XML does not allow for definition of dependent properties, so "module" and "scenario" were defined as the first two properties of each indicator property set in addition to properties defined in the main body of the standard. This method also involves duplicating property sets (Level 1 Properties in XML) for each module. Due to IFC's restriction against assigning multiple property sets with identical names to a single entity, the property sets would still have to be renamed with a suffix that indicates the module and, when relevant, the scenario. An illustration of this approach is provided in Table **??**, where the values are listed using the IfcPropertySingleValue property type.

Table 5.2: Implementation of modules and scenarios using IfcPropertySingleValue, based on Table D.5 of EN ISO 22057

Pset.Name:	LCAPset_EN15804+A2CoreLCIAIndicators_A1_S1		
Property Name	**NominalValue**	**Type**	**Unit**
Module	A1	IfcLabel	-
Scenario	S1	IfcLabel	-
GWP_Total	3.2	IfcReal	kgCO2-eq
GWP_Biogenic	3.8	IfcReal	kgCO2-eq
...	...	...	...

Option C — Implementation of Modules and Scenarios Using IfcPropertyTableValue

In addition to IfcPropertySingleValue, IFC encompasses several other property types designed for more compact information representation. One notable example is the IfcPropertyTableValue, which facilitates the definition of two columns of values, termed "Defining Values" and "Defined Values". Each column can specify its data types and units, closely resembling the key-value pair or "dictionary" structures familiar in programming languages like Python. This structure allows for the detailed listing of results for each indicator across separate modules, as demonstrated in Table 5.3.

The primary advantages of using IfcPropertyTableValue include its compactness and visual efficiency in data storage, alongside the capability to define units and data types for each column separately, enhancing the clarity and utility of the stored information. However, as the previous methods, this option also necessitates the repetition of module rows for each indicator, reducing its efficiency.

Scenarios could be implemented in this approach by duplicating each module row with an added scenario suffix, such as "A1_S1" and "A1_S2", placing scenarios at the same hierarchical level as modules. However, this structure complicates programmatic differentiation between scenarios and modules and relies heavily on user-defined property naming, which is less than ideal for maintaining consistency and clarity.

An alternative strategy involves organising indicators into property sets, for instance, "LCAPset_GlobalWarmingPotentialTotal", with modules defined as properties within these sets, and scenarios represented by the defining values. Although this method, illustrated in Table 5.4, might be semantically clearer, it diverges from the structure outlined in EN ISO 22057 and results in a high number of properties and property sets, further reducing efficiency.

Both approaches share a significant limitation: the need to modify property names for each specific case, which contradicts the principle of digital standardisation by preventing the

Table 5.3: Implementation of modules using IfcPropertyTableValue

Pset.Name:	LCAPset_EN15804+A2CoreLCIAIndicators					
Property Name	**Defining Values**	**Defining Value Type**	**Defined Values**	**Defined Value Type**	**Defining Unit**	**Defined Unit**
GWP_Total	A1	IfcLabel	3.4	IfcReal	-	kgCO2-eq
	A2	IfcLabel	4.6	IfcReal		
	A3	IfcLabel	2.8	IfcReal		
	...	...	...	...		
GWP_Biogenic	A1	IfcLabel	2.3	IfcReal	-	kgCO2-eq
	A2	IfcLabel	3.7	IfcReal		
	A3	IfcLabel	5.1	IfcReal		
	...	...	...	...		

Table 5.4: Implementation of modules and scenarios using IfcPropertyTableValue

Pset.Name:	LCAPset_GlobalWarmingPotentialTotal					
Property Name	**Defining Values**	**Defining Value Type**	**Defined Values**	**Defined Value Type**	**Defining Unit**	**Defined Unit**
A1	S1	IfcLabel	2.7	IfcReal	-	kgCO2-eq
	S2	IfcLabel	3.1	IfcReal		
A2	S1	IfcLabel	2.3	IfcReal	-	kgCO2-eq

pre-definition of property names in a data dictionary. This challenge underscores the need for a balance between flexible data representation and the adherence to standardised naming conventions to facilitate digital interoperability and clarity.

Option D — Indicator Values in a Table

Option D introduces an approach to representing indicator values in a table format for enhanced efficiency and compactness of information. Unlike the IfcPropertyTableValue, which is limited to two, predefined columns, IfcTable supports the creation of any number of custom columns for a more flexible data representation. IfcTable typically functions as an independent element but can be associated with a property through the use of the IfcPropertyReferenceValue property type and its PropertyReference attribute. This structure enables the creation of compact tables akin to those found in standard EPDs in PDF format, arranging indicators as row values and modules as columns, as depicted in Table 5.5.

The IfcTable is composed of IfcTableRow and IfcTableColumn objects, with the former containing a list of values in their respective IfcValue types, and the latter offering a more intricate configuration. IfcTableColumn enables the specification of an “identifier” attribute, allowing it to be referenced across multiple tables. It also supports the definition of “de-

Table 5.5: Implementation of modules using IfcPropertyReferenceValue and IfcTable

Pset.Name:	LCAPset_EnvironmentalIndicators					
Property Name	**PropertyReference**					
	Table.Name: EN15804+A2CoreLCIIndicatorsResults					
	Indicator	**Unit**	**A1**	**A2**	**A3**	**...**
EN15804+A2CoreIndicators	GWP_Total	kg CO2-eq				
	GWP_FossilFuels	kg CO2-eq				
	GWP_Biogenic	kg CO2-eq				
	...	...				

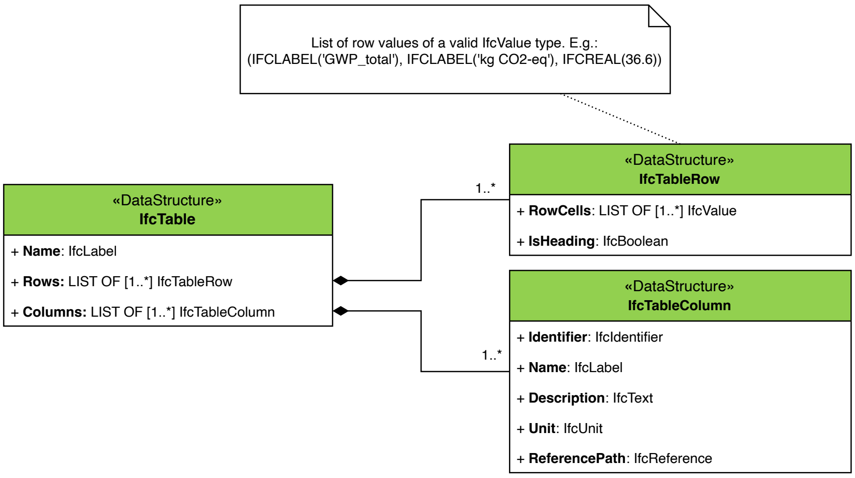


Figure 5.10: Schematic diagram of a table in IFC

scription", "unit", and a "reference path" that links to the object and attribute targeted by the column's data via the IfcReference entity. The nesting capability of IfcReference entities further allows for direct linkage of an IfcTableColumn to a particular property within a property set of a specific object. The schematic built-up of IfcTable is shown on Figure 5.10.

Given that IfcTableColumns can define units while IfcTableRows cannot, an alternative approach involves transposing the table, positioning indicators as columns and modules as rows. Unlike modules, indicators require unit definitions, and assigning them proper IFC units enhances semantic clarity and computational interpretability, compared to merely listing them as IfcLabels in an additional column. However, this approach would complicate the direct referencing of modules to their defining property sets, and it may be more user-friendly to adhere to the conventional table format familiar from PDF EPDs.

A potential drawback of this approach is that IfcTables may not be visually represented in BIM software. Additionally, the "IfcExternalReferenceRelationship", utilised for linking properties to external definitions such as those in the bSDD, is not applicable to IfcTableRows. This constraint implies that while individual indicators would be able to be directly linked to their definitions in a data dictionary, the overarching property could reference a compiled list of indicators, ensuring a degree of standardisation and clarity.

Further discussion on the application of this approach to scenario implementation is reserved for the "Implementing alternative scenarios" section.

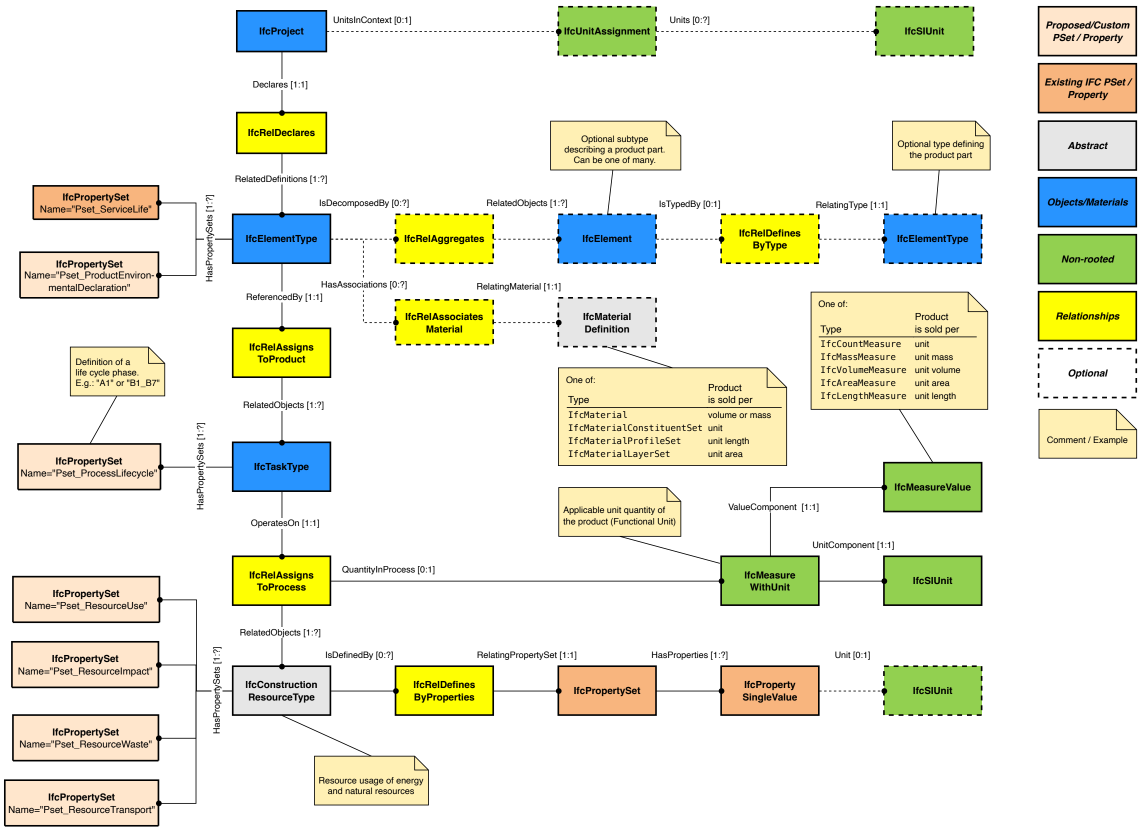


Figure 5.11: Approach defined in the "Industry Report on Environmental Impact Indicators" [53]

Option E — Implementation of Modules Using IfcTask and IfcResource

The "Industry Report on Environmental Impact Indicators"[53], presents an approach worth noting, in which information modules are implemented through the use of IfcTaskTypes and IfcConstructionResourceTypes. In this method, a IfcTaskType is designated to define each module, with corresponding property sets under IfcConstructionResourceTypes enumerating values for each indicator within that module. Figure 5.11 presents a comprehensive overview of the model architecture proposed by the report.

The report recommends the creation of a number of new PropertySets to describe general EPD information, as well as various indicator values.`PEnum_LifeCyclePhase` is an existing property enumeration used in the property "`LifeCyclePhase`" in the existing property set `Pset_EnvironmentalImpactIndicators`. But the enumeration suggested in the document is not exactly the same as the existing IFC definition. For one, the report uses names for phases as defined in EN 15804, e.g. "A3" instead of descriptive names like "MANUFACTURE" used in the IFC definition. Secondly, `PEnum_LifeCyclePhase` defined in the report is not a one to one mapping of the IFC defined enumerations — some new values have been added and others removed.

In terms of adapting this approach to represent modules using IfcTask and IfcResource classes, this strategy comes with several drawbacks:

- It does not inherently address the representation of scenarios, although in theory, this could be managed by nesting IfcTaskTypes.
- The approach is not in alignment with the CODview2 / EN 17549-2 standard, as

both IfcTaskTypes and IfcConstructionResourceTypes are not included in that Model View Definition (MVD), limiting its compatibility with the previously chosen method.

- Employing IFC concepts such as IfcTaskTypes and IfcConstructionResourceTypes for purposes beyond their original intent could lead to confusion among users.
- The structure needed to be represended is quite complex, involving repeated nesting of objects, which might not be supported in most BIM software.

This approach, while innovative, faces significant barriers in terms of standard compatibility, user clarity, and software support, necessitating careful consideration before adoption.

Module Implementation Strategy

Options A, B, and to a degree also C and E, share a common challenge, which was also highlighted by the German project "Life cycle assessment and BIM in sustainable construction" ("Ökobilanzierung und BIM im Nachhaltigen Bauen"). These approaches tend to generate an extensive number of properties. In the instance of "Life cycle assessment and BIM in sustainable construction" connection option B, approximately 983 properties were identified, raising concerns about ensuring smooth performance on standard computing systems. The primary disadvantages of these methods in general include inefficiency, leading to larger file sizes and slower performance; confusion and clutter in the user interface of BIM applications; and the necessity to modify standard module or property set names when incorporating scenarios, further complicating the process.

Conversely, Option D stands out as the most user-friendly, concise, and efficient in terms of file size. It offers an effective mechanism for referencing module scenario definitions directly. Despite the possibility that some software may not currently support IfcTables, adapting them to do so could be relatively simple and would significantly streamline the process of integrating modules into the IFC framework.

Thus, employing IfcTable through IfcPropertyReferenceValue emerges as the optimal strategy for module implementation within the IFC schema. However, the approach discussed so far has not tackled the implementation of scenarios, which will be addressed in the subsequent section.

Implementation of Alternative Scenarios

The EN ISO 22057 standard is ambiguous regarding the handling of different results for alternative scenarios. In the main body of the standard, it suggests, as illustrated in its "Figure 8", the creation of multiple data sheets for a single construction product when declaring more than one scenario per information module. Conversely, as mentioned previously, Annex D's smart CE implementation, particularly in section "D.3.4 Scenarios", proposes a different approach. It recommends using unique identifiers, such as numbering, to distinguish between scenarios of the same type, given that scenarios are identified by the name of their "property level 1" (or property set), which should be unique. It then defines "module" and "scenario" as the first two properties within each indicator property set, with "transport scenario 1" serving as a sample scenario. This implies that in cases of multiple transport scenarios, they would be accommodated within the same data sheet, with indicator property sets being duplicated accordingly.

Thus, EN ISO 22057 standard presents two distinct approaches for handling scenarios: (1) creating separate data sheets (in this context; library construction objects) for each alternative scenario, and (2) consolidating alternative scenarios within the same data sheet. Both of these methods have their own advantages, therefore an exploration was conducted to determine how each approach could be implemented within the IFC framework.

Figure 5.12 illustrates the application of the first scenario approach and the previously

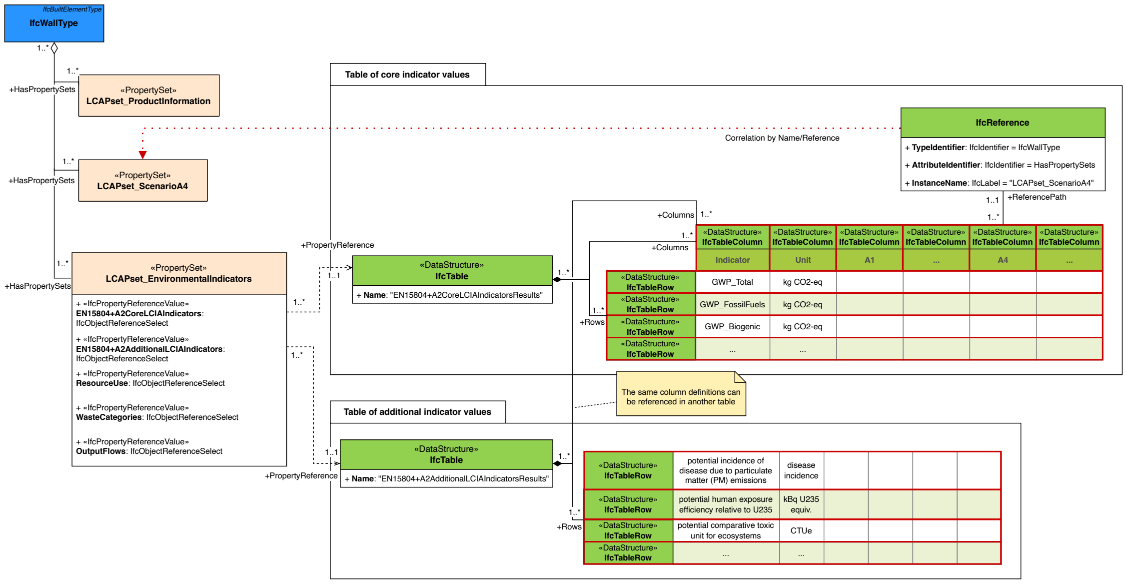


Figure 5.12: Alternative scenarios defined in different construction objects.

discussed option D. In this setup, emission values are organized in a table linked to the "EN15804+A2CoreLCIAIndicators" property. While the standard suggests "EN15804+A2CoreLCIAIndicators" should be its own property set, the use of a table for consolidating indicator results requires the usage of only a one property. Creating a property set, with only a single property in it, would not be a concise way to convey information. Therefore, a new property set, "LCAPset_EnvironmentalIndicators", was established to house all relevant indicator values, with each referring to their own IfcTable for data representation.

As mentioned before, IfcTableColumns can be referenced by multiple tables, allowing for a more efficient definition of results. The ReferencePath attribute in IfcTableColumns, alongside an IfcReference object, points to the specific property set that corresponds to the module scenario, as outlined for modules A4 to D in the standard. In this approach defines only a single scenario per module, suggesting that for alternative scenarios, the entire structure would be duplicated to create variations of the object (for instance, an alternative IfcWallType).

Figure 5.13 presents an alternative method in which scenarios are integrated within the same object definition. In this model, it's possible to establish multiple property sets that delineate various scenarios, all of which are instead linked through the "BaseScenarioResults" and "AlternativeScenarioResults" properties within the "LCAPset_EN15804+A2CoreLCIAIndicators" property set. "LCAPset_ScenarioA4Alternative" and the related property "AlternativeScenarioResults" are only examples — the names of properties and property sets relating to definitions of alternative scenarios would need to be defined in a customised manner per project or object. However, the foundational definition — the base scenario, is the one that would be defined in a data dictionary and would remain unchanged. The content within the alternative scenario property set would also need to align with the base scenario, requiring users to only define the names of subsequent property sets and their associated result properties.

To minimise the repetition of information across different scenarios, result tables for alternative scenarios should function as overlays on the base scenario table. Given that a

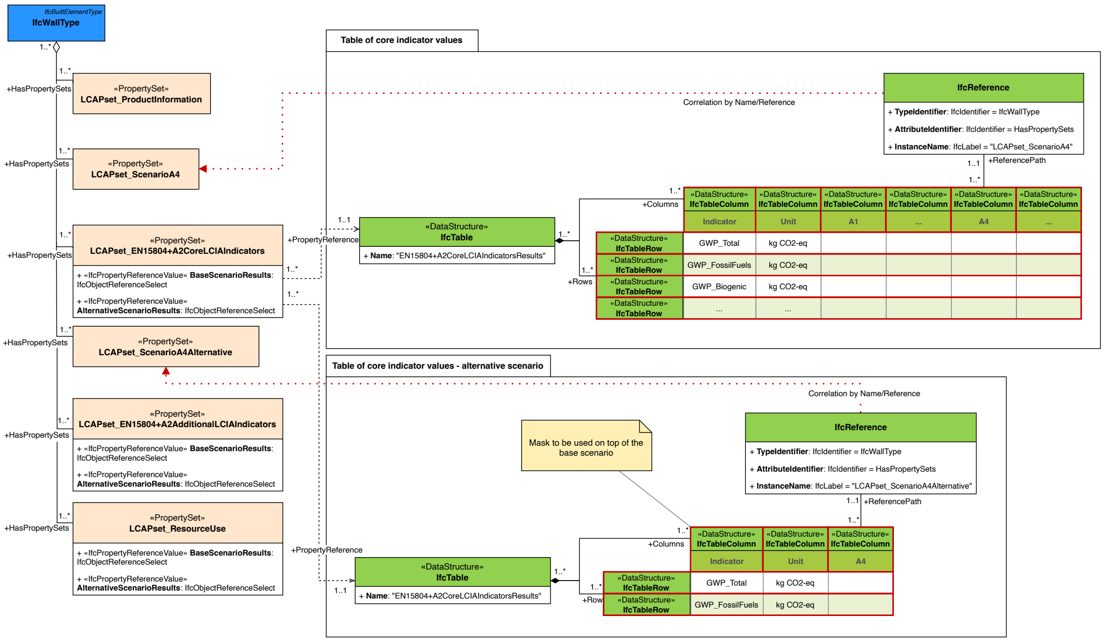


Figure 5.13: Alternative scenarios defined as part of the same construction object.

scenario typically impacts only a select number of modules or indicators, utilising these result tables as masks facilitates a streamlined and effective method to document variations.

Approach (1), which involves defining separate construction objects for each scenario, presents a straightforward and schematically clearer method. This approach is particularly suitable for the later stages of design, where the building LCA's primary goals is documentation (accounting in LCA terms) and securing long-term storage of product information. In such contexts, the utility of storing various alternative scenarios for every product, as suggested by approach (2), may not be directly relevant. However, if LCAs were re-imagined not merely as calculations yielding a single or a few numeric results but as comprehensive uncertainty analyses in and of itself resulting in a range of potential outcomes, approach (2) could become relevant even in final LCAs.

Nonetheless, even today, approach (2) might be more appropriate in the early design phases, where the LCA's objective is analysis aimed at decision-making. Here, comparing different end-of-life scenarios at both component and building levels can offer valuable insights.

For the purposes of this project, and to follow the guidelines outlined in the main text of the EN ISO 22057 standard, approach (1) is designated as the primary methodology. Nevertheless, both strategies are viable and may be suitable for different applications, suggesting that the choice between them should be guided by the specific requirements and objectives of the LCA project at hand.

Implementation of Sub-scenarios

Section 8.4.1 of EN ISO 22057 introduces the concept of sub-scenarios. A sub-scenario is defined as a smaller scenario, for example "waste handling", which contains properties that are applicable to several information modules, in the case of "waste handling" — A5, B2, B3 and C1. The goal of creating sub-scenarios is to: *"[...] ensure their reuse within different information modules and allow for the possibility to query information about*

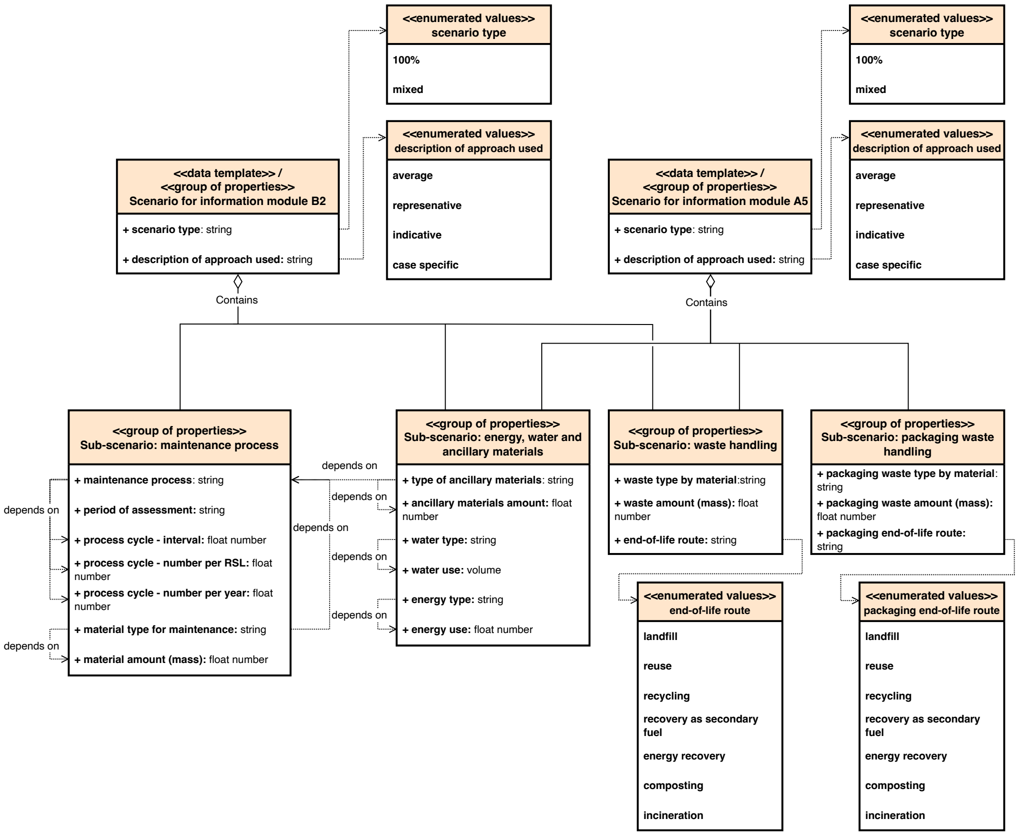


Figure 5.14: Sub-scenarios for information modules B2 and A5 as defined in the section 8.4.1 in EN ISO 22057.

particular subjects, e.g. waste handling, transport, from either one information module or several information modules." [47].

Figure 5.14 illustrates the intricate definition of sub-scenarios and their intricate property dependencies in the case of information modules B2 and A5. The dependency relationships shown in Figure 5.14 are more semantic in nature and don't have any dependency equations defined. This complexity, as shown in Annex D for the smart CE XML, could be simplified by repeating all properties relevant to a module scenario. Consequently, "LCAPset_ScenarioA5" and "LCAPset_ScenarioB2" would each, independently, encompass all properties from the "Sub-scenario: energy, water and ancillary materials" and "Sub-scenario: waste handling".

However, the IFC framework does offer a mechanism for defining nested property sets through IfcComplexProperty, facilitating a more efficient organisation and reuse of information. IfcComplexProperty allows grouping several properties under a single entry within an IfcPropertySet, enabling these complex properties to be embedded within various IfcPropertySets. This capability for nesting, while subject to specific view definitions and implementer agreements, introduces another layer of flexibility in data structuring. Despite their potential, complex properties are underutilised and vary in implementation across BIM software. Therefore, they are treated in this context as a beneficial yet optional feature, used solely where a direct alternative, through the redefinition of properties for each module scenario, exists.

Further illustrating this approach, Figure 5.15 details how sub-scenarios outlined in Fig-

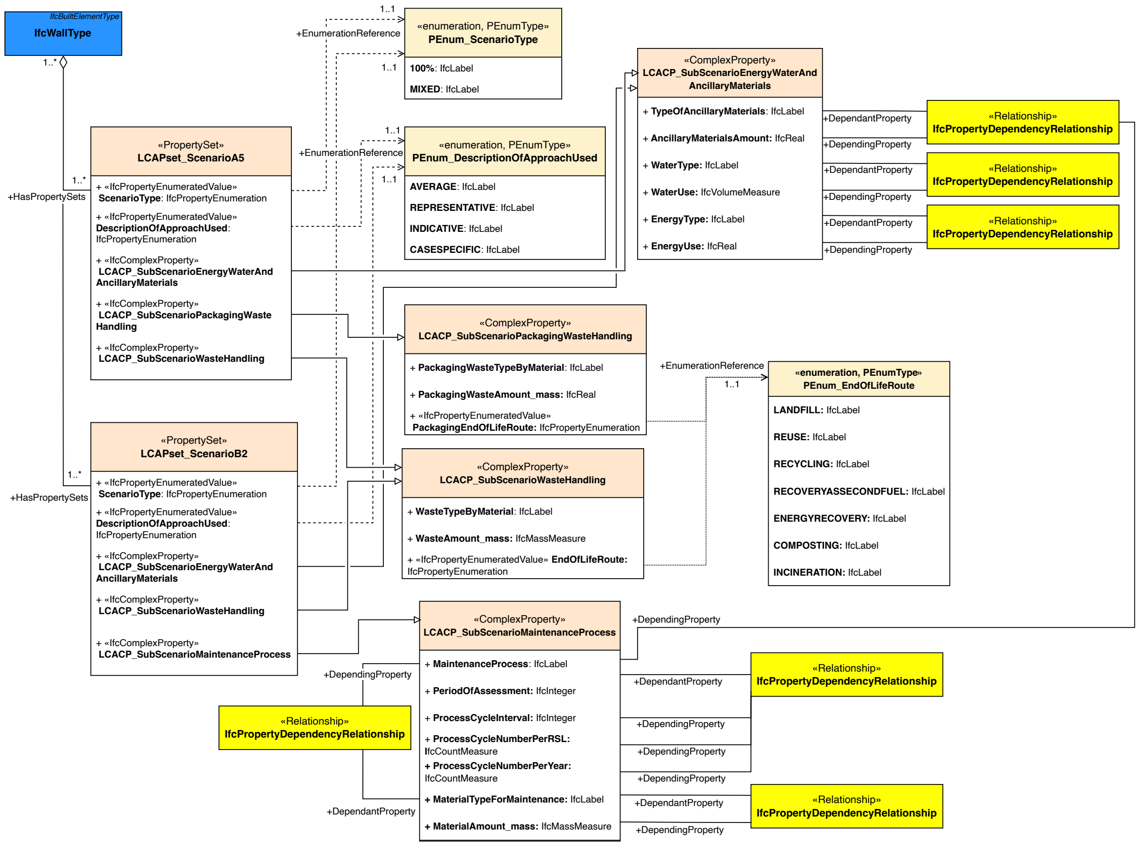


Figure 5.15: Sub-scenarios for information modules B2 and A5 implemented in IFC through IfcComplexProperty and IfcPropertyDependencyRelationship

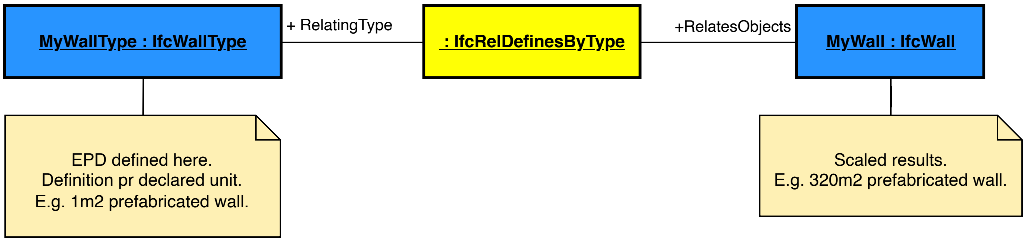


Figure 5.16: Construction object EPD definition on element level

ure 5.14, can be actualised within the IFC model using IfcComplexProperty and IfcPropertyDependencyRelationship to establish property dependencies. The DependProperty attribute mirrors the 'depends on' relationship stipulated in the EN ISO 22057 standard. A larger version of the final implementation of information modules and scenarios including the integration of sub-scenarios, is available in Annex A.3.

5.4.4 Strategies for Representing EPDs at Different Modelling Levels

Construction objects including an EPD can represent objects of various level of detail and should thus be able to be defined at multiple levels in the BIM model.

For EPDs that represent entire building elements —such as prefabricated sandwich walls or doors — the EPD can be directly associated with the element level. In this context, the element types are used to define the LCIA indicator values per declared unit as specified in the original EPD. Since element types are designed to be universally applicable and typically do not have quantities assigned to them, they serve as a basis for applying EPD values universally. The specific instance of the element type, equipped with a defined quantity through an IfcQuantitySet, is responsible for storing the scaled results of the EPD values. These results can be managed in two ways: for purposes that require communication or visualisation, the scaled values may be explicitly defined in IfcTables. Alternatively, if detailed storage of scaled values is not necessary, it is sufficient to store only the scaling factor and a reference to the element type. This approach is exemplified in Figure 5.16 where an IfcWallType specifies $1m^2$ of a prefabricated wall, and the IfcWall instance represents the scaled results for $320m^2$ of the wall.

However, the process of defining construction objects isn't always straightforward. In some cases, the objects in question are not complete building elements but rather smaller components or raw materials. For instance, Figure 5.17 demonstrates a more detailed object definition through IFC material definitions. The IfcMaterialLayer "InsulationPanel150" exemplifies how an object, serving as part of a larger built-up (represented by the IfcMaterialLayerSet for an insulated sandwich panel), can be defined without the need for further scaling. At this granularity, the IfcMaterialLayer can have IfcPropertySets attached, allowing the EPD to be assigned directly at this level, akin to the assignment at the element type level. Defining EPDs at the type level is crucial for maintaining high-quality modelling and ensuring that the numerous property sets specifying the EPD are not redundantly repeated within the model. This approach helps to minimise file size and maximise information density.

Conversely, there are instances where EPDs specify materials that require scaling, typically defined either per cubic meter or kilogram. To handle products that need scaling, ISO 22057 introduces a set of properties termed "Reference quantity and scaling factor" in section 8.3.4. While it doesn't specify particular properties, it offers examples like "scaling factor" and "thickness" to facilitate the application of a single EPD across various thick-

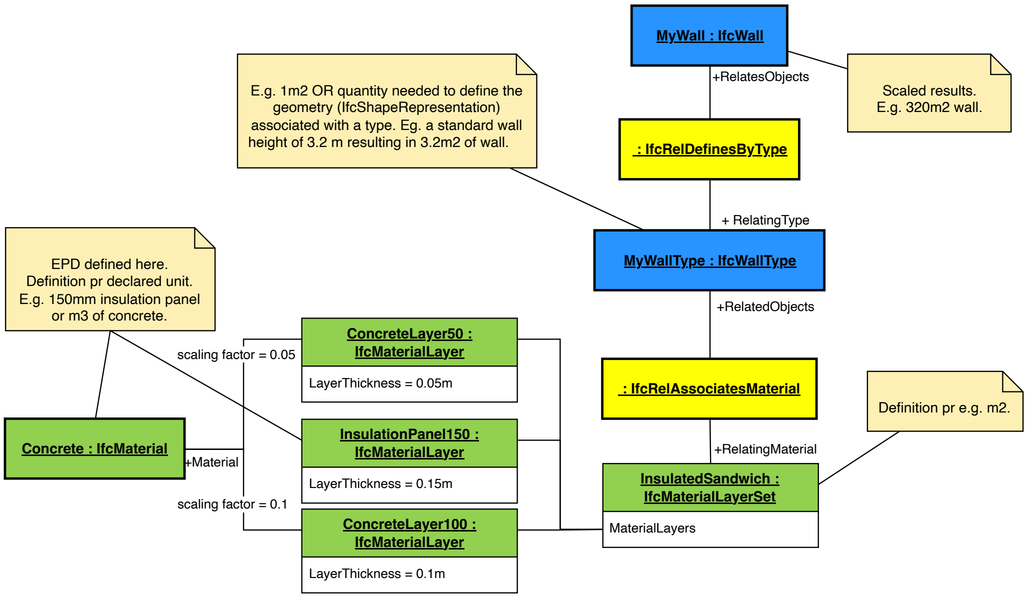


Figure 5.17: Construction object EPD definition on material level

nesses or sizes of the same product. The LayerThickness attribute of IfcMaterialLayer, in conjunction with these user-defined scaling properties, enables the material's EPD to be defined at the IfcMaterial level. This definition can then be scaled appropriately and incorporated into different material set definitions, such as IfcMaterialLayerSet, IfcMaterialProfileSet, and IfcMaterialConstituentSet, showcasing the versatility in applying EPDs within different material contexts.

Assigning EPDs at the material level—whether for a single material or a material set—facilitates their reuse across not only element type occurrences, but also across different types altogether, enhancing the model's operational efficiency even further.

Element decompositions and the use of IfcBuildingElementPart class offer an additional a nuanced method for representing objects that are smaller than a complete building element, such as an entire IfcWall, but where material definitions alone do not suffice. This need arises for example in scenarios where these parts require their unique geometry—since materials lack a geometry definition—or necessitate other element-level information. An illustrative example would be the studs within a wall, which, while integral to the wall's structure, can, depending on modelling requirements, require a distinct representation due to their independent geometry and information needs.

These parts can be defined either as standalone entities or aggregated within another IfcElements through the IFC's "Element Composition/Decomposition" concept. This mechanism allows for one IfcElement to aggregate other IfcElements using the IfcRelAggregates relationship, facilitating a hierarchical organisation of building components.

Furthermore, the less commonly known IfcRelDefinesByObject relationship introduces a nuanced approach to defining sub-types within other element types. This contrast to the common IfcRelDefinesByType relationship, which links objects to a common type for uniform property application. The IfcRelDefinesByObject relationship enables an object-to-object inheritance, essentially allowing an object to be defined based on the instance of another object, which in turn is defined by another type object. Figure 5.18 exemplifies this intricate relationship, showcasing how a "whole" product type can be connected to a ”part” product type. This concept is useful for representing complex object hierarchies and dependencies, ensuring that each construction object is accurately defined by a type. Moreover, it guarantees that any modification to a defining object propagates to all related objects, thus maintaining consistency throughout the model.

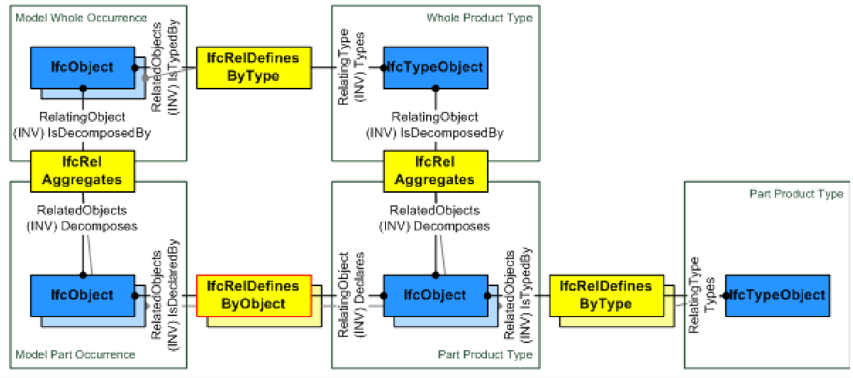


Figure 5.18: IfcRelDefinesByObject relationship in IFC. Source: IFC 4x3 documentation.

5.4.5 Product Level IFC Definition

This section outlines the finalised definitions for product level IFC information, which are comprehensively detailed in the accompanying spreadsheet referenced in Appendix B.3. The spreadsheet is organised into multiple tabs, each specifying various part of the definition such as properties, property sets, complex properties, enumerations, as well as the structure of tables through columns and rows. The main columns used to define the the properties are described in 5.6.

The LCAPset_EnvironmentalIndicators property set, crucial for tabulating results as depicted in 5.4.3, is defined separately within the ”22057IFC_tablerows” sheet. Correspondingly, the definitions for table columns are detailed in the ’table column’ sheet.

The IFC ”specification” attribute establishes a URI reference for all properties, linking to the bSDD dictionary ”LCA indicators and modules” where further details can be found. Since the dictionary hasn’t defined all properties present in the standard yet (especially properties referring to scenarios are missing), URIs adhering to the same naming convention were inserted where the property couldn’t be found in the dictionary.

PropertyForDependance and PropertyDependsOn are attributes of IfcProperty, which reference one or more IfcPropertyDependencyRelationships. IfcPropertyDependencyRelationship defines the DependingProperty and DependantProperty depicting the property dependencies represented in ISO 22057, as described in the 5.4.3 section.

Table 5.6: Types of data used to define IFC data for product level information.

Column Name	Description
PropertySetName	This column defines the name of the property set that groups related properties. For example, ”LCAPset_ProductInformation”. In the complex property sheet it defines the name of the complex properties.

Table 5.6: Types of data used to define IFC data for product level information.

PropertyName	This column specifies individual property names within a property set, such as ”NameOfOwner”. This field also references the complex property, defined in the complex property sheet, by name.
IFCType	Indicates the class of IFC entity or attribute that is being defined, such as ”IfcPropertySingleValue,”, ”IfcPropertyListValue” or ”IfcTableColumn”.
Description	Description as defined in ISO 22057 Annex A.
DataType	Specifies the IFC appropriate type of IfcValue for the property, such as ”IfcLabel” or ”IfcMassMeasure”. Types were mapped based on the data types (”string”, ”float number”, ”boolean”, ”date” and ”volume”) defined for each property in the ISO 22057 text. Data type was omitted for IfcPropertyEnumeratedValue’s.
Unit	Indicates the unit of measurement for the property as defined in ISO 22057.
EnumerationReference	For properties of IfcPropertyEnumeratedValue this column references a an IFC property enumeration defined in the enumeration sheet.
Mandatory/Optional	Specifies whether the property is mandatory (”M”) or optional (”O”) as defined in ISO 22057 text.
ISO22057GUID	GUID as defined in ISO 22057 Annex A.
Specification	A URI reference to the property defined in the bSDD ”LCA indicators and modules” dictionary. Where properties were not present in the dictionary, an URI following the same naming pattern was used.
PropertyForDependance and PropertyDependsOn	The depending and dependant properties to be used in the IfcPropertyDependencyRelationship definition. Dependencies defined as in ISO 22057.

5.5 Building Level Information

The setup for building-related IFC information draws from a comparison spreadsheet of different LCA information sources, as detailed in the spreadsheet referenced in Appendix B.1. The ”MVP acc. to BR18” and ”Full LCA” columns served as the foundation for two distinct sets of building LCA definitions. One is a minimum viable product (MVP), outlining only the essential properties for completing a building LCA under Danish legislation. The other is a more extensive LCA that aligns with broader European requirements.

5.5.1 Comprehensive Building LCA

The comprehensive LCA primarily relies on EN 15798, incorporating insights from the Level(s) framework, EeBGuide, and various software tools to ensure a unified interpretation of EN 15798 guidelines into data fields. It focuses on the general information about the LCA, project, and object assessment by establishing functional equivalency with a technical description of the building and operational areas, along with energy and water usage information (Modules B6 and B7). It also includes most important information about assumptions, omitted processes, and results. The results are presented in two forms: one is a property set summarising key outcomes like normalised and total GWP and impacts of main LCIA indicators and resource use per module or total per indicator. The other method directly references the LCAPset_EnvironmentalIndicators property set from the product level IFC definition. This property set, along with its tables, can be applied at the building level or any other aggregation level chosen by the user. This flexibility also applies to the property sets for key results and those defining energy and water usage, whether for IfcBuilding, IfcBuildingElement, or IfcGroup.

Properties initially defined in the EeBGuide were converted into IfcPropertyEnumeratedValue with corresponding enumerations, including ReviewType, LCAObjective, BuildingStatus, LCAPurpose, and ComplexityLevel. This approach also reused the "PEnum_InformationModule" enumeration from the product level. The IfcPropertyTableValue type was chosen for detailing assumptions, omissions, and deviations from EN15978 for each life cycle stage.

This "Comprehensive LCA" still represents a scaled down version of building LCA. For example it doesn't define scenarios or describe the modelling of modules in detail.

Table 5.7 lists the IfcPropertySets included in this definition, providing a brief overview of their content. The complete details of these property sets and properties are available in the spreadsheet mentioned in Appendix B.4, under the "FullLCABuildingPsets" tab. Property enumerations are defined in the "Enumerations" tab.

Table 5.7: Thematic content of property sets for the comprehensive building LCA.

Property Set Name	**Description**
LCAPset_GeneralInformation	Contains foundational details such as identification, assessment context, and administrative details for the LCA project.
LCAPset_IntendedUse	Outlines goals, scope, and audience for the LCA, clarifying the purpose and expected outcomes.
LCAPset_FunctionalEquivalentAndRSL	Details technical and functional benchmarks for the building, setting parameters for comparison in the LCA.
LCAPset_TechnicalDescriptionBuilding	Provides an account of the building's structural and physical characteristics, relevant to its life cycle performance.
LCAPset_TechnicalDescriptionOperationalArea	Describes the operational areas including designed use, occupancy, and supporting systems of the building.
LCAPset_SystemBoundaries	Defines the extent of life cycle stages considered, detailing assumptions, omissions and deviations from EN15978 for each life cycle stage. Also defines the life cycle stages included and the system used to define the scope of included building elements (e.g. BR18 Table 6).
LCAPset_B6EnergyUses	Module B6. Details all forms of energy consumption within the building.
LCAPset_B7WaterUses	Module B7. Catalogs all water-related uses within the building.
LCAPset_EnvironmentalIndicators	Reference to property set defined as part of product level definition.

Property Set Name	Description
LCAPset_KeyResults	Summarizes key results of the LCA, highlighting impact in terms of GWP, main environmental indicators and resource use.

5.5.2 Minimal Building LCA According to BR18

This version includes the necessary information defined in BR18 directly and the interpretation of it thorough legislation compliant LCAbyg report and other verified sources. It covers general information and sets up a functional equivalent by defining the building type, reference service life, and unit. In addition it focuses on operational use and BR18 specific areas and result definitions, including legislative boundaries and classes. An optional property set, BR18LCAPset_EPDInformation, provides basic EPD information for those cases where detailed ISO 22057 data isn't available or can realistically be implemented. This property set can be applied at the IfcBuildingElement or IfcMaterialDefinition level, using the same method as defined in section 5.4.4. Like the comprehensive LCA, BR18LCAPset_KeyResults can be applied at the IfcBuilding, IfcBuildingElement, or IfcGroup levels. The rest of the property sets are specific to IfcBuilding.

Table 5.8 presents the property sets that are part of this definition along with a brief description of them. The complete details of these property sets and properties are available in the spreadsheet mentioned in Appendix B.4, under the ”MVPLCABuildingPsets” tab.

Table 5.8: Thematic content of property sets for the MVP building LCA according to BR18.

Property Set Name	Description
BR18LCAPset_General-Information	Includes general information about the LCA project such as project name, address, assessment details, client, and LCA tool description.
BR18LCAPset_Functional-Equivalent	Contains data on the building type, reference unit, service life, study period, and construction year, providing a basis for functional equivalence in the assessment.
BR18LCAPset_Areas	Details the various areas defined in BR18, such as useful floor, heated, and additional areas, including integrated garages and reference areas.
BR18LCAPset_OperationalUse	Outlines the operational energy and resource use including heating, electricity, subsidies for these utilities, and the sources of energy.
BR18LCAPset_KeyResults	Summarizes key outcomes of the LCA according to BR18, including boundary value requirements, emission classes, and total and net climate impact.
BR18LCAPset_EPDInformation	(Optional) Contains basic information about EPDs such as UUID, name, service life, dataset details, and converted amounts for the building products.

5.6 Developing IFC Models with Integrated LCA Data

To showcase a practical implementation of the IFC definitions for product and building level information, as outlined in Sections 5.4 and 5.5 respectively, each was realised through an IFC STEP file format.

The building level implementation is divided into two parts: the MVP BR18 model and the more comprehensive LCA model. Each of these was developed as separate demo IFC models incorporating property sets derived from spreadsheets defined at the building level.

At the product level, the IFC model represents an implementation of a reusable construction object within an IFC project library. Here, two types of models were created: one includes all defined property sets and properties, populated with proxy values to demonstrate the entirety of the defined implementation; the other is based on a real EPD for a selected construction object.

5.6.1 Product Catalogues According to CODview2

The CODview2 MVD, as defined in EN 17549-2, along with the accompanying example IFC files, lies at the heart of the implementation presented in this project. EN 17549-2 includes an example of a product catalog implemented as an IFC Project Library in its Annex B.2.4, titled ”Product Catalogue.” This example is illustrated in the IFC4 STEP file ”B.2.4_product-catalogue.ifc” and showcases a complex case of a parametric silencer. It is defined implicitly by sets of rules and tables that dictate and limit the permissible combinations of values. Furthermore, it demonstrates the use of constraints via IfcObjectives and the application of dynamic property dependencies using JavaScript functions to establish relationships based on expressions. Additionally, it connects all defined properties and property sets to a fictional construction dictionary through IfcLibraryReference.

This parametric definition approach enables the specification of an object with a vast array of potential variants. A fragment that highlights the definition of allowed value combinations is presented in listing 5.1.

```
/*
********************************
  Value combinations for properties described in a multi-column table:

  allowed values for properties numberOfSplitters and KindOfPort
*********************************
*/

#2070= IFCOBJECTIVE ('allowed combinations of numberOfSplitters and KindOfPort
    ', $,.NOTDEFINED.,$,$,$,$, (#2071),$, .USERDEFINED., 'defines the allowed
    value combinations for numberOfSplitters and KindOfPort');
#2071= IFCMETRIC ('linkToCombinationTable',$,.NOTDEFINED.,$,$,$,$,.EQUALTO.,$,
    #2072,$);
#2072= IFCTABLE('CombinationTable',(#25030,#25031,#25032,#25033,#25034,#25035,
    #25036),(#2073,#2074));
#2073= IFCTABLECOLUMN('kindOfFrame','kindOfFrame','Nominal kindOfFrame of the
    silencer',$,#2290);
#2074= IFCTABLECOLUMN('numberOfSplitters','numberOfSplitters','Nominal
    numberOfSplitters of the silencer',$,#2320);
#2075= IFCRELASSOCIATESCONSTRAINT ('39pdaAHcz17fqXm2DkcYS4', $,$,$, (#1000), '
    Values of Properties numberOfSplitters and kindOfFrame', #2070);
```

Listing 5.1: Fragment of EN 17549-2 / CODview2 product catalogue example

Although this project does not utilise the more advanced possibilities, such as definitions of complex relationships and objectives presented in EN 17549-2, the structure and restrictions defined therein serve as a guiding example for the implementation of this project. This meant omitting certain IFC classes that are not part of this definition.

CODview2 does not provide any entity with construction specific semantics and merely recommends the use of IfcBuildingElementProxy as a class for product catalogue objects. It specifies that external data dictionaries based on EN ISO 12006-3:2022, like bSDD, should be the sole sources of construction semantics.

This usage of data dictionaries as the single source of truth is also the reasoning behind CODview2 not recommending the usage of IFC property and property set templates:

> *"This document selects this mechanism to refer to elements of data dictionaries. Hence, IFC template classes, IfcPropertyTemplate and IfcPropertySetTemplate, are not part of CODview2 and shall not be used."[54]*

IFC property templates would otherwise be an ideal choice for the use case; defining reusable IfcProperty and IfcPropertySet definitions without any specified data. IFC property templates also allow for specifying the intended data type of properties, which can't be done if the value of a property is simply left as `None` (`$` in IFC STEP format). To be able to specify the IFC data type, a value must be defined, and the value itself must align with the chosen data type. This complicates the implementation of an example product catalogue without, because a separate proxy value for each primitive data type has to be defined. It can however be accomplished by first finding the primitive type of an IfcValue type and then applying the following mapping:

- Boolean: False
- Integer: 0
- Float: 0.0
- String: "NaN"

This approach was employed in the custom script tool described below.

5.6.2 Developing a Custom Script Tool

These IFC models were created through a custom script utilising the capabilities of the IfcOpenShell Python library [55]. The IfcOpenShell library is a well-established free software library, designed to enable the creation and manipulation of IFC files efficiently. It facilitates not only the interpretation and manipulation of existing IFC models but also enables native authoring of IFC models directly through its C++ or Python libraries. It support for a variety of IFC serialisation formats such as IFC-SPF (STEP), IFCJSON, IFCXML, and ensures compatibility with multiple IFC schema versions, including IFC2X3 and IFC4. Additionally, IfcOpenShell offers a suite of related tools ranging from generating IDS files through IfcTester, facilitating integration of BCF and bSDD, and a collection of utilities designed for editing and resolving issues in IFC models, including IFCpatch, IfcClash, and IfcDiff.

Notably, the growing BlenderBIM [56] project is also part of the IfcOpenShell family. BlenderBIM, which is largely based on the core IfcOpenShell library, is an add-on for the open-source 3D modelling software Blender [57], providing a graphical platform for native IFC authoring.

Table 5.9: Select functions defined in the Python script generating IFC models with LCA information.

Function Name	Description
`find_value_by_guid`	Searches a nested structure (list or dict) for an item with a specific GUID and returns a user-defined type of value from that item.
`convert_value_type`	Dynamically converts a value to the correct Python primitive data type based on the provided IFC data type. Can also generate proxy data in the correct type.
`generate_basic_ifc_model`	Generates a basic IFC project library with predefined settings, adds a user defined object type and makes it a reusable asset.
`add_propertysimple-value`	Calls the correct function creating a simple property of either IfcPropertySingleValue, IfcPropertyList-Value, IfcPropertyEnumeration or IfcPropertyReference-Value type.
`add_environmental_indi-cators`	Adds environmental indicators as IfcPropertyReference-Value to a property set.
`add_complexproperty`	Calls the add_propertysimplevalue to create simple properties and adds them to a new IfcComplexProperty.
`add_columns`	Adds columns to a table if existing columns aren't already present. Creates references through IfcReference to correct scenario property sets.
`add_tablerows`	Adds rows to a table either for values present in the source file or generates proxy values.
`add_table`	Creates and adds an IfcTable. Calls for generation of the appropriate columns and rows.
`main`	Main function to generate a basic IFC model with specified properties and environmental indicators. Sets the flag if demo data should be inserted or if a data should come from a real product JSON file.

The custom script serves a dual purpose; creation of building-level IFC models, as well as the generation of reusable IFC project library objects, both augmented with custom property sets. The source code of the tool can be found in the attachment as `generateIFCmodels.py`. Information about the custom IFC definitions was sourced from each tab of the Excel spreadsheets discussed earlier and exported to CSV.

Table 5.9 provides a brief description of select main functions utilised in the script. The logic starts with the `main()` function which delegates the creation of the basic IFC model, either as a regular IFC project or an IfcProjectLibrary, populated with information about units, and reference libraries. A main IFC object—either an IfcBuilding or a user-defined element type in the case of products - to which all subsequent LCA data is added, is also defined here. This model acts as a foundational framework for further customisation. Further, the `main()` function calls for the addition of new property sets with either simple or complex properties or the creation of the special property set LCAPset_EnvironmentalIndicators which stores LCIA indicator results in IfcTables. References to bSDD were created for all properties using the ”specification” attribute of IfcProperty, and the bSDD dictionary ”LCA indicators and modules” was established as an IfcLibrary.

Data for these custom properties can be populated in two distinct ways; by generating proxy values for a generic template according to the mapping described in Section 5.6.1, or by incorporating data from real-life EPDs. Values from EPDs are integrated through JSON implementation of the ISO 22057 standard developed by EPD-Norway in the pilot project ”EPD in ISO22057 format” [58].

Although the script is tailored for the EPD-Norway’s adoption of ISO 22057, it is versatile enough to process any JSON file, regardless of its structure. This flexibility is due to the script’s ability to locate specific values through references to unique GUIDs as defined in ISO 22057, ensuring it can adapted to various data formats.

As an illustrative example, the EPD for ”Massiv betongelement - Vegg, lavkarbonbetong” from EPD-Norge was selected. This EPD has been converted into the ”ISO22057IFC” format and is presented in the ”22057IFC_Example_massiv_betonelement.ifc” file, which can be found in the attachments. Listing 5.2 showcases a fragment of that file, specifically showing the first few properties of the LCAPset_ProductInformation property set. Figure 5.19 shows the IFC file imported into BlenderBIM. BlenderBIM can’t view IfcTables or IfcPropertyReferenceValues yet, therefore the property set ”LCAPset_EnvironmentalIndicators” appears to be empty.

```
#13=IFCPROPERTYSET('3PqJDfAD140QLz7fZhO18q',$,'LCAPset_ProductInformation','
    Document reference: EN ISO 22057 8.2.2 - Table 2 and Table 3',(#14,#15,#
    16,#17,#18,#19,#20,#21));
#14=IFCPROPERTYSINGLEVALUE('NameOfOwner','https://identifier.buildingsmart.org
    /uri/LCA/LCA/3.0/prop/nameofowner',IFCLABEL('Jaro AS'),$);
#15=IFCPROPERTYSINGLEVALUE('UniqueIdentifier','https://identifier.
    buildingsmart.org/uri/LCA/LCA/3.0/prop/uniqueidentifier',IFCIDENTIFIER('
    976 241 053'),$);
#16=IFCPROPERTYSINGLEVALUE('WebDomain','https://identifier.buildingsmart.org/
    uri/LCA/LCA/3.0/prop/webdomain',IFCURIREFERENCE('http://www.jaro.no/'),$);
#17=IFCPROPERTYSINGLEVALUE('ProductName','https://identifier.buildingsmart.org
    /uri/LCA/LCA/3.0/prop/productname',IFCLABEL(' Massiv betongelement - Vegg,
     lavkarbonbetong'),$);
```

Listing 5.2: Fragment of the ”Massiv betongelement - Vegg lavkarbonbetong” EPD from EPD-Norge in IFC

Due to the lack of information on scenarios in any of the EPDs digitised for the ”EPD in ISO22057 format” pilot project – the only section where complex properties are typically employed — a version supplemented with proxy data was developed. This approach was taken to fully demonstrate the implementation, including complex properties, IFC references, and various IFC property types. A full IFC model with proxy values for all properties can be found in the attachments under the name ”22057IFCDemoObject.ifc” Listing 5.3 displays a segment of the IFC file that defines the LCAPset_ScenarioC1 property set. This excerpt demonstrates the implementation of IfcPropertyEnumerations, IfcPropertyEnumeratedValues, and IfcComplexProperty. Figure 5.20 shows the IFC file imported into BlenderBIM. BlenderBIM also lacks the capability to display complex properties and IFC references; therefore, only properties of simple types are visible in the imported file.

```
#93=IFCPROPERTYENUMERATION('PEnum_ScenarioType',(IFCLABEL('100%'),IFCLABEL('
    MIXED')),$);
```

```
#96=IFCPROPERTYENUMERATION('PEnum_DescriptionOfApproachUsed',(IFCLABEL('
    AVERAGE'),IFCLABEL('REPRESENTATIVE'),IFCLABEL('INDICATIVE'),IFCLABEL('
    CASESPECIFIC')),$);
#177=IFCPROPERTYSET('1cXJ$cF1H8sg3xAyS8bmuc',$,'LCAPset_ScenarioC1','Document
    reference: EN ISO 22057 8.4.8 Table 24.',(#178,#179,#183,#119,#128));
#178=IFCPROPERTYENUMERATEDVALUE('ScenarioType','https://identifier.
    buildingsmart.org/uri/LCA/LCA/3.0/prop/scenariotype',(IFCLABEL('100%')),#
    93);
#179=IFCPROPERTYENUMERATEDVALUE('DescriptionOfApproachUsed','https://
    identifier.buildingsmart.org/uri/LCA/LCA/3.0/prop/
    descriptionofapproachused',(IFCLABEL('AVERAGE')),#96);
#180=IFCPROPERTYSINGLEVALUE('DemolitionProcessType','https://identifier.
    buildingsmart.org/uri/LCA/LCA/3.0/prop/demolitionProcessType',IFCTEXT('NaN
    '),$);
#181=IFCPROPERTYSINGLEVALUE('MaterialTypeForDemolition','https://identifier.
    buildingsmart.org/uri/LCA/LCA/3.0/prop/materialTypeForDemolition',IFCTEXT(
    'NaN'),$);
#182=IFCPROPERTYSINGLEVALUE('MaterialAmountMass','https://identifier.
    buildingsmart.org/uri/LCA/LCA/3.0/prop/materialAmountMass',IFCMASSMEASURE
    (0.),$);
#183=IFCCOMPLEXPROPERTY('LCACP_SubScenarioDemolitionDeconstructionProcess',$,'
    LCACP_SubScenarioDemolitionDeconstructionProcess',(#180,#181,#182));
```

Listing 5.3: Demo IFC product catalogue with proxy values

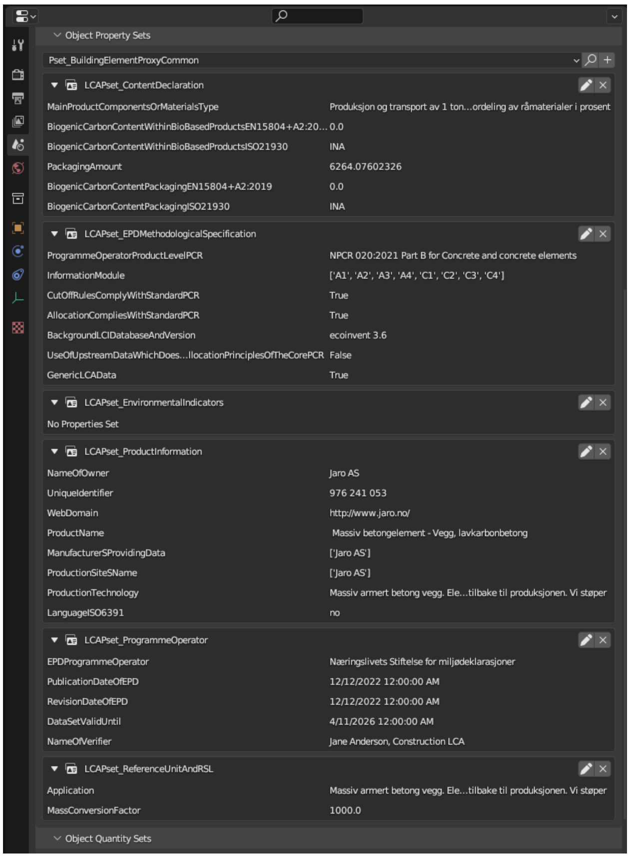


Figure 5.19: "Massiv betongelement - Vegg" EPD

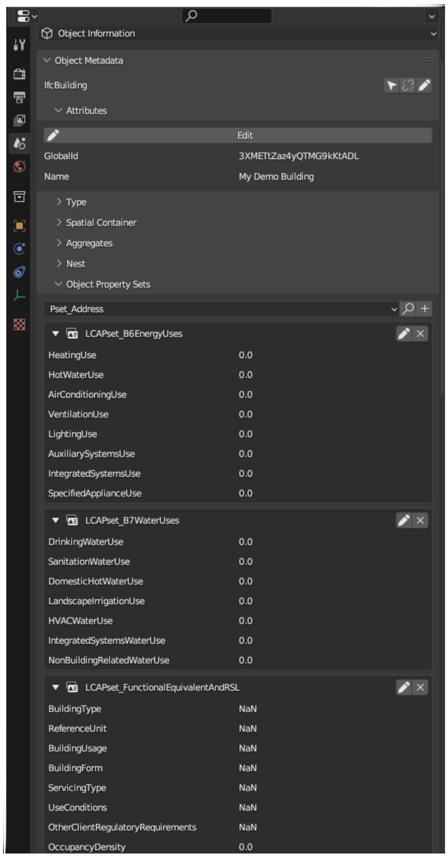


Figure 5.20: Demo Object

Figure 5.21: Two IFC product catalogue objects shown imported into BlenderBIM.

The implementation of building level property sets follows the method outlined for product level information. Instead of an IFC Project Library, a regular IFC project was instantiated with an IfcBuilding inside.

Property sets, properties and enumerations outlined in Section 5.5 were exported to CSV format and used to generate these models. The two versions of building level information; the minimum viable product according to BR18 and the more comprehensive LCA were also tested using BlenderBIM (shown in Appendix A.4).

6 Discussion

6.1 Evaluation and Challenges of the Proposed Solution

6.1.1 Different IFC Model Architectures

An aspect complicating the adoption of any solution including a BIM or IFC model at its centre, not explicitly addressed by the proposed solution, is the various architectures of IFC models. In a practical setting, the multidisciplinary collaboration of different professionals very often requires the adoption of separate discipline models. To ensure that a solution can be implemented in a robust way, it should be reviewed with a focus on how product data is stored and referenced, as well as the implications of deciding between centralised IFC models versus discipline-specific models.

The architecture of IFC models can also be differentiated based on the organisation of the model itself, whether as a centralised IFC model that encompasses all disciplines within a single file or as separate discipline-specific models that are linked together. Centralised models offer a holistic view of the project, facilitating overarching analysis and coordination. In contrast, discipline-specific models allow for more focused and detailed work within individual disciplines, potentially improving performance and manageability for large projects. If a separate LCA discipline model was to be created, the choice between copying relevant information from other files or referencing other discipline models is significant. This choice impacts the model's flexibility and the ease of updating and managing the data.

The complexity of managing product data within IFC models is further compounded by the diverse approaches to storing relationships and references. As outlined by Section 4, product data can be stored in four distinct ways:

- Integrated directly into the model, meaning the data does not reference external sources.
- Stored adjacent to the model in IFC format, utilising local IFC references to enable interconnected IFC models.
- Positioned next to the model but in a separate format, leveraging external references like the IfcDocumentReference entity for a more adaptable data structure.
- Hosted on the web, using external references to link to remotely stored data, which can be accessed and updated dynamically.

The project "IFC Extension: Multiple Levels of Development Model Container" [59] from the Technical University of Munich proposes an IFC extension model that supports multiple Levels of Development (LOD) within a single IFC file or across multiple linked files. It analyses following possibilities;

- A single IFC file that contains multiple Levels of Development (LOD).
- Multiple discipline models contains relationships or links to other IFC files.
- A compilation of all IFC files from different LODs, along with another, separate file containing the relationships, into a single zip file.

These approaches highlight the diversity of strategies available for managing product data within IFC models. The choice of architecture—whether centralised, discipline-specific, or a hybrid approach—along with the method of data storage and referencing, should be chosen based on the needs of each individual project.

6.1.2 Potentials for Embedding with Existing Systems

The integration of the proposed solution with other existing systems presents significant opportunities for enhancing its utility and operational efficiency. By exploring synergies with established standards and frameworks, the capabilities and applicability of the proposed solution can be extended, ensuring a more seamless and comprehensive approach to data handling and interoperability within the construction and engineering sectors.

Integration with the European SMART CE Framework
The European SMART CE (Construction Engineering) framework, specifically through document 22057, provides a detailed mapping of concepts from smart construction engineering. It outlines how an Electronic Product Data (EPD) should be structured within the SMART CE XML format. This integration is crucial as it aligns with the objectives of the proposed solution, facilitating a more structured and standardised approach to handling construction-related data. Embedding the system within the SMART CE framework leverages established protocols and standards, enhancing the robustness and scalability of the solution.

ETIM Standard for Product Data Exchange
The ETIM classification standard represents a significant opportunity for integration. Focusing on the taxonomic identification of technical products, ETIM offers a well-established format for sharing and exchanging product data among B2B professionals. Aligning the solution with the ETIM standard ensures that the data managed and exchanged through the system adheres to an internationally recognised classification system, facilitating clearer communication and interoperability between different stakeholders in the construction and engineering sectors.

Adaptation to LOIN for Complex Data Models
The LOIN framework presents an opportunity for adapting the solution to handle more complex definitions of data models that span different phases of a project and involve multiple levels of detail. This adaptability is crucial for projects that evolve over time, requiring a dynamic and flexible approach to data management. Integrating LOIN's capabilities into the solution caters to the nuanced and phase-specific data requirements of various projects, enhancing the system's versatility and effectiveness.

Future Integration with Standards prEN ISO 22014 and ISO 16757
The forthcoming standards EN 16757 and ISO 22014 are anticipated to provide additional frameworks for integration of library objects and product catalogues. prEN ISO 22014 seeks to unify library objects across the AECO industry, facilitating easier sharing and integration of digital resources. Meanwhile, the ISO 16757 series, particularly through parts 4 and 5, focuses on organising dictionary structures for product catalogues and establishing a standardised product catalogue exchange format, respectively. This ensures streamlined data categorisation, access, and exchange, improving efficiency and reducing inconsistencies. The solution could incorporate these standards once they become available, further enriching its interoperability and compliance capabilities.

Overall, these integrations underscore a strategic approach to leveraging existing and forthcoming standards to bolster the proposed solution's effectiveness, making it a versatile and comprehensive tool for professionals in the construction and engineering sectors.

6.2 Critical Discussion of Alternative Approaches

Apart from the methods and approaches discussed throughout the thesis, a number of alternative approaches were also considered but ultimately not pursued after detailed consideration. The most significant among these, warranting a critical discussion, are the EPDx and LCAx projects along with Linked Data.

EPDx and LCAx

In the evolving landscape of sustainable construction and building design, the development of digital tools and open data formats for LCA and EPD has become a focal point for industry professionals seeking to enhance the transparency, accessibility, and interoperability of sustainability data. LCAx and EPDx is the collaborative initiative developed by specialists from Arkitema and Ramboll. It introduces two novel, custom schemas aimed at standardising the exchange of product-level (EPD) and building-level information. This effort responds to the pressing need for more accessible and open LCA calculations, facilitating cross-disciplinary collaboration and ensuring quality assurance across different software platforms.

However, the emergence of LCAx and EPDx as alternatives to existing frameworks such as ILCD+EPD, ISO22057 and even openEPD, raises critical questions about the rationale behind creating new formats in light of established solutions. The critique of these schemas underscores potential redundancies and complexities introduced by adding another layer to the already intricate landscape of LCA and EPD data exchange. The insistence on simplicity by the creators of LCAx and EPDx may overlook the nuanced requirements of LCA data handling, which established standards, developed with extensive input from experts and stakeholders. This approach contrasts with critiques of the ILCD+EPD's complexity, which overlook the fact that it isn't designed to be manually created or manipulation by users. Tools like the EPD-editor by GreenDelta, the EPD2Digi Creator by EPD-Norway, and a new tool from "International EPD" enable efficient generation and management of ILCD+EPD data automatically. Additionally, the ILCD Validation Tool supports the automatic validation of ILCD+EPD files, streamlining the process further.

Moreover, the critique extends to the openness and long-term sustainability of these formats. Any solution that is officially recognised or widely utilised should be developed in accordance with open standard principles. The definition of an open standard involves not only the technical openness but also the governance and maintenance model that ensures its long-term viability and adaptability. The choice of licensing, the approach to integrating with existing and potentially international standards, and the method of ensuring data transparency and continuity are all pivotal in the broader context of establishing a genuinely open and widely accepted solution.

The dialogue around LCAx and EPDx thus unfolds within a broader discourse on innovation versus standardisation in the sustainability domain. While innovation drives progress and adapts to emerging needs, the fragmentation of standards can hinder the interoperability and collective progress toward sustainability goals. The critical questions posed to the creators of LCAx and EPDx reflect a deeper inquiry into the balance between innovation and cohesion, the responsibility of software-, format- and standard- developers to the wider community, and the strategic decisions that shape the future of sustainable building practices. As the building industry continues to grapple with these challenges, the evolution of LCAx and EPDx will likely serve as a case study in the ongoing effort to harmonise sustainability standards in a way that serves both the immediate needs of practitioners and the long-term goals of the global community.

6.2.1 Linked Data and the Longevity of Data

Linked Data has emerged as a promising technology for enhancing data interoperability and management within BIM. Linked Data transforms structured data by interlinking it, enhancing its utility through semantic queries. This approach, when applied to the domain of buildings, materialises as Linked Building Data (LBD), marking a significant stride in managing the complexities inherent in building information.

Central to the application of Linked Data in buildings is the concept of ontology. In essence, ontology offers a structured framework that defines a set of concepts within a domain and the relationships between them. This framework is pivotal for semantic integration, allowing disparate data sources to communicate through a common language. The significance of this in the context of buildings cannot be overstated; it is the linchpin for achieving semantic interoperability across various systems and applications used in building design, construction, and operation.

A cornerstone in the ontology landscape within this domain is the Building Topology Ontology (BOT). BOT has been crafted to represent complex building structures in a manner that is both simplified and comprehensive, enabling stakeholders across the AEC industry to navigate the intricacies of building information with greater ease. It standardises the description of buildings' spatial elements and their interrelations, paving the way for more informed decision-making throughout the building lifecycle by enhancing interoperability and data analysis.

The technological backbone supporting the implementation of these ontological frameworks is the Resource Description Framework (RDF) and the Shapes Constraint Language (SHACL). RDF provides a versatile and extensible method to represent data about resources on the web, including building components and their attributes, in a machine-readable format. This facilitates the integration and querying of building data from varied sources, a critical capability in managing the vast and diverse datasets typical in the building industry.

Complementing RDF, SHACL plays a crucial role in ensuring the integrity, consistency, and quality of building data. It allows for the definition of constraints and validation rules that RDF graphs must adhere to, addressing the critical need for reliable and high-quality data in building analysis and decision-making processes.

Linked Data in the Context of LCA The application of Linked Data technologies in the field of LCA offers new perspectives on sustainable design and management within the built environment. The studies ”Linked data for the life cycle assessment of built assets” by Boje et al. and ”Building product ontology: Core ontology for Linked Building Product Data” by Wagner et al. provide insights into the potential of Linked Data to address specific challenges in environmental impact assessments of buildings and building products.

Boje et al.'s research [60] introduces the SemanticLCA ontology, designed to create semantic links between the domains of LCA and the built environment. This initiative stems from the recognized challenge of conducting LCA for buildings due to poor interoperability between LCA tools and BIM systems. By adopting Semantic Web (SW) technologies, SemanticLCA aims to improve web interoperability, automate information flows, and clarify the impacts of complex contexts.

The paper presents a case study that demonstrates the potential of semantic alignments between BIM models, LCA data, and sensing devices to streamline access to contextualised information. Although the approach underscores the technical feasibility of enhancing LCA with Linked Data, it also brings to light the practical and implementation challenges that lie ahead.

Wagner et al. [61] address the difficulties in distributing digital product models through the Building Product Ontology (BPO), a schema for Linked Building Product Data. They present a current landscape, dominated by schemas that either lack flexibility or impose significant overhead on manufacturers, complicating the uniform search and automated processing of product data. The BPO aims to mitigate these issues by proposing a system that combines modular product descriptions with Semantic Web technologies. However, the adoption and effectiveness of such a system depend on its integration with existing standards and the willingness of industry stakeholders to embrace this new approach.

Critique and Discussion of Longevity of Data The application of Linked Data in the context of BIM is not without its challenges and criticisms. The primary critique levied against Linked Data is its lack of standardisation, a significant departure from the structured approach embodied by IFC. This flexibility, while ostensibly a boon for user-defined data representation, inadvertently resurrects the familiar issues of data compatibility and mapping that have long plagued the BIM community. The criticism that Linked Data proponents dismiss IFC for its perceived rigidity fails to acknowledge the intrinsic value of IFC's comprehensive object model. This model not only facilitates a standardised data structure but also proves compatible with Linked Data principles, as evidenced by successful integrations of IFC with RDF triples through the IFC OWL project.

Moreover, the debate extends into the realm of data longevity, a pivotal concern for both BIM and Linked Data, given the intrinsic long life span of buildings. The nuances of data longevity in relation to BIM and IFC, were explored in an interview with Thomas Krijnen. Krijnen's insights into the separation of artifact and metadata, and the subsequent handling of technical and descriptive metadata, offer a glimpse into the strategies aimed at preserving the integrity and utility of BIM data over extended periods. The distinction between merely storing data for future access and the more ambitious goal of maintaining its active usability through querying and integration poses a fundamental challenge to both Linked Data and BIM communities.

When discussing the longevity of data, it's crucial to understand the various forms of corruption that can compromise its integrity over time. These corruptions broadly fall into several categories.

Firstly, there's hardware corruption, which occurs when the physical media storing the data deteriorate or sustain damage. This can result from a variety of factors, including wear and tear over time, exposure to harmful environmental conditions, physical impacts or malicious attacks.

Another significant type of corruption concerns the logical representation of files. In this scenario, the structure or format that organises and interprets the data becomes unavailable or destroyed. This disruption means that, even though the data may still physically exist, accessing or making sense of it becomes difficult or impossible.

This issue is exemplified in the context of IFC files in the STEP file format. The STEP file lacks descriptive attribute names, presenting only values. While in some cases, the purpose of these values can be intuitively understood (e.g., three float numbers representing coordinates), in many instances, deciphering them is nearly impossible. Although IFCXML provides descriptions of attribute names, it still falls short by not offering definitions that make the data comprehensible. For example, even if a Profile definition is mentioned, without a clear explanation of what it is and how it is defined, the information remains cryptic.

Software-related corruption introduces another layer of complexity, referring not just to bugs or glitches, but also to software obsolescence. This type of corruption occurs when newer versions of software cannot open files created in older versions, a problem that is highly prevalent in the AEC industry. A prime example of this is found in proprietary software like Revit, where specific versions of the software are unable to open models created in just slightly older versions. This issue, observed even over short periods, highlights the challenges of maintaining long-term access to and usability of digital data when employing proprietary formats.

Lastly, in the context of a linked data approach, a particular form of logical corruption can occur when references or links between data points go missing. Linked data relies on these connections to provide context and meaning, so missing references can significantly degrade the utility and completeness of the dataset. This concern is not merely theoretical but impacts the practical utility of BIM models over time. Strategies for mitigating these risks involve following the ”5 star linked data” principles, but can be difficult to guarantee in practice.

This interplay between the promise of Linked Data in enhancing BIM processes and the critical issues of standardisation and data longevity encapsulates the complex landscape of digital information management in the construction industry. As professionals navigate this terrain, the balance between innovation and sustainability becomes paramount, urging a careful consideration of how best to leverage technologies like Linked Data in the service of building more integrated, efficient, and durable digital infrastructures.

6.3 Future Outlook

This section explores the future directions in automatic compliance checking, the development of digital logbooks, and the potential for next-generation IFC, that would enhance a solution such as the one proposed in this project in the long term.

6.3.1 Automatic Compliance Checking and Continuous Integration

Automatic compliance checking against building regulations and standards is gaining traction through tools like BART (Byggeriets Automatisk Regeltjek) and methodologies proposed in academic research, such as the work by Moult, Dion, and Krijnen (2020) [62]. These approaches, particularly utilising the Gherkin language within Continuous Integration (CI) frameworks, promise several advancements:

Integration with Software Engineering Practices: Adopting practices from software engineering, such as Behaviour Driven Development (BDD) and CI/CD, can enhance the reliability and efficiency of compliance checking in the AEC industry. The Gherkin language, with its plain-text definitions, allows for the creation of readable and reusable tests, making compliance checking more accessible to professionals without a programming background.

Open Standards and Interoperability: The use of open standards like IFC and open-source tools for compliance checking (e.g., the IfcGherkin rules) facilitates interoperability and collaboration across the industry. This approach lowers the barriers to entry and encourages the adoption of automated compliance checking.

Future Research Directions: There is potential for expanding the scope of automatic compliance checking to cover more aspects of building design and performance, such as spatial requirements and sustainability criteria. Further integration with BIM authoring tools and other industry initiatives, like the BCF API and OpenCDE specifications, could streamline workflows and enhance the effectiveness of compliance checks.

6.3.2 Digital Log Book

The concept of a Digital Building Logbook (DBL) is evolving as a central repository for building-related information, supporting goals of energy efficiency, sustainability, and smart operation. Key developments include:

Hybrid Data Storage Approaches: Projects like the EUB SuperHub are adopting hybrid models for data storage in DBLs, combining direct data storage with links to external databases. This model ensures that the DBL remains a dynamic and up-to-date source of information, catering to the diverse needs of stakeholders. EU Framework and Initiatives: The European Union is actively supporting the development of frameworks and platforms for DBLs, aiming to standardise and promote their use across member states. This includes defining approaches for data storage and integration with other digital tools, such as planning and verification tools. Future Enhancements: As DBLs continue to mature, further innovations in how data is collected, stored, and utilised can be anticipated. Enhancements in data analytics, AI, and machine learning could provide deeper insights into building performance, facilitate predictive maintenance, and support decision-making processes. But more importantly, DBLs could provide a suitable solution to the long-term, open-access storage of data.

In conclusion, the future outlook is marked by increased digitisation and integration of advanced technologies. The ongoing development in areas such as automatic compliance checking, digital logbooks, and IFC standards are crucial steps towards a more efficient, sustainable, and collaborative industry.

7 Conclusions

The imperative to reduce the environmental footprint of the construction industry is more critical than ever if we are to achieve objectives like climate neutrality by 2050. This thesis has focused on Life Cycle Assessment (LCA) and Building Information Modelling (BIM) as pivotal tools in this pursuit.

A number of challenges within current building LCA workflow were articulated, including; fragmented communication and information flow across disciplines and project phases, the complexity of conducting LCAs due to lack of unified information and requirements, and the workload involved in obtaining and processing EPD data effectively. And thus, the integration of LCA data into the IFC schema and openBIM workflows was identified as a potential solution to these challenges.

This research has been centred around the question:

> *How can the IFC schema and openBIM workflows be utilised to encapsulate building LCA data effectively today?*

To answer this question, the research set out with specific objectives:

1. Identifying and mapping the LCA information requirements needed to perform a Whole Building Life Cycle Assessment (WBLCA).
2. Developing a structured methodology for integrating LCA data into openBIM workflows and the IFC schema.
3. Evaluating the effectiveness of this methodology through a proposed implementation.

The first objective was addressed by performing a comprehensive overview and comparative analysis of the main sources of LCA data used, both of the building level and product level. Due to the difficulty in locating dependable sources that provide the necessary quantitative data at the building level, two sets of information requirements were formulated, drawing on a consensus among existing sources. One answered the direct short-term needs of the minimum amount of data needed to perform a carbon footprint assessment compliant with Danish building regulations. The other one explored a more comprehensive scope of a WBLCA in the broader European context. On the product level, the new standard EN ISO 22057, which defines EPDs as product data templates, was chosen as the primary source of and schema for environmental product data.

Different specification methods for storing and communicating these information requirements were analysed, identifying data dictionaries (DD), product data templates (PDTs) and information delivery specification (IDS) as the most relevant. Strategies for storing and sharing product data in IFC were explored, focusing on representing product catalogues in the IFC format. As part of this, the CODview2 MVD, defined in the new standard EN 17549-2, was identified as a suitable and flexible solution to storing environmental product data in IFC. The proposed data model presented a methodology combining the definition of environmental PDTs inside common DD with a close connection to primary sources. These DD data were referenced by product data sheets (PDS) specified in Manufacturer Product Catalogues, which could be presented in a variety of data formats, CODview2 IFC being the main one. The data model then showed how these PDS can be integrated with IFC through IFC Project Libraries. Information requirements and verification was streamlined through the use of a building LCA specific IDS.

This data model was evaluated through an implementation into the IFC STEP Physical Format (SPF-IFC). Firstly, a new, modernised graphical notation for IFC diagrams was developed based on the Unified Modelling Language (UML). This allowed a concise and effective communication of proposed extensions of the schema. BR18's table of required building components was proposed to be implemented as a national classification defined in the bSDD. Conceptual solutions for the structure of a comprehensive DD and IDS for WBLCA were also presented.

The implementation of the schema defined in EN ISO 22057 was explored in detail, considering various solutions to the implementation of complex information modules and scenarios, including alternative scenarios. Solutions to implementing EPDs of differing conceptual level, e.g. prefabricated product components vs raw materials, were recommended. The implementation of building level information, through property sets, mirrored the two sets of information requirements defined earlier. Both product level and building level data were generated as SPF-IFC files using a custom script tool written in Python, using the IfcOpenShell library. The EN ISO 22057 EPD implementation was exemplified with a real-world example based on a EPD from EPD-Norge. The validity of these files was verified in the BlenderBIM software.

Finally, the challenges yet unsolved in the current solution were discussed. The difficulty of implementing federated discipline models, or models with multiple LOIN, were addressed proposing potential solutions. Potentials for embedding the solution with other existing systems, like the European SMART CE framework, ETIM, LOIN, and future standards like prEN ISO 22014 and ISO 16757, were outlined. An important point, justifying the proposed solution, is the critical discussion of alternative approaches of custom schemas like EPDx and LCAx and the linked data community, focusing on its impact on the longevity of data. Lastly, further work in automatic compliance checking and the development of a common European Digital Log Book are recommended.

This thesis has contributed new insights in integrating LCA data tightly into the IFC schema and openBIM workflows with the intention of using them natively, aligned with the NativeIFC mindset. This contribution aims to aid the development of our built environment in a way that is harmonised with our habitat. The collective efforts in this direction will not only benefit the current generation but also safeguard the planet for generations to come, making the adoption of these practices not only a strategic but a moral imperative.

Bibliography

[1] Chermaine Lee. *COP28 Deal a ‘Disappointing’ Win, Experts and Activists Say*. en. Dec. 2023. URL: https://www.voanews.com/a/cop28-deal-a-disappointing-win-experts-and-activists-say-/7396512.html.

[2] *2023 In Review: Climate disasters claimed 12,000 lives globally in 2023*. en. Dec. 2023. URL: https://reliefweb.int/report/world/2023-review-climate-disasters-claimed-12000-lives-globally-2023.

[3] Jos Lelieveld et al. “Air pollution deaths attributable to fossil fuels: observational and modelling study”. en. In: *BMJ* 383 (Nov. 2023), e077784. ISSN: 1756-1833. DOI: 10.1136/bmj-2023-077784.

[4] Joshua M. Pearce and Richard Parncutt. “Quantifying Global Greenhouse Gas Emissions in Human Deaths to Guide Energy Policy”. en. In: *Energies* 16.1616 (Jan. 2023), p. 6074. ISSN: 1996-1073. DOI: 10.3390/en16166074.

[5] *2023 shatters climate records, with major impacts*. en. Nov. 2023. URL: https://wmo.int/news/media-centre/2023-shatters-climate-records-major-impacts.

[6] Yale Center for Ecosystems + Architecture United Nations Environment Programme. “Building Materials and the Climate: Constructing a New Future”. In: (Sept. 2023). URL: https://wedocs.unep.org/20.500.11822/43293.

[7] en. Sept. 2022. URL: http://www.unep.org/news-and-stories/press-release/co2-emissions-buildings-and-construction-hit-new-high-leaving-sector.

[8] Banu Sizirici et al. “A Review of Carbon Footprint Reduction in Construction Industry, from Design to Operation”. In: *Materials* 14.20 (Oct. 2021), p. 6094. ISSN: 1996-1944. DOI: 10.3390/ma14206094.

[9] Katie Skillington et al. “A review of existing policy for reducing embodied energy and greenhouse gas emissions of buildings”. In: *Energy Policy* 168 (Sept. 2022), p. 112920. ISSN: 0301-4215. DOI: 10.1016/j.enpol.2022.112920.

[10] Bygningsreglementet. *Bygningsreglementet: Tekniske bestemmelser - BRV Version 2: Bygningers klimapaavirkning*.

[11] European Commission. *ILCD Handbook: General guide for Life Cycle Assessment - Detailed guidance*. https://eplca.jrc.ec.europa.eu/uploads/ILCD-Handbook-General-guide-for-LCA-DETAILED-GUIDANCE-12March2010-ISBN-fin-v1.0-EN.pdf.

[12] Marco Scherz et al. “Implementation of Life Cycle Assessment (LCA) in the Procurement Process of Buildings: A Systematic Literature Review”. In: *Sustainability* 14 (Dec. 2022). DOI: 10.3390/su142416967.

[13] *Introduction to BIM - BlenderBIM*. URL: https://blenderbim.org/docs/users/introduction_to_bim.html.

[14] buildingSMART. *buildingSMART: What We Do*. https://www.buildingsmart.org/about/what-we-do/.

[15] *NativeIFC - A white-paper introducing a collaborative BIM using open standards and open protocols*. en. URL: https://github.com/brunopostle/ifcmerge/blob/main/docs/whitepaper.rst.

[16] Kaveh Safari and Hessam AzariJafari. “Challenges and opportunities for integrating BIM and LCA: Methodological choices and framework development”. In: *Sustainable Cities and Society* 67 (Apr. 2021), p. 102728. ISSN: 2210-6707. DOI: 10.1016/j.scs.2021.102728.

[17] RILEM. *Sustainable Development and Life Cycle Assessment (LCA)*. https://www.rilem.net/images/publis/917db4447994958c78e8f7a51ca2677d.pdf.

[18] International Organization for Standardization (ISO). *ISO 14040: Environmental management – Life cycle assessment – Principles and framework*. https://www.iso.org/standard/37456.html.

[19] European Commission. *European Platform on Life Cycle Assessment (EPLCA)*. https://eplca.jrc.ec.europa.eu/LCDN/home.html.

[20] Marc-Andree Wolf et al. *International Reference Life Cycle Data System (ILCD) Handbook - General guide for Life Cycle Assessment - Detailed guidance*. JRC Publications Repository. ISBN: 9789279190926 ISSN: 1018-5593. Jan. 18, 2011. DOI: 10.2788/38479. URL: https://publications.jrc.ec.europa.eu/repository/handle/JRC48157 (visited on 01/09/2024).

[21] *ISO 14025:2006 Environmental labels and declarations – Type III environmental declarations – Principles and procedures*. Available from: International Organization for Standardization. Geneva, Switzerland: International Organization for Standardization, 2006.

[22] International Organization for Standardization (ISO). *ISO 21930:2007 – Sustainability in building construction – Environmental declaration of building products*. https://www.iso.org/standard/40435.html.

[23] H. Figl and O. Kusche. *ÖKOBAUDAT Manual: Technical and formal information and rules for the ÖKOBAUDAT database*. Version 2.1. Version 2.1. 2021.

[24] J.D. Jansen and V. Bazjanac. *Implementation of Industry Foundation Classes in building information modeling for energy efficiency and life cycle assessment support*. https://www.itcon.org/papers/2012_9.content.01913.pdf.

[25] buildingSMART. *buildingSMART: About openBIM® workflows*. https://user.buildingsmart.org/knowledge-base/openbim-workflows-explained/.

[26] Karen Saavedra-Rubio et al. "Stepwise Guidance for Data Collection in the Life Cycle Inventory (LCI) Phase: Building Technology-Related LCI Blocks". In: *Journal of Cleaner Production* 366 (2022), p. 132903. DOI: 10.1016/j.jclepro.2022.132903. URL: https://doi.org/10.1016/j.jclepro.2022.132903.

[27] Roberta di Bari et al. "Step-by-Step Implementation of BIM-LCA". In: (2019). URL: https://publica.fraunhofer.de/handle/publica/407518.

[28] L. Wastiels and R. Decuypere. "Identification and Comparison of LCA-BIM Integration Strategies". In: *IOP Conference Series: Earth and Environmental Science* 323.1 (2019), p. 012101. DOI: 10.1088/1755-1315/323/1/012101. URL: https://doi.org/10.1088/1755-1315/323/1/012101.

[29] Egle Klumbyte et al. "Enhancing Whole Building Life Cycle Assessment through Building Information Modelling: Principles and Best Practices". In: *Energy and Buildings* 296 (Oct. 2023), p. 113401. DOI: 10.1016/j.enbuild.2023.113401. URL: https://doi.org/10.1016/j.enbuild.2023.113401.

[30] Sebastian Theißen et al. "Suggestions for the Technical Integration of Life Cycle Assessment Data Sets of ÖKOBAUDAT into Building Information Modeling and Industry Foundation Classes". In: *Progress in Life Cycle Assessment 2019*. Ed. by Stefan Albrecht et al. Cham: Springer International Publishing, 2021, pp. 113–128. DOI: 10.1007/978-3-030-50519-6_9. URL: https://doi.org/10.1007/978-3-030-50519-6_9.

[31] M. Lambertz et al. *Ökobilanzierung und BIM im Nachhaltigen Bauen | LCA and BIM in sustainable construction*. Berlin, Germany: Bundesinstitut für Bau-, Stadt- und Raumforschung (BBSR) im Bundesamt für Bauwesen und Raumwesen (BBR). 2019. URL: https://www.bbsr.bund.de/BBSR/DE/forschung/programme/zb/Auftragsforschung/2NachhaltigesBauenBauqualitaet/2019/oekobilanz-bim/01-start.html.

[32] Rafael Horn et al. “The BIM2LCA Approach: An Industry Foundation Classes (IFC)-Based Interface to Integrate Life Cycle Assessment in Integral Planning”. In: *Publica Fraunhofer* (2020). URL: https://publica.fraunhofer.de/handle/publica/264986.

[33] Carmen LLatas et al. “BIM-Based LCSA Application in Early Design Stages Using IFC”. In: *Automation in Construction* 138 (June 2022), p. 104259. DOI: 10.1016/j.autcon.2022.104259. URL: https://doi.org/10.1016/j.autcon.2022.104259.

[34] Sebastian Theißen et al. “Using Open BIM and IFC to Enable a Comprehensive Consideration of Building Services within a Whole-Building LCA”. In: *Sustainability* 12.14 (July 2020), p. 5644. DOI: 10.3390/su12145644. URL: https://doi.org/10.3390/su12145644.

[35] K. Lukka. “The Constructive Research Approach”. In: *Case Study Research in Logistics*. Ed. by B. L. Ojala and O.-P. Hilmola. Turku School of Economics and Business Administration, 2003, pp. 83–101.

[36] ISO. *SMART standards*. 2024. URL: https://www.iso.org/smart.

[37] *QI Digital - Smart Standards*. en. URL: https://www.qi-digital.de/en/smart-standards.

[38] Artur Tomczak et al. “A review of methods to specify information requirements in digital construction projects”. In: *IOP Conference Series Earth and Environmental Science* 1101 (Nov. 1, 2022). DOI: 10.1088/1755-1315/1101/9/092024.

[39] Jane Anderson and Anne Rønning. “Using standards to maximise the benefit of digitisation of construction product Environmental Product Declaration (EPD) to reduce Building Life Cycle Impacts”. en. In: *E3S Web of Conferences*. Ed. by Stefan Albrecht, Carla Scagnetti, and Matthias Fischer. Vol. 349. Gothenburg and online, May 2022, pp. 10003–10008. URL: https://oro.open.ac.uk/83386/.

[40] R Frischknecht et al. “Comparison of the Environmental Assessment of an Identical Office Building with National Methods”. In: *IOP Conference Series: Earth and Environmental Science* 323.1 (Aug. 2019), p. 012037. DOI: 10.1088/1755-1315/323/1/012037. URL: https://doi.org/10.1088/1755-1315/323/1/012037.

[41] Kai Kanafani et al. “Adopting The EU Sustainable Performance Scheme Level(s) In The Danish Building Sector”. In: *IOP Conference Series: Materials Science and Engineering* 471 (2019), p. 092070. DOI: 10.1088/1757-899X/471/9/092070.

[42] C Vandervaeren, S M Fufa, and J Kallaos. “Level(s) Compared to European and Norwegian Standards for Life Cycle Assessment of Buildings”. In: *IOP Conference Series: Earth and Environmental Science* 1078.1 (2022), p. 012056. DOI: 10.1088/1755-1315/1078/1/012056.

[43] Natalia Nawrocka et al. “Influence of BIM’s Level of Detail on the Environmental Impact of Buildings: Danish Context”. In: *Building and Environment* 245 (2023), p. 110875. DOI: 10.1016/j.buildenv.2023.110875.

[44] B Soust-Verdaguer et al. “Implications of Using Systematic Decomposition Structures to Organize Building LCA Information: A Comparative Analysis of National Standards and Guidelines- IEA EBC ANNEX 72”. In: *IOP Conference Series: Earth and Environmental Science* 588.2 (2020), p. 022008. DOI: 10.1088/1755-1315/588/2/022008.

[45] Ramboll. *Comparing differences in building life cycle assessment methodologies*. Tech. rep. July 2023. URL: https://brandcentral.ramboll.com/share/Xq3jpUKSqvPu5dpmRaDs.

[46] Andre Borrmann et al. “Industry Foundation Classes: A Standardized Data Model for the Vendor-Neutral Exchange of Digital Building Models”. In: *Building Information Modeling: Technology Foundations and Industry Practice*. journalAbbreviation: Building Information Modeling: Technology Foundations and Industry Practice. Sept. 2018, pp. 81–126. ISBN: 978-3-319-92861-6. DOI: 10.1007/978-3-319-92862-3_5.

[47] *Sustainability in buildings and civil engineering works – Data templates for the use of environmental product declarations (EPDs) for construction products in building information modelling (BIM)*. ISO 22057:2022. International Organization for Standardization. 2022.
[48] buildingSMART International. *IFC2x3 Final Release Documentation*. https://standards.buildingsmart.org/IFC/RELEASE/IFC2x3/FINAL/HTML/. 2007.
[49] buildingSMART International. *UML Model Report – Part 1: Introduction to the IFC Harmonised Schema Extensions*. https://www.buildingsmart.org/standards/bsi-standards/standards-library/#stds. 2020.
[50] Kasimir Forth, Jimmy Abualdenien, and Andre Borrmann. *NLP-based semantic model healing for calculating LCA in early building design stages*. Sept. 2022, p. 84. ISBN: 978-1-00-335422-2. DOI: 10.1201/9781003354222-10.
[51] Dion Moult. *IfcClassification*. https://github.com/Moult/IfcClassification. 2020.
[52] *LCA Indicators and Modules*. https://search.bsdd.buildingsmart.org/uri/LCA/LCA/3.0. Version 3.0. buildingSMART International.
[53] Hansueli Schmid et al. *Industry Foundation Classes (IFC) for data sharing in the Construction and Facility Management Industries — Integration of Life-Cycle Phases and Environmental Impact Indicators in bSDD*. Nov. 2022. URL: https://www.lignum.ch/files/images/Downloads_deutsch/Industry_Report_on_Environmental_Impact_Indicators_221116.pdf.
[54] *EN 17549-2:2023 - Building Information Modelling - Information Structure Based on EN ISO 16739-1 to Exchange Data Templates and Data Sheets for Construction Objects - Part 2: Configurable Construction Objects and Requirements*. Standard. EN. European Committee for Standardization (CEN), 2023.
[55] *IfcOpenShell: An Open Source IFC Library and Toolkit*. http://ifcopenshell.org.
[56] *BlenderBIM: OpenBIM Workflow in Blender*. https://blenderbim.org.
[57] *Blender: A Free and Open Source 3D Creation Suite*. https://www.blender.org.
[58] Environmental Product Declarations Norway. *EPD in ISO22057 Format*. https://digi.epd-norge.no/iso-22057/. 2023.
[59] Peeranut Chindanonda. “IFC Extension: Multiple Levels of Development Model Container”. Chair of Computational Modeling and Simulation, Department of Civil, Geo and Environmental Engineering. IDP. Technical University of Munich, Apr. 2019.
[60] Calin Boje et al. “Linked data for the life cycle assessment of built assets”. In: (2023).
[61] Anna Wagner et al. “Building product ontology: Core ontology for Linked Building Product Data”. In: *Automation in Construction* 133 (Jan. 2022), p. 103927. ISSN: 0926-5805. DOI: 10.1016/j.autcon.2021.103927.
[62] Dion Moult and T. F. Krijnen. “Compliance Checking on Building Models with the Gherkin Language and Continuous Integration”. In: *Proceedings of the EG-ICE 2020 Workshop on Intelligent Computing in Engineering*. 2020.

A Figures

A.1 Rambøll tables comparing LCA adaptations in across Europe

A.1.1 System boundaries

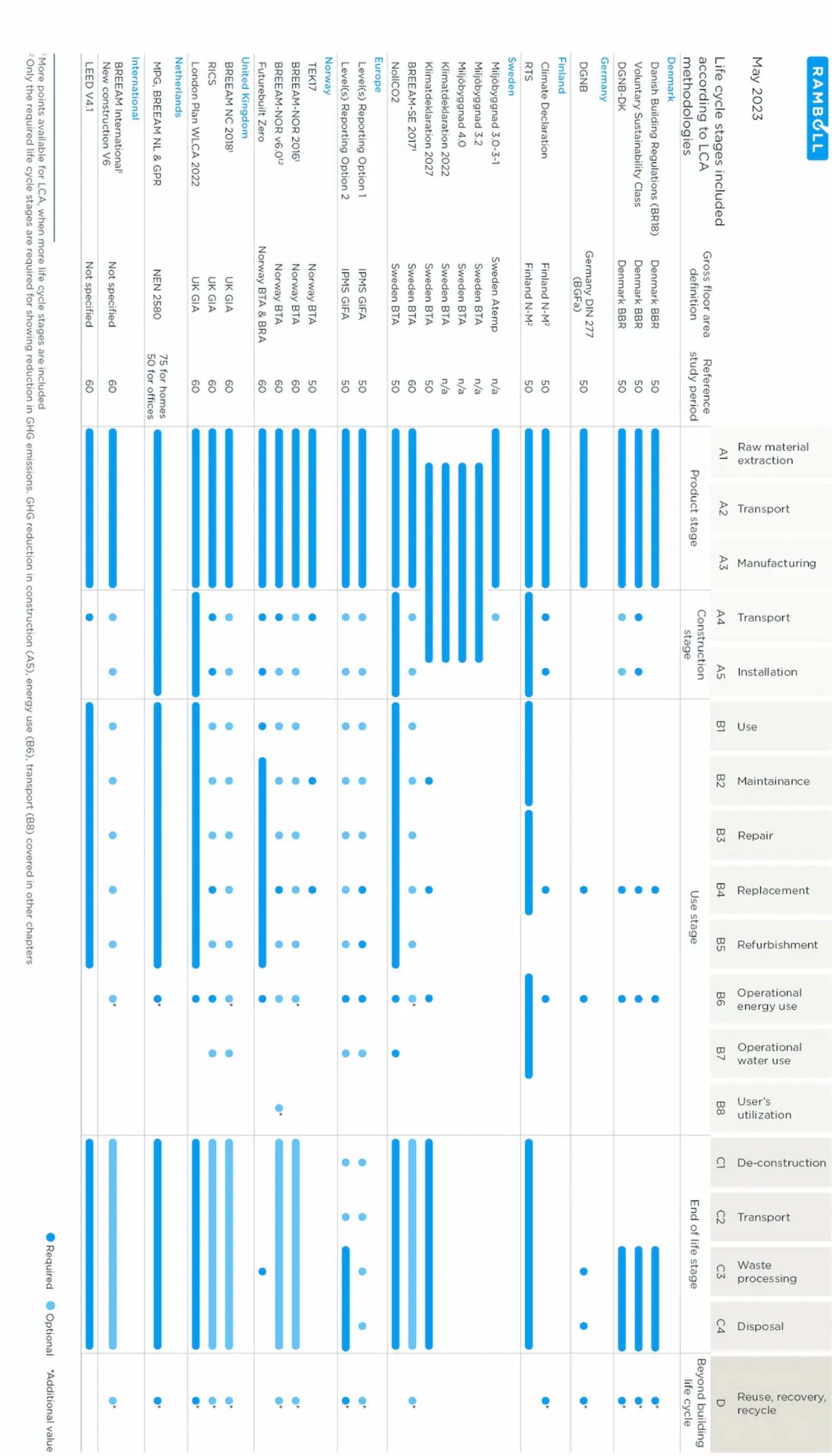


Figure A.1: Comparison of system boundary requirements of life cycle assessments. Source: Rambøll[45]

A.1.2 Building element groups

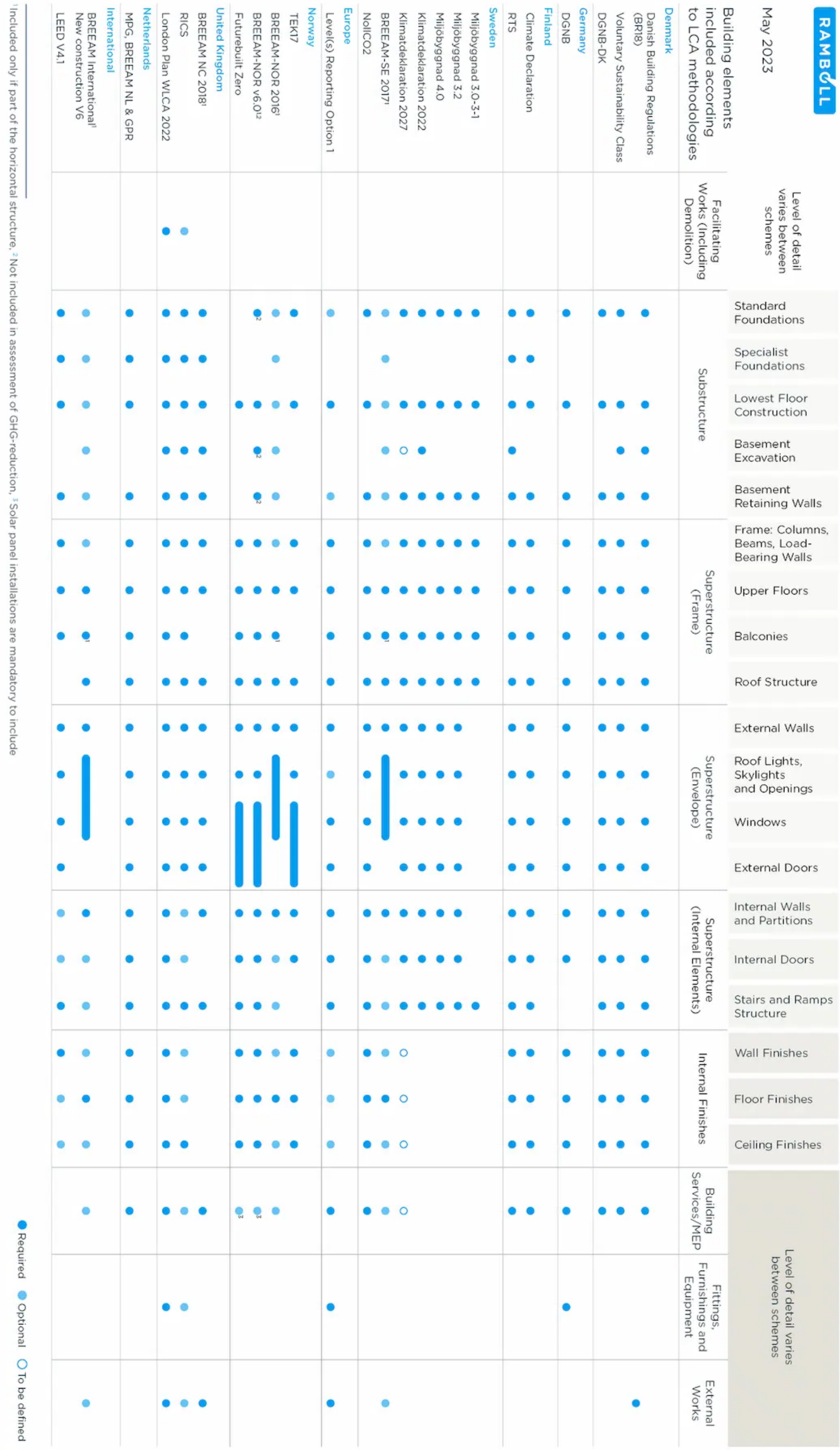


Figure A.2: Comparison of building element groups by life cycle assessment, by country. Source: Rambøll[45]

A.2 Data model diagram

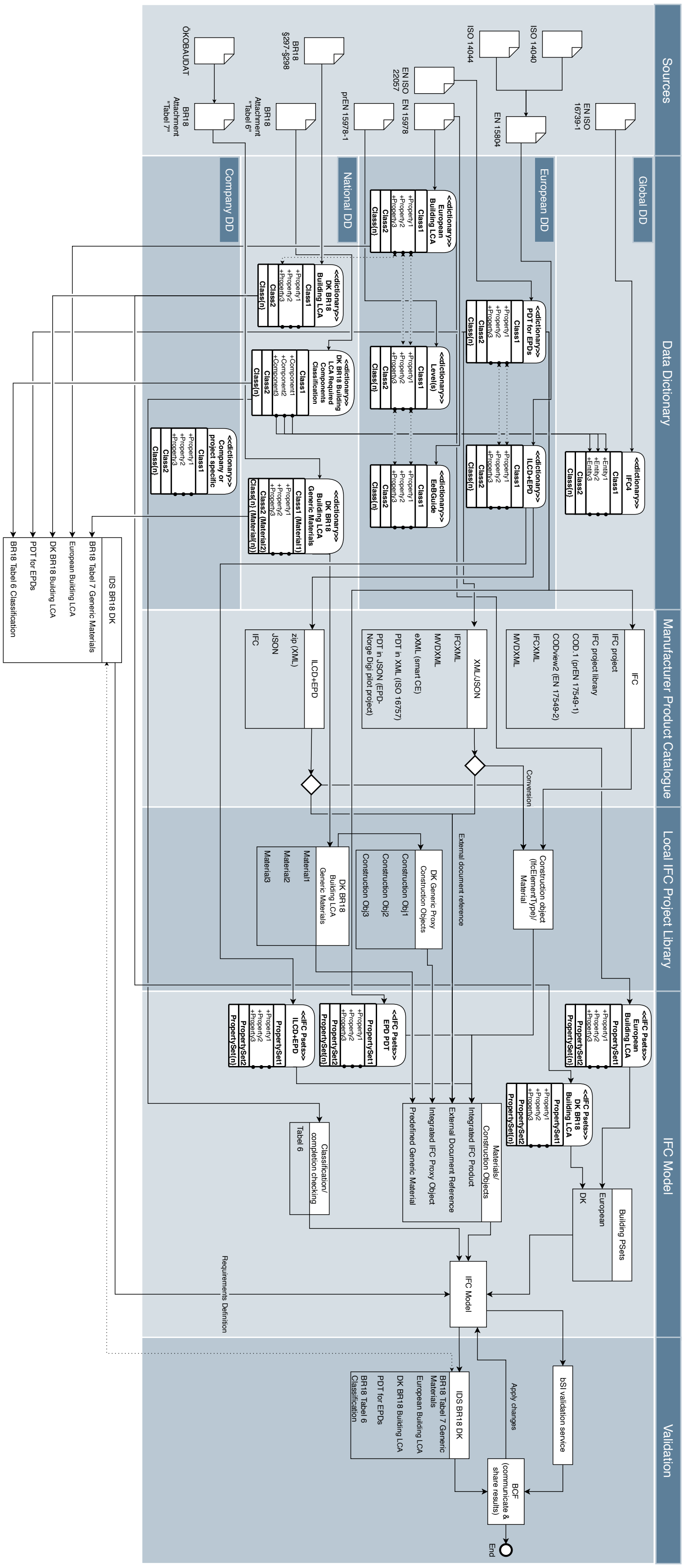


Figure A.3: Data flow diagram of LCA information in a BIM context.

A.3 Implementation of scenarios

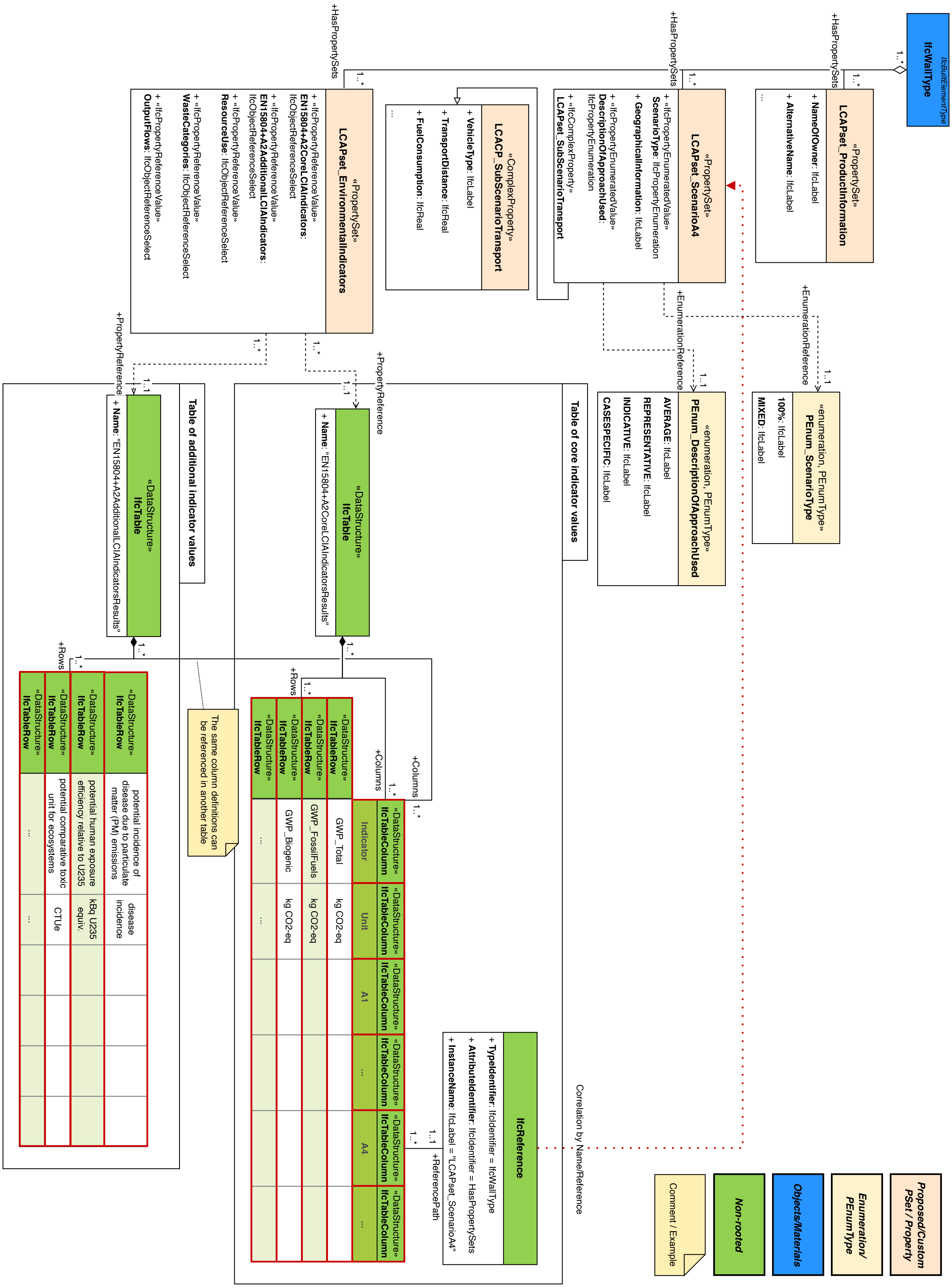


Figure A.4: Alternative scenarios defined in different construction objects - with sub-scenarios.

A.4 IFC models enriched with building level information imported into BlenderBIM

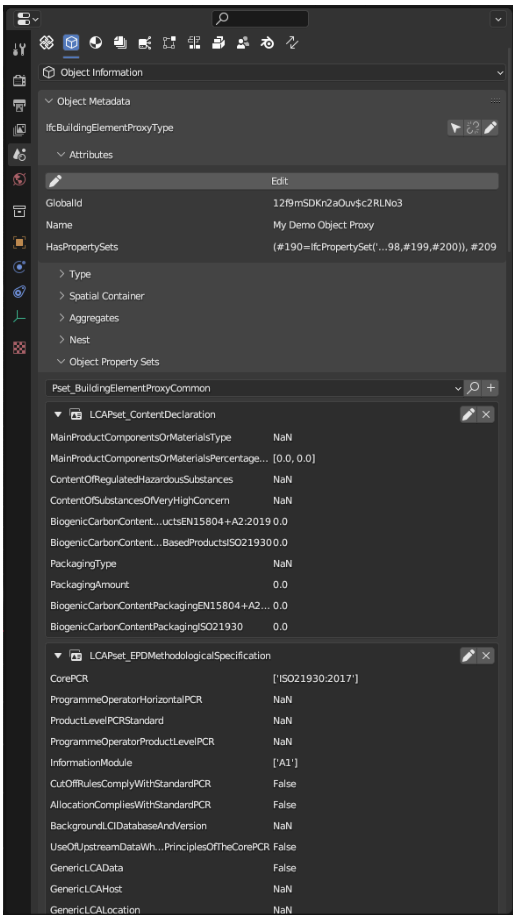


Figure A.5: Comprehensive LCA

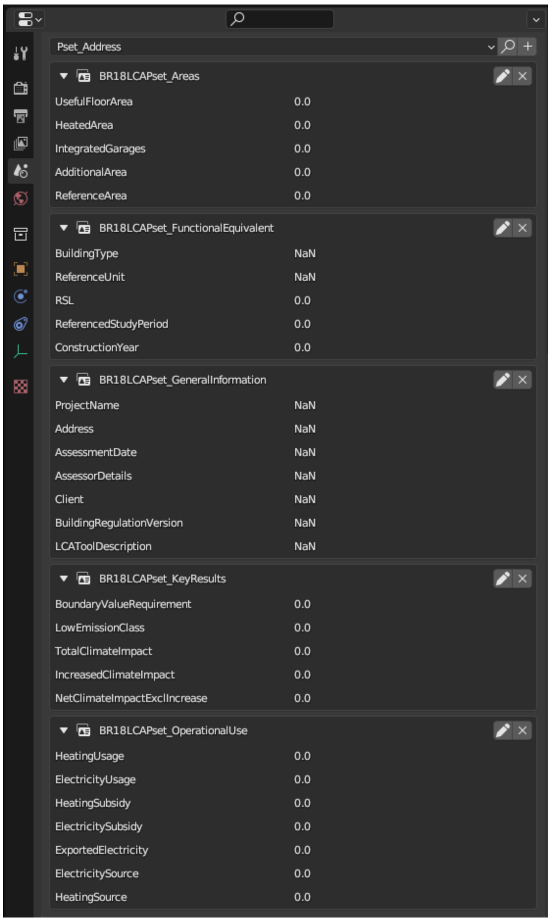


Figure A.6: BR18 MVP LCA

Figure A.7: Properties of IfcBuilding for the two building level variants shown imported into BlenderBIM.

B Spreadsheets

B.1 LCA Information Requirements

Detailed comparison of the LCA Information Requirements according to various sources can be found in the BuildingLCAInformationRequirementsComparison.xlsx file attachment.

B.2 BR18 – Table 6 – IFC mapping

A proposed mapping of all required building elements from the BR18 Table 6, including an english translation of the table and proposed numeric categories to be used in a clsification system can be found in the BR18Tabel6IFCmapping.xlsx file attachment.

B.3 Product Level IFC Definitions

Detailed IFC definitions for product level information including property, property set, enumertations, and table definitions can be found in the ProductLevelIFCDefinitions.xlsx file attachment.

B.4 Building Level IFC Definitions

Detailed IFC definitions for building level information including property, property set and enumerations definitions can be found in the BuildingLevelIFCDefinitions.xlsx file attachment.

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