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Efficient data management in a BIM-based framework for circularity of products and materials

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European Master in Building Information Modelling

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European Master in Building Information Modelling

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STATEMENT OF INTEGRITY

I hereby declare having conducted this academic work with integrity. I confirm that I have not used plagiarism or any form of undue use of information or falsification of results along the process leading to its elaboration.

I further declare that I have fully acknowledged the Code of Ethical Conduct of the University of Minho.

Achushankar Anil

RESUMO

A indústria da arquitetura, engenharia e construção (AEC) é uma das que mais contribui para a degradação ambiental e o esgotamento dos recursos. Por conseguinte, ao longo dos últimos anos, tem-se verificado uma ênfase crescente na sustentabilidade, levando a uma mudança para práticas mais responsáveis. A digitalização do sector é uma das principais formas de racionalizar as práticas empresariais e de construção, tornando-as mais eficientes e permitindo uma melhor gestão dos recursos. A Modelação da Informação da Construção (BIM) tem sido uma ferramenta transformadora para melhorar a sustentabilidade no ambiente construído. O estudo analisa o estado atual das práticas de construção e demolição, o quadro jurídico e as normas da indústria no contexto europeu e português, destacando os desafios da gestão dos resíduos de construção e demolição (RCD) na indústria AEC. Esta investigação explora a integração do BIM no contexto da interoperabilidade da informação, planeamento da demolição e desconstrução, bem como o potencial de reutilização e reciclagem de materiais de resíduos de construção e demolição.

A investigação também procura ajudar o projeto RecycleBIM, um esforço de várias partes interessadas destinado a desenvolver um quadro integrado para a circularidade dos materiais de construção e demolição utilizando metodologias BIM. Desenvolve-se especificamente na formulação de requisitos de informação e normas de modelização adequados com base nos requisitos das normas ISO 19650:2018 e EN 17412-1-1:2020 que garantem um quadro normalizado e interoperável que permite aos proprietários de ativos especificar as suas necessidades de informação. É explorado o papel do formato aberto Industry Foundation Class (IFC) para a interoperabilidade e como contentores de informação para a circularidade. Os objectivos específicos da dissertação são (i) Desenvolvimento de modelos de dados de produtos para objectos e materiais BIM para circularidade da informação. (ii) Criação de um quadro de Nível de Necessidade de Informação baseado na EN 17412-1 para todos os principais elementos de construção num Modelo de Informação de Desconstrução (DIM). (iii) Desenvolvimento de um modelo de Requisitos de Informação de Intercâmbio (EIR) para um processo de desconstrução digitalizado, que inclui uma inspeção, um levantamento do edifício utilizando a digitalização a laser e a criação de um modelo BIM. (iv) Definição de um fluxo de trabalho para validação automática de modelos IFC utilizando a especificação de entrega de informações.

O registo dos parâmetros de circularidade e das informações relativas à reutilização e à reciclagem facilita a utilização dos RCD como materiais secundários e a potencial utilização do parque imobiliário existente como bancos de materiais. Os PDTs desenvolvidos, o Quadro de Nível de Necessidade de Informação e o modelo EIR contribuem para o crescente corpo de conhecimentos em torno das práticas de construção sustentável. Salienta o papel fundamental que a tecnologia BIM pode desempenhar no avanço dos esforços da indústria no sentido de um processo de demolição e desconstrução mais responsável, eficiente em termos de recursos e amigo do ambiente.

Palavras chave: Desconstrução, Requisitos de Intercâmbio de Informações, Nível de Necessidade de Informação, IFC, Modelo de dados do Produto

ABSTRACT

The Architecture Engineering and Construction (AEC) industry is one of the substantial contributors to environmental degradation and resource depletion. Therefore, over the last few years there has been a growing emphasis on sustainability, prompting a shift towards more responsible practices. Digitizing the sector is one of the major ways of streamlining the business and construction practices, making it more efficient and enabling better management of resources. Building Information Modelling (BIM) has been a transformative tool for enhancing sustainability in the built environment. The study reviews the current state of the construction and demolition practices, legal framework, industry standards in the European and Portuguese context, highlighting the challenges of Construction and Demolition Waste (CDW) management within the AEC industry. This research explores the integration of BIM in the context of information interoperability, demolition, and deconstruction planning, as well as the reuse and recycling potential of construction and demolition waste materials.

The research also seeks to aid the RecycleBIM project, a multi-stakeholder effort aimed at developing an integrated framework for circularity of materials of construction and demolition using BIM methodologies. It develops specifically on the formulation of appropriate information requirements and modelling standards based on ISO 19650:2018 and EN 17412-1-1:2020 requirements that guarantee a standardised, interoperable framework that enables asset owners to specify their information demands. The role of open format Industry Foundation Class (IFC) for interoperability and as information containers for circularity are explored. The specific objectives of the dissertation are (i) Development of Product Data Templates for BIM objects and materials for circularity of information. (ii) Creating a Level of Information Need framework based on EN 17412-1 for all major building elements in a Deconstruction Information Model (DIM). (iii) Developing Exchange Information Requirements (EIR) template for a digitized deconstruction process, which includes an inspection, building survey using laser scanning and creation of a BIM model. (iv) Defining a workflow for automated validation of IFC models using Information Delivery Specification.

Recording the circularity parameters and information pertaining to reuse and recycling facilitates the use of CDW as secondary materials and the potential use of existing building stock as material banks. The developed PDTs, Level of Information Need Framework and the EIR template contributes to the growing body of knowledge surrounding sustainable construction practices. It emphasizes the critical role that BIM technology can play in advancing the industry's efforts towards a more responsible, resource efficient and environmentally friendly demolition and deconstruction process.

Keywords: Deconstruction, Exchange Information Requirements, Level of Information Need, IFC, Product Data Template

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1. INTRODUCTION

As the population of the world increases, the demand for housing and infrastructure also increases. The Architecture, Engineering and Construction (AEC) sector consumes significant quantities of resources (almost 50% of extracted material), generates high levels of waste, and creates many negative environmental impacts including carbon emissions. The conventional linear model of construction has resulted in excessive waste generation and is the largest waste stream in the European Union (EU), accounting for 35% of the EU's total waste. The extraction of materials, manufacture of construction products, construction activities and renovation also lead to the generation of 5-12% of total Green House Gas (GHG) emissions (European Commission, 2020b). While demand for new construction is growing, the existing building stock is aging. This calls for a well-defined way to manage the end-of-life scenarios of these buildings. Based on the European Circular economy action plan, the EU aimed to increase re-use, recycling and material recovery of construction and demolition waste to 70% by 2020.

The conventional practice of demolishing buildings at the end of their economic or technical lifecycle, using destructive techniques result in the loss of much of the embodied energy associated with the mining of raw materials, processing, manufacturing, stockpiling, and transportation. The opportunity to reclaim and reuse products directly and avoid construction and demolition waste (CDW) generation is also lost (Ajayebi et al., 2020). These problems are characteristic of linear value chains. In contrast, a circular economy approach to building construction has the potential to moderate these problems. The Green Deal of the European Commission adopts a Circular Economy Action Plan (CEAP), which includes measures to stimulate Europe's move transition to a circular economy and for the management of the entire lifecycle of products, including buildings and infrastructure (European Commission , 2020a).

The Portuguese environmental regulations (Decree-Law 73/2011) set a target of 70% for the reuse and recycling of construction and demolition debris and at least 5% recycled materials in construction contracts. The primary goal of Portugal's protocol for managing building and demolition waste is to encourage waste recycling and use of recycled materials, to promote sustainability by using fewer natural resources and to meet the country's waste recovery targets. However, the actual percentage of material recovery is much lower and large amounts of waste are still being transferred to landfills or incineration. (Marinho et al., 2022)

One of the priority areas of the transition to a Circular Economy is Digital transformation, announced as part of 'Europe's Digital Decade'. Innovation and digitalization were seen as the major drivers for tracking, tracing, and mapping secondary resources in the 2020 CEAP. It aims to reduce dependency on natural resources and dematerialise the economy (Çetin et al., 2021). Building Information Modelling (BIM) is one of the technologies that has a major role in digitization and circularity in the construction sector. The work aims to dive into a BIM-based approach for CDW management and digitization of the demolition process. When employing BIM methodologies, it is important to consider proper information and data management standards, such as those defined in ISO 19650 series and EN 17412-1:2020. It is also crucial to consider open data standards such as Industry Foundation Classes (IFC), Bim Collaboration Format (BCF), Information Delivery Specification (IDS) developed by buildingSMART international as interoperable systems are essential for adoption of digital technologies.

The dissertation aims to streamline the BIM approach for CDW management, demolition planning and digital representation of to-be-demolished buildings as material banks. This is done through various methods 1) the development of Product Data Templates for recording properties pertaining to the circularity of building products and materials. 2) Defining Exchange Information Requirements and a Level of Information Need framework for Demolition. 3) Creating an IFC model that complies with the proposed framework and validation of the created file. The dissertation's goals align with the guidelines and objectives of the European project "RecycleBIM", which aims to use the wealth of information provided by BIM to propose an integrated framework for circularity of materials, making use of technologies like scan-to-BIM, open data formats and 3D printing.

Brief Description by Chapter

Chapter 2 provides an overview into the latest literature, industry reports, legal framework, marketplaces, and initiatives on CDW management. The building typologies in Portugal in the 20th century was studied to get an understanding about the to-be-demolished building stock. A study of major reusable and recyclable materials of demolition waste and their properties was undertaken. This chapter elaborates on the RecycleBIM project, which is a multi-stakeholder effort towards the creation of an integrated framework for circularity of materials and construction using Building Information Modelling.

Chapter 3 explores the use of IFC for interoperability and as open format information containers, going in depth into IFC schema, exploring building elements, the associated property sets and quantity sets. Product Data Templates (PDT) were developed for recording properties pertaining to the circularity of building products and materials. The alphanumerical information, quantity information required from each major building elements and key materials are defined.

Chapter 4 defines the information requirements for a building inspection for demolition and subsequent creation of a Deconstruction Information Model (DIM). It explores Exchange Information Requirements based on the ISO 19650 series and defines a sample EIR for a DIM based on CEN recommendations. Level of Information Need for Demolition is defined based on EN 17412-1. The associated actors, controls, methods, inputs, and outputs are identified, and a process model is illustrated. Geometric requirements from the model to accurately store and calculate volume information are defined for major building elements. Modelling rules and required level of detail are also established.

Chapter 5 demonstrates the modelling of building elements and information management following the Level of Information Need, EIR and modelling rules. It involves the addition of required properties, quantity information, exporting to IFC with adequate information and validation of the IFC using Information Delivery Specification workflow. To use urban building stock acts as a reservoir for future extraction

2. CIRCULARITY OF CONSTRUCTION AND DEMOLITION WASTE

2.1. Circular Economy Practices and Regulations

There is a need to rethink the lifecycle of an asset from a linear model to a circular model by moving from demolition to deconstruction. The first step towards the circularity of buildings and closing material loops is the re-use of building components and materials. Circular value chains must be in place to meet recycling conditions, including logistics between demolition site, recycling facilities and re-manufacturing site. Construction and demolition materials and waste streams should be assessed prior to deconstruction and renovation. (Dodd, Donatello, et al., 2021; Ritzen et al., 2019)

Design for Disassembly (DfD) is a concept where buildings are designed to facilitate future changes and eventual dismantlement for recovery of components, systems, and materials. The recovery of materials and reuse of systems is intended to maximize economic value, minimize environmental impact, and facilitate reuse and recycling.

The European Commission (EC) suggests the use of materials that are easy to recycle and reuse, which will facilitate waste management and making use of existing environmental product regulations, product safety sheets and ensuring that the demolition process complies with Construction Products Regulation, which will enable designers to explore possibilities of using materials and products that already exist in buildings. (European Commission , 2020a). To use urban building stock acts as a reservoir for future extraction and to estimate when the embedded materials will become available for usage, the material intensity, the inputs, the outputs, and storage over the building lifetime must be considered. (Turan et al., 2017). Adoption of circular economy principles can help slow down the depletion of natural resources by injecting salvaged materials back into the economy as “secondary raw materials”.

2.1.1. Urban Mines and Material passports

Enabling in-use building stocks as a repository of products for future reuse is referred to as urban mining. A key stage in the shift to viewing buildings as material banks is to be able to quantify stocks of construction materials and assess their direct reuse potential as products against criteria such as their location, age, type, and embodied carbon. Many studies of building stocks have focused on producing aggregated quantities of materials, regardless of the required information for assessing the potential value streams of future reuse. (Ajayebi et al., 2020).

According to (European Commission , 2020a), various aspects of materials should be considered, such as size, volume, weight, etc to manage the demolition process. Hierarchical relations between elements and systemisation, functional decomposition, element specifications, assembly sequences, geometry and type of connections, recyclability of materials and reusability of products should also be recorded. Material passports are one such methodology developed with the goal of enabling circularity of materials. It will enable materials, products, and components to keep or increase their value over time, enables circular product design, material recovery, makes decision making easier for developers, managers, and renovators. They can help in management of supply and demand, assessment and forecast of potential secondary raw materials. It helps in the logistics of reclamation of products, materials, and components. It helps in viewing CDW as secondary raw materials and as resources rather than as waste, helps to reduce the use of virgin resources, and provides a tool to move from a linear system to a circular one (Çetin et al., 2023; Heinrich & Lang, 2019).

A material passport can consist of many hierarchical levels as elaborated in Figure 1. In the material level, it can specify its value for recovery and for products and systems, it can define characteristics that make them valuable for recovery, their ease of disassembly, how a product is linked to a building etc, which are essential to understand its value for recovery.

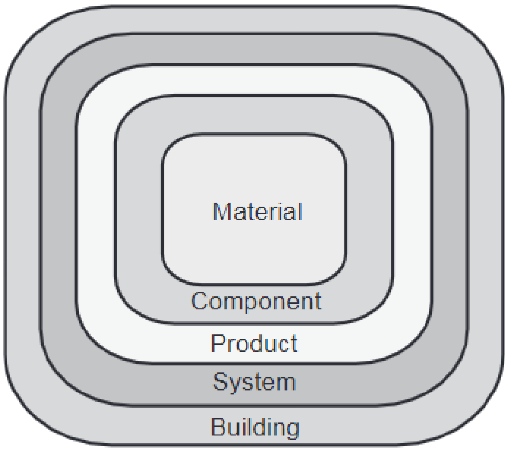

Figure 1 - Hierarchy levels in Material passports (Heinrich & Lang, 2019)

2.1.2. Regulations on management of CDW

The EC has introduced a Construction & Demolition Waste Management Protocol as guidelines for industry practices which aims to improve waste identification, source separation and collection, improve waste logistics and processing, quality control by setting appropriate policies and framework conditions. The protocol fits within the Construction 2020 strategy and the more ambitious Circular Economy Package of the EU (European Commission, 2016).

Level(s) is an EU framework for building projects which includes several core indicators of sustainability to report on and to improve their performance by encouraging and enabling users to methodically plan for the reuse, recycling, or recovery of components, materials, and wastes during building, restoration, and demolition activities. It states that a pre-demolition audit or waste management audit is to be undertaken before any renovation or demolition project so that materials that can be reused or recycled and any hazardous waste can be identified and recorded. Figure 2 shows the CDW management recommendations based on Level(s) framework.

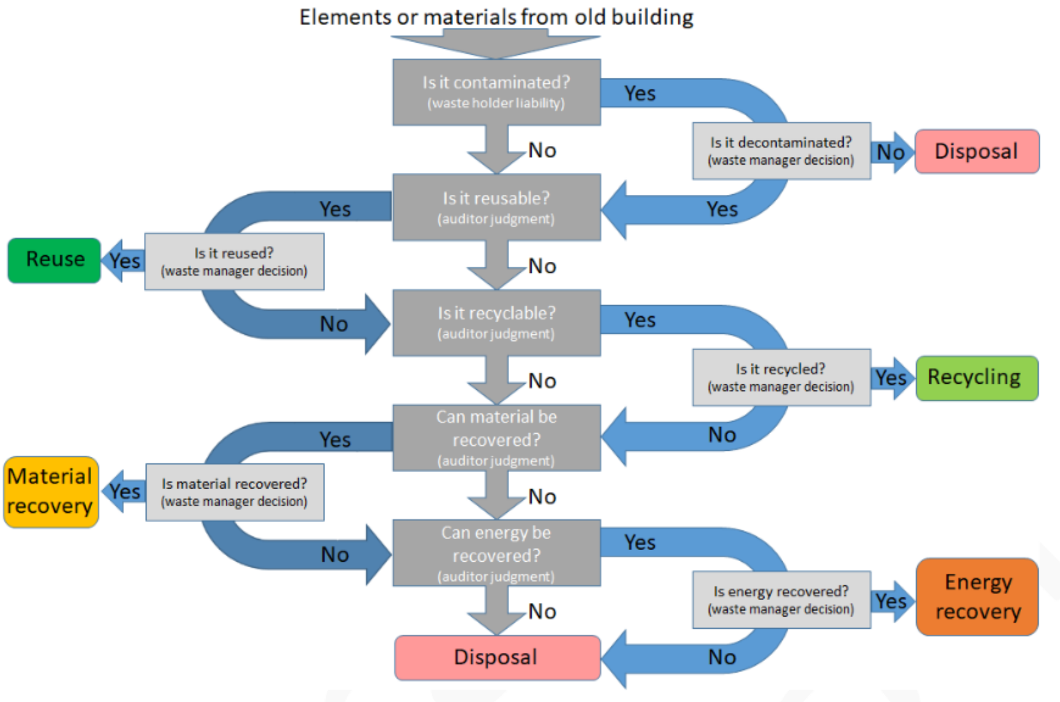

Figure 2 - CDW management recommendation from Level(s) (European Commission, 2020c)

Construction techniques and assembly systems of construction products that allow clean deconstruction and dismantling should be chosen. The European guidelines for waste audits before demolition and renovation works of buildings (European Commission, 2018) state that assessment of materials during a demolition should include the following:

- The type of the material, classified as inert waste, non- inert, non- hazardous or hazardous waste, the European LoW code, and description.
- Quantification of the waste in relevant unit of measurement such as tonnes, cubic meters.
- Inventory of elements recommended for deconstruction and reuse.
- Location of waste materials and elements in the building to maximize efficiency and safety of the demolition.

The percentage of CDW being reused and recycled in Portugal has increased in the past decade thanks to EU frameworks on circular economy and the Portuguese CDW legal framework Decree-Law 46/2008 of 12 March. Some of these include the Decree Law 18/2008 establishes the elaboration and implementation of a CDW prevention and management plan for all public construction works. Decree Law 73/2011 introduces the target of incorporating at least 5% of recycled materials or materials containing recycled components, regarding the total amount of raw materials used in public construction. Decree Law 26/2010 obliges the CDW holder from private construction works to keep records of CDW generated. The classification of CDW in Portugal follows the European LoW (Gomes & Santos, 2015).

The Decree-Law 46/2008 of 12 March establishes the legal framework for CDW management in Portugal. It states that the management of CDW in construction works must comply with national and

EU standards, or in their absence, with technical guidelines defined by the National Laboratory for Civil Engineering (Gomes & Santos, 2015). This entity establishes four technical requirements-

- E 471/2009 – Guide for the use of recycled coarse aggregates in concrete, which establishes the minimum requirements that the coarse recycled aggregates covered by EN 12620 must comply with, in order to be used in concrete.
- E 472/2009 – Guide for the production of recycled hot mix asphalt
- E 473/2009 – Guide for the use of recycled aggregates in unbound pavement layers
- E 474/2009 – Guide for the use of construction and demolition recycled materials in embankments and capping layers.

Material recovery is incentivized through the Waste Management Fee (WMF), which ensures that waste producers incur higher costs depending on the destination given to the waste. The regulation establishes that operations involving CDW such as prevention, reuse, transportation, storage, sorting treatment, recovery and disposal are necessary to reduce its environmental impact. (Marinho et al., 2022)

2.1.3. Barriers to circularity of Construction and Demolition Waste

There are several physical, technological, and legal barriers to the reuse of building products and use of recycled materials. The non-competitive pricing of recycled materials, low cost of virgin materials, construction methods, lack of capabilities and skills contribute to the down cycling and reduction of potential value at end of life of materials. Non-compliance for demolition practices with legal framework and lack of enforcement by inspection and auditing authorities, lack of legal and technical specifications for selective demolition are some of the legal barriers. There is also a lack of coordination between stakeholders, a comparatively high cost of management for proper CDW management, and lack of data cross checking and verification of CDW for small and medium construction companies. Gomes & Santos, 2015).

Lack of confidence in the quality of CDW recycled materials and uncertainty about the potential health risk for workers is another common hurdle to recycling reusing CDW in the EU. This lack of confidence restricts the demand for recycled materials, which inhibits the development of CDW management and recycling infrastructures in the EU. (Fabbri et al., 2020)

2.2. Historical Building Typologies and Regulations in Portugal

To gain insights into construction methods and materials used in Portugal, for anticipating significant materials for recovery, and assessing potential deconstruction and demolition techniques, an analysis of historical building typologies and construction practices was undertaken.

2.2.1. Historical Building Typologies

Historically, buildings in Portugal were made with load bearing walls, of stonework and usually of a poorer mix of small stones, bricks, and lime mortar. Raised floors and interior walls were built of wooden elements. Roofs were built with wooden structures and covered with clay tiles. Exterior finishes included mortar renders, painted, or washed with lime. The walls played a structural role and could be of stone (40 cm or above), rammed earth (60-70 cm), pressed earth blocks or structural bricks. (De Brito &

Santos, 2007; Mateus, 2004). The building stock before the 20th century could have heritage value and are hence not considered as potential to-be-demolished typology.

'Pombaline' construction emerged as a response to the earthquake in 1755 in Lisbon. It resulted in strict anti-seismic regulations based on a cage structure, resulting in austere, efficient, and modular architectural designs that significantly advanced construction techniques. The wooden floors were connected to the wall structure with turnbuckles, bridles and dovetailed diagonal iron bars. The interior walls had wooden cages which helped in structural integrity (Branco et al., 2012). The Pombaline typology and pre-Pombaline typology are elaborated in Figure 3.

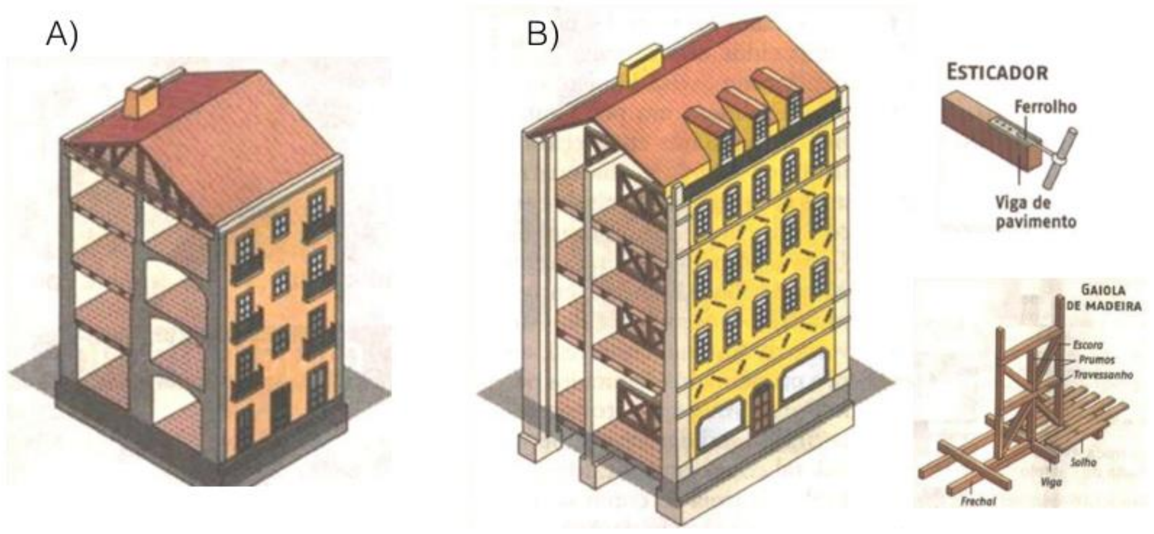

Figure 3 - A) Pre-Pombaline building B) Pombaline building
(Branco et al., 2012)

The 'Gaioleiro' building typology was common in urban areas during the early 20th century, which was usually built by private investors for profit. The buildings were large in plan and height and was characterized by masonry exterior walls, reduced wall thickness, worse quality materials and thinner walls due to lack of standards and regulations leading to worse seismic performance than the Pombaline style. During the early 20th century, there were significant advancements in concrete technology, including the use of reinforced concrete. These innovations allowed for the construction of taller and more robust buildings. Regulations in reinforced concrete construction were introduced in 1918 and 1935 as it was necessary to ensure that these new technologies were used safely and effectively. There was a 'Mixed' construction typology which made use of reinforced concrete floors, with sturdy masonry walls. These buildings could achieve a higher number of floors and the reinforced concrete floors with strict regulations ensured better seismic resistance than its predecessors. Gaioleiro and Mixed construction building typologies are shown in Figure 4.

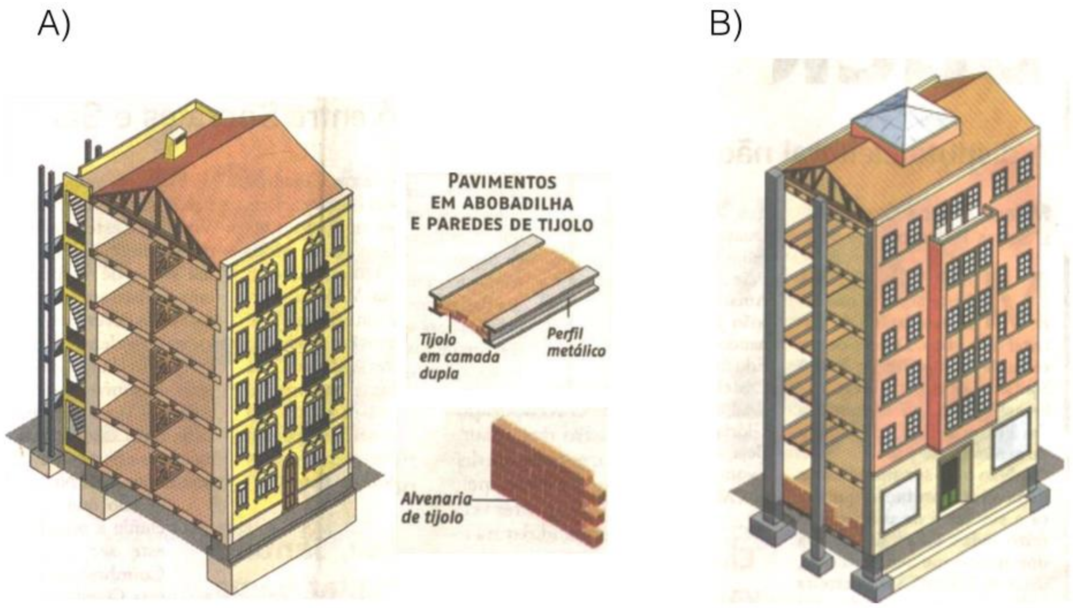

Figure 4 - A) Gaioleiro building B) Mixed construction building

(Branco et al., 2012)

The 1960s saw the introduction of concrete frame structures with columns and beams and reinforced concrete slabs. The typical residential and office buildings were built with reinforced concrete frames, single or cavity walls with ceramic brick, finished with mortar and stone facings. Reinforced load bearing cores in taller buildings helped in providing better seismic resistance. In the first iterations of this typology, the lack of expertise led to its application not being the most adequate. (Branco et al., 2012). Figure 5 shows a typical Reinforced concrete frame building.

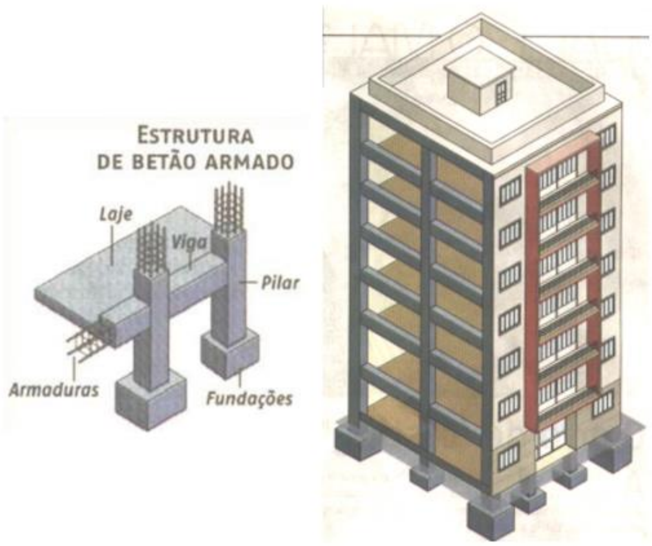

Figure 5 - Typical Reinforced concrete frame building

(Branco et al., 2012)

The most used building solutions for residential buildings have remained unchanged in Portugal for several years. The construction system consists of a framed structure with pillars and beams in reinforced concrete and lightened slabs. For the outer walls, a simple solution of ceramic bricks is used. In 2011, 48.6% of the residential buildings had reinforced concrete structures and 31.7% of buildings has masonry walls with reinforced concrete slabs. The main roof type (93.1%) was inclined roof covered with ceramic or concrete tiles. (OERCO2, 2013).

The typification of Portuguese residential buildings by Brandão de Vasconcelos et al., (2015) summarises the typologies and building methods of the last century. Single family houses and multi-family buildings till the 1910s were built with resistant brick walls and wood structure slabs. Slabs with reinforced concrete built on resistant brick walls were common till 1940s. Reinforced concrete with beam and block floor systems were used till the 1900s. The currently used reinforced framing system became common in the 1990s for both single family and multi-family apartment buildings.

Aging buildings with no architectural heritage value are especially susceptible to demolition due to real estate and economic market factors. (Turan et al., 2017). The most common candidates for demolition or deconstruction are monolithic constructions, where almost all elements are interconnected by chemical bonds and where the possibility of disassembly and material harvesting is low. (De Brito & Santos, 2007)

2.2.2. Portuguese Regulations for Concrete and Steel

The early regulations for concrete defined the minimum strength requirement for concrete through a simple compression test, where strength of a 20cm cube at 28 days after casting, should be higher than 120 Kg/cm^2 (1918 regulation) and 180 Kg/cm^2 (1935 regulation). The 1918 regulations refer to plain steel of natural hardness with an ultimate yield strength of 3800 to 4600 Kg/m^2 and greater than 3700 Kg/m^2 (1935 regulation), and high ductility greater than 22% (1918 regulation) and 24% (1935 regulation).

The 1967 regulation introduces the concept of strength classes (B180, B225, B300, B250, B400) for concrete defined by characteristic strength in Kg/cm^2 obtained in tests of cubes at 28 days to simple compression. It also introduces strength classes for steel (A24, A40, A50, A60) defined by the characteristic value of the yield stress. The concept of minimum reinforcement, the adoption of stirrups for shear resistance and two types of smooth and ribbed bars are also introduced.

The 1983 regulation extends the concrete strength classes (defined in International Units MPa), up to B55. It introduces regulations for high strength reinforcement (prestressing) and adopts the three strength classes A230/A400/A500 referred to the characteristic value of the yield stress expressed in MPa. In 1990, the ENV 206 was published, which is a concrete behaviour, production, placement, and compliance criterion. Currently the Eurocode 2 ENV1992 and ENV 206 is implemented, with strength classes extended up to C90/105. In Eurocode 2, the strength classes adopted for steel are 400/500/600 (Almeida et al., 2022).

2.3. Major components of Construction and Demolition Waste

CDW mostly consists of materials such as concrete, brick, steel, timber, asphalt, plasterboard, ceramic, clay, aluminium, glass, and plastic. There already exists a significant market for materials like glass and metals. Metals have the highest recycling rates among materials recovered from demolition sites due to their value. The highest volume of waste is in the form of concrete, bricks, and blocks, which are typically landfilled due to limited demand for their recycled form. Recent research shows increasing opportunities for concrete and brick materials to be crushed and repurposed for recycled aggregates for road base and sub-base construction (Caldera et al., 2020).

According to Liu et al. (2011), concrete waste and brick waste account for approximately 80% of the total of CDW. Recycling and reusing concrete and brick waste resulting from the production process of concrete not only reduce the problem of CDW disposal, but also reduce the overdependence of the construction industry on natural raw materials. Concrete and ceramic waste are processed into recycled aggregate, which feeds into a variety of secondary production processes, such as road construction, concrete paver block production and structural concrete (Turan et al., 2017). Figure 6 elaborates the conventional demolition scenario and scenario with selective deconstruction for concrete and ceramic products.

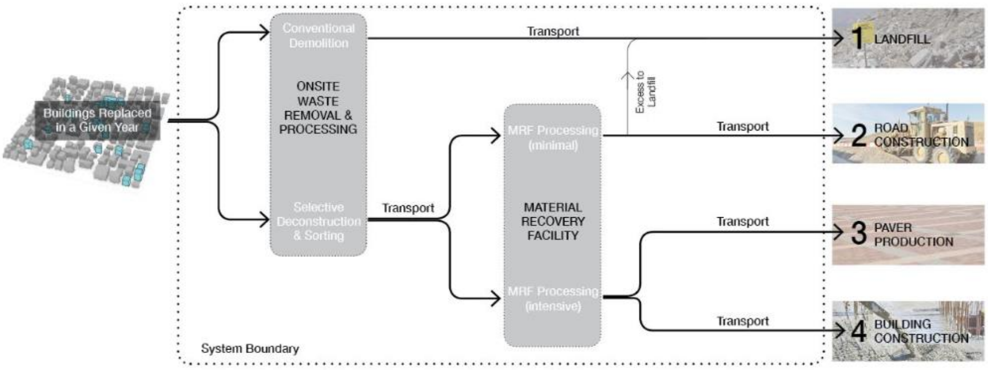

Figure 6 - Concrete and ceramic waste processing and recycling scenarios
(Turan et al., 2017)

The composition and physical properties of Recycled Aggregate should be determined prior to its acceptance for use in concrete production. This will allow a better understanding of the material and of its likely performance, facilitate its certification and help boost stakeholder confidence. Ascertaining the chemical composition of RA is important because the history and properties of the original materials of CDW are not likely to be known. Considering the vast range of environments and conditions that these materials have been exposed to, their chemical composition (e.g., sulphate, chloride, and alkali content) could compromise the performance of concrete. Therefore, the chemical composition of the RA must be known for limitations to be imposed that will result in good quality aggregates, thus preventing complications arising from their use (Manuel & Lopes De Brito, 2007; Silva et al., 2014).

In addition to the chemical properties of RA, the physical properties can also determine the quality of recycled concrete. (Almeida et al., 2022) has conducted an in-depth study into the properties of 20th century reinforced concrete, which states that the size of average largest aggregate dimension has reduced from 50.0mm in 1938 to 30.6mm in 1975 to 22.5mm in 2002. Aggregate size is an important metric to be considered when concrete is crushed to get recycled aggregates. Figure 7 shows the average largest aggregate dimension of recycled aggregates in the last century.

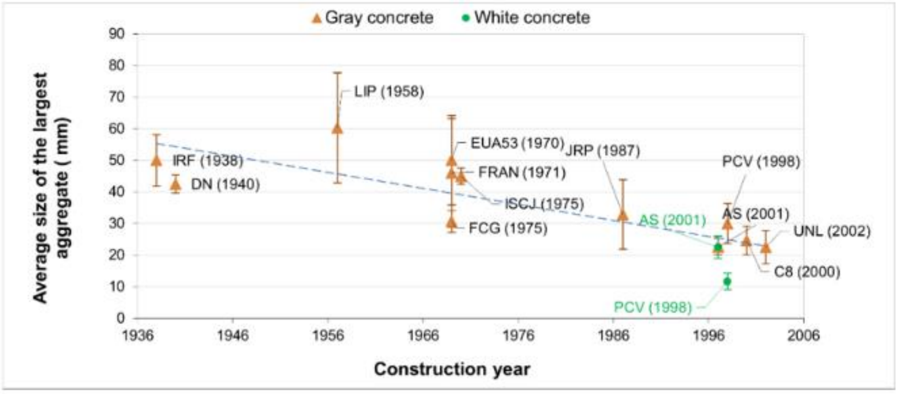

Figure 7 - Evolution of largest aggregate dimension over time
(Almeida et al., 2022)

EN 1090-2 for execution of steel structures states that for structural steel members, mechanical properties such as yield strength (fy), tensile strength (fu), elongation after fracture (ef), heat treatment delivery condition must be determined (Coelho et al., 2020). Structural products such as steel are often recycled back to rebars, while bricks and concrete are downcycled to form aggregate which degrades the intrinsic characteristics of the material. (Ajayebi et al., 2020).

The market for repurposed steel construction materials remains limited because the tasks involved in refurbishing and obtaining a CE marking drives up costs, rendering the process more expensive compared to material recycling. Furthermore, the reuse of individual structural steel elements proves to be challenging since they are usually tailored and manufactured for a particular building design (Coelho et al., 2020). Figure 8 illustrates several cases of the reuse of steel components based on levels of disassembly. It ranges from reuse of the entire steelwork or parts (several modules or bays) without disassembly, to reuse of disassembled steel work, to the reuse of fabricated components (sandwich panels, columns, etc) to the reuse of constituent products (sections, plates). Recycling the steel components is the most energy intensive and hence least desirable option in this case.

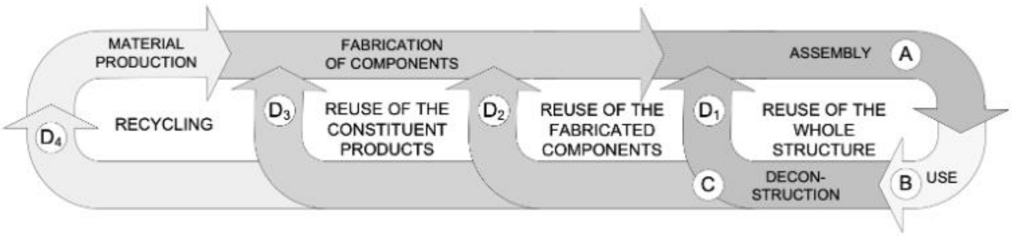

Figure 8 - Steel reuse scenario
(Coelho et al., 2020)

2.3.1. Marketplaces for CDW

Markets for recycled CDW is seen as one of the solutions to divert the increasing volume of CDW waste going into landfills, which benefits both the society and the industry. The benefits include lower disposal costs for the waste producer and lower environmental costs for society. However, the market for trading recycled construction material is still in its infancy due to its requirement of a high level of planning, investment, and resources. (Caldera et al., 2020). Figure 9 elaborates a CDW diagram for marketplaces.

Figure 9 - CDW resale flow diagram (Euroseparadora)

It is important to meet the quality requirements to attract buyers who were originally going to purchase natural raw material. Cost minimization is a critical factor that could enable markets for recycled CDW. Transportation and additional processing costs for using waste material are also key factors for buyers and subsidies could make CDW waste use more viable as it reduces the cost of recycling and recycled aggregates. A price can be charged to the CDW makers to subsidise the cost borne by recycling centres. Client awareness about recycled waste should be improved and they should be encouraged to choose recycled aggregates. Figure 10 shows an example of a marketplace where reclaimed doors are traded.

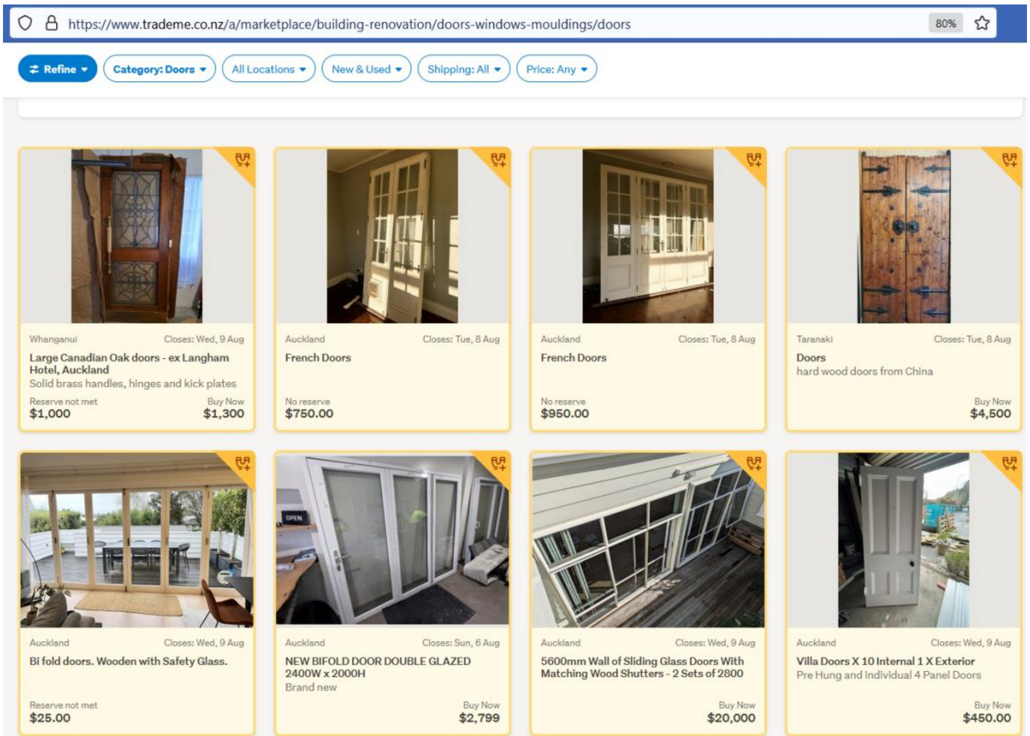

Figure 10 - Marketplace for selling CDW. (https://www.trademe.co.nz/a/)

The US, France, the UK, and Canada are the top 4 countries with the most developed marketplaces for waste trading. CDW holds the sixth position of most traded waste after metals and alloys, plastics and polymers, biotic resources, and E-waste. (Shooshtarian et al., 2020). ScrapAd, MyWaste, Euroseparadora, TradeMe, Yours2Take, ASPIRE, Buy Recycled, Business Recyling, Green Hands, Marketplace Hub International, Salza, Austin Materials Marketplace are some of the existent marketplaces. They have varying functionalities some being business to business reuse opportunities, other where owners can notify the platform when a building is to be demolished and potential customers, architects and designers can discover valuable elements that could be reused in their projects.

There is an existing market for recycled aggregates which are used for filling, road construction, etc. The size of the aggregate and where it came from is mentioned in the marketplaces. Steel products are usually scrapped and sold as scrap metal based on the weight and type of steel. Structural steel members are also sold as elements if the quality is good and if it is not affected by deformation.

Marketplaces need information about the condition of the product, the dimensions such as width, height, length if is a reusable product, material information, the quantity available such as volume and a brief description of the product covering important features.

2.4. BIM Integration for Circularity and CDW Management

BIM can be used to streamline the entire lifecycle of a building, from initial design through construction, operation, and ultimately, demolition or deconstruction. The EC suggests the use of BIM tools, material passports of construction products and materials for building deconstruction and to enable fast and accurate assessment of recovery, reuse and recycling potentials of products and systems (European Commission , 2020a). For this to happen, designers must work together with end-of-life contractors to tackle waste through efficient deconstruction or disassembly at the assets EOL.

The potential of BIM to support the implementation of circular economy were explored by various authors regarding energy simulations, cost studies, sustainability simulations and facility management activities. The improvement of project cost and schedule management has led to a huge interest in enhancing 3D BIM models with 4D and 5D functionalities. Graphical and non-graphical data in the virtual model enable several useful applications such as operation and maintenance, refurbishment, and even EOL management, waste minimisation and deconstruction.

The integration of a digital twin with BIM models to build a closed loop between physical and virtual spaces can help in the management of demolition projects. Figure 11 shows the workflow which consists of the physical space, the virtual space, demolition management service platform and building demolition digital twin database. The core of the virtual space is the BIM model, which involves modelling geometry information of building components, assigning BIM object category to components, and adding related properties such as material type, demolition cost, and recycling methods and establishing relationships between components. (Kang et al., 2022). A BIM workflow using digital twins for building demolition service is elaborated in Figure 11.

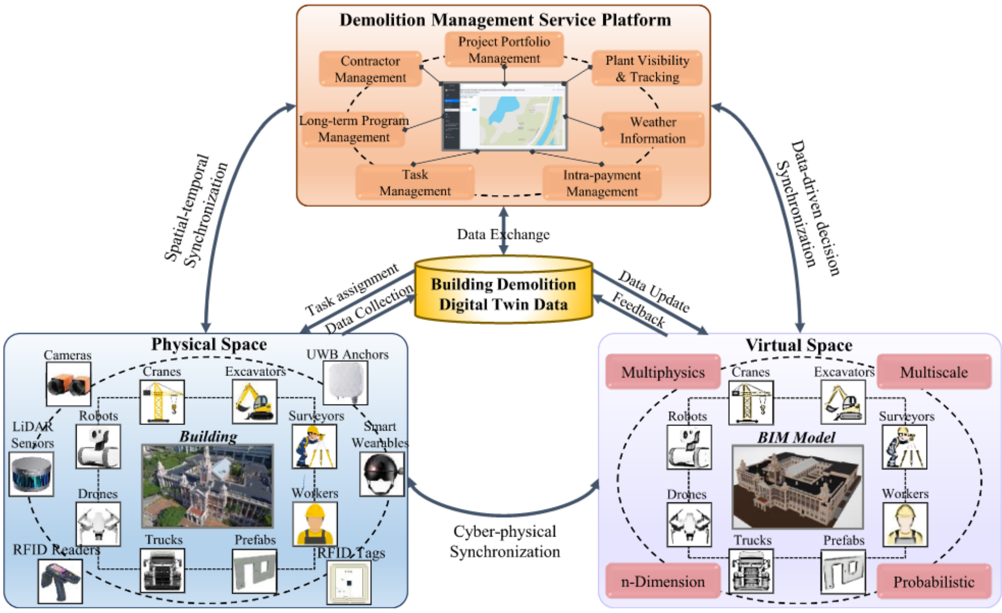

Fig. 4. Workflow of building demolition service.

Figure 11 - Building demolition service using BIM workflow

(Kang et al., 2022)

A Deconstruction Information Model (DIM) is a digital model that will provide data to control and manage deconstruction strategy and tasks. It can help deconstruction managers facilitate the waste management plan, waste sorting, waste analysis and classification, quantity extraction and pre-demolition audits by allowing easy access to information of components, their quantities and specific requirement for their dismantlement, reuse, recycling, and disposal. It will help to plan the activities and virtually simulate the process to avoid unexpected events and costs, and helps to decrease unplanned waste, avoid raw material depletion by reintroducing CDW into the material loop (Charef, 2022). The creation of DIM for end-of-life management is elaborated with 2 workflows in Figure 12.

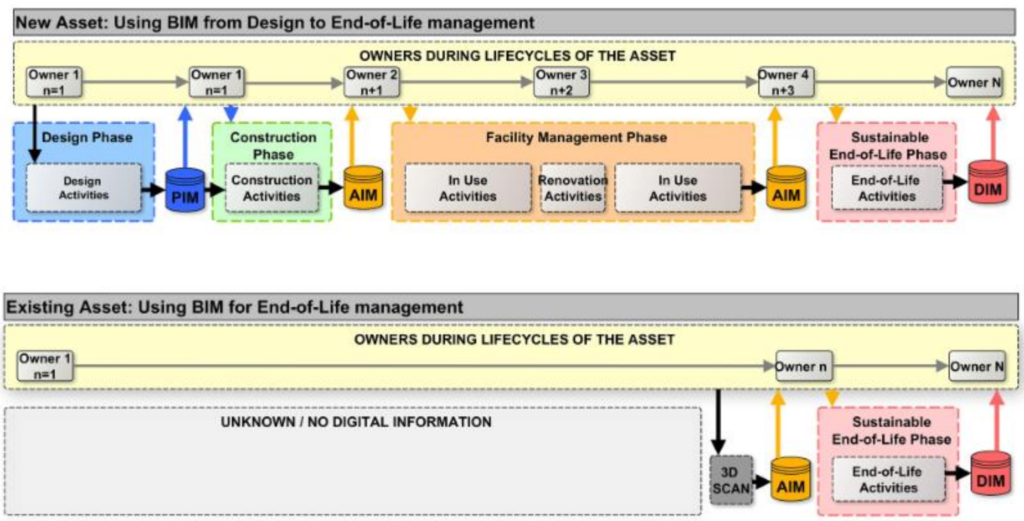

Figure 12 - BIM for End-of-Life Management

(Charef, 2022)

2.4.1. RecycleBIM Project

The RecycleBIM project is a multi-national, multi-stakeholder project which aims to create an integrated framework for circularity of raw materials of construction and demolition using BIM methodologies. The project framework includes the development of a methodology for scan-to-BIM of to-be-demolished buildings, a to-be-demolished BIM model framework which should include enough information to support all the analysis and integration functionalities by the downstream applications, such as life cycle analysis, connection to CDW marketplaces and the establishment of adequate information requirements and modelling rules based on the requirements of ISO 19650:2018 and EN 17412-1:2020, that ensure all relevant information for deconstruction planning and circularity of materials is recorded in the BIM model. This means the model needs to be set up in a standardised, machine structure, which facilitates asset owners to set their requirements for information.

The project also involves the creation of an IFC based tool, optimisation of deconstruction strategies, connection to marketplaces, and a strategic and optimised use of recycled demolition waste in 3D printed concrete. The final part of the project deals with developing tools for Municipalities to use in the process of issuing demolition permits and new building permits based on BIM models in openBIM IFC format, for issuing municipal approvals based on traceable data and keeping accurate records of material circularity. (Parente et al., 2023). An overview of RecycleBIM project is shown in Figure 13.

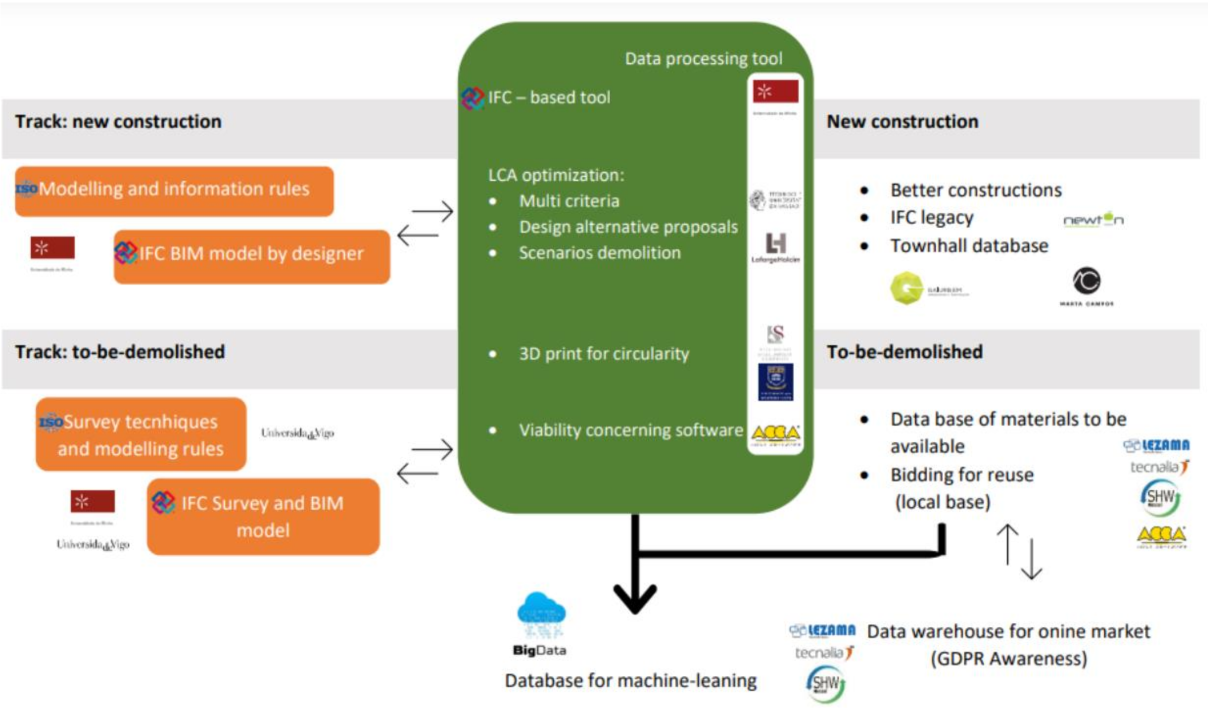

Figure 13- RecycleBIM Project Overview (RecycleBIM , 2022)

The data specifications follow a "Lean" approach for the creation of a specific set of information management rules according to ISO and CEN standards and translation of the rules into ISO 19650 compliant EIR and BEP templates for owners and appointed parties. OpenIFC formats are followed to ensure interoperability between the information in the BIM models and the other tools and applications developed in the project. A database of Product Data Templates (EN23386 and EN23387) is put forward by the project to achieve the goals in the context of circularity of construction materials.

2.4.1.1. Product Data Templates

Product Data Templates are a description of the information required for products, materials, systems, assemblies, spaces etc. They are used for information exchange for planning, design, construction, or operation of constructed facilities and building projects. Product data templates in the context of recycling and circularity of materials were proposed in the thesis work of Artur Kuzminykh (Kuzminykh, 2022).

Property	**Data type**	**Mandatory/ Optional**	**Source**	**Example**
Object class	text	M (auto)	IFC entity	IfcWindow
Tier 1 building aspect	text	O	Level(s)	Shell
Tier 2 building aspect	text	O	Level(s)	Facades
Classification	text	O	Uniclass	Pr_30_59_98
Declared Unit	text	M	EPD/Waste audit report	m2/m3/pcs/kg
DeclaredQuantityPerUnit	float	M	EPD/Waste audit report	7.0
MaterialCompoundPerDeclaredUnit	text array	M	EPD/Waste audit report	wood, glass
MaterialQuantityPerDeclaredUnit	float array	M	EPD/Waste audit report	20,5
ItemCanBeReused	bool	M	Waste/reclamation audit report	1/True
ItemCanBeRecycled	bool	M	Waste/reclamation audit report	1/True
WasteCode(s)	text array	M	EWC/ Level(s)	17_02_01,17_02_02
ItemTypeOfJoints*	integer	O	User specific/ reclamation report	1, 2, 3
ItemHasPotentialDanger	bool	M	Waste/reclamation audit report/Level(s)	0/False
Quantity	float	M (auto/user defined)	IFC Qto/User specific	7.77, 5.0
Image	text	O	Waste/reclamation audit	"...window_1_1.jpg"

Figure 14 – Proposed PDT for reuse and recycle potential.
(Kuzminykh, 2022)

The properties in the data template Figure 14 were derived from the study of several information sources such as the Level(s) framework, Environmental Product Declaration, ISO 22057:2022, ISO 23386:202 and ISO 23387:2020, EC guidelines for waste audit and reclamation audit, IFC property sets, NBS data templates and BAMB material passport report. Identification and classification of the product is done in accordance with IFC entity ac bsDD, Level(s) tiers classification, EWC and Uniclass classification. The quantification information is assigned manually with declared units, declared quantity and material quantity per declared unit. The reuse and recycling potential of the product/ material can be declared and the ‘ItemTypeOfJoints’ is used to denote the products deconstruction possibilities. It will be assigned a value ranging from 1 to 3, 1 being fully dismountable mechanical joints without use of wet processes, 2 being dismountable joints that require extra effort for disassembly and 3 being attached/ welded elements that require extra human effort or machinery for disassembly. The potential danger of hazardous materials in the construction is also recorded. An image of the product is requested as an attachment to visually assess the condition (Kuzminykh, 2022)

2.5. Data in Open Format: Interoperability

An important issue with semantic interoperability has been the openness of systems. The way information systems interact with their environment can be less or more open. Less open systems are more difficult to pass information to and more difficult to use information exiting the system (Turk, 2020). Industry Foundation Classes (IFC) is a standardized, digital description of built assets and is an open international standard (ISO 16739-1:2018), which promotes vendor neutral usable capabilities across a range of hardware devices, software platforms and interfaces. (Building SMART International, 2020) Since information silos and interoperability issues in BIM are some of the hindrances to the adoption of digital technologies, open formats such as IFC, IDM, BCF from buildingSMART help end users collaborate better and cooperate, regardless of the software application used.

2.5.1. IFC 4.0 Design Transfer View and Reference View

The main objective of IFC4 Design Transfer View is to enable collaboration on design elements impacting multiple disciplines. It is intended to provide building information with support for editing of interconnected elements impacting multiple disciplines. This will enable inserting, deleting, moving, and modifying building elements and spaces. For such editing to be possible, higher level design parameters must be preserved for the elements that affect multiple disciplines, and applications must generate downstream geometry according to such parameters. (Building SMART International, 2020)

Design Transfer View supports all geometry, including Constructive Solid Geometry (CSG) and Non-Uniform Rational B-Spline (NURBS) geometry, along with geometry defined within the Reference View such as Boundary Representation (BREP) tessellation. Therefore, Design Transfer View can be considered a superset of Reference View.

- Object Typing associates the model element occurrence to the corresponding predefined element type in IFC.
- Property Sets which hold sets of individual properties are assigned to model element occurrences of element type.
- Quantity Sets which hold sets of individual quantities are assigned to model element occurrences.

Reference models emphasize the preservation of the source, parametric behaviour, and intellectual property of BIM information with the originator. The ownership and accountability for model correctness also firmly rest with the originator, and the receiver's role is primarily analytical and extractive without modifying the model directly. Conversely, design transfer models offer more flexibility by allowing for the sharing or transfer of BIM information and intellectual property. The responsibility for model accuracy can also shift if needed. The receiver in this case has the option to modify the model and extract information without requiring full access to the model's content, even having the ability to make direct changes if necessary. In essence, while both workflows facilitate information exchange, reference models maintain a more conservative approach, preserving the integrity of the original model, while design transfer models provide a more flexible framework that can accommodate modifications and shared responsibilities.

2.5.2. Information Delivery Specification for IFC validation

IDS is a standard developed by buildingSMART for defining information requirements which can be read by humans and interpreted by computers. It helps people in the built asset industry to define their exchange requirements, adds clarity among stakeholders and ensures that asset owners can specify what they want and allows project participants a better understanding of what they need to deliver. IDS can be used to check properties, quantities, materials, classifications, entity types and object dependencies. The workflow of IDS is elaborated in Figure 15. IDS is best suited for validation of data that is structured according to IFC standard and works with IFC 4.0. The IDS xml file can contain multiple requirements which are independent blocks that have no reference to other requirements in the file. The objective of IDS is for automated workflows and scripts to receive information in a way which can be automatically processed. (Building SMART International, 2020)

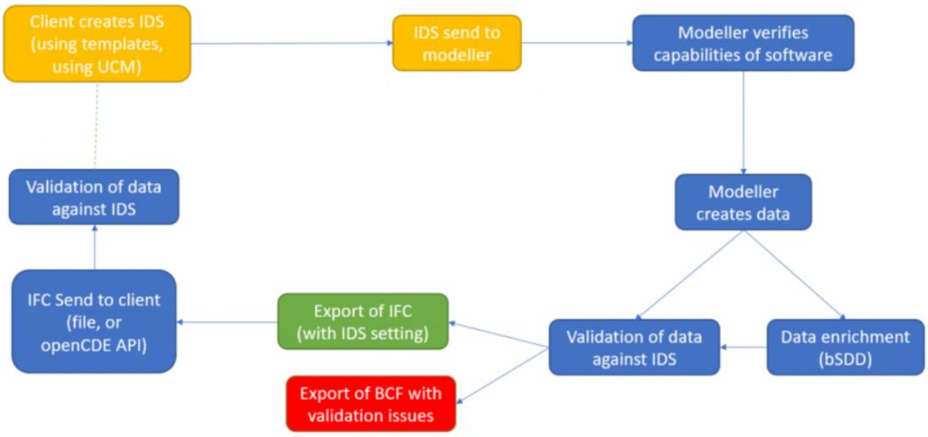

Figure 15 - IDS Verification workflow (Building SMART International, 2020)

2.6. Information Requirements

The European standard EN 17412:1 specifies concepts and principles to specify Level of Information Need and Information deliveries in a consistent way when using BIM. This standard along with the context of the ISO 19650 series, provides insights into the requirements for information exchange. Figure 16 shows the relationships between ISO 19650 series and EN 17412:1. One of the purposes of defining the level of information need is to prevent the delivery of excess information which is not requested or required. It ensures that the right alphanumerical information, geometrical information, and documentation is delivered in the right detail and the right granularity for the agreed purposes. EN 17412:1 states the following prerequisites to be identified and considered for defining the Level of Information Need for a deliverable-

- Purposes for the information to be delivered.
- Delivery milestones for the information.
- Actors who request the information and actors who will deliver the information.
- Objects concerned, organised in a breakdown structure.

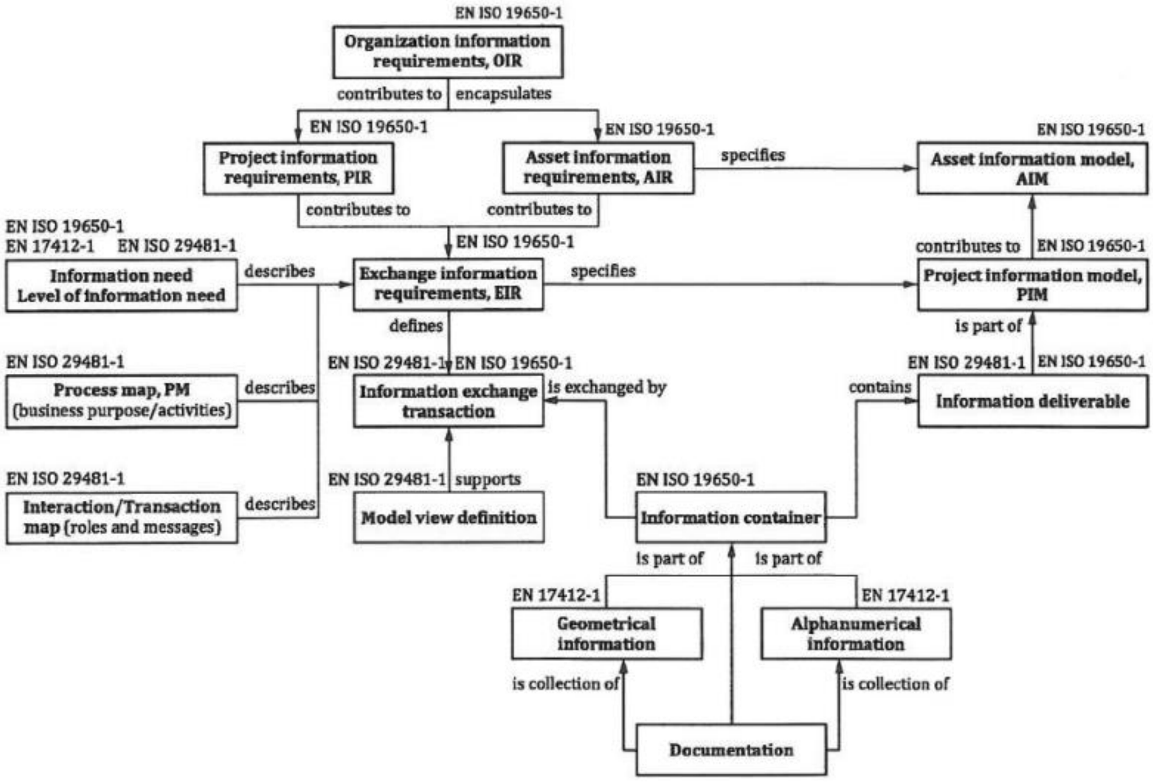

Figure 16 - Relationship diagram between ISO 19650 AND EN 17412

According to EN 17412:1 (British Standards Institution, 2020), to specify the alphanumerical information for an object or set of objects, the identification and information content should be specified.

Identification – To identify an object within a breakdown structure. Name, Object Class, Classification, WBS structure etc can be used for identification.

Information Content – Elaborates the list of all properties required to fulfil a specific purpose.

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3. PRODUCT DATA TEMPLATES FOR CIRCULARITY OF PRODUCTS AND MATERIALS

Product Data Templates can play an important role in ensuring exchange of machine-readable information between involved parties for the purpose of deconstruction, and to ensure circularity of construction and demolition waste. They help in standardization in the field of structured semantic life-cycle information for the built environment and can enable traceability and provide essential input for decision making (Vasco Viera et al., 2023). The PDT will be filled with information from on-site investigations and mapped with the real characteristics of objects, and materials. This work builds on the PDTs developed in 'Integrated Planning and Recording Circularity of Construction Materials through Digital Modelling'(Kuzminykh, 2022) as elaborated in section 2.4. The properties derived from various sources were adapted into PDTs as defined in EN ISO 23387.

3.1. Exploration of IFC Schema

The use of OpenBIM concepts and open format IFC for exchange, the capability of IFC elements to store object geometry, properties, and quantities to accurately define the requirements are explored in this chapter. The capability of IFC 4.3 as Information Containers for Demolition Information are also explored. The properties and quantities that are requested from products and materials can be stored in IFC property sets and quantity sets when the model is created and exported to IFC. The open format methodology also aligns with the prerequisites of the RecycleBIM project, which the study aims to contribute to.

3.1.1. Property Sets for storing properties

Property sets hold a set of properties grouped by a common theme. The name of the property set indicates this theme, and each individual property has a name, a description, a value of a given data type, and a unit. The data type of an individual property can be single value, enumerated value, bounded value, table value, reference value or list value. An Object occurrence can be related to a single or multiple property sets and a property set contains a single or multiple properties. Property sets for object type define the common properties for all the occurrences of the same type.

Property sets in IFC allow you to attach metadata and attributes to building products, and these associations are established through property set assignments, creating a structured way to manage and exchange information about building components within the IFC data model. Property sets in IFC which are relevant to reuse, and recycling of materials are analysed in this section.

Pset_MaterialCommon, as elaborated in Figure 17, is an innate property set of all materials. It contains the properties MassDensity, MolecularWeight, and Porosity. "MassDensity" is a critical property to determine the quality of the recovered material and can be measured by an onsite test.

8.10.4.2 Pset_MaterialCommon

8.10.4.2.1 Semantic definition

A set of general material properties.

8.10.4.2.2 Applicable entities

PSET_MATERIALDRIVEN The property sets defined by this IfcPropertySetTemplate are to be encoded in an IfcMaterialProperties entity and assigned to an IfcMaterialDefinition.

- IfcMaterial

8.10.4.2.3 Properties

Name	Property Type	Data Type	Description
MolecularWeight	IfcPropertySingleValue	IfcMolecularWeightMeasure	Molecular weight of material (typically gas).
Porosity	IfcPropertySingleValue	IfcNormalisedRatioMeasure	The void fraction of the total volume occupied by material (Vbr - Vnet)/Vbr.
MassDensity	IfcPropertySingleValue	IfcMassDensityMeasure	Material mass density.

Table 8.10.4.2.A

Figure 17 - Pset_MaterialCommon (BuildingSMART, 2022)

There are property sets in IFC for specific materials, such as Pset_MaterialConcrete, Pset_MaterialWood, Pset_MaterialSteel with properties which are common and relevant for that material.

As elaborated in section 2.3, the size of aggregates in concrete is important information to be known for recycled concrete and can be done by performing a crushing test in a laboratory. This property is stored in Pset_MaterialConcrete under the property “MaxAggregateSize”, as shown in Figure 18.

8.10.4.3 Pset_MaterialConcrete

8.10.4.3.1 Semantic definition

A set of extended mechanical properties related to concrete materials.

8.10.4.3.2 Applicable entities

PSET_MATERIALDRIVEN The property sets defined by this IfcPropertySetTemplate are to be encoded in an IfcMaterialProperties entity and assigned to an IfcMaterialDefinition.

- IfcMaterial

8.10.4.3.3 Properties

Name	Property Type	Data Type	Description
CompressiveStrength	IfcPropertySingleValue	IfcPressureMeasure	The compressive strength of the object or material.
MaxAggregateSize	IfcPropertySingleValue	IfcPositiveLengthMeasure	The maximum aggregate size of the concrete.
AdmixturesDescription	IfcPropertySingleValue	IfcText	Description of the admixtures added to the concrete mix.
Workability	IfcPropertySingleValue	IfcText	Description of the workability of the fresh concrete defined according to local standards.
WaterImpermeability	IfcPropertySingleValue	IfcText	Description of the water impermeability denoting the water repelling properties.
ProtectivePoreRatio	IfcPropertySingleValue	IfcNormalisedRatioMeasure	The protective pore ratio indicating the frost-resistance of the concrete.

Figure 18 - Pset_MaterialConcrete (BuildingSMART, 2022)

Pset_MaterialWood contains the property “Species” which can be used to store the species of wood in the product. Knowing the species of reclaimed wood can be very useful information for potential buyers. “StructuralGrade” in Pset_MaterialSteel can also be useful to know for reuse and recycling.

There are property sets for building elements which have characteristics and properties based on the common materials used for those elements. Elements which could have concrete as a material have a property set “Pset_ConcreteElementGeneral” which can be used to store very useful information about the strength of the concrete, reinforcement etc. “ReinforcementStrengthClass”, “ReinforcementVolumeRatio”, “StrengthClass”, are some of the properties identified which can determine the quality of recycled concrete from concrete elements.

7.11.4.1.3 Properties

Name	Property Type	Data Type	Description
AssemblyPlace	IfcPropertyEnumeratedValue	PEnum_AssemblyPlace	Enumeration defining where the assembly is intended to take place, either in a factory, other offsite location or on the building site.
CastingMethod	IfcPropertyEnumeratedValue	PEnum_ConcreteCastingMethod	The method of casting the concrete into its designed form.
StructuralClass	IfcPropertySingleValue	IfcLabel	The structural class defined for the concrete structure (e.g. '1').
StrengthClass	IfcPropertySingleValue	IfcLabel	Classification of the concrete strength in accordance with the concrete design code which is applied in the project.
ExposureClass	IfcPropertySingleValue	IfcLabel	Classification of exposure to environmental conditions, usually specified in accordance with the concrete design code which is applied in the project.
ReinforcementVolumeRatio	IfcPropertySingleValue	IfcMassDensityMeasure	The required ratio of the effective mass of the reinforcement to the effective volume of the concrete of a reinforced concrete structural element.
ReinforcementAreaRatio	IfcPropertySingleValue	IfcAreaDensityMeasure	The required ratio of the effective area of the reinforcement to the effective area of the concrete At any section of a reinforced concrete structural element.
DimensionalAccuracyClass	IfcPropertySingleValue	IfcLabel	Classification designation of the dimensional accuracy requirement according to local standards.
ConstructionToleranceClass	IfcPropertySingleValue	IfcLabel	Classification designation of the on-site construction tolerances according to local standards.
ConcreteCover	IfcPropertySingleValue	IfcPositiveLengthMeasure	The protective concrete cover at the reinforcing bars according to local building regulations.
ConcreteCoverAtMainBars	IfcPropertySingleValue	IfcPositiveLengthMeasure	The protective concrete cover at the main reinforcing bars according to local building regulations.
ConcreteCoverAtLinks	IfcPropertySingleValue	IfcPositiveLengthMeasure	The protective concrete cover at the reinforcement links according to local building regulations.
ReinforcementStrengthClass	IfcPropertySingleValue	IfcLabel	Classification of the reinforcement strength in accordance with the concrete design code which is applied in the project. The reinforcing strength class often combines strength and ductility.

Table 7.11.4.1.A

Figure 19 - Pset_ConcreteElementGeneral (BuildingSMART, 2022)

“LoadBearing” is a Boolean property that belongs to the ‘Pset_Common’ of all IfcBuiltelements other than windows and doors, which denotes whether the object is intended to carry loads or not.

For properties that are not semantically declared with the IFC schema, custom property sets with custom properties can be declared as an “IfcPropertySet” to store user defined information and properties required from the model elements or materials.

3.1.2. Quantity Sets for storing Quantity Information

A Deconstruction Information Model requires the quantity information of various elements to be stored in the model. IFC quantity sets hold the set of quantities pre calculated by the authoring software for each model element occurrence. Each individual quantity has a name, an optional description, a value corresponding to the quantity measure of a given datatype (length, area, volume, time weight, etc), a unit, and a quantity formula describing how the quantity was calculated. The semantic meaning of each quantity is provided by its name.

Quantity sets are defined by instances of IfcElementQuantity, where the Name attribute is the common designator of the quantity set. There exists a number of predefined quantity sets and template definitions for each of them. Each element has a quantity set template which is specified as “BaseQuantities” of the element. The name prefix for quantity sets “Qto_” is used to denote quantities within the scope of IFC. Figure 20 shows an example of Qto_SlabBaseQuantities, with all the quantities possible to store in Ifc that are innate to the IfcSlab element.

6.1.5.13 Qto_SlabBaseQuantities

6.1.5.13.1 Semantic definition

Base quantities that are common to the definition of all occurrences of slabs.

6.1.5.13.2 Applicable entities

QTO_TYPEDRIVENOVERRIDE The element quantity defined by this IfcPropertySetTemplate can be assigned to subtypes of IfcTypeObject and can be overridden by an element quantity with same name at subtypes of IfcObject.

- IfcSlab
- IfcSlabType

6.1.5.13.3 Properties

Name	Data Type	Description
Width	IfcQuantityLength	The width of the object. Only given, if the object has constant thickness (prismatic).
Length	IfcQuantityLength	The length of the object. Only provided if rectangular.
Depth	IfcQuantityLength	The depth of the object. Depth (one direction of the non-projected foot print area) of the slab. It shall only be provided, if the slab is rectangular.NOTE Also referred to as width, but not to be confused with the "Width" quantity, that denotes the thickness in the context of the slab.
Perimeter	IfcQuantityLength	Perimeter of the object. Perimeter measured along the outer boundaries of the slab. Only given, if the slab is prismatic (constant thickness).
GrossArea	IfcQuantityArea	Gross Area of the object. Openings, recesses, projections and cut-outs are not taken into account. Indicates the extruded area of the element. Only given, if the element is prismatic.
NetArea	IfcQuantityArea	Total net area of the object. Openings, recesses and cut-outs are taken into account by subtraction, projections by addition. Indicates the extruded area of the object. Only given when prismatic.
GrossVolume	IfcQuantityVolume	Total gross volume of the object. Openings, recesses, enclosed objects and projections are not taken into account.
NetVolume	IfcQuantityVolume	Total net volume of the object, taking into account possible processing features (cut-out's, etc.) or openings and recesses. Total net volume of the slab. Openings and recesses are taken into account by subtraction, projections by addition.
GrossWeight	IfcQuantityWeight	Total Gross Weight of the object without any add-on parts and not taking into account possible processing features (cut-out's, etc.) or openings and recesses.
NetWeight	IfcQuantityWeight	Total net weight of the object without add-on parts, taking into account possible processing features (cut-out's, etc.) or openings and recesses.

Figure 20 - Qto_SlabBaseQuantities (BuildingSMART, 2022)

3.1.3. Classification Information

IfcClassification is used for arranging objects into categories according to a common purpose or their possession of common characteristics. It is a taxonomic scheme, arranged in a hierarchical tree structure. IfcClassification identifies the classification system and source to which the classification reference refers to. The classification system declared may be either a formally published classification or may be a locally defined method of classifying.

Example: #249= IFCCLASSIFICATION ('https://toolkit.thenbs.com/articles/classification', 'April2023', '2023-05-11','Uniclass 2015','Uniclass 2015 is a unified classification for the UK industry covering all construction sectors.','https://toolkit.thenbs.com/articles/classification',$);

IfcClassificationReference is used to reference the classification system, including the relationship between items. The ReferencedSource attribute of IfcClassificationReference links the classification item to the parent item and the parent item to the IfcClassification.

Example: #250= IFCCLASSIFICATIONREFERENCE($,'Pr_25_30_36','Handrails',#249,$,$)

IfcRelAssociatesClassification handles the assignment of a classification item to object occurrences (subtypes of IfcObject) and object types. The relationship is used to assign a classification system or classification item to objects.

Example: #252= IFCRELASSOCIATESCLASSIFICATION('0OpXBir0LeWKVKUplZLERg',#12, 'Uniclass 2015 April 2023',$,(#180,#494,#824,#1010,#1301,#1502,#1799,#1977,#2274,#2452, #2653,#2854,#3151,#3323,#3518),#250);

3.1.4. IfcBuildingElement

The object class for products in a Deconstruction Information Model is an IFC entity, and their use as a digital representation for actual building elements was explored. IfcBuildingElement starts from IfcRoot, which serves as the most fundamental superclass in the IFC hierarchy and provides basic attributes and properties that are applicable to all IFC entities. Building element comprises of physically existent and tangible things that are part of the building construction. Typical examples of IfcBuildingElements include elements within a space separation system, elements within enclosure systems such as facades, elements within a fenestration system, elements within a load bearing system and foundation system (Building SMART International, 2020). Figure 21 shows the inheritance of the properties IfcBuiltElement from IfcRoot to all the individual built elements.

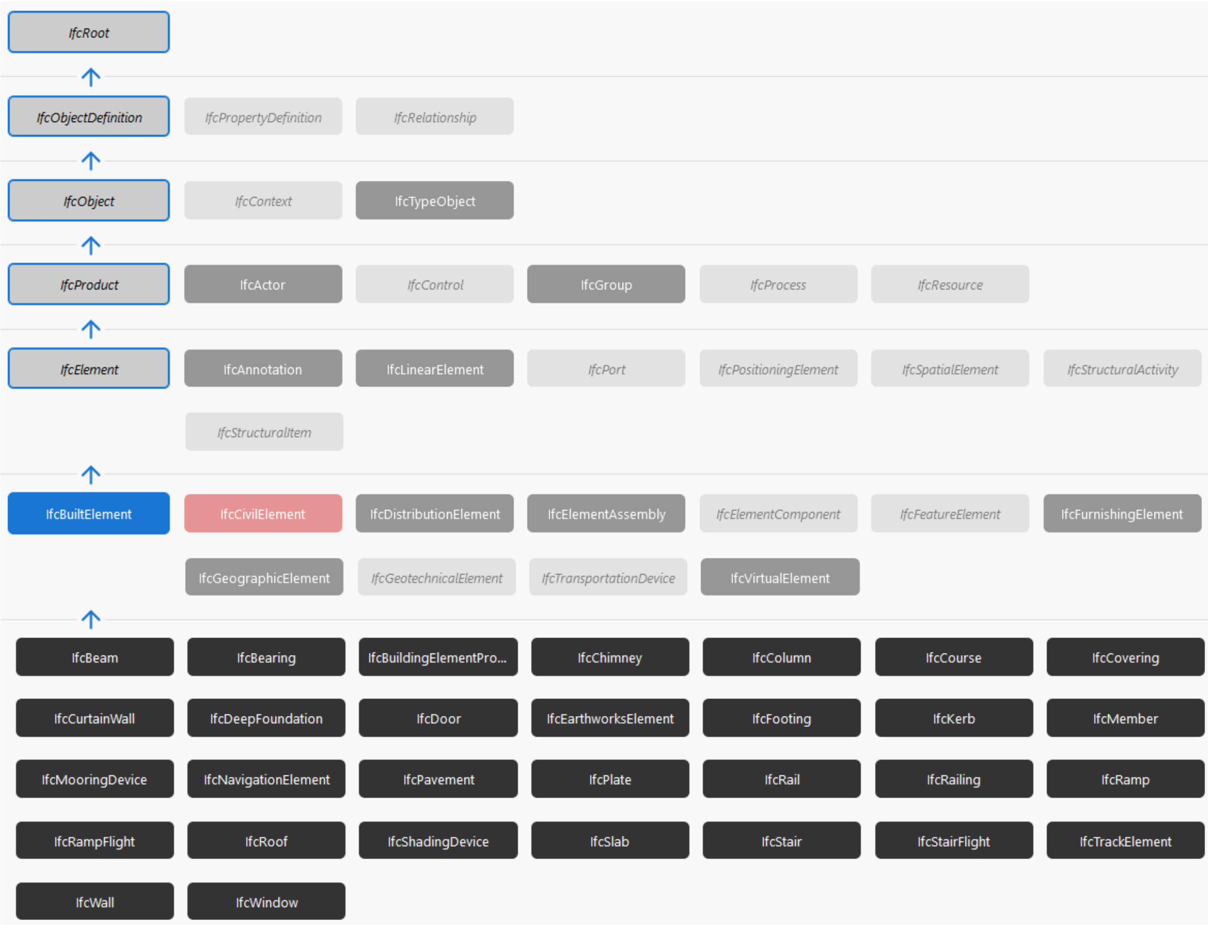

Figure 21 - Inheritance diagram of IfcBuildingElement (BuildingSMART, 2022)

Figure 22 describes the breakdown of the relationships of IfcSlab and how property sets, and quantity sets are associated with an IfcBuiltElement. Materials are associated with IfcRelAssociatesMaterial relationship and Classification is assigned using IfcRelAssociatesClassification relationship. Understanding the relationships between elements, materials, and how properties, quantities and classifications are stored in Ifc is essential to create models which have better interoperability, for defining modelling rules for these models and also to perform data validation of exchanged information models.

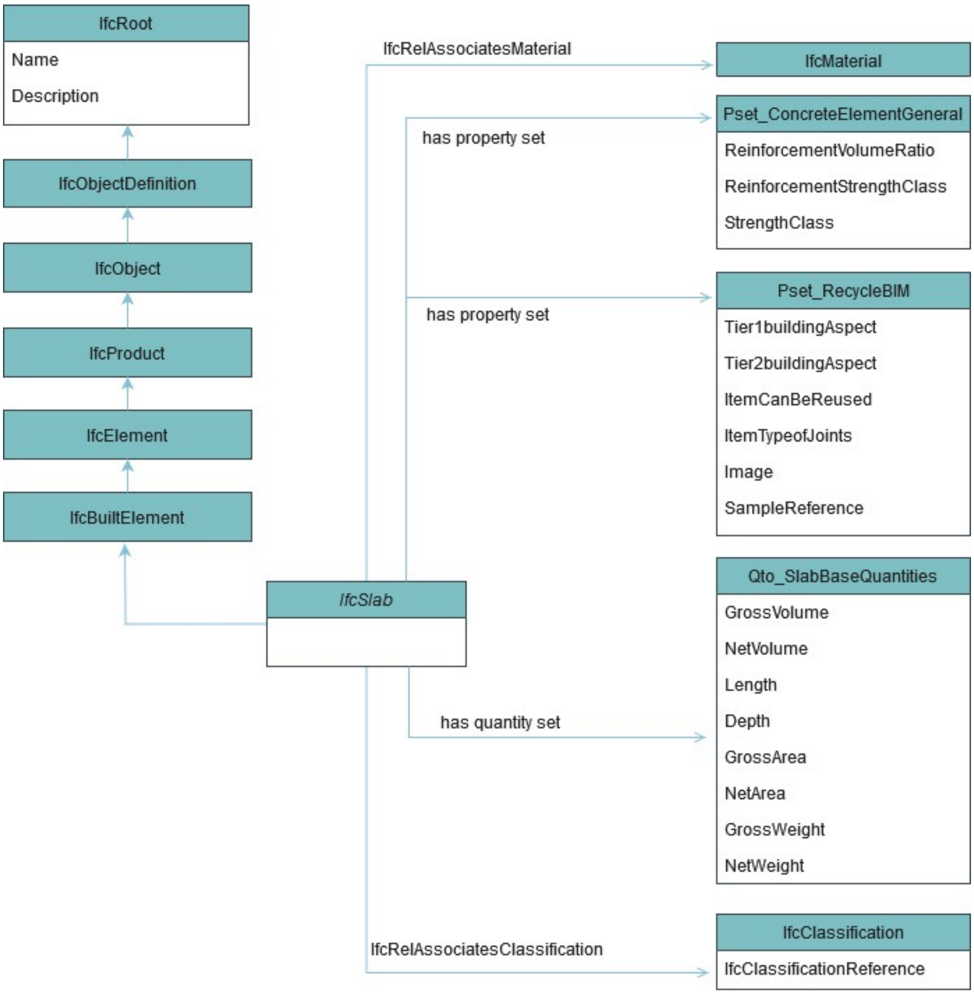

Figure 22 - Hierarchy and relationships for the case of IfcSlab

IfcWall

Wall represents a vertical construction that bounds or subdivides spaces. Usually vertical and planar elements, walls may or may not be load bearing. Walls can have openings for niches, recesses and for hosted elements such as windows and doors. Openings are defined by IfcOpeningElement attached to the walls using HasOpenings pointing to IfcRelVoidsElement. There are 3 cases for wall occurrences:

- IfcWallStandardCase is used for all walls with non-changing thickness along the wall path are defined with IfcMaterialLayerSetUsage, where the thickness parameter can be fully described by a material layer set as shown in Figure 23. Thickness of each wall layer is saved separately, allowing the storage and extraction of the quantities of each material of the wall.
- IfcWallElementedCase is used for occurrences of walls which are made from component elements which are expressed by IfcRelAggregates relationship.
- IfcWall is used for other wall occurrences where they have changing thickness along the wall path or non-rectangular cross sections. These walls will not have layer quantities and will have only total wall quantities.

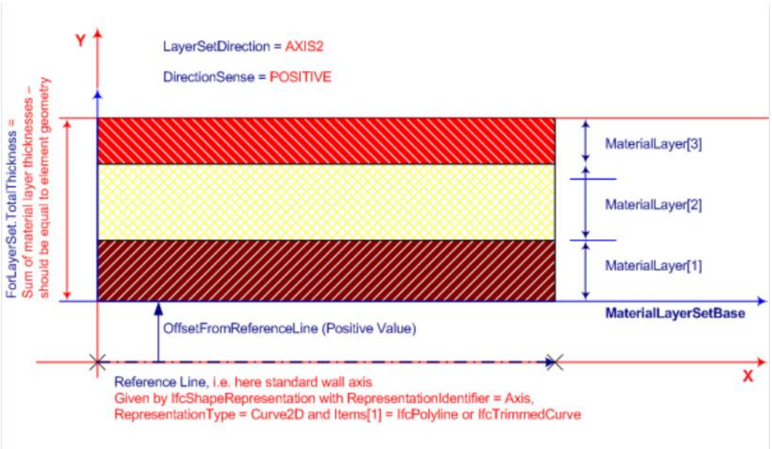

Figure 23 - Wall Material Layers (BuildingSMART, 2022)

Qto_WallBaseQuantities contains Length, Width, Height, GrossFootPrintArea, NetFootPrintArea, GrossSideArea, NetSideArea, GrossVolume, NetVolume, GrossWeight and NetWeight.

IfcSlab

IfcSlab is a construction component that encloses a space vertically which can be floor slabs or roof slabs. A landing is also a type of slab, which connects one or more stair flights or ramp flights. There are 3 cases for slab occurrences:

- IfcSlabStandardCase is used for all occurrences of slabs, where the thickness parameter can be described by IfcMaterialLayerSetUsage.
- IfcSlabElementedCase is used for occurrences of slabs which are aggregated from component elements which are expressed with IfcRelAggregates relationship.
- IfcSlab is used for all other occurrences of slabs, especially slabs with non-planar surfaces and slabs with changing thickness.

Qto_SlabBaseQuantities contains Width, Length, Depth, Perimeter, GrossArea, NetArea, GrossVolume, NetVolume, GrossWeight and NetWeight.

IfcRoof

IfcRoof are represented as either an assembly that aggregates parts such as slabs, beams with their own representation or as a single roof without decomposition including all shape representations in the roof entity. Figure 24 shows IfcRoof as an assembly of sloped IfcSlabs with their respective local placements.

Qto_RoofBaseQuantities does not include Volume information and only has NetArea, Gross Area, and Projected Area and if volume information is required, it will have to be declared with constituent elements.

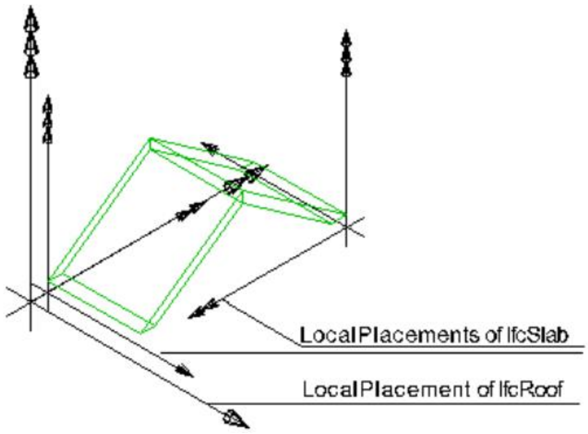

Figure 24 - Roof Decomposition and placement (BuildingSMART, 2022)

IfcBeam and IfcColumn

For beams and columns, IfcBeamStandardCase and IfcColumnStandardCase is used for all occurrences of beams and columns which have a defined profile along an axis. This accommodates a uniformly changing tapered profile as well. IfcMaterialProfileSetUsage is used to assign materials to the object.

IfcBeam and IfcColumn is used for other occurrences where the profile sizes change non uniformly along the sweep or have non-linear extrusions and they will only have ‘Brep’ geometry representation.

IfcWindow

IfcWindow can be inserted into an IfcOpeningElement using IfcRelFillsElement relationship or be part of an element assembly using IfcRelAggregates relationship. It can also be a free-standing window without FillsVoids or Decomposes attributes.
Qto_WindowBaseQuantities includes Width, Height, Perimeter and Area.

IfcDoor

IfcDoor can be used to fill an opening in a wall element, with a IfcRelFillsElement relationship. It can be part of an assembly such as in an IfcCurtainWall with IfcRelAggregates relationship, or as a free-standing door. IfcDoor can be defined as one of 2 entities:

- IfcDoorStandardCase is used for all occurrences that are defined by a ‘Profile’ shape representation, to which shape parameters for lining and framing properties apply.
- IfcDoor is used for all other occurrences of doors, especially those that have only ‘Brep’ or ‘SurfaceModel’ geometry without applying shape parameters. IfcDoor specifies the door width and height and the door opening direction.

Qto_DoorBaseQuantities includes Width, Height, Perimeter and Area.

IfcStair and IfcRamp

Stair and Ramps can be represented as an assembly entity that aggregates parts such as stair flight or ramp flight and landing with their own shape representation, as demonstrated for stairs in Figure 25, or as a single stair or ramp entity including all shape representation without decomposition.

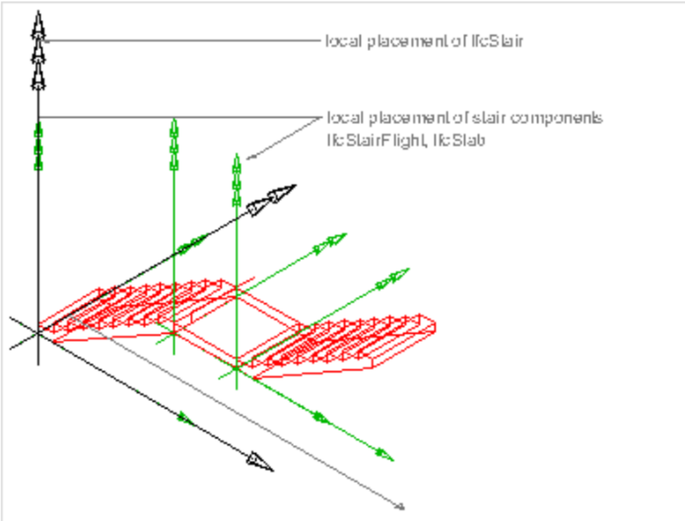

Figure 25 - Stair decomposition and placement (BuildingSMART, 2022)

Aggregated elements are connected to the component elements through the IfcRelAggregates relationship. The connection between component elements is expressed through IfcRelConnectsElements relationship.

IfcStairFlight and IfcRampFlight

IfcStairFlight and IfcRampFlight are aggregated with an IfcStair and IfcRamp with the IfcRelAggregates relationship. They connect two different storeys, often connected by a landing, which is declared as IfcSlab. The relationship between IfcStairflight and IfcSlab is expressed with IfcRelConnectsElements relationship.

Qto_StairflightBaseQuantities contains Length, GrossVolume and NetVolume.
Qto_RampflightBaseQuantities contains Length, Width, GrossArea, NetArea, GrossVolume, and NetVolume.

IfcCurtainWall

IfcCurtainWall is represented as a building element assembly and that uses IfcRelAggregates relationship. The geometric representation is given by IfcProductDefinitionShape, which allows multiple geometric representations.

- If the Curtain wall is defined as an aggregate, the geometric representation is the sum of the representations of the components within the aggregate.
- Independent ‘Body’ geometric representation should only be used when the IfcCurtainWall is not defined as an aggregate.

Qto_CurtainWallBaseQuantities contains Length, Height, Width, GrossSideArea, and NetSideArea.

IfcRailing

IfcRailing is a frame assembly used adjacent to circulation spaces or space boundaries in lieu of walls. It can be declared as an assembly of aggregate components like plate and member or as a single component with ‘Brep’ geometry.
Qto_RailingBaseQuantities contains only Length.

IfcMember

IfcMember represents a linear structural element, which is not required to be load bearing. The orientation of the member is not relevant to its definition. Member occurrences can be of two types:

- IfcMemberStandardCase is used for all occurrences that have a profile swept along an axis. The profile may be changed uniformly by a taper. They need to have a corresponding IfcMaterialProfileSetUsage assigned.
- IfcMember is used for all other occurrences which have changing profile sizes along the extrusion or nonlinear extrusion, defined by ‘Brep’ geometry.

Qto_MemberBaseQuantities contains Length, CrossSectionArea, OuterSurfaceArea, GrossSurfaceArea, NetSurfaceArea, GrossVolume, NetVolume, GrossWeight and NetWeight.

IfcPlate

IfcPlate is a planar, usually flat part with constant thickness. It can be horizontal, vertical, or sloped and are usually add-on parts to container elements such as IfcElementAssembly or IfcCurtainWall, represented by IfcRelAggregates decomposition mechanism. It can be of two types:

- IfcPlate with IfcMaterialLayerSetUsage is used where the plates are prismatic with constant thickness parameter and represented by ‘SweptSolid’ geometry.
- IfcPlate without IfcMaterialLayerSetUsage is used for other occurrences, with changing thickness, or non-planar surfaces, with ‘Brep’ geometry.

Qto_PlateBaseQuantities includes Width, Perimeter, GrossArea, NetArea, GrossVolume, NetVolume, GrossWeight and NetWeight.

IfcChimney

Chimneys are typically vertical parts of the construction of a building. Often constructed by pre-cast or in-situ concrete or by bricks. Qto_ChimneyBaseQuantities contains only Length.

IfcFooting

Footing is a part of the foundation of a structure that transmits the load to the ground. Geometry and MaterialLayerSetUsage is undefined for footings in IFC.
Qto_FootingBaseQuantities contain Length, Width, Height, CrossSectionArea, OuterSurfaceArea, GrossSurfaceArea, GrossVolume, NetVolume, GrossWeight and NetWeight

IfcBuildingElementProxy

IfcBuildingElementProxy is a proxy element that provides the same functionality as other subtypes of IfcBuiltElement, without having the definition of the type of building element it represents. It can be used to exchange unique types of elements which do not have a semantic definition in IFC or in the authoring platform. Qto_BuildingElementProxyQuantities includes NetSurfaceArea and NetVolume.

3.2. Product Data Templates for Built Elements

In the PDT (2.4.1.1) proposed in the thesis 'Integrated Planning and Recording Circularity of Construction Materials through Digital Modelling' (Kuzminykh, 2022), the data template is used to declare properties for products and materials. In the case where a built element cannot be reused as a complete system, it will be broken down into its constituent materials and then reused or recycled. The information required to facilitate reuse of an element such as a door are different from those required from a material such as wood. Therefore, the PDT proposed in this work consists of 2 levels, namely the product level PDT, as elaborated in this section 3.2 and the material level PDT, as elaborated in the next section 3.3, with specific requirements for each type. Several of properties are adapted directly from the PDT proposed by Artur Kuzminykh, and others changed from being user declared properties to being model-dependent and automatically derived, following property and quantity set information storage capacities of IFC elements and materials. The derived properties in the proposed PDT for Built Elements are:

- 'Tier1BuildingAspect', which specifies the scope of the part and 'Tier2Building Aspect' which defines the functionality of the building part according to Level(s) tiers classification, as elaborated in Figure 26.

Scope of parts	Building parts
Structure	○ Load bearing structural frame ○ Load bearing external walls ○ External and internal columns ○ Floor and roof structures ○ Foundations
Shell	○ Non-load bearing external walls ○ Facades (including windows and doors) ○ Cladding and internal linings of external walls ○ Roof coverings and linings
Core	○ Fit out (flooring, ceilings and linings) ○ Non-load bearing internal walls ○ Services: – Lighting – Energy – Ventilation – Sanitation

Figure 26 - Assessment scope of Building parts according to Level(s)
(Dodd, Donatello, et al., 2021)

- ‘Classification’ code will be used to classify all building products according to Uniclass 2015, which is useful for a standardised and granular identification of the products in the market. Classification is stored with IfcClassificationReference and IfcRelAssociatesClassification relationships in IFC.
- ‘ItemCanBeReused’ denotes whether the product can be used as such after disassembly or deconstruction, without the need of further processing or recycling into constituent materials.
- ‘ItemTypeOfJoints’ is used to denote the products deconstruction possibilities. It will be assigned a value ranging from 1 to 3, 1 being fully dismountable mechanical joints without use of wet processes, 2 being dismountable joints that require extra effort for disassembly and 3 being attached/ welded elements that require extra human effort or machinery for disassembly.
- ‘Image’ will be used to provide a link to a photo document of the product, which can be used to evaluate the condition of the product, especially relevant for products which can be resold in the market.
- The ‘Description’ property should be used to provide a brief description of the product, which should include relevant information not part of the other parameters, including the condition of the product. Description is an attribute of IfcRoot and is an innate property of every IfcBuiltElement.

As per ‘Synthetic manual on survey-planning for to-be-demolished constructions’ by RecycleBIM, samples will be taken from several building products to test the quality of the recovered material as part of the on-site testing. Inspection forms will be filled according to the onsite inspection and test results. To identify which element the sample came from and for selective demolition according to the test results, a new property ‘SampleReference’ is proposed to be added. It is important to declare whether an element is loadbearing or not, because it can determine the quality of the materials used and can help determine the sequence of demolition and deconstruction. ‘LoadBearing’ is a property which is a part of Pset_Common of relevant built elements and is proposed to be added to the PDT of built elements.

The properties ‘Tier1BuildingAspect’, ‘Tier2BuildingAspect’, ‘ItemCanBeReused’, ‘ItemTypeOfJoints’, ‘Image’, and ‘SampleReference’ are not semantically defined in existing IFC property sets and are defined with a custom property set ‘Pset_RecycleBIM’. The selection of quantity parameters depends on the type of object, the capacity of the IfcBuiltElement to store that quantity and whether it is relevant to this use case. Knowing the volumes of generated CDW can help in the estimation of revenue generated and can help in planning logistics of transportation and storage. The properties and quantities in the data template were tested for the selected building products to check which properties and quantities are relevant for each product. The building elements which have relevant reuse or recycle potential, and significant volumes and hence considered for the Deconstruction Information Model include multi-layered elements IfcSlab, IfcWall, IfcRoof, monolithic elements IfcBeam, IfcColumn, opening elements IfcDoor, IfcWindow, component elements IfcMember, IfcPlate, IfcStairflight, IfcRampflight, IfcFooting, IfcChimney

Table 1 and Table 2 elaborates the Properties and Quantities in the proposed Data Template and their applicability across the selected Built Elements. Table 3 shows the example of a filled Product Data sheet for a Beam element.

Table 1 – Product Data Templates for Built Elements I

Element	Wall	Slab	Roof	Beam	Column	Window	Door
Alphanumerical Information							
Tier1BuildingAspect	Y	Y	Y	Y	Y	Y	Y
Tier2BuildingAspect	Y	Y	Y	Y	Y	Y	Y
Classification	Y	Y	Y	Y	Y	Y	Y
ItemCanBeReused	Y	Y	Y	Y	Y	Y	Y
ItemTypeOfJoints	Y	Y	Y	Y	Y	Y	Y
Image	Y	Y	Y	Y	Y	Y	Y
Description	Y	Y	Y	Y	Y	Y	Y
SampleReference	Y	Y	Y	Y	Y	-	-
LoadBearing	Y	Y	Y	Y	Y	-	-
Quantity Information							
Height	-	-	-	-	-	Y	Y
Width	-	Y	-	-	-	Y	Y
Length	-	-	-	Y	Y	-	-
NetVolume	Y	Y	-	Y	Y	-	-
NetArea	-	-	Y	-	-	-	-
Per each Material Layer							
MaterialVolume	Y	Y	Y	Y	Y	-	-
MaterialSideArea	Y	-	-	Y	Y	-	-
MaterialWeight	Y	Y	Y	Y	Y	-	-
MaterialThickness	Y	Y	Y	Y	Y	-	-

Table 2 - Product Data Templates for Built Elements II

Element	Stair flight	Ramp flight	Member	Plate	Fastener	Chimney	Footing
Alphanumerical Information							
Tier1BuildingAspect	Y	Y	Y	Y	Y	Y	Y
Tier2BuildingAspect	Y	Y	Y	Y	Y	Y	Y
Classification	Y	Y	Y	Y	Y	Y	Y
ItemCanBeReused	Y	Y	Y	Y	Y	Y	Y
ItemTypeOfJoints	Y	Y	Y	Y	Y	Y	Y
Image	Y	Y	Y	Y	Y	Y	Y
Description	Y	Y	Y	Y	Y	Y	Y
SampleReference	Y	Y	-	-	-	Y	Y
LoadBearing	Y	Y	Y	Y	Y	Y	Y
Quantity Information							
Height	-	-	-	-	-	-	-
Width	-	-	-	Y	-	-	-
Length	-	Y	Y	-	-	Y	-
NetVolume	Y	Y	Y	Y	-	-	Y
NetArea	-	-	-	-	-	-	-
Per each Material Layer							
MaterialVolume	Y	Y	Y	Y	-	Y	Y
MaterialSideArea	-	-	-	-	-	-	-
MaterialWeight	Y	-	-	-	-	-	-
MaterialThickness	-	-	-	-	-	-	-

Table 3 - Product Data Sheet example for Beam

Property	Data Type	Unit	Location	Example
Tier1BuildingAspect	IfcLabel	-	Pset_RecycleBIM	Shell
Tier2BuildingAspect	IfcLabel	-	Pset_RecycleBIM	Load Bearing Structural Frame
Classification	IfcClassification	-	IfcClassification	Pr_20_85_08_15
ItemCanBeReused	IfcBoolean	-	Pset_RecycleBIM	FALSE
ItemTypeOfJoints	IfcInteger	-	Pset_RecycleBIM	3
Image	IfcText	-	Pset_RecycleBIM	https://thumb_concrete_beam.jpg
Description	IfcText	-	IfcRoot	Reinforced Concrete Beam
SampleReference	IfcText	-	Pset_RecycleBIM	A_8765
LoadBearing	IfcBoolean	-	Pset_BeamCommon	TRUE
Quantity Information				
Length	IfcQuantityLength	m	Qto_BeamBaseQuantities	9.5
NetVolume	IfcQuantityVolume	m^3	Qto_BeamBaseQuantities	1.479
Per each Material Layer				
MaterialVolume	IfcQuantityVolume	m^3	IfcPhysicalComplex Quantitiy	1.479
MaterialSideArea	IfcQuantityArea	m^2	IfcPhysicalComplex Quantitiy	0.16
MaterialWeight	IfcQuantityWeight	kg	IfcPhysicalComplex Quantitiy	3550
MaterialThickness	IfcQuantityLength	mm	IfcPhysicalComplex Quantitiy	400

3.3. Product Data Templates for Materials

When built elements need to be broken down into its constituent materials for reusing and recycling, the relevant information regarding the contained materials should be filled in the PDT for materials. The properties adapted from the PDT mentioned in section 2.4.1.1 are:

- ‘WasteCode’, where each material waste is assigned according to waste type by a six-digit code according to the European List of Wastes (LoW). The LoW defines 839 waste types which are structured into 20 chapters according to the source of the waste. (European Commission, 2010)
- ‘ItemCanBeReused’, used to denote whether the material can be reused in its current form without extra processing.
- ‘CanBeRecycled’ to indicate if the material cannot be reused but can be recycled.
- ‘ItemTypeOfJoints’ describes how complex the process of disassembly of the material will be from a scale of 1 to 3.

Additional properties are proposed according to the materials study in section 2.3 and the IFC property set study elaborated in section 3.1.1. According to the European guideline for waste audits, (European Commission, 2018), it is important to determine which materials are hazardous and which are not during the waste audit. Therefore, a property ‘Hazardous’ was added to the data template for materials, which will be filled with True or False accordingly. The strength of the material, if the information is available from existing documentation, or determined through on-site testing, is important in determining the quality of the recovered material. ‘CompressiveStrength’ for concrete and reinforced concrete, ‘StructuralGrade’ for steel are proposed additions to the PDT. ‘ReinforcementVolumeRatio’ is useful to determine the amount of steel that can be extracted from the concrete elements. The ‘Species’ of wood can be very useful when it comes to taking decisions regarding its reuse.

Building elements are related using IfcRelAssociatesMaterial to either a single material or composite materials, which are defined by:

- Layer sets where layered materials with thickness fills a boundary, defined by IfcMaterialLayerSet.
- Profile sets where materials are extruded along a profile shape, defined by IfcMaterialProfileSet.
- Constituent set where materials are homogenously mixed or arbitrarily placed, defined by IfcMaterialConstituentSet.

Since volumes are contained in the built element and not in the material, volume information is not requested in the PDT for materials.

Table 4 elaborates the applicability of the proposed PDT for common building materials.

Table 5 shows the example of a filled Product Data Sheet for steel material.

Table 4 – Product Data Template for Materials

Property	Default Material	Concrete	Reinforced Concrete	Steel	Wood
Name	Y	Y	Y	Y	Y
WasteCode	Y	Y	Y	Y	Y
CanBeRecycled	Y	Y	Y	Y	Y
ItemCanBeReused	Y	Y	Y	Y	Y
ItemTypeOfJoints	Y	Y	Y	Y	Y
Hazardous	Y	Y	Y	Y	Y
MassDensity	Y	Y	Y	Y	Y
CompressiveStrength	-	Y	Y	-	-
ReinforcementVolumeRatio	-	-	Y	-	-
StructuralGrade	-	-	-	Y	-
Species	-	-	-	-	Y

Table 5 - Product Data Sheet example for Steel material

Property	Data Type	Unit	Location	Example
Name	IfcLabel	-	IfcMaterial	Steel
WasteCode	Classification	-	IfcClassificationReference	17 04 05
CanBeRecycled	IfcBoolean	-	Pset_RecycleBIM	TRUE
ItemCanBeReused	IfcBoolean	-	Pset_RecycleBIM	TRUE
ItemTypeOfJoints	IfcInteger	-	Pset_RecycleBIM	2
Hazardous	IfcBoolean	-	Pset_RecycleBIM	NO
MassDensity	IfcMassDensityMeasure	kg/m3	Pset_MaterialCommon	7850
StructuralGrade	IfcLabel	-	Pset_MaterialSteel	A36

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4. EXCHANGE INFORMATION REQUIREMENTS AND LEVEL OF INFORMATION NEED

4.1. Information Requirements for Demolition

The ISO 19650 standard series is a global framework for effectively managing information throughout the entire lifecycle of a constructed asset using Building Information Modelling. It is being actively used across the EU for developing BIM frameworks. It provides a framework to manage information including exchanging, recording, versioning and organising for all involved actors. The document is applicable to the whole life cycle of a built asset, including end-of-life and deconstruction. It states that Exchange Information Requirements define the managerial, commercial, and technical aspects of producing project information. It includes the information standard and production methods and procedures to be followed by delivery teams. EIR is identified whenever appointments are established. (European Committee for Standardisation, 2018)

The deliverable of information exchange is an 'Information Container' and the standard EN 17412-1 specifies the Level of Information Need of Geometrical and Alphanumerical Information for these information containers. This chapter focuses on defining Information Requirements for a digitized demolition process and the creation of a Deconstruction Information Model for a sample 2-storey building. A Deconstruction Information Model (DIM) is a type of Building Information model specifically tailored for the planning and execution of building deconstruction. It provides comprehensive, visual, and data-integrated representation of a building structure, facilitating collaboration among stakeholders and supports informed decision making. While BIM spans the entire building lifecycle from design to operation, a DIM focuses exclusively on the end-of-life phase, emphasizing deconstruction planning and sustainable material management. Identifying the actors and their roles and responsibilities, the purpose of the model, the process workflow and flow of information is essential to determine the amount of information that is to be included in the model. (UK BIM Framework, 2021)

4.1.1. Actors in the demolition process

The European Commission has published the European Demolition Protocol and a document "Guidelines for the waste audits before demolition and renovation works of buildings" (European Commission, 2018) which defines the best practices to be followed for demolition projects across the EU. It aims to maximize recovery of materials and components from demolition or renovation of buildings and infrastructure. In the national level, the Portuguese National Waste Authority, the Regional Waste Authorities are responsible for the oversight of demolition activities and to ensure that the due process is followed, and that construction and demolition waste is managed properly. The Level(s) framework has indicators of sustainability that can be applied to building projects and has a chapter for Construction and demolition waste and materials (Donatello, Dodd, et al., 2021). The actors involved in the demolition process are elaborated in Figure 27.

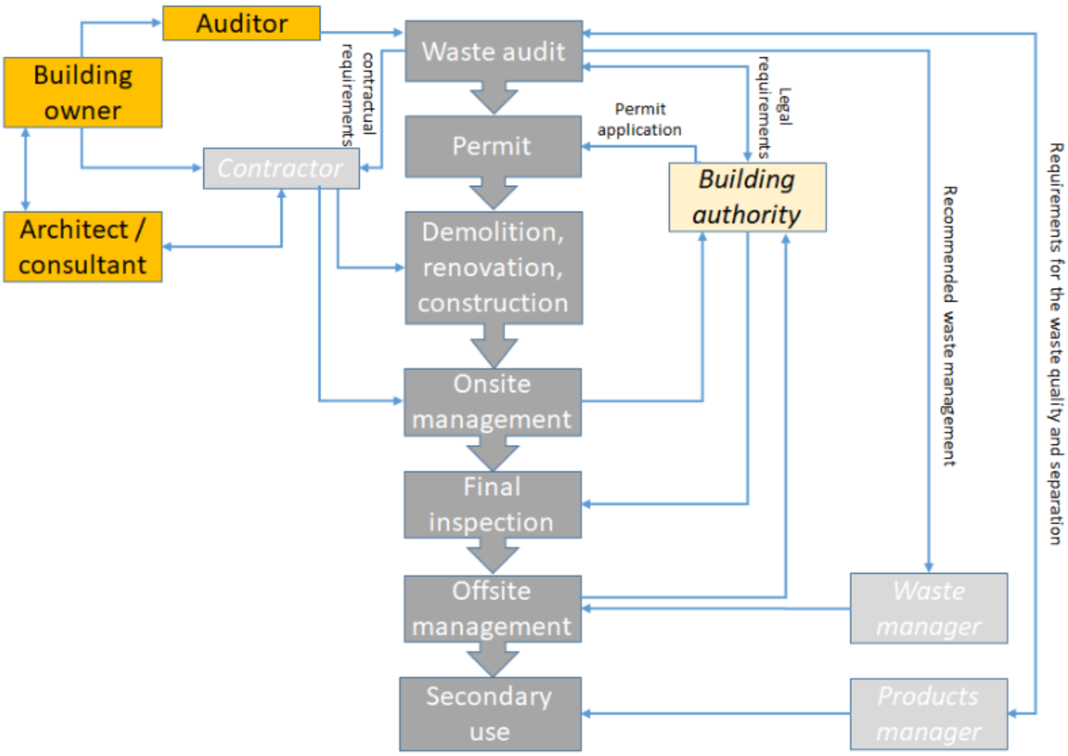


Figure 27 - Roles and responsibilities relating to CDW management
(Donatello, Dodd, et al., 2021)

The 'Property owner' is responsible for audit prior to invitation to tender for demolition. Level(s) framework defines that the audit can be done by an 'Auditor' who is familiar with construction and demolition techniques, history and state of the local market and building typologies. They will work together with a 'Waste manager' to prepare a pre-demolition audit that meets the requirements set by the building authority and forms the basis for a Waste Management Plan. After the building authority grants a permit for the demolition, a contract can be awarded to a 'Demolition company' who will be responsible for site activities and the physical demolition process. The demolition contractor will make their own survey and audit.

The addition of BIM to the workflow involves a reality capture using Scan-to-BIM methodology, which will be done by a 'Digital Surveyor' and modelling of a Deconstruction Information Model by a 'BIM Modeller' which could be done by the same party or appointed separately. The materials and building products recovered from the demolition will be routed to 'Recycling Facilities' where they are processed and to 'Marketplaces' where they can start a new lifecycle, ensuring circularity. Hazardous materials which cannot be processed directly will be routed to 'Waste Treatment Facilities'. The leftover materials which have no reuse or recycle potential will be used for energy recovery or landfilled.

Figure 28 shows the suggested appointment hierarchy in the digitized demolition process. In this scenario, the demolition company is considered the Appointing party who specifies the EIR requiring information for the inspection, building scan and creation of a DIM.

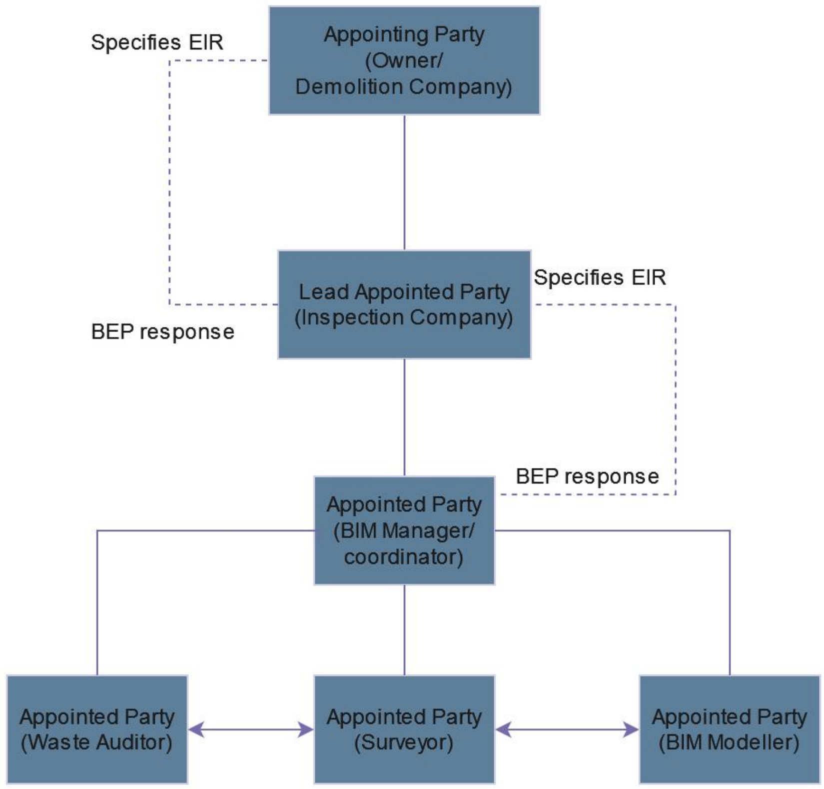


Figure 28 - Appointment hierarchy for building inspection and modelling

The 'Guideline for implementation of BEP and EIR on European level based on EN ISO 19650-1 and -2' (European Committee for Standardization, 2021), states that an EIR needs to specify the following:

- Information requirement
- Acceptance Criteria
- Supporting Information
- Information delivery milestones

4.1.2. Information Requirement

According to ISO 19650, for information exchange between the various parties involved in an appointment, the following information requirements must be considered:

Organisation Information Requirements - OIR is the starting point for all Information management activities. It details the high-level information required by an organization across its whole asset portfolio and its different departments such as human resources, information technology, finance, facilities management, and operations. The OIR helps the stakeholders understand the key information about assets as they go through their whole lifecycle. This is beneficial for the organization's leadership to make informed decisions and to know what information their clients and stakeholders require.

Policies that might inform the OIR of a demolition company can include:

- Vision, Mission, and Values of the Company
- Sustainable Development Goals
- Environmental Policy
- Construction and Demolition Waste Management Policy
- Digitization of Construction Activities

Project Information Requirements - PIR explains the information needed to inform high level strategic objectives within the appointed party in relation to a built asset project. They are identified from project and asset management processes. The PIR should include the project scope, the intended purpose for which the information will be used by the appointing party, project plan of work, the intended procurement method, the key decisions and decision point milestones and the questions to which the appointing party needs answers, to make informed decisions. The project considered is a fictional 2 storey to-be-demolished building, the PIR of which is elaborated in Table 6.

Table 6 - Project Information Requirements

The Project scope	Inspection, Scan capture and BIM model of a 2-storey building
The Intended purpose	• Identification and quantification of building elements • Identification and quantification of materials • Demolition planning • Optimized waste stream routing
Plan of work	• Direct appointment and mobilization of resources • Workshop with appointed parties • Onsite Inspection and Scan capture • Producing the model • Approval of model and information requirements • Support during demolition
Intended procurement route	Lump sum contract after approval of BEP
The number of key decision points throughout the project	Decision point 1 - dd/mm/yy Decision point 2 - dd/mm/yy
Decisions to be made at each point	Decision 1 Decision 2
The questions to which the appointing party needs answers	Does the model accurately capture existing asset information? Does the model satisfy the information requirements?

Asset Information Requirements - AIR sets out managerial, commercial, and technical aspects of producing asset information. It includes the information standard and production methods, defining the graphical and non-graphical data, information and documentation needed for the lifetime operation and management of a built asset. Since the concerned process is a demolition, information about lifetime operation and management of the built asset is not requested.

4.1.3. Acceptance Criteria

Acceptance criteria are conditions used to check that the information is delivered correctly. It comprises of the project's information standard, the project's information production methods and procedures and reference information and shared resources. They ensure that all deliverables are compliant with the information requirements.

Project Information Standards

Information shall be produced in line with the project's information standard to ensure successful exchange with other technologies, using open data formats wherever possible. All project information production and management should adhere to the following standards.

- ISO 19650 Series for information management
- BS EN 17412-1:2020 for Level of information need specification
- ISO 16739-1 – IFC Data schema
- ISO 23387 for definition of data templates
- ISO 22057 for definition of data templates for the use in EPD
- ISO 23386 – definition of properties in accordance with existent data dictionaries
- Level(s) framework for asset sustainability assessment
- Extract Regulation (EC) 2150/2002

The project information standards should specify the units of measurement to be used by all parties to maintain consistency throughout the project. Table 7 elaborates the project units to be followed in the appointment.

Table 7 - Project Units

Type	Unit	Symbol
Length	Metre	m
Area	Square metre	m^2
Volume	Cubic metre	m^3
Angle	Degree	°
Currency	Euro	€

Mass Density	Kilogram per cubic metre	kg/m^3
Time	Seconds	s
Weight	Kilogram	kg
Distance	Metre	m
Speed	Kilometre per hour	km/h
Temperature	Degree Celsius	°C

Information Production procedure

A Deconstruction Information Model aims to streamline the process of information management and remove some of the barriers to CDW Recycling and reuse. The purpose of a DIM is to facilitate role of to-be-demolished buildings as Urban Mines and promote circularity of materials. The information from the model can be used to populate a database of available reusable materials and products which is then connected to the marketplaces for reselling to customers. The Deconstruction Information Model is to be made when an appointment is made to demolish a building. It will be made with information from existing documentation about the building, a digital survey such as laser scan, and on-site inspection.

The addition of a BIM model to the process of demolition is aimed at better quantity estimation with more accuracy and easier decision making. However, the creation of a BIM model for a 'to-be-demolished' construction should not be so complex that it makes the whole process more expensive and hence outweighs the benefits (Parente et al., 2023). The model should provide specific information that is requested about the various building elements and materials, and these are the alphanumerical and geometric information requirements as specified according to the Level of Information Need. Figure 29 shows the process model where the inputs, the actors, the controls and expected outputs regarding a Deconstruction Information Model are specified.

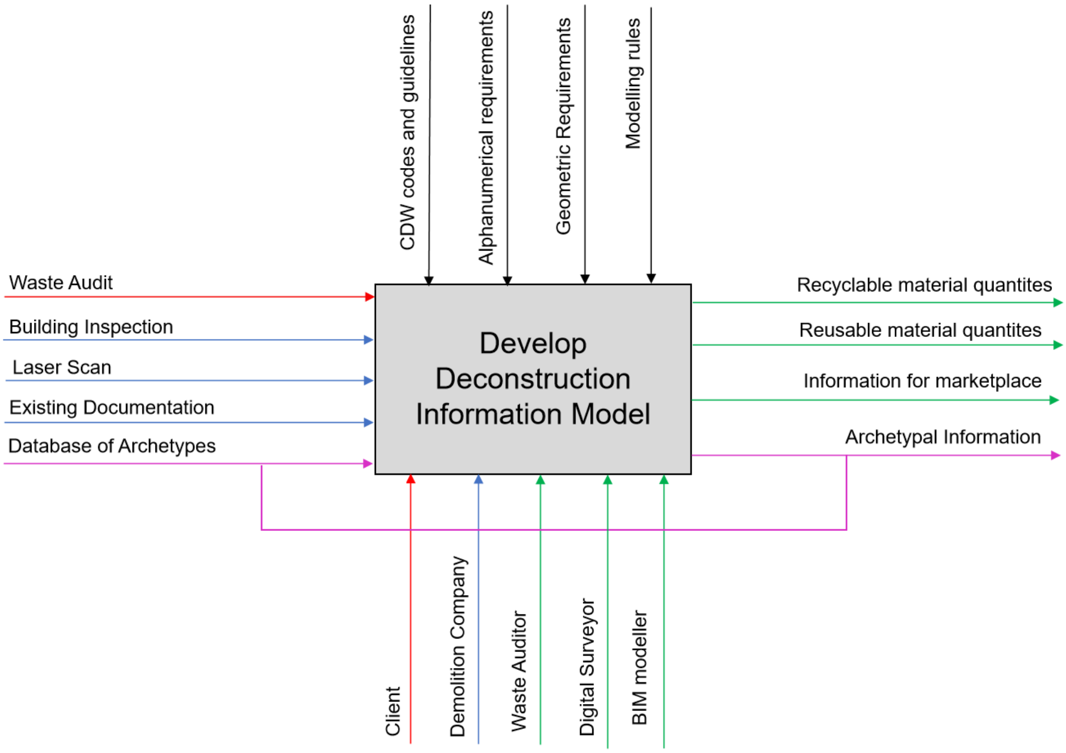


Figure 29 - Process model for creating a DIM

A responsibility matrix can be used to define the parties participating in the major tasks associated with the project and assigns responsibilities to each involved party. The suggested responsibilities for the demolition appointment are elaborated in Table 8 in the form of a RACI matrix. A RACI matrix is a project management and organizational tool used to define and clarify roles and responsibilities for tasks and activities within a project or business process. R- Responsible for undertaking activity, A – Accountable for activity completion, C- Consulted during activity, I – Informed following activity completion.

Table 8 - RACI Matrix

Deliverable	Demolition Company	Waste Auditor	Surveyor	BIM Coordinator	BIM Modeller
Building Inspection	C	C	R	A	I
Capture of Existing Condition	I	I	R	C	I
Design Authoring	I	-	C	A	R
Model Coordination	I	-	-	R	C
Model Quality Control	I	-	-	R	C

The software specifications and file format versions should also be specified so that information can be shared seamlessly within the delivery teams and with the appointing and lead appointed parties. The authoring software and exchange formats for the appointment are specified in Table 9.

Table 9 - Data Authoring Software and Formats for Exchange

Type	Software	Symbol
Model Authoring	Archicad 26	.pln
Model Exchange	IFC 4.0.2.1	.ifc
Clash detection	Navisworks	.nwf, .nwc
Reports	-	.pdf, .doc, .xls
Images	-	.jpg, .jpeg, .png
Laser scan point cloud	-	e57 and rcp

Common Data Environment

Details about the Common Data Environment should be specified, and the appointing party will manage the CDE and provide access to the delivery team and appointed parties, meeting all project security requirements. All information containers (reports, drawings, models, specifications) will be shared via the CDE.

- The platform will be Autodesk BIM360.
- All shared documents should follow ISO 19650 standards for BIM implementation.
- The nomenclature of models, files and folder structure should be done according to discipline.

Model Quality Control and Validation

Clash detection should be undertaken by the modelling party to ensure integrity of geometrical information. The model should be validated with an IDS that will be provided by the appointing party to ensure basic quality check and presence of information. The model should meet the alphanumerical information requirements based on the Product Data Templates of building products and materials.

4.1.4. Supporting Information

This study focuses on to-be-demolished buildings which do not have existing BIM models. Therefore, it is important to collect the existing documentation of the building in all available forms. It includes existing documentation that could be used and referred to by the appointed party for producing information deliverables and preparing tender response. The appointing party should make all relevant existing information available to help the lead appointed party better understand and evaluate the requirements and acceptance criteria.

Architectural drawings such as building plans, elevations, sections, sanction drawings, site and topography surveys, documentation of services such as electrical drawings, plumbing drawings, structural drawings, etc should be collated so that the BIM model can be made accurately and to make sure that existing information is not lost while making critical decisions. The drawings can support the scan-to-BIM workflow by providing supplementary information, which is not easily accessed through a laser scan or on-site inspection. Information can also be supplemented from a database of archetypes and new digital models can enrich existing databases with more information. All existing documents, drawings, models will be shared by the appointing party to the appointed parties to prevent redundancy of work. Libraries of objects and required templates will be shared for use in the project.

The following guidance material regarding demolition practices will be shared to all appointed parties:

- Inspection Manual from RecycleBIM
- Laser Scanning guide from RecycleBIM
- Level of Information Need Tables from RecycleBIM
- European guidelines for demolition and reclamation audits.
- Level(s) indicator 2.2: Construction and Demolition waste and materials. https://susproc.jrc.ec.europa.eu/product-bureau/sites/default/files/2020-10/20201013%20New%20Level(s)%20documentation_2.2%20C&d%20waste_Publication%20v1.0.pdf
- Guidance on classification of waste according to EWC-Stat categories. https://ec.europa.eu/eurostat/documents/342366/351806/Guidance-on-EWCStat-categories-2010.pdf/0e7cd3fc-c05c-47a7-818f-1c2421e55604
- Construction and Demolition Waste management in Portugal. https://www.researchgate.net/publication/283255176_Construction_and_Demolition_Waste_Management_in_Portugal
- Material Passports - Best practices. https://www.bamb2020.eu/news/publication-materials-passports/

4.1.5. Information delivery milestones

The project's information delivery milestones specify when the information is needed by the appointed party. This should accommodate the time required to accept the information. This can be a date, frequency, or relative to an event. Milestones allow the appointing party and appointed parties to plan and mobilize resources for the project. Table 10 elaborates a sample of how each activity milestone can be specified, with the required deliverables and on a specified date.

Table 10 - Information delivery milestones

Work Stage	Milestone	Work package	Deliverable	Date
Inspection	Milestone 1	Visual inspection	Inspection report	<Date>
	Milestone 2	Scan capture	Point cloud	<Date>

BIM Model Creation	Milestone 1	Model authoring	BIM Model	<Date>
	Milestone 2	Model validation	Model in Ifc	<Date>

4.2. Level of Information Need

Level of Information Need defines the extent and granularity of information to be exchanged. According to BS EN 17412-1 (British Standards Institution, 2020), the level of information need is described by three different concepts: alphanumerical information, geometrical information, and documentation.

4.2.1. Alphanumerical Requirements

To specify the alphanumerical information for an object or set of objects, the identification and information content should be specified.

Identification – To identify an object within a breakdown structure. Name, Object Class, Classification, WBS structure etc can be used for identification. All objects should be declared according to accurate IFC classes, such as IfcWall for walls, IfcWindow for windows, IfcSlab for slabs, etc.

Information Content – Elaborates the list of all properties required to fulfil a specific purpose. As discussed in chapter 3, Product Data Templates are used to declare the required properties and information of materials and building elements to act as digital passports to improve circularity.

4.2.2. Geometrical Requirements

The EN 17412:1 state that to specify the geometrical information of an object in a BIM model, the following aspects need to be considered:

- Detail - describes the complexity of the object geometry from simplified to detailed, compared to the real-world object. The level of detail required depends on the type of object and the information that is required from the object. Since the asset considered is about to be demolished, it is not necessary to have complex geometry for the objects as they will be used mostly for quantity estimation and scheduling for demolition planning. To keep the model lean and to avoid excess detail and information, 'Simplified' detail is proposed for the building elements in the DIM. Even though simplified geometry is requested, care should be taken that specific objects includes all requested material layers and layer quantities.
- Dimensionality – defines the number of spatial dimensions of the object, ranging from zero dimensional, one dimensional, two dimensional and three dimensional. The dimensionality depends on what information is requested from the object and as we require most objects to include volume information, it should be in 3D. Non geometric objects can be represented as 0D or 1D.
- Location –The 'Absolute' location of an object is expressed by its orientation and position within a reference system based on grids, or a reference point such as survey point. 'Relative' location is expressed by an object's position and orientation in terms of relationships with other

objects, such as window with reference to a wall and component objects within assembled objects.

- Appearance –In the DIM, different colours are requested for different layers within objects for easy identification. Textures are not requested as visual appearance is not an important factor.
- Parametric Behaviour – In the case of a DIM, the geometry is produced for a singular use case, i.e., to calculate the quantity of recoverable materials, products and for demolition planning. Since there is no need of design transfer for further development, parametric behaviour and shape modification for objects is not requested and 'Explicit geometry' is sufficient for most of the requested objects.

4.2.3. Documentation Requirements

The documentation required for an object or model to support processes, for decision making, verification of deliverables and providing approval should be specified as a set of documents.

Structured information includes geometrical models, schedules, and databases. Examples of unstructured information include documentation, video clips and sound recordings.
Physical sources of information, such as soil and product samples, should be managed using the information management process described in the EIR document through appropriate cross-references.

4.2.4. Modelling Rules

- Elements should be modelled with the corresponding type in authoring software, such as walls using wall tool, columns using column tool, wherever possible. If an object does not have a specific tool for modelling in authoring software, it can be modelled with a generic model tool but should be mapped to the correct IFC Object Type.
- Four types of objects with different geometric requirements are defined -
    - Multi Layered Object - Model element should contain layers for each constituent material with accurate thicknesses. Openings for hosted elements. Should include accurate Quantities.
    - Monolithic object - Objects which do not require layers and should include accurate unit size (width, height, length) as applicable. Should include accurate Quantities.
    - Assembled object – Objects which are an assembly of component objects. Does not require accurate quantity information or alphanumerical information as the information will be contained in the component object.
    - Component objects - basic objects which are components of assembled objects. Should include accurate quantity information.
    - Elements such as doors and windows should be assigned to their respective levels with accurate displacements from the corresponding level.
- IfcBuildingElementProxy should be used to declare only reference codes of samples.
- All aggregate/ assembled objects should be declared with as an assembly of component parts.
- Geometries of different objects should not overlap and create duplicate quantities.
- Multi Layered Objects where material layers have different conditions of re-usability and recyclability should be modelled with separate objects.

- Multi Layered objects where layers have different heights should be modelled accurately, either by setting the layer heights within the object or modelling the layers separately with the corresponding heights
- Object instances which have different properties (Eg., Load bearing/Non load bearing) should be divided into different instances.

Based on the requirements of the Level of Information need, tables were created for each building element, where the milestone, the purpose/s, the actor/s are defined and the geometrical requirements, alphanumerical requirements and documentation requirements are elaborated. Table 11 - Level of Information Need (Walls, Slabs), Table 12 - Level of Information Need (Roof, Members), Table 13 - Level of Information Need (Doors, Windows), Table 14 - Level of Information Need (Column, Beam), Table 15 - Level of Information Need (Railing, Curtain Wall), Table 16 - Level of Information Need (Plate, Member), Table 17 - Level of Information Need (Stair, Ramp), Table 18 - Level of Information Need (Stair Flight, Ramp Flight), Table 19 - Level of Information Need (Fastener, Chimney) specify the Level of Information Need of mentioned elements.

The subsequent chapter deals with the demonstration of modelling in authoring software and exchange in IFC following the EIR and Level of Information Need specification. The steps taken to ensure compliance with the modelling rules and geometrical requirements and structure of information is elaborated. An automated validation process to check the presence and quality of requested information is also defined.

Table 11 - Level of Information Need (Walls, Slabs)

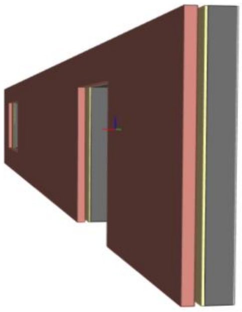
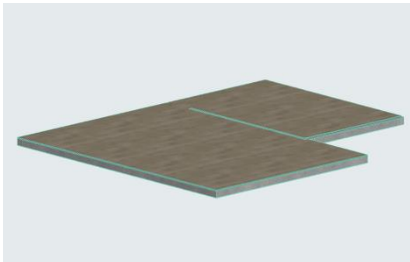
Milestone	Demolition and waste stream planning	
Purpose	CDW management, Quantity Estimation	
Actor	Inspection Company (BIM Modeller)	
Object	**Walls**	**Slabs**
	Geometrical Information	
Detail	Simplified – Multi Layer Object	Simplified - Multi Layer Object
Dimensionality	3D	3D
Location	Absolute	Absolute
Appearance	Different colours for each layer. Textures not requested	Different colours for each layer. Textures not requested
		
Parametric Behaviour	Explicit geometry	Explicit geometry
	Alphanumerical Information	
Identification	Object type IfcWall. Uniclass2015. Classified according to type of Walls. Eg., EF_25_10_25	Object type IfcSlab. Uniclass2015. Classified according to type of Slab Eg., Pr_20_85_14_16
Information Content	As per PDT of Wall	As per PDT of Slab
Documentation	Model in IFC, linked images, sample information	Model in IFC, linked images, sample information

Table 12 - Level of Information Need (Roof, Members)

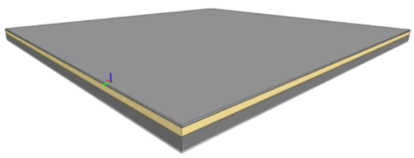
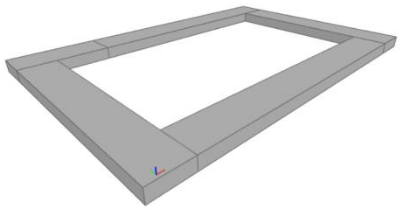
Milestone	Demolition and waste stream planning	
Purpose	CDW management, Quantity Estimation	
Actor	Inspection Company (BIM Modeller)	
Object	**Roof**	**Footing**
	Geometrical Information	
Detail	Simplified – Multi Layer Object	Simplified - Monolithic Object
Dimensionality	3D	3D
Location	Absolute	Relative
Appearance	Different colours for each layer. Textures not requested	Single colour. Textures not requested
		
Parametric Behaviour	Explicit geometry	Explicit geometry
	Alphanumerical Information	
Identification	Object type IfcRoof Uniclass2015. Classified as Roofs EF_30_10_30	Object type IfcFooting Uniclass2015. Classified according to footing type. Eg., Pr_20_85_13_32
Information Content	As per PDT of Roof	As per PDT of Member
Documentation	Model in IFC, linked images	Model in IFC, linked images

Table 13 - Level of Information Need (Doors, Windows)

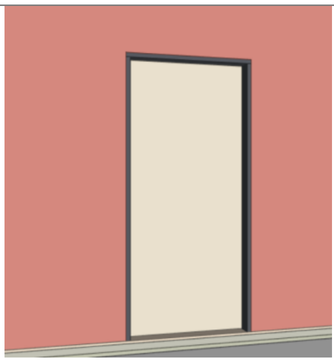
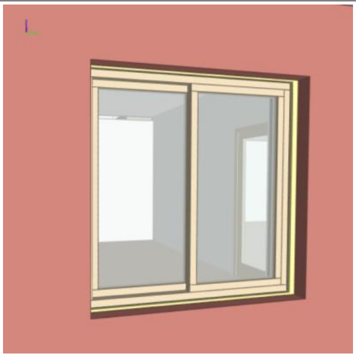
Milestone	Demolition and waste stream planning	
Purpose	CDW management, Quantity Estimation	
Actor	Inspection Company (BIM Modeller)	
Object	**Doors**	**Windows**
	Geometrical Information	
Detail	Simplified - Monolithic Object. Frame and panel required. Other details are omitted.	Simplified - Monolithic Object. Frame and panel required. Other details are omitted.
Dimensionality	3D	3D
Location	Relative	Relative
Appearance	Colours and textures not requested	Colours and textures not requested
		
Parametric Behaviour	Explicit geometry	Explicit geometry
	Alphanumerical Information	
Identification	Object type IfcDoor Classified according to type of Doors. Eg., EF_25_30_25	Object type IfcWindow Classified according to type of Window. Eg. Pr_30_59_98_02
Information Content	As per PDT of Window	As per PDT of Window
Documentation	Model in IFC, linked images,	Model in IFC, linked images

Table 14 - Level of Information Need (Column, Beam)

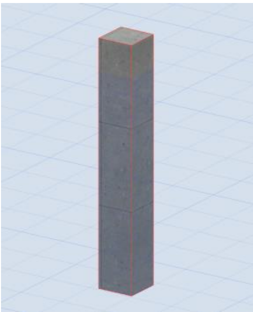
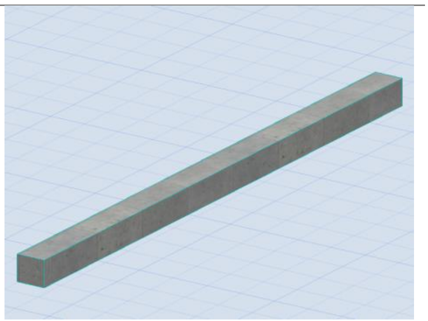
Milestone	Demolition and waste stream planning	
Purpose	CDW management, Quantity Estimation	
Actor	Inspection Company (BIM Modeller)	
Object	**Column**	**Beam**
	Geometrical Information	
Detail	Simplified - Monolithic Object	Simplified - Monolithic Object
Dimensionality	3D	3D
Location	Absolute	Absolute
Appearance	Single colour. Textures not requested	Colours and textures not requested
		
Parametric Behaviour	Explicit geometry	Explicit geometry
	Alphanumerical Information	
Identification	Object type IfcColumn Classified according to type of Column. Eg., Pr_20_85_16_15	Object type IfcBeam Classified according to type of Beam. Eg., Pr_20_85_08_15
Information Content	As per PDT of Column	As per PDT of Beam
Documentation	Model in IFC, linked images, sample information	Model in IFC, linked images, sample information

Table 15 - Level of Information Need (Railing, Curtain Wall)

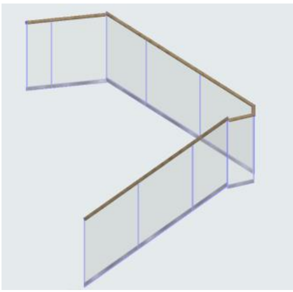
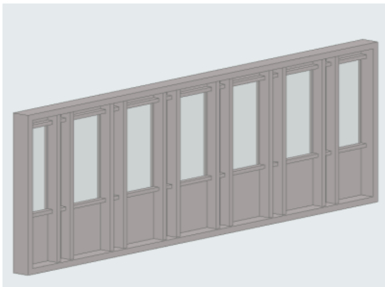
Milestone	Demolition and waste stream planning	
Purpose	CDW management, Quantity Estimation	
Actor	Inspection Company (BIM Modeller)	
Object	**Railing**	**Curtain Wall**
	Geometrical Information	
Detail	Simplified - Assembled Object	Simplified - Assembled Object
Dimensionality	3D	3D
Location	Absolute	Absolute
Appearance	Different colours for handrail, baluster, and panel. Textures not requested	Different colours for panels and mullions. Textures not requested
		
Parametric Behaviour	Explicit geometry	Explicit geometry
	Alphanumerical Information	
Identification	Handrails and balusters defined as IfcMember and Panel as IfcPlate Classified as Handrails Pr_25_30_36	Panels defined as IfcPlate, Mullions defined as IfcMember Classified as Curtain walling systems Ss_25_10_20 .
Information Content	As per PDT of Member and Plate	As per PDT of Member and Plate
Documentation	Model in IFC, linked images	Model in IFC, linked images

Table 16 - Level of Information Need (Plate, Member)

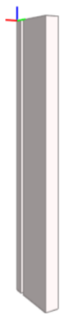
Milestone	Demolition and waste stream planning	
Purpose	CDW management, Quantity Estimation	
Actor	Inspection Company (BIM Modeller)	
Object	**Plate**	**Member**
	Geometrical Information	
Detail	Simplified - Component Object	Simplified - Component Object
Dimensionality	3D	3D
Location	Relative	Relative
Appearance	Symbolic geometry. Colours and textures not requested	Symbolic geometry. Single colour. Textures not requested
		
Parametric Behaviour	Explicit geometry	Explicit geometry
	Alphanumerical Information	
Identification	Object type IfcPlate Classified according to type of Plate. Eg., Pr_35_90_33_20	Object type IfcMember Uniclass2015. Classified according to member type. Eg., Pr_20_76_51_02
Information Content	As per PDT of Plate	As per PDT of Member
Documentation	Model in IFC, linked images	Model in IFC, linked images

Table 17 - Level of Information Need (Stair, Ramp)

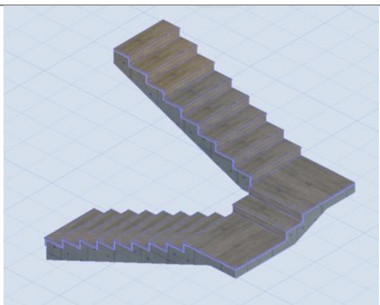
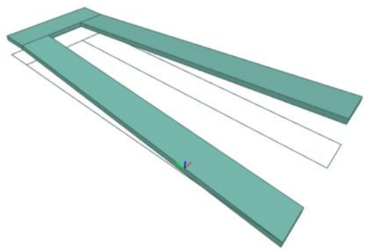
Milestone	Demolition and waste stream planning	
Purpose	CDW management, Quantity Estimation	
Actor	Inspection Company (BIM Modeller)	
Object	**Stair**	**Ramp**
	Geometrical Information	
Detail	Simplified - Assembled Object	Simplified – Assembled Object
Dimensionality	3D	3D
Location	Absolute	Absolute
Appearance	Symbolic geometry. Different colour for each layer. Textures not requested	Symbolic geometry. Single colour. Textures not requested
		
Parametric Behaviour	Explicit geometry	Explicit geometry
	Alphanumerical Information	
Identification	Stairs defined as an assembly of IfcStairflight and IfcSlab Classified according to type of stair Eg., EF_35_10_40	Ramp defined as assembly of IfcRampflight and IfcSlab Classified as Ramps EF_35_20
Information Content	As per Product Data Template of IfcStairFlight and IfcSlab	As per Product Data Template of IfcRampflight and IfcSlab
Documentation	Model in IFC, linked images	Model in IFC, linked images

Table 18 - Level of Information Need (Stair Flight, Ramp Flight)

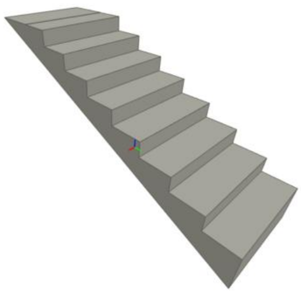
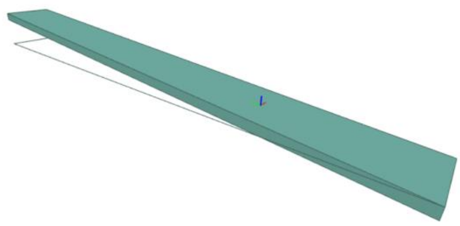
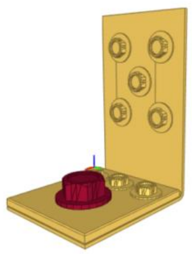
Milestone	Demolition and waste stream planning	
Purpose	CDW management, Quantity Estimation	
Actor	Inspection Company (BIM Modeller)	
Object	**Stair Flight**	**Ramp Flight**
	Geometrical Information	
Detail	Simplified - Component Object	Simplified - Component Object
Dimensionality	3D	3D
Location	Relative	Relative
Appearance	Symbolic geometry. Different colour for each layer. Textures not requested	Symbolic geometry. Different colour for each layer. Textures not requested
		
Parametric Behaviour	Explicit geometry	Explicit geometry
	Alphanumerical Information	
Identification	Object type IfcStairFlight Classified as Stairflight Pr_25_30_90	Object type IfcRampflight Classified according to type of Ramp. Eg., Pr_30_59_01
Information Content	As per PDT of Stair flight	As per PDT of Rampflight
Documentation	Model in IFC, linked images, sample information	Model in IFC, linked images, sample information

Table 19 - Level of Information Need (Fastener, Chimney)

Milestone	Demolition and waste stream planning	
Purpose	CDW management, Quantity Estimation	
Actor	Inspection Company (BIM Modeller)	
Object	**Fasteners**	**Chimneys**
	Geometrical Information	
Detail	Simplified - Component Object	Simplified - Monolithic Object
Dimensionality	3D	3D
Location	Relative	Absolute
Appearance	Symbolic geometry. Single colour. Textures not requested	Symbolic geometry. Single colour. Textures not requested
		
Parametric Behaviour	Explicit geometry	Explicit geometry
	Alphanumerical Information	
Identification	Object type IfcFastener Classified as Stairflight Pr_25_30_90	Object type IfcChimney Classified according to type of Ramp. Eg., Pr_30_59_01
Information Content	As per PDT of Fastener	As per PDT of Chimney
Documentation	Model in IFC, linked images, sample information	Model in IFC, linked images, sample information

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5. DEMONSTRATION OF MODELLING, EXPORT TO IFC AND VALIDATION USING IDS

5.1. Model in Authoring Software

The next objective was to create a model that aligns with the Level of Information Need and Exchange Information Requirements detailed in section 4.2. This was done to test the workflow of modelling the elements according to modelling rules, addition of custom properties requested according to the PDTs, checking the quantity information of building elements, creating property sets, exporting to IFC format for exchange and validating the model. Archicad26 was selected as the authoring software for its streamlined IFC export and management capabilities. As specified in the EIR, a 2-storey framed structure building, which includes relevant built elements and major materials was created, as shown in Figure 30. In the actual workflow specified by RecycleBIM, the model will be created based on a point cloud.

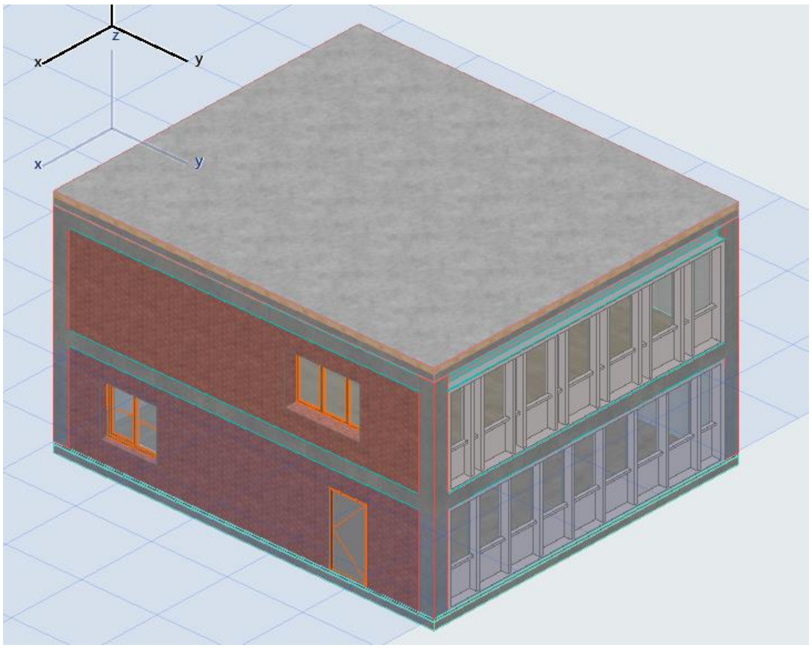


Figure 30 – Model in Archicad

According to the modelling rules, all elements are modelled with tools specific to the element. When modelled with the specific tools, the objects are automatically mapped to the accurate IFC class and predefined type. The object class can be changed or specified by modifying the instance properties.

According to the Level of information need, walls with different layers of materials need to be modelled with accurate layer thicknesses and material properties. Composites have multiple layers, where each layer thickness can be specified and can be assigned different materials. This can be used to model the multi-layer elements such as Walls, Slabs, and Roofs, as elaborated in Figure 31. The 'Building materials' manager allows us to edit the properties of each material, add specific information, classification, modify the visual characteristics, etc.

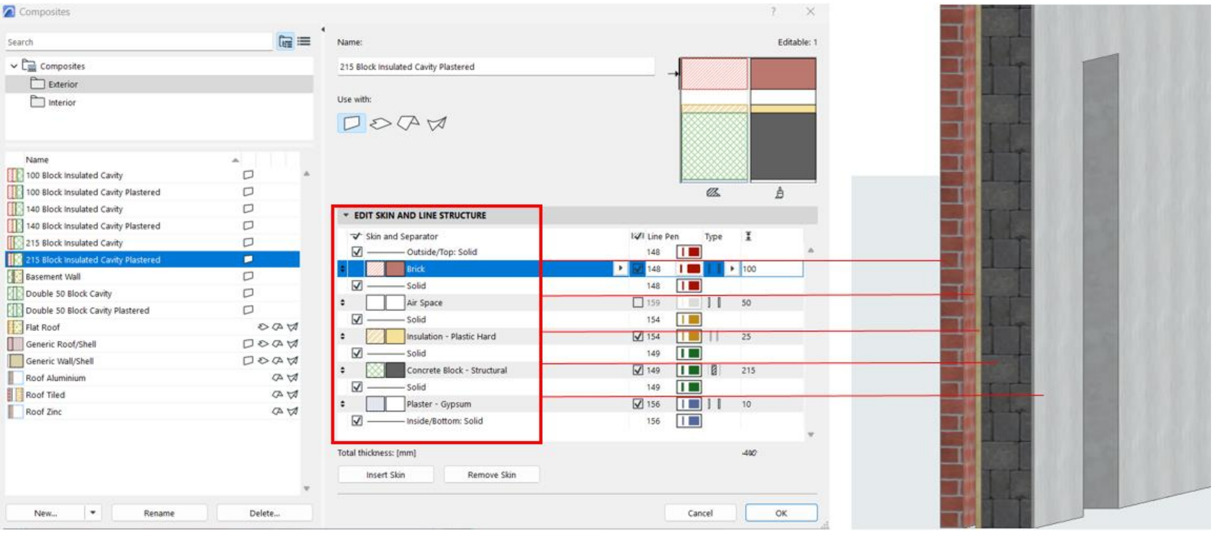


Figure 31 - Defining composite materials

The required properties according to the PDTs, as elaborated in section 4.2, were created and grouped in a property set in the 'Property Manager' as shown in Figure 32. The type of the property was defined as per the data type as String, Boolean, Text, Label, Integer, etc. The properties can be made available for all or specific item classifications according to the requirement. For example, 'SampleReference' is added only for building elements, and 'ItemCanBeRecycled' is added only for materials.

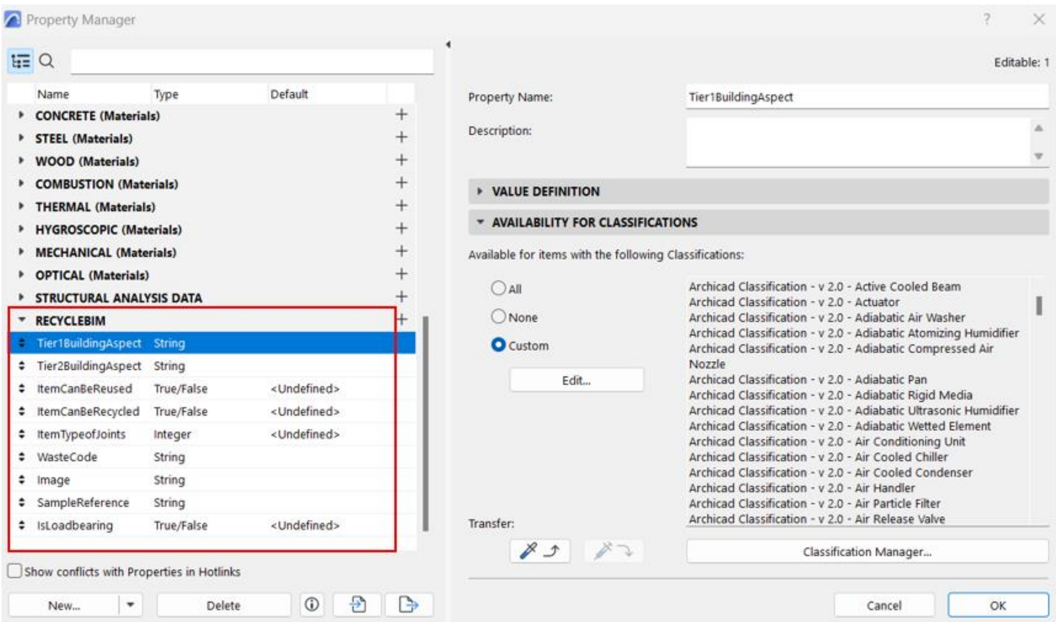


Figure 32 - Creating new properties in Property Manager

After creating the properties, each building element was populated with the circularity parameters, description, links to images which originate from the visual documentation and inspection forms filled out during the building inspection, which includes identification of construction elements, and other objects of interest, materials, etc. (Díaz-Vilariño & Tsiranidou, 2023). All required information is digitized and saved in the model to be used for downstream functionalities.

Information about component elements is added from within the assembled element, as elaborated in Figure 33 for the case of stairs. Stair flight, landing is included in the structure of the stair assembly and riser, tread in the finish. Information for component elements plates and members in curtain wall are also populated with information in this way. This ensures that when the object decompositions are defined according to the IFC relationships, the component objects will contain all required information.

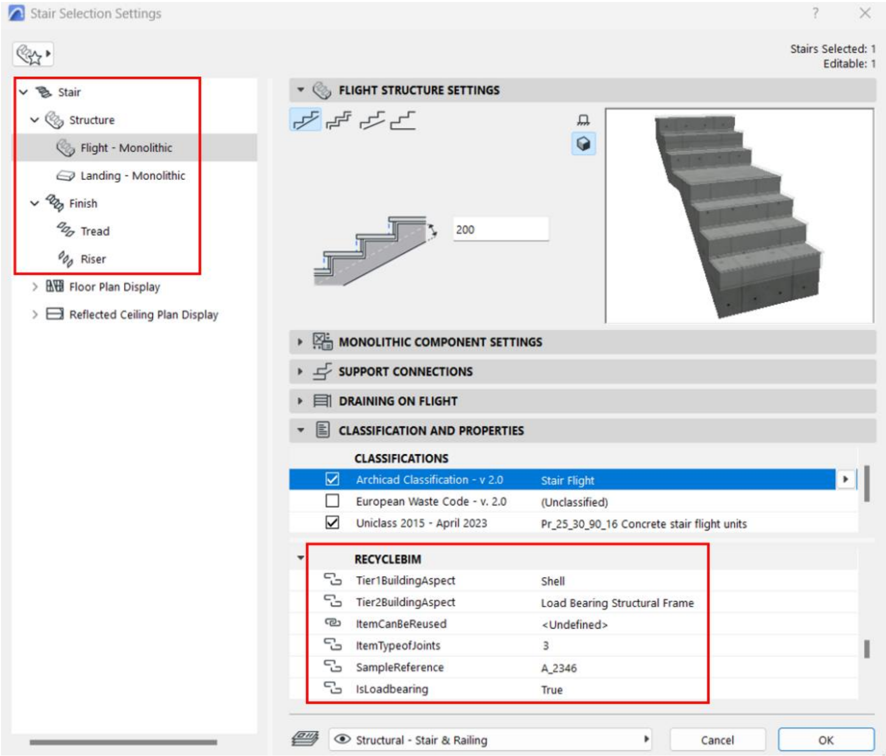


Figure 33 - Adding information for component elements

Classification information is added in the classification manager, where the Name, Version, Date, Source and Description of the chosen classifications are specified. Uniclass 2015 for building products and European Waste Codes for materials are used in this work. A classification XML file with the breakdown structure and object hierarchy is uploaded to provide all the necessary classification information. For example, Pr_30_59_98_02 is the Uniclass 2015 code for Aluminium window units and Pr_30_59_98_96 for Wood window units. Including the classification code to each building element and material allows element standardisation and better identification and product granularity for the marketplace.

5.2. IFC Export

Exporting the model from the authoring software to IFC following the modelling and geometry rules includes setting up the export correctly with various mapping and conversion settings (Graphisoft, 2018). IFC 4.0 Reference View was used as the template for exchange with custom settings to ensure compliance with the EIR. The IFC translator in ArchiCAD allows the use of conversion presets for Model filtering, Type mapping, Geometry conversion, Property mapping, Data conversion and Unit conversion, as shown in Figure 34.

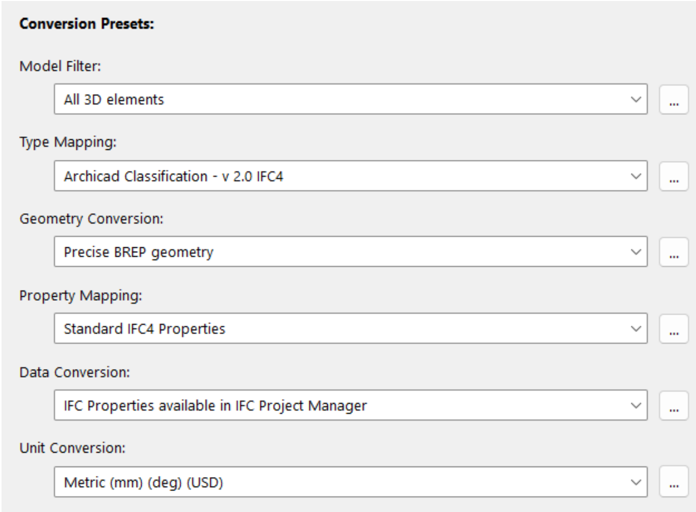


Figure 34 - IFC conversion presets in Archicad

Model Filter is used to filter the elements that are necessary for the DIM. Elements that are not considered for the demolition planning are left out from the IFC export to make sure that the model for exchange remains lean with only the essential information. Type mapping allows the custom mapping of building elements to specific IFC object classes.

Geometry conversion rule sets are used to control the export of model geometry. It allows us to export the gross geometry of elements or to export them as parts, preserving the structure of assembled elements like curtain walls, stairs, and railings, thereby ensuring that element breakdown occurs accurately and that the individual component elements are also included in the export. It also allows us to choose whether to export the model with BREP geometry or CSG geometry with parametric capabilities.

In the Data Conversion tab, the type of ArchiCAD data to be exported is specified. ArchiCAD allows the export of component information, where the properties and quantification information of material layers can be exported. It is also possible to export classification information, and the properties and classification of building materials.

In the Property Mapping tab, new properties are created for each of the required parameters and rules are mapped to connect the properties in the model to a property set in the IFC file 'Pset_RecycleBIM', as shown in Figure 35. The data type of declared properties in the native file should match with the data type declared in the IFC mapping.

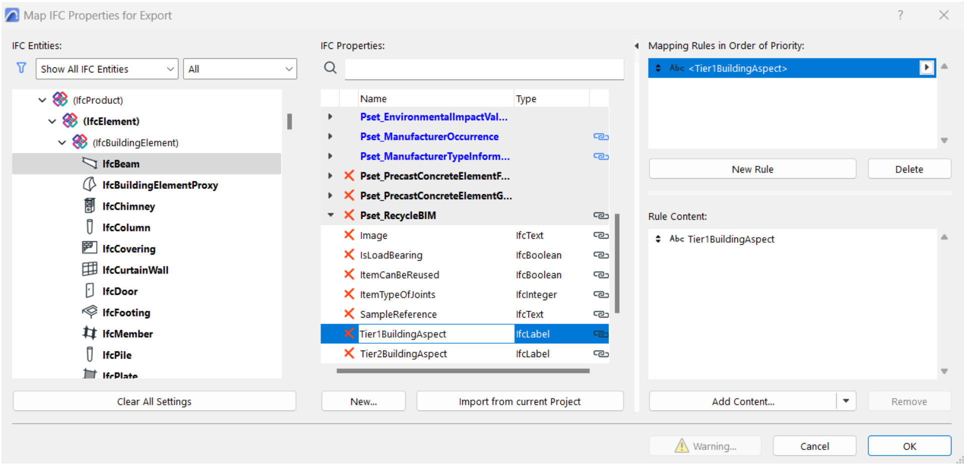


Figure 35 - IFC Property mapping for Export

After exporting the IFC file, a visual check of the geometry and properties was done using open-source BIM Vision IFC viewer. The presence of required information sets such as Name, Description, 'Pset_RecycleBIM' with the alphanumerical information, Quantity sets with required quantity data, Component quantities with quantities of each layer, Classification information for objects and materials, were checked.

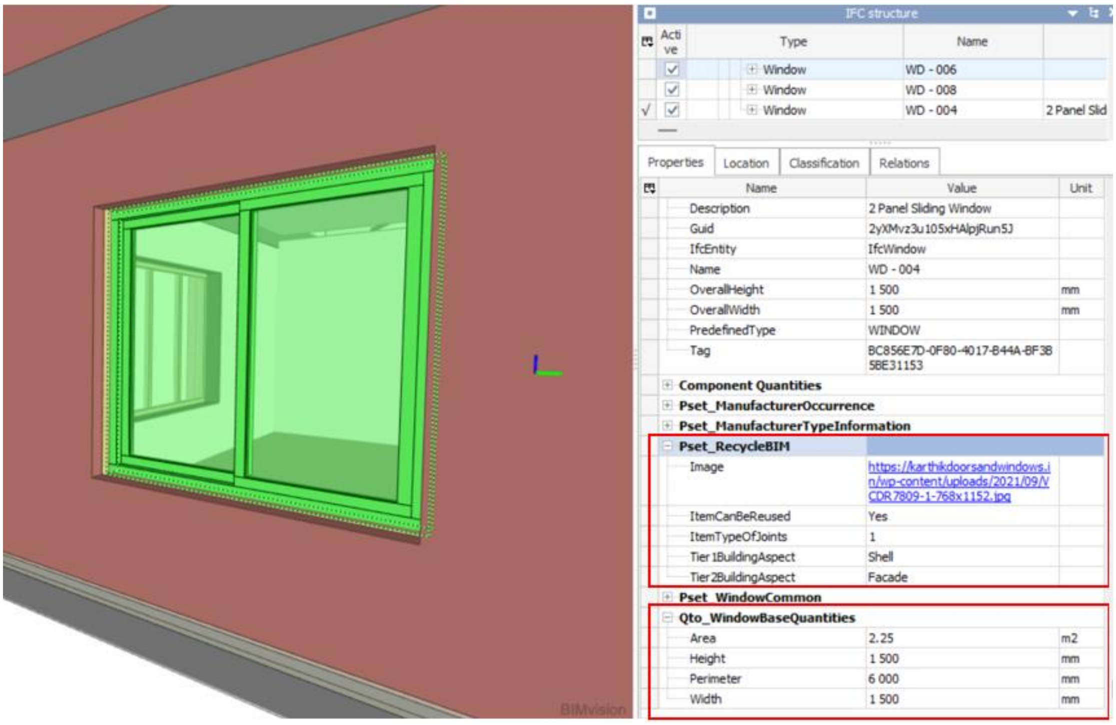
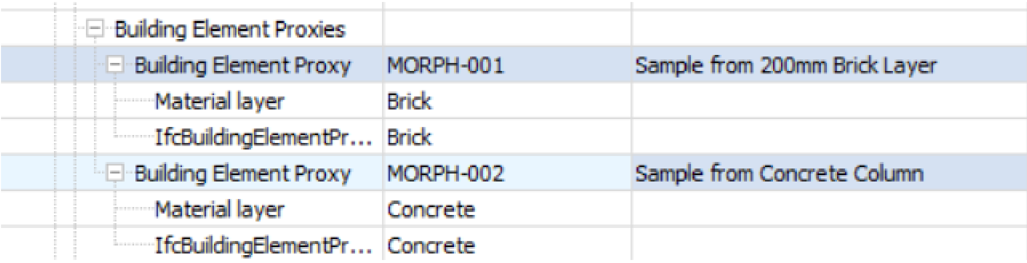


Figure 36 - Properties of a Window element with Pset_RecycleBIM

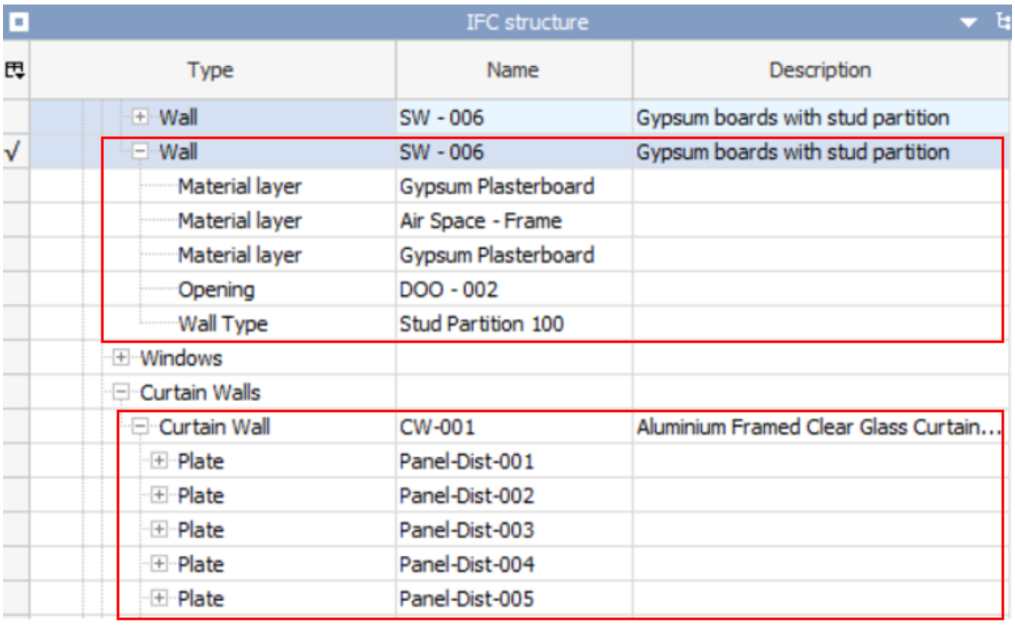
Several modelling requirements from the model were checked, such as the use of IfcBuildingElementProxy to store information about samples as shown in Figure 37. It is possible to store the material information, including a description and the location from where the sample was collected.



Building Element Proxies		
Building Element Proxy	MORPH-001	Sample from 200mm Brick Layer
Material layer	Brick	
IfcBuildingElementPr...	Brick	
Building Element Proxy	MORPH-002	Sample from Concrete Column
Material layer	Concrete	
IfcBuildingElementPr...	Concrete	

Figure 37 - IfcBuildingElementProxy to store sample information

The breakdown of multilayer objects such as walls into its component layers with component quantities and properties for each layer was ensured. The decomposition of assembled objects such as curtain walls, railings, stairs into component objects such as panel and member was also ensured as can be seen in Figure 38.



IFC structure

Type	Name	Description
Wall	SW - 006	Gypsum boards with stud partition
Wall	SW - 006	Gypsum boards with stud partition
Material layer	Gypsum Plasterboard	
Material layer	Air Space - Frame	
Material layer	Gypsum Plasterboard	
Opening	DOO - 002	
Wall Type	Stud Partition 100	
Windows		
Curtain Walls		
Curtain Wall	CW-001	Aluminium Framed Clear Glass Curtain...
Plate	Panel-Dist-001	
Plate	Panel-Dist-002	
Plate	Panel-Dist-003	
Plate	Panel-Dist-004	
Plate	Panel-Dist-005	

Figure 38 - Object decomposition

Although a visual check is enough to ensure that all types of information breakdowns are present, for larger models, there needs to be an automated workflow to ensure the compliance of the model with the information requirements. The use of Information Delivery Specification (IDS) to perform automatic validation of IFC models is explored in the subsequent section.

5.3. IFC Validation using Information Delivery Specification

IDS is a computer interpretable document that can be used by the model creator and receiver to check the compliance of the model to the exchange information requirements. It can be used to define how objects, properties, classifications, values, and units need to be exchanged during delivery. The IFC validation workflow using IDS followed in this work is elaborated in Figure 39. The model created in ArchiCAD following the alphanumerical, geometrical, and modelling requirements specified in the EIR is exported to IFC format for exchange. The IFC file is checked against an IDS XML, which is also derived from the EIR based on information requirements, using Blender. It semantically checks the rules in the IDS XML with the IFC file to check the compliance of the information in the IFC.

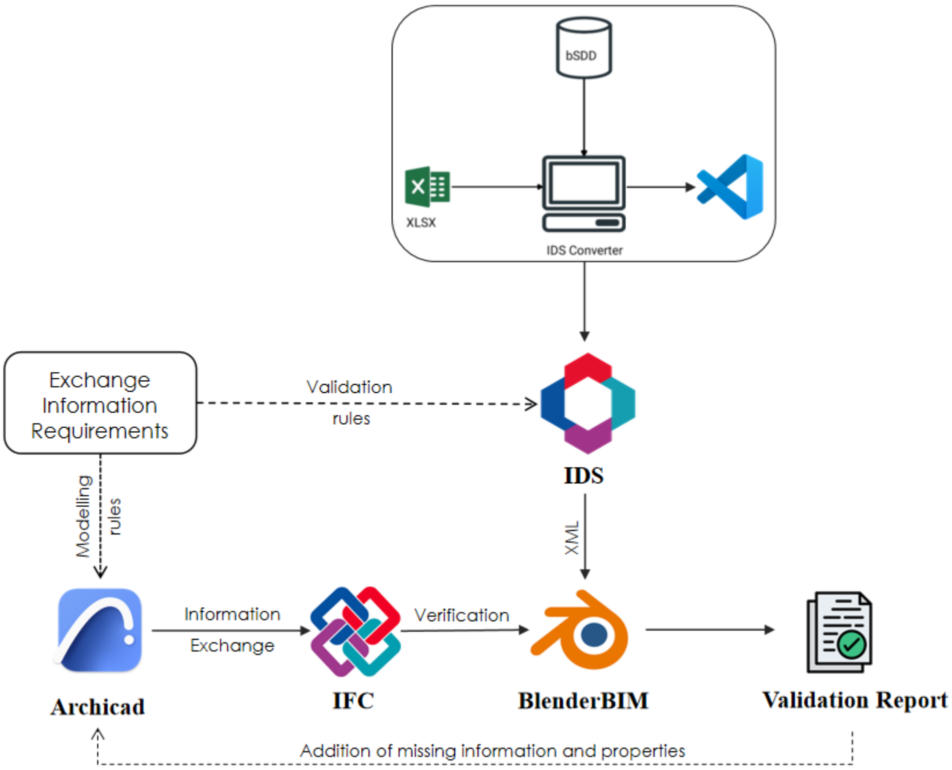


Figure 39 – IDS Validation workflow

The IDS XML was created with an open-source web tool called ‘IDS Converter’, which uses IFCOpenShell to convert an input excel data sheet with requirements specified according to the EIR, to a machine-readable XML. Specifications in IDS should be defined for each property that needs to be checked. The type of value and the correctness of the value can also be checked., a sample specification code is shown below:

```
<specification name="ItemCanBeReused_Windows" ifcVersion="IFC4" description="Windows
should have this Property" minOccurs="0" maxOccurs="unbounded">
      <applicability>
        <entity>
          <name>
            <simpleValue>IfcWindow</simpleValue>
          </name>
        </entity>
      </applicability>
      <requirements>
        <property measure="IfcBoolean" minOccurs="1" maxOccurs="unbounded">
          <propertySet>
            <simpleValue>Pset_RecycleBIM</simpleValue>
          </propertySet>
```

```
            <name>
                <simpleValue>ItemCanBeReused</simpleValue>
            </name>
        </property>
    </requirements>
</specification>
```

The specification includes a name, the IFC version, a brief description of the rule, and the condition for occurrence. The object to be checked is specified with an applicability rule, which is the name of the entity in this example. Then the requirement from the entity is specified, which states that the property ‘ItemCanBeReused’ in the property set ‘Pset_RecycleBIM’ should have a property measure of ‘IfcBoolean’, where the ‘minOccurs=1’ meaning the property should not be void. This is used to check whether the property value exists or not.

The IDS converter as of the date of usage does not include the functionality to check the classification information in objects. To check for classification information, new specification rules were added for all objects in the XML file in Visual Studio Code, as shown in Figure 40.

```
<specification name="Classification_IfcBeam" ifcVersion="IFC4" description="All Beams need Uniclass2015 classification" minOccurs="0" maxOccurs="unbounded">
    <applicability>
        <entity>
            <name>
                <simpleValue>IfcBeam</simpleValue>
            </name>
        </entity>
    </applicability>
    <requirements>
        <classification>
            <system>
            <simpleValue>Uniclass 2015</simpleValue>
            </system>
        </classification>
    </requirements>
</specification>
```

Figure 40 - Specification rule for Classification in IDS XML

BlenderBIM has IFC quality control functionality with an Ifc Tester, which enables the checking of IFC files against IDS rules sets. The validation report created by BlenderBim provides a summary of the test parameters and whether the elements in the IFC meet the conditions that were set in the IDS. The information quality check can be done for quantity and classification information as well. Figure 41 elaborates that all 10 instances of Walls have information in the ItemCanBeReused property in Pset_RecycleBIM, but the property Tier1BuildingAspect was filled only for 8/10 instances and Tier2BuildingAspect for 6/10 instances. The GUID of elements that do not meet the conditions are displayed and this allows us to enrich the given elements with the missing information in the authoring software.

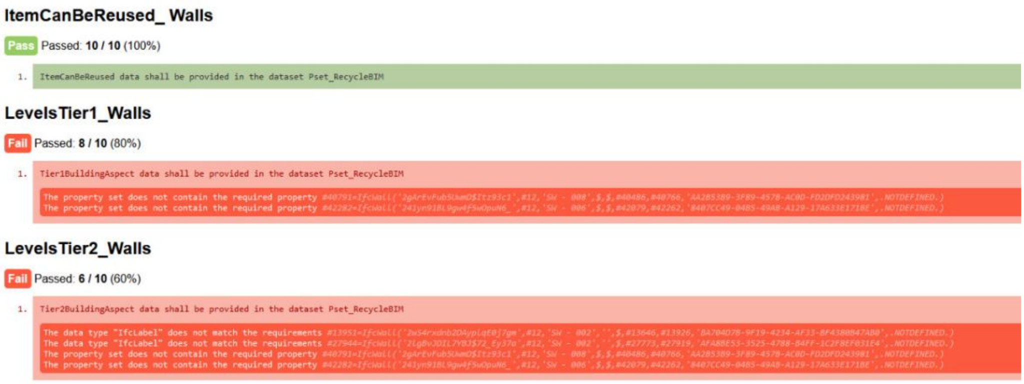


Figure 41 - Validation report showing missing properties

The validation process can be run again after enrichment of the missing information to ensure that all elements have the requested information. According to Figure 42, 2 slabs are missing width information. Based on examining the model, it was found that these slabs were stair landings with varying slab thickness, and this was the reason the width information is not available in the IFC. There might be exceptions to the rule compliance like in this instance and it is important to consider these when calculating the quantities.

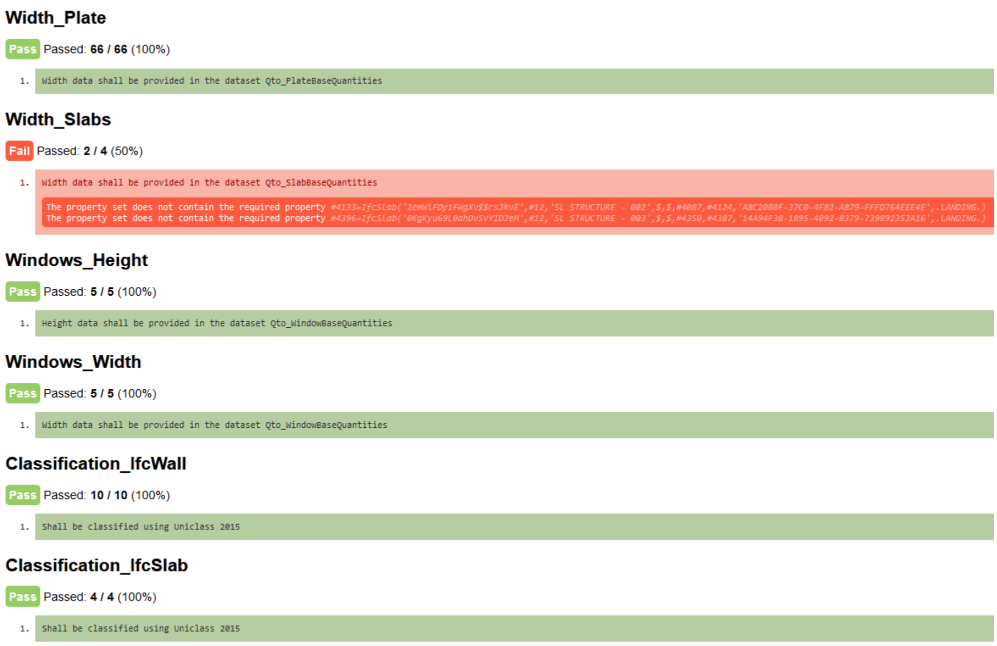


Figure 42 - Validation report showing quantity and classification

IDS serves as a critical quality assurance tool, guaranteeing data integrity and adherence to specified information requirements, thereby reducing errors, and enhancing data consistency. This validation process fosters seamless interoperability between diverse software applications, facilitating smoother collaboration among project stakeholders, enables efficient quality control of IFC and can be used for preliminary validation of the model before it is uploaded into the web-platform of RecycleBIM for downstream functionalities, such as market integration, optimization of deconstruction strategy, life cycle analysis and life cycle costing.

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6. CONCLUSIONS

6.1. General Conclusions

In conclusion, effective data management is of paramount importance in the AEC industry, particularly in the context of extensive collaboration among diverse stakeholders and the management of substantial project data. While the adoption of BIM has surged in the past decade, significantly enhancing data management and process optimization in construction, it is crucial to acknowledge that the demolition sector has lagged in terms of digitization. This dissertation has concentrated on addressing critical processes in the digitization of demolition activities. By leveraging digital technologies and embracing an open source, open data format approach, the demolition sector can overcome the deficiency in digitization and reap the benefits of improved efficiency that BIM brings to the table.

To gain insights into the current state of demolition practices in Portugal, a comprehensive study was undertaken into several key areas. This included an examination of existing legislation within the European Union regarding demolition, the guidelines governing CDW management, the maturity of the market concerning reclaimed materials, and the distinctive building typologies that define the Portuguese context. Given the European Union's stringent regulations aimed at achieving net zero emissions, fostering sustainability, and promoting circularity within the construction industry, it becomes evident that the circular management of CDW is an imperative domain demanding dedicated research and development efforts. The research attempted to ascertain the potential for recycling and reusing CDW, thereby facilitating their optimal utilization in line with these overarching sustainability goals.

The first step of this process was to define the relevant information and parameters required from demolished products and materials to make decisions regarding their second life. Product Data Templates were developed to standardize the life cycle information and to enable traceability. These PDTs are meant to be populated with information about materials and building parts obtained from on-site inspection, and existing documentation about the asset. The integration of BIM methodology in the demolition process was explored and a key connection was made between building components considered in the PDT and IFC built elements which are the information containers used for creating the BIM model and storing building data. The alphanumerical and quantitative information was analysed for each major construction element and this connection streamlines the process of creation of a model with the generation of relevant information for the PDT.

Addition of a BIM model to the demolition process adds to the expense and complexity of the project. To ensure that information is produced as per the actual requirement, taking care to not produce excess information which leads to wastage of resources and time, a framework following the ‘Level of Information Need’ is established to accurately describe the amount and granularity of required alphanumerical and geometrical information from the model. Modelling rules are also established to ensure the quality and standard of produced geometry. An Exchange Information Requirements template was developed for the demolition process according to ISO 19650 series and CEN recommendations. The Level of Information Need for demolition developed in this work is one of the first such frameworks developed for the demolition process. It is estimated to be a significant contribution to the body of knowledge of circular economy and sustainable practices in the construction industry.

A sample building model was created following the proposed framework to test the modelling rules and geometric requirements and addition of alphanumerical information. Rule sets were defined for the export of an IFC file so that all required information is available and exported according to the specified relationships and hierarchies. An automated validation of the IFC was tested using IDS XML to ensure the quality of the exported file. This workflow will be very relevant when the scale of the project is large and includes many element types and properties and manual checking becomes tedious.

The stated objectives of the thesis are considered achieved. The development of a database of building Archetypes in the Portuguese context was a secondary objective considered but discontinued to limit the scope to match the time constraints.

6.2. Future Development

The potential continuation and further development of the work can include:

- Developing a database of Archetypes in the Portuguese context to supplement information which is not readily available from on-site testing and laser scans. This will help in better categorization of building elements and can make quantity and property estimation more reliable and faster.
- The framework can be extended for new constructions and modern construction techniques such as prefabricated elements with an increased focus on deconstruction.
- Expansion of the Level of Information Need tables to include elements of electrical and plumbing disciplines such as lighting fixtures, pipes, fittings, furniture can be considered.
- The inspection part of the reimagined demolition process includes a Scan to BIM workflow. An automated workflow for converting point cloud data to BIM objects can be developed.
- Connection and integration with the RecycleBIM web platform which is under development.
- A quantification workflow leveraging model geometry, rather than necessitating explicit value export requests, can be established. This workflow enables the extraction of essential quantities directly from the model using the IFCOpenShell within the RecycleBIM platform.

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LIST OF ACRONYMS AND ABBREVIATIONS

AEC	Architecture, Engineering and Construction
AIR	Asset Information Requirements
BEP	BIM Execution Plan
BIM	Building Information Modelling
bSDD	Building Smart Data Dictionary
CDW	Construction and Demolition Waste
CE	Circular Economy
EC	European Commission
EIR	Exchange Information Requirements
EPD	Environmental Product Declaration
EU	European Union
EWC	European Waste Codes
IDM	Information Delivery Manual
IDS	Information Delivery Specification
IFC	Industry Foundation Classes
MVD	Model View Definition
OIR	Organisational Information Requirements
PDT	Product Data Template
PIR	Project Information Requirements