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Integrated Planning and Recording Circularity of Construction Materials through Digital Modelling

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Universidade do Minho
Escola de Engenharia

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Master Dissertation
European Master in Building Information Modelling

Work conducted under supervision of:
Prof. Miguel Ângelo Dias Azenha
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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.

RESUMO

Planeamento Integrado e Registo da Circularidade de Materiais de Construção através da Modelação Digital

Actualmente, a indústria AEC está a ser transformada pela tecnologia, inovação, e modelos de negócio orientados para a informação para resolver problemas que dificultam um futuro sustentável. O sector da construção é uma importante fonte de impacto ambiental, uma vez que as suas operações comerciais conduzem ao esgotamento das matérias-primas, à contaminação ambiental e às emissões de gases com efeito de estufa. Esta dissertação centra-se no processo de demolição, uma vez que os actuais resíduos gerados e as taxas de reciclagem indicam que é necessário um funcionamento mais eficaz para permitir a circularidade dos materiais de construção, uma vez que a maioria deles tem potencial para ser reutilizada ou reciclada. O principal objectivo do estudo é representar a abordagem orientada pelo BIM no levantamento de bens, gestão de resíduos de demolição de construção e a sua representação digital como uma composição de materiais e produtos numa aplicação baseada na web para uso público aberto. O trabalho revela metodologias existentes, aplicações, avanços, e contém uma revisão das normas e da base legislativa em relação à aplicação das tecnologias de informação e metodologias de gestão da informação no contexto da economia circular. Utilizando uma abordagem de reengenharia de processos empresariais, foi definido o modelo atual do processo de demolição e a sua análise de lacunas, e foi proposto um novo modelo atualizado com metodologias orientadas para o digital. Estas metodologias referem-se a: (i) uma abordagem eficiente à recolha de dados e modelação de um bem a ser demolido; (ii) modelos de dados de produto para objetos BIM para circularidade de informação; (iii) nível de informação necessário para casos de demolição para estabelecer requisitos de informação na entrega de projetos conduzidos pelo BIM. Foram discutidos os papéis dos formatos de dados abertos, abordagens de fonte aberta e aplicações baseadas na Web na promoção da economia circular no sectorda construção e no fornecimento de tecnologias acessíveis para uso público generalizado. Com base nos potenciais e vantagens identificados, foi implementado o protótipo de uma plataforma baseada na web para o processamento de modelos IFC BIM, fornecendo um input automatizado para os mercados de resíduos e produtos de demolição. Para justificar o novo fluxo de trabalho proposto, foi demonstrado um estudo de caso com a aplicação de metodologias de processo de reengenharia e a proposta de um plano de execução BIM. A apresentação do estudo de caso começou com o levantamento e auditoria pré-demolição, seguido da elaboração do modelo BIM, terminando com a utilização da plataforma web desenvolvida, mostrando o seu funcionamento bem-sucedido. A implementação do fluxo de trabalho proposto mostrou a sua eficiência, aplicabilidade e viabilidade. Os objetivos propostos foram avaliados como tendo sido alcançados.

Palavras chave: economia circular, demolição, gestão de informação, BIM aberto, plataforma baseada na web

ABSTRACT

Today, the AEC industry is being transformed by technology, innovation, and data-driven business models aiming to solve problems obstructive to a sustainable future. The construction sector is one of the leading sources of environmental impact since its business operations lead to raw material depletion, environmental contamination, and greenhouse gas emissions. This dissertation focuses on the demolition process, as currently generated waste and recycling rates indicate that more effective operation is needed to enable circularity of construction materials since most of them have potential to be reused or recycled. The main purpose of the study is to represent the BIM-driven approach for asset survey, construction demolition waste management, and its digital representation as a composition of materials and products in a web-based application for open public use. The work discloses existing methodologies, applications, breakthroughs, and contains a review of standards and legislation base in relation to the application of information technologies and information management methodologies in circular economy context. Using business process reengineering approach, the current process model of demolition practice and its gap analysis were defined, and the new upgraded model was proposed with digital-driven methodologies. These methodologies refer to: (i) a cost-effective approach to data capture and modelling of an asset to be demolished; (ii) product data templates for BIM objects for information circularity; (iii) level of information need framework for demolition use case to establish information requirements in BIM driven project delivery. The roles of open data formats, open-source approaches, web-based applications in promoting circular economy in the construction sector and providing affordable technologies for widespread public use were discussed. Based on identified potentials and advantages, the prototype of a web-based platform for IFC BIM model processing was implemented, providing an automated input for marketplaces for demolition waste and products. To justify the proposed new workflow, a case study was demonstrated with the application of methodologies of reengineered process and the proposal of a BIM execution plan. The presentation of the case study included the survey and pre-demolition audit, BIM model elaboration, and the use of the developed web-based platform, showing its successful operation. The implementation of the proposed workflow showed its efficiency, applicability, and viability. The stated objectives were assessed as achieved.

Keywords: circular economy, demolition, information management, open BIM, web-based platform

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1. INTRODUCTION

The construction sector is one of the leading sources of environmental impact, since its business operations lead to raw materials depletion, environmental contamination, and greenhouse gas (GHG) emissions: it is responsible for consumption of about half of extracted materials, causing 5-12% of GHG emissions (European Commission, 2020a). It is projected that by 2060, barring any change, raw material extraction will rise to 167 Gt. Back in 2017 this rate was 89 Gt and 27 Gt in 1970 (OECD, 2019). Over the last 50 years, the extraction of raw materials has extended more than three times, and these numbers are expected to grow due to the increase of population, industrialization, and higher living standards in developing countries. It is estimated that up to 85% of all extracted materials finally become waste (Pacheco-Torgal et al., 2020). Construction and demolition waste (CDW) constitute around 25-30% of all generated waste in the EU (European Commission, 2021), while the biggest part of it is inert waste, meaning that materials can be taken back to the cycle, contributing to the circular economy (CE). Today, the largest amount of CDW is either downcycled (e.g., used as backfilling or aggregates) or is being disposed in landfills (Heinrich & Lang, 2020).

To achieve the Sustainable Development Goals (SDG), it becomes clear that the linear economy model of "take-make-dispose" shall be substituted by circular approach with the "3R" model of "reduce-reuse-recycle", which is complemented by some scholars with extra actions, such as refuse, rethink, repair, refurbish, repurpose, remanufacture and recover (Kirchherr et al., 2017). The CE approach directly contributes to clean water and sanitation (SDG6), affordable and clean energy (SDG7), decent work and economic growth (SDG8), responsible consumption and production (SDG12), life on land (SDG15) (Schroeder et al., 2018). The major purpose of the CE is to keep the initial value of materials and construction products by closing the loop between the end of lifecycle and extraction, basically decreasing the raw material acquisition, applying the "3R" approach.

Considering the high rates of raw materials consumption and waste disposal, CDW management should be upgraded, as the EU target metric of 70% regarding the recycling rate of building materials by 2020 (Horizon 2020 targets) has not yet been achieved; by 2018, only an average of 50% was gained (Pacheco-Torgal et al., 2020). The rates of the state members vary from 10% to 90% (Eurostat, 2018). Even though these values are affected by differences in legislation, the gap in development shows that better performance is possible. For this purpose, the European Commission initiated "Circular Economy Action Plan", where the main objectives are directly related to the construction sector with a high potential of circularity and waste reduction. The CE approach for AEC industry can be described as "*a lifecycle approach that optimizes the buildings' useful lifetime, integrating the end-of-life phase in the design and uses new ownership models where materials are only temporarily stored in the building that acts as a material bank*" (Leising et al., 2018).

At this point, the problem of traceability arises with the question of how we can track the material throughout all life-cycle stages, following the cradle-to-cradle principle. To be able to perceive any construction product as a storage of materials, we need to aggregate all the data about constituting elements and components into an integral database. Thus, the data management challenge becomes forefront. For this purpose, information modelling and management methods with digital technologies can promote the adoption of environmentally sustainable practices, bringing their innovations.

Building Information Modelling (BIM), as a progressive methodology in the AEC sector arose at the end of the 20^{th} century, enables integrated planning and holistic design approaches, which can potentially facilitate better industry performance, allowing to foresee and prevent errors as well as optimize processes in order to provide better and more sustainable solutions throughout the assets' lifecycle. Taking into account the principle of recording information about an asset, constituting the so-called Digital Building Logbook (DBL) (European Commission, 2020b), BIM can potentially provide the availability of data required to enable circular approach and materials traceability. Studies show that the digital twin market is expected to increase in the upcoming 5 years with a 35% annual growth rate (McKendrick J, 2022). Even though the expected data set standing behind the term "digital twin" can vary, depending on its purpose and the represented stage of an asset's lifecycle, increased use and adoption of digital technologies, including BIM, is expected to contribute to all the stages, especially at the end of lifecycle, to promote circular concepts.

Meanwhile, information silos and interoperability issues in BIM are some of the hindrances to the use and adoption of digital technologies. Interoperable systems are intrinsic characteristics of Industry 4.0 (Ustundag & Cevikcan, 2018). Therefore, to provide a unified approach for information creation, use, sharing and storing standards in information management plays a huge role in promoting interoperability (legal, organizational, semantic and technical) and eliminating fragmentation, which is characteristic of the AEC industry due to emerging specializations (Turk, 2020). Open data standards, such as IFC, IDM, bSDD, BCF (ISO 16739-1, 2018; ISO 29481-1, 2016) from buildingSMART, are aimed to close these gaps. Besides that, open-source strategies also facilitate the progress, providing software-independent communication and making data more available and easier to access. Developing open-source BIM solutions capable of integration with open-data formats is a contribution to bringing knowledge and up-to-date methodologies to the wider part of the market, which can facilitate the dissemination of new technologies. Another contributing factor is the use of web-based solutions for information sharing. The benefits of such an approach can be referred to cross-platform compatibility and accessibility, device customization, integration with other systems, flexibility and scalability, reduced costs, and increased security (KCS, 2021; Khamooshi, 2019).

Considering the stated above, this work aims to assess the challenges and opportunities of digital technologies, namely BIM, in CE model for construction products and materials. The main purpose is to represent the BIM-driven approach for CDW management, demolition survey and asset digital representation as a bank of materials in a web-based application for open public use. The objectives of the dissertation are set in accordance with the framework of the European project "RecycleBIM" and are expected to contribute to the project development. The objectives are set as follows: 1) to provide justified workflow and requirements for demolition audit; 2) to set adequate BIM modelling rules (and information requirements) that allow the BIM model to host information for the deconstruction analysis and quantity take off regarding the materials available for reuse and recycling; 3) to design a prototype of a web-based IFC platform enabling BIM models' validation and analysis that would represent the building as a material bank.

Brief description by chapter

Chapter 2 represents research on current initiatives, guidelines, and frameworks to synthesize the state of the art and to implement gap analysis. The chapter's objective is to disclose existing methodologies, applications, and breakthroughs, as well as standards and legislation base in relation to the application of information technologies and information management methodologies in circular economy context.

Chapter 3 defines the current state of demolition process and waste management. Basing on gap analysis of existing practice and priorities promoting circularity, new methodologies were proposed. These methodologies are related to digital modelling and refer to: (i) new approach of data capture of an asset to be demolished; (ii) product data templates for BIM objects for information circularity; (iii) level of information need for demolition use case to establish information requirements in BIM driven project delivery. For business process reengineering, models, including their "as-is" and "to-be" representations, were used.

Chapter 4 introduces the prototype of a web-based platform for BIM model validation and providing automated input for marketplaces for CDW trade. The description includes the platform’s logic and concepts, applied technological solutions, database structure, and BIM models’ processing procedures. At the end, some potential service developments are outlined.

Chapter 5 contains a description of a case study and demonstrates the application of proposed methodologies of reengineered process, starting from the survey and pre-demolition audit, BIM model elaboration, and finishing with the use of the developed web-based platform. A conceptual BEP for project implementation is also outlined.

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2. CIRCULARITY IN CONSTRUCTION. CHALLENGES AND OPPORTUNITIES OF DIGITALIZATION

2.1. Legal framework and guidelines

Recycling rates of some EU countries go up to 90% (Eurostat, 2018), which is undoubtfully contributing to achievement of CE. However, it is not sufficient for sustainable CE and can be referred as "recycling" economy, which is perceived as an intermediate stage (Figure 1).

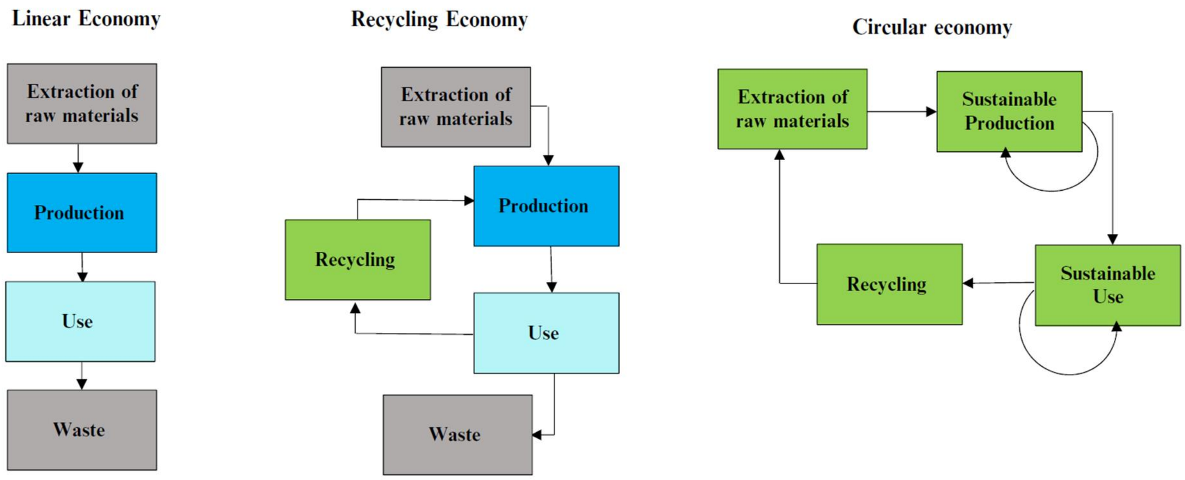

Figure 1 - Product life cycle in linear, recycling, and circular economy (Pacheco-Torgal et al., 2020)

Barriers in any change can be referred to 4 main domains: technological, social, economic and political, as in any business environment. If we still have raw materials to extract and it is economically effective and efficient for current production and business models, the tendency of resource depletion will not change. The problem is that by 2050, the resource capacity "equivalent of almost three planets could be required to provide the natural resources needed to sustain current lifestyles" (United Nations, 2015). Therefore, legislation and regulatory framework play a huge role in enabling CE, since technologies are not necessarily able to provide better business performance, especially at the emerging stage, and social and economic barriers can be overcome indirectly through the policies. Moreover, it is stated that taxation and enforced regulation are one of the most effective ways to promote the CE approach (European Commission, 2018b; Pacheco-Torgal et al., 2020).

In 2015, the UN's 2030 Agenda for Sustainable Development and the Paris Agreement set a vision for sustainability. Currently, the 59000 series of ISO standards are under development that address CE. The European Union, promoting itself as a prospective leader in sustainable development, is aimed at climate neutrality by 2050 and has established a "Circular Economy Action Plan" (European Commission, 2020a). The plan, aiming to unite the effort to achieve climate neutrality, states the following objectives to promote circularity: by revision of CPR (Construction Product Regulation), by developing digital building logbooks (DBL), by using Level(s) for LCA integration and by revision of legislation for CDW.

In the proposal for revision of CPR (European Commission, 2022), it is stated that currently it does not enable establishing environmental requirements. Digital information on construction products is assessed as insufficient to enable CE and address sustainability issues. Starting from the application of digital tools, thereby creating a “Digital Product Passport”, data on construction products is expected to be stored in DBL for future use, enabling market surveillance and reducing bureaucracy. The concept of DBL, which is also described sometimes as a building passport, unites a set of relevant building data, representing the record of changes throughout the whole lifecycle and is intended to enable circularity (European Commission, 2020b). Recently proposed by the EU framework to assess building sustainability performance, Level(s) (European Commission, 2021) , includes 6 macro-objectives, one of which refers directly to CE: resource’s efficiency and materials circularity. The initiative suggests a way to estimate the material composition of a building, classifying and quantifying it parts, which is strongly related to CDW management.

As stated by the EPC (European Policy Centre) in comprehensive report (Hedberg & Šipka, 2020), transition to CE is impossible without the application of digital technologies, since otherwise information does not travel with products, making it difficult to track them and apply the knowledge for the future use. Indeed, it is claimed that both transitions, digital and CE, should be aligned, creating “*a competitive advantage when supplying the market with products and services for a CE*” (Figure 2). The problem is that according to Gartner’s metrics, the sector of construction, resources, and materials has the smallest IT expenditure (Bolpagni et al., 2021).

Figure 2 - Integration of Digital revolution with CE (Hedberg & Šipka, 2020)

An undisputable challenge for digital technologies to be integrated into CE is that circularity does not necessarily lead to more sustainable choices (Hedberg & Šipka, 2019). One of the contradictions is that digital devices and data centers, which information and communication technology (ICT) industry is dependent on, contribute to GHG emissions and an increase of e-waste.

To monitor the progress of the transition to CE, a set of indicators was set (Eurostat, 2022), such as waste generation, recycling rates, trade of recycled materials, new patents in the domain, etc. Since the

CDW constitute an enormous part of all the waste (almost third by mass and the biggest by volume), its management needs better performance, where digital technologies can facilitate the progress.

2.2. CDW management practices and IT integration

Deconstruction and demolition in CE are considered as a source of materials and products for reuse and recycling. More than 90% of the buildings and structures consist majorly of reversible materials (masonry and concrete) and the aim of 100% recycling is possible, but only percentage itself cannot be perceived as a final goal since the quality of recycled materials plays a huge role. Contamination, hazardous substances, and aggregation of materials caused by wet processes during construction are the barriers to achieving high rates of recycling without compromising quality (Lauritzen, 2019). The high cost of separation, labor intensity, and lack of legal support are the hindrances to CDW reuse and recycling (Marinho et al., 2022).

CDW constitutes 30% of all the waste worldwide (Han et al., 2021) and the challenge to minimize it and manage efficiently is faced by many countries. In EU legal framework for the CDW management is different across the Member States and its procedure is a highly variable subject (European Commission, 2018c); advanced countries define obligatory pre-treatment, demolition audits, management plans and percentage of recycled materials (European Commission, 2018b). Pre-treatment implies preliminary study of a project when the available data is gathered and being analyzed. This dataset allows to depict the current state of a building asset and historical review. It includes design documents and records of use, description of construction and present contaminated or hazardous materials, environmental constraints, access and local recycling facilities, project time and budget (European Commission, 2018c; Lauritzen, 2019). A pre-demolition audit is a crucial inspection procedure prior to the actual work, since estimating factors can drastically affect the project outputs - any available documentation is not as important as the actual site visit (J. Diven & Shaurette, 2010). The waste audit aims to help in qualitative and quantitative assessment of building elements as well as to ensure in compliance with EHS (Environmental, Health and Safety) requirements with contribution to recovery strategy management (reuse, recycle, energy recovery). The waste audit is perceived as a required step towards CE (European Commission, 2018c).

Results processed and generated after the field survey serve as an input for waste management, which significantly affects the efficiency of future demolition plan. The decision-making process proposed by the Level(s) framework and adopted from the EC Guideline for the waste audit is shown in Figure 3. The main CE principle in managing CDW is to maintain the material value and apply selective demolition and deconstruction. However, it is worth mentioning that selective demolition does not necessarily mean a better option in terms of sustainability (Hedberg & Šipka, 2019; Pantini & Rigamonti, 2020), which is another subject of systematic assessment and is dependent on many pecularities. Effective CDW management and careful estimating not only contribute to CE, but can also generate additional income for the demolition company: salvage sales can constitute a reasonable part of income since the markets for CDW become more commonplace (J. Diven & Shaurette, 2010).

The trend of using IT solutions in CDW management is going up fast, as well as the number of scientific papers on this matter (Li et al., 2020; Oluleye et al., 2022; Pellegrini et al., 2021). The most occurring are BIM, GIS, Big Data, RFID, image recognition, image analysis, GPS, barcodes. There are also innovative approaches to using AI and neural network algorithms, e.g., to estimate the volume of waste during demolition with cameras on containers, thereby disclosing the data about all taken apart elements and giving relatively precise information (Davis et al., 2021). But the lack of this methodology is that the demolition process cannot be planned in a holistic approach beforehand.

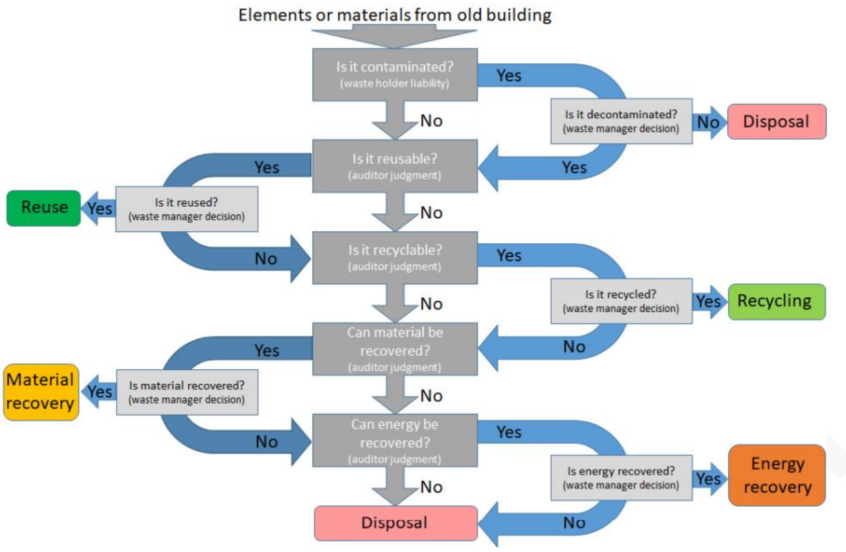

Figure 3 – CDW management recommendations in Level(s) (European Commission, 2020d)

Even though BIM is the most mentioned methodology for waste reduction and decreasing environmental impact among IT solutions, it has been rarely used for the building end of lifecycle (Kang et al., 2022) which is considered as undeveloped domain (Nikmehr et al., 2021). Also, in the EU report on innovation in CDW recycling infrastructure of 2018, there is no mention of digital technologies or BIM, indicating the shortfall of real case studies (European Commission, 2018a). Nevertheless, information modeling is mentioned in Level(s) as a methodology to precisely and in semi-automated way quantify materials of CDW (European Commission, 2020c).

CDW management is performed not only for demolition projects, but also during construction, operation, and refurbishment (Figure 4). BIM integration is mostly studied today in management and reduction aspects, especially during the design phase.

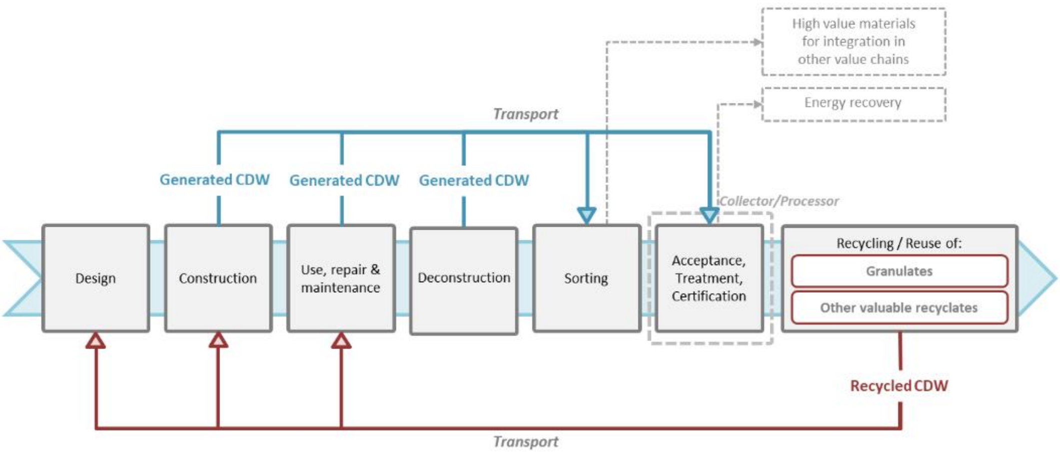

Figure 4 - CDW value chain (European Commission, 2018b)

The application of BIM in deconstruction activity can be related to quantification of materials to estimate volume of recycle aggregates and performing of 4D simulation for demolition schedule optimization (Ge et al., 2017; Guerra et al., 2020; Won & Cheng, 2017). Some proposals have been made for a pre-demolition audit (García et al., 2017). The obstacles of using BIM are referred to the lack of BIM models of existing assets as well as the lack of databases with interoperable datasets (Li et al., 2020; Sobhkhiz et al., 2021; Wang et al., 2022). Even if the BIM model from the design stage exists, it's not necessarily a digital twin and requires updates made in the operational phase, which increases the project's costs.

The research agenda for CDW management at the end of lifecycle is defined by three main aspects: (i) efficient and effective data collection; (ii) automation and ease of BIM model creation; (iii) integrated planning for CDW management (Han et al., 2021; Volk et al., 2014).

2.3. Digital technologies for field survey

To estimate CDW, data collection can be performed by direct (hand measurements, digital data capture) or indirect (parametric or based on research and statistics estimation) methods (Cha et al., 2017). For recent construction, the data for the pre-demolition audit can be obtained from design documents and specifications. However, if there is no available information on this matter, reality capture and field survey become the first step in any demolition activity. The guidelines for demolition/reclamation audit establish the templates for the survey report, defining it as a possible digital form in spreadsheets with attachments of images for better identification. To represent the spatial relations between building elements, these images can be done with 360° pictures with further automatic creation of 3D tours, which has recently started to be used for construction progress tracking (e.g., Dalux SiteWalk).

Depending on the precision requirements, data capture can be implemented with compact tools, such as cameras that operate with the software for data processing, or with handheld laser scanners for better precision (Zeiss, 2019). Using cameras with photogrammetric software allows to represent the object as a 3D structure (e.g., DotProduct, Matterport) and automatically generate 3D tours with "doll house", which is widely used in the real estate business. However, the registration to position the stations may cause uncertainties in the structures' thickness. Since masonry and concrete waste are dominating positions, accounting for 40-80% of CDW (Han et al., 2021; Pacheco-Torgal et al., 2020), certain accuracy in volumetric data on main building elements, such as slabs and walls for typical construction, is required. This leads to the necessity for more precise data acquisition. Engineering survey techniques, depending on the object size and complexity, that are used for historical digital modelling are shown in Figure 5. Taking into account the object size and quantity of output measurements, the two most applicable and progressive ones for the field survey used widely today for as-built data capture are photogrammetry and laser scanning. The main concepts are shown in Table 1. With the development of technologies, these survey techniques can be done by portable devices, increasing the efficiency of the survey and generating the point cloud data in minutes (Figure 6).

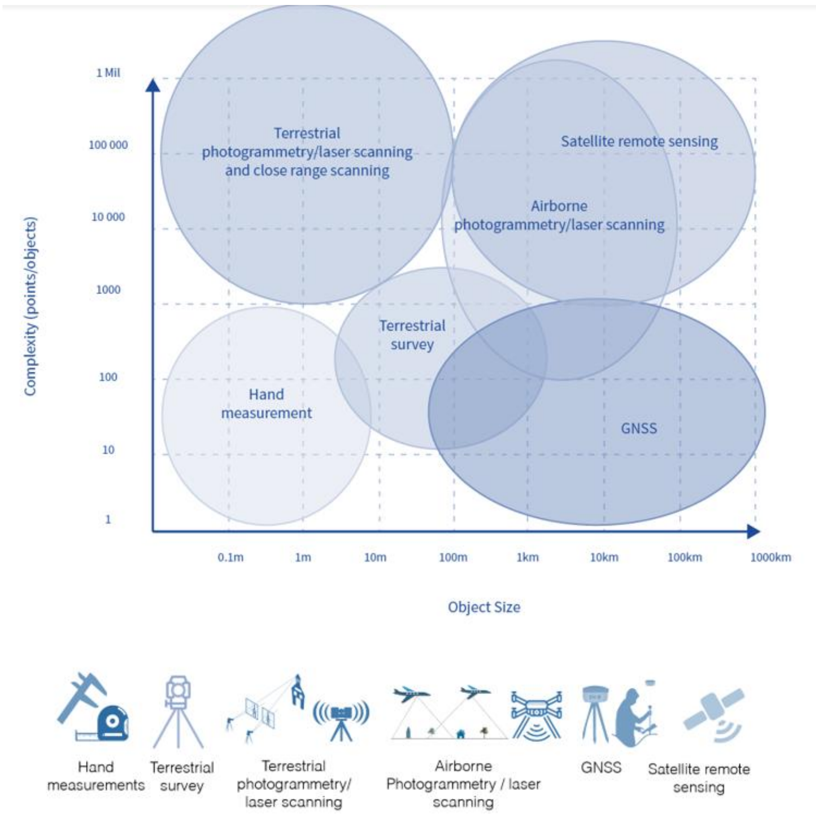

Figure 5 - Survey techniques defined by object complexity and size (Historic England, 2018)

Table 1 - Concepts of laser scanning and photogrammetry

	Terrestrial laser scanning (TLS)	**Photogrammetry**
Work principle	Triangulation, time of flight and phase comparison	Main aerial and close range (ground based) photogrammetry principle - triangulation
Pros and cons	Accurate and efficient, easy to use for 3D data acquisition, but is a work of high cost	High-quality imagery and color information to the resulting data, inexpensive digital cameras, but the entire process can be long and labor intensive
Outcome	Point clouds	Point clouds, triangulated surface models and textured surface models

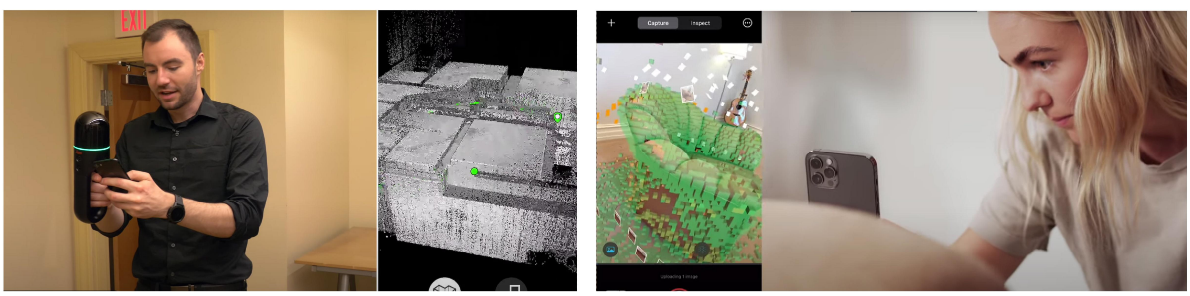

Figure 6 - Handheld laser scanner and live photogrammetry application (Leica Geosystems, 2022; CapturingReality, 2022)

However, in a CDW management context, a survey with output consisting of only digital spatial representation is insufficient: information about the building elements' compound is required. Construction materials might be hidden behind finishing and structures, creating an obstacle and uncertainty. The usual practice of materials' data acquisition during the audit is selective demolition and uncovering with sample taking to ensure the absence of hazardous materials and justify the composition of a structure. This process can be digitized with non-destructive methods, such as terahertz technology (Pawar et al., 2013). Terahertz has been proposed for CDW estimation since it allows to define the material compound and hazardous substances; but its application currently can be economically inefficient and requires the spectrum library for better productivity (Abina et al., 2022). Therefore, traditional methods of local interventions in structures can be perceived today as more applicable for material characterization.

Digital technologies such as point cloud data capture in field survey facilitate further BIM model creation, enabling semi-automated methods. These methods include point cloud segmentation and the generation of BIM objects with procedural modelling (Chiabrando et al., 2016). Using photogrammetric techniques and drones, it is possible to automate the generation of solid forms representing the construction objects with algorithms. However, the issues with this approach refer to the necessity of indoor data capture and disability to generate complex shapes (Hu et al., 2022).

2.4. BIM use in the circular economy model

BIM model elaboration using survey data, also referred as "Scan-to-BIM", is usually implemented starting with data acquisition, point cloud segmentation, object recognition, and, finally, with modelling itself (Figure 7). However, it has been claimed that the time and effort it takes to create the BIM model only for demolition purposes without having any available digital documentation can be economically unreasonable, making BIM use in CDW management a questionable practice (Han et al., 2021).

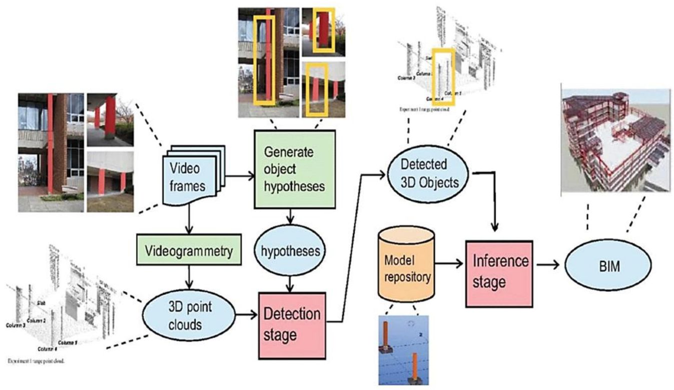

Figure 7 – Generic scan-to-BIM workflow (Xie et al., 2022)

Nowadays, international plans of work do not include the end of lifecycle stage of a building asset, apart from ACE (Europe) (Charef, 2022; RIBA, 2020), which points to the separation of this phase from integral planning. The main 4 phases, considered in the BIM Uses (PennState, 2013) are plan-design-construct-operate; even though capturing existing conditions, authoring design, and 4D model can be referred to demolition, there is no distinctive mention of the use of BIM as a way to manage deconstruction activities. BIM Initiative define demolition planning as a model use, describing it as a way to "plan or monitor demolition activities of existing structures (or parts of existing structures)" (BIMe Initiative, 2020). Some authors propose new uses that are aimed to be specific for demolition activities, such as analysis of existing as-built, definition of objects for reuse and recycle and 4D simulation of deconstruction (van den Berg et al., 2021).

When applying digital technologies, information overload complicates the CE approach, as well as the lack of information (Hedberg & Šipka, 2019). In this way, to promote the use of ICT, it is necessary to establish the set of information to provide only the data required for a specific purpose. Addressing this matter, ISO 19650-1 introduces the notion of "level of information need" as a "*framework which defines the extent and granularity of information*" and is "*determined by the minimum amount of information to answer each relevant requirement*"; "*…anything beyond this minimum is considered as waste*" (ISO 19650-1, 2018). Therefore, to handle the data and promote the use of digital technologies for CE there is a necessity to establish requirements for information containers, since the legal basis as external drivers is still in early stages (Chen et al., 2022).

The level of information need (EN 17412-1, 2020) framework allows us to define these dataset requirements in terms of geometry, alphanumeric data, and documentation. It allows to characterize the set of specific data and consider its purposes, actors, milestones, and object breakdown structure. Even though the concept of level of information need "*describes information requirements that can be human and machine interpretable*", the more machine readability is achieved, the more interoperable information systems will be obtained, facilitating computer integration and automation.

"*To support digital processes using machine-readable format*", data templates are developed (ISO 23387, 2020). A data template is a collection of standard-based properties which can be traced to credible sources, such as harmonized standards under the CPR, etc. (Cobuilder, 2021). The properties put in a data template correspond to a specific characteristic of a construction product defined in a document, such as in DoP (Declaration of performance) or EPD (Environmental product declaration). The framework for properties' definition in accordance with existent data dictionaries and their validation is standardized (ISO 23386, 2020). The relevance of data templates to other standards is shown in Figure 8.

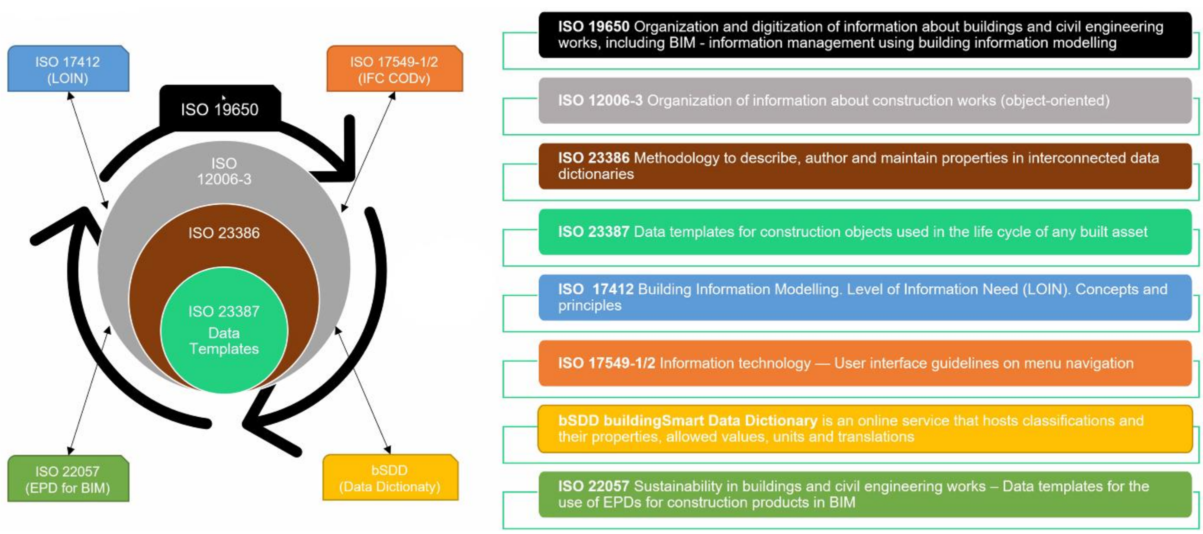

Figure 8 - Data templates' relevant standards (Growing Circle, 2022)

A data template applied to a specific construction product, a product data sheet, can be used for different purposes by different actors at different project stages. Some services already provide BIM objects libraries for construction products and propose data templates for them (NBS, 2022). However, the progress in this area is in an early stage, as evidenced by the development of new standards (e.g., ISO 22057:2022) and a growing number of initiatives and collaborations on this topic with the absence of a well-established database. Even though commercial service for PDT definition exists (Cobuilder, 2022), there are open initiatives (e.g., PDT database by BIM-ISISE) to promote common effort and to involve different stakeholders. Data template connected challenges relate to many aspects, such as who is responsible for the information and its content, who owns the data, how to make it compatible and traceable, and what properties should be present in a template. Another uncertainty is the domain covered in the data template, since construction products can be represented by a single material or by complex prefabricated building units (Figure 9). In short perspective the PDT are expected to be implemented in priority to products with high environmental impact and of major interest in construction that can be reused and recycled (Mêda et al., 2021).

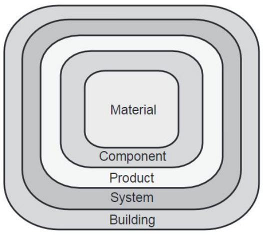

Figure 9 - Hierarchy levels of material passports (Luscuere, 2019)

In relation to CE, as proposed by the “Growing Circle” project (Figure 10), data templates are essential to enable circularity in construction products and materials, as well as in data flows. There is a digital template proposal such as the product circularity datasheet (PCDS, 2022) and at current stage its format implies a pdf form with a list of questions with yes/no options, covering 5 domains: general product data, composition, design for better use, design for disassembly, design for reuse. However, integration with digital modelling tools and interoperability due to the current configuration can be questioned. Several proposals for using BIM with CE integration have been developed, defining the information requirements for constituent data. The concept of buildings as materials banks (BAMB, 2020) and its implementation with digital technologies arose recently and was recognized on a political level, in the European “Circular Economy Action Plan”, proposing the concept of material passport as a “digital report containing circular economy relevant data” (Heinrich & Lang, 2020) (Figure 11). The concept of material databanks is perceived as a way to close the resource loops (Çetin et al., 2021).

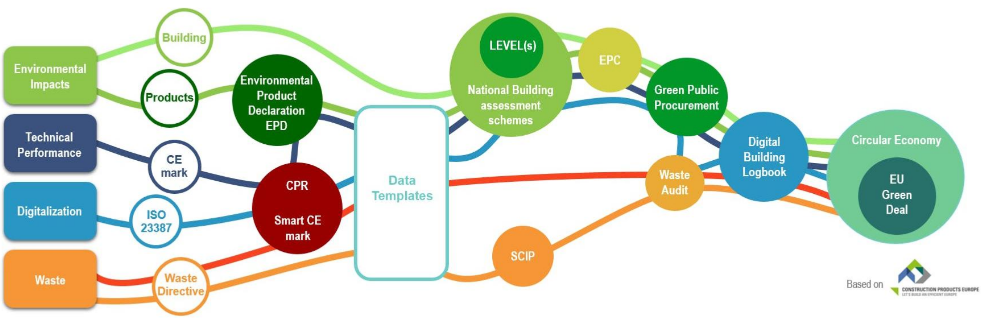

Figure 10 - Data drivers and streams for CE. Origin: (Growing Circle, 2022)

Many scholars, projects and initiatives put forward BIM to establish the "banks", stating it as a technological opportunity (Atta et al., 2021; Copeland & Bilec, 2020). One of the concepts describes material bank as way to connect construction operators, demolition companies, government and public (Figure 12). Another proposed approach is to perform new design based on the available data on objects to be deconstructed (mostly for steel structures), so called stock, with parallel LCA to achieve better sustainability metrics (Figure 13) (Bertin et al., 2020).

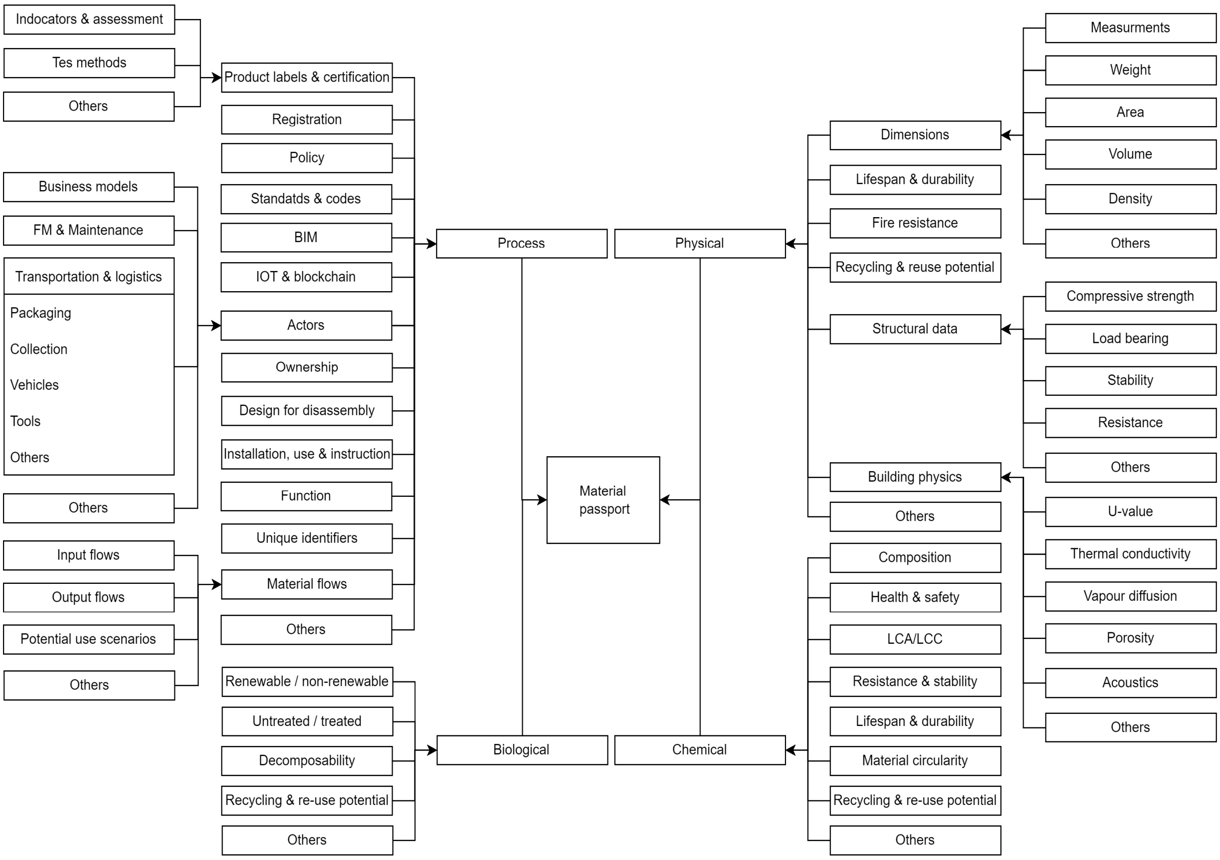

Figure 11 - Information requirements for material passport (adopted from Heinrich & Lang, 2020)

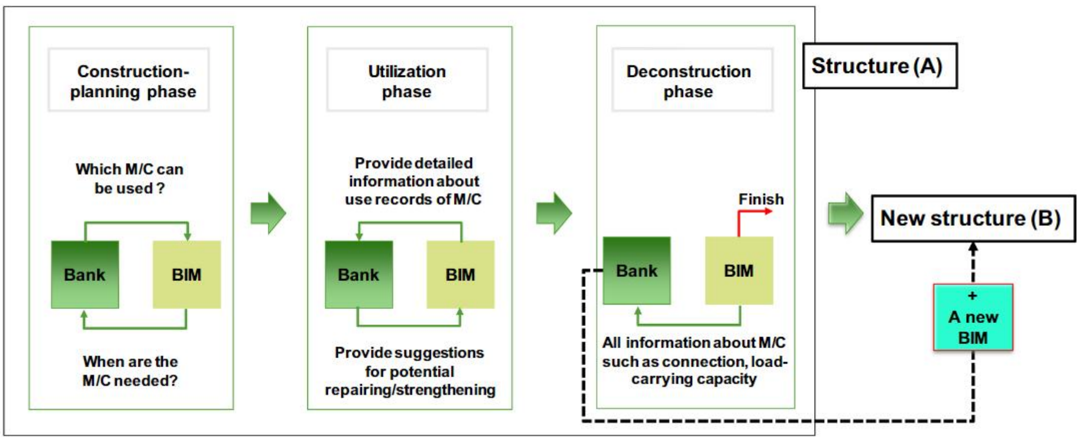

Figure 12 – Operation of material bank with integrated BIM (Cai & Waldmann, 2019)

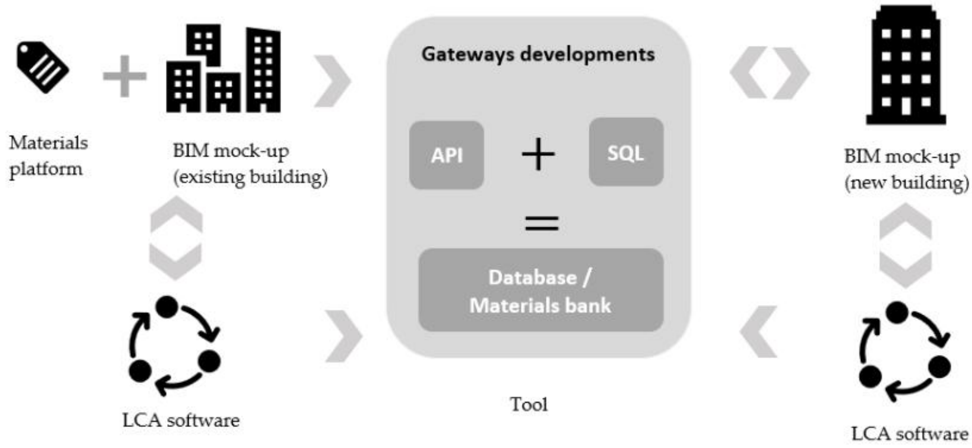

Figure 13 - Concept of material bank as a tool for decision making (Bertin et al., 2020)

In general, many digital solutions today are related to sustainability aspects, such as LCA: there are variety of available stand-alone applications as well as integrated tools. However, most of them do not consider the information management challenges and data interconnectivity, being applied in a discrete and fragmented way (Jalaei et al., 2021; Obrecht et al., 2020; Xue et al., 2021). This fact does not allow to approach the CE problems in a systematic way, making information management a paramount aspect of data interconnectivity. BIM should be perceived as a centermost technology and methodology for ICT system integration (Yu et al., 2022), constituting an incremental digital twin that cannot exist without traceable interoperable digital data, which is a first step towards circularity in the construction industry (Mêda et al., 2021). Generally, interoperability is one of the major problems of the use of BIM with sustainability and circularity assessment software and tools (Bertin et al., 2020). Standardization, open data strategy, and open-source solutions can be perceived as methods to overcome interoperability problems.

2.5. Open-data formats and open-source applications

Interoperable systems are intrinsic characteristics of Industry 4.0 (Ustundag & Cevikcan, 2018). At system-system level, interoperability can be referred to 4 domains: legal, organizational, semantic and technical, constituting the basis for interoperability governance as defined in the European interoperability framework (European Commission, 2017 - Figure 14). To provide a unified approach for information creation, use, sharing and storing, standardization plays a huge role and is aimed to promote interoperability and eliminate fragmentation, which is characteristic of the AEC industry due to emerging specializations (Turk, 2020). Open data standards, such as IFC, IDM, bsDD (ISO 12006-3, 2007; ISO 16739-1, 2018; ISO 29481-1, 2016), BCF, are aimed at closing these gaps. The leading international authority providing standardization of BIM workflows is buildingSMART, which unifies the stakeholders through open and format-neutral data sharing and establishes the basis for open-source collaboration. Open-source strategies facilitate progress, enabling software-independent communication and making data more available and easier to access.

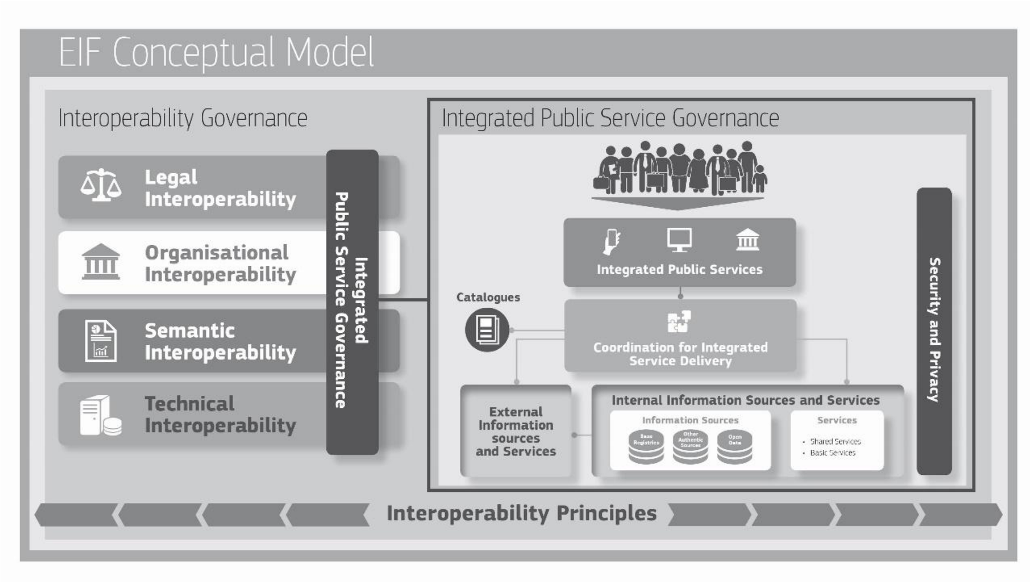

Figure 14 – European interoperability framework. Conceptual model (European Commission, 2017)

Developing open BIM platforms is a contribution to bringing knowledge and up-to-date methodologies to the wider part of the market, which can facilitate the dissemination of new technologies. To implement the CE approach and represent the buildings as temporary warehouses of materials, as materials banks, we need to provide reuse of any related information, storing it in a database. However, it is noted that the lack of databases with interoperable data is one of the major hindrances to the integration of digital twins into CE (Yu et al., 2022). In this way, open data strategy should be perceived favorable for digital transition to CE model, since dependance on specific proprietary data format limitates the future use, which is a contradiction for data traceability requirement.

Moreover, information should be available to the public to avoid the digital divide caused by wealth distribution inequality (Hedberg & Šipka, 2020). For this purpose, the EC established an open-source software strategy to encourage data sharing and reuse and deliver better service with lower costs (European Commission, 2020e). The main benefits of the strategy are: political and vendor independence, flexibility, trust and transparency, open audit and public service, collaboration and common contribution (European Commission, 2020e).

There are many initiatives supporting open-source strategy for the AEC industry and the list of free software is growing (OSArch, 2022), representing both: upstream (authoring software) and downstream applications (analysis, simulation, checkers, etc.) (Jia-Rui Lin, 2020). One of the benefits of open source is scaling and customization, which enables users to perform complex operations and integrate different uses into one app by using API. There has been a recent trend towards the use of open-source applications in web browsers. BIM today does not necessarily have to be linked to any installed application: data within the model can be analyzed, modified, and verified directly in the web browser (IFC.js, Moult, Sigma, Speckle, Xeolabs).

2.6. Web applications for circularity promotion

Web applications have been improved over time, allowing usual software to be upgraded and shifted to websites that serve as an interface and execute commands on a server without requiring high computing hardware from the user. The benefits of such an approach can be referred to cross-platform compatibility and accessibility, device customization, integration with other systems, flexibility and scalability, reduced costs, and increased security (KCS, 2021; Khamooshi, 2019).

Web-based applications enable information sharing, providing concurrent work processes and collaboration as well as efficient information dissemination. To promote sustainability in the AEC sector, there are many proposed free web services and applications, including mobile versions. They include tools for LCA/LCC, energy efficiency assessment, resource planning, product information, and EPD databases. The European Urban Mine Platform is an example of DB facilitating CE through B2B and B2C relationships, where the products are exposed to the marketplace. It is claimed that a market for secondary raw materials is a necessity for an increase in reuse and recycling rates (Hedberg & Šipka, 2020). The usual claimed danger of web commerce is its possible reverse effect: marketplaces for purchasing and sharing might contribute to increased consumerism since the trade becomes easier. However, such solutions in the CE model theoretically are outside the rebound effect as they are aimed at promoting reuse, hence reducing the demand for new materials.

There are existent web marketplaces for CDW and products for reuse and recycling (Aspire, Austin Materials Marketplace, Backacia, MyWaste, Oogstkaart, Opalis, Recycle2Trade, Waste outlet). The interfaces of some of them are shown in Figure 15. The goal of the Genbyg project was to enable the tracking of materials within the building before demolition is implemented (Horup et al., 2017). It is identified that in one of the studies, students proposed using 3D models to provide virtual reality for better marketing (Figure 16), which can be perceived as an attempt to integrate the asset's digital model into the marketplace. The American Material Marketplace program, under the United States Business Council Sustainable Development (US BCSD), is present in different locations (Austin, Tennessee, Michigan, Ohio, Ontario, Washington) and promotes upcycling strategy with workshops on building new houses and artistic installations from waste. Opalis and Oogstkaart have a huge range of building materials and products with comfortable and intuitive categorization and location specification on a map. The Dutch EME (Excess Materials Exchange) and French Backacia for B2B trade are another solutions promoting CE, however, either it is not free to access (EME) or with a trade fee (40% in Backacia). Recycle2Trade and MyWaste (meuResíduo) are assessed to be in an early development stage but with a distinctive planned feature - a mobile application.

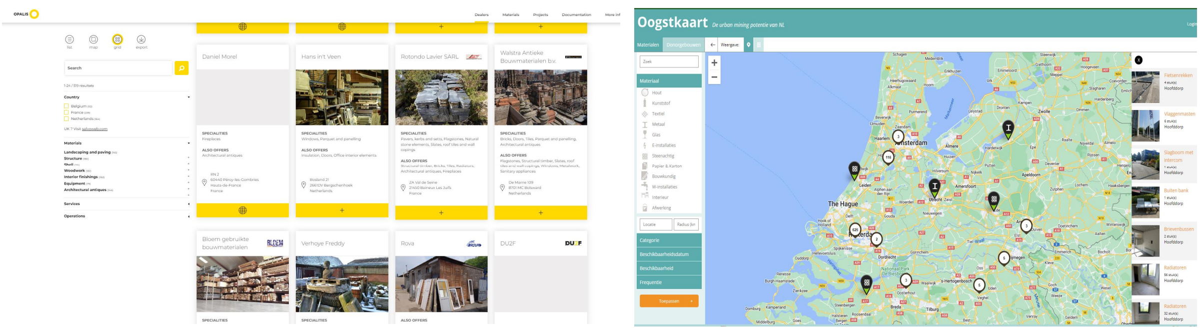

Figure 15 – Example marketplaces of used materials and products. Opalis and Oogstkaart


Figure 16 - GenByg project's case study enhanced with 3D model (GenBygData, 2017)

The business model of such platforms is usually information as a product or advertising as a service. Users of these web applications are supposed to exchange the data using pictures and text description for product definition; therefore, the shortcoming of these solutions is the lack of focus on integrative approach with the use of digital modelling and operation mostly as human-input interfaces (Silva & Gil, 2020). The comparison of marketplaces is shown in Table 2 and is based on publicly available data.

Table 2 – Comparison of existent marketplaces and platforms for waste trading and products' reuse

	Scope	Origin	Content	Free to use	Registration rights	Input data
Gen Byg Data (Genbyg)	Country	DK	Used building materials and products	n/a	n/a	Descriptive by user
Aspire	Country	AU	Industrial waste	No	Organization	Descriptive by user
Materials Marketplace	Regions	USA	Industrial waste	n/a	Requires invitation	Descriptive by user
Backacia	Region	FR	Construction products, equipment, and furniture	Yes, with trade fee	Publicly open	Descriptive by user
Oogstkaart	Country	NL	Industrial waste, products, equipment, and furniture	Yes	Publicly open	Descriptive by user
Opalis	BL, FR, NL	EU	Construction products and materials, objects for reuse and reclamation, antique furniture	Yes	Publicly open	Descriptive by user
Recycle2Trade	n/a	GB	Plastic waste	n/a	n/a	Descriptive by user
Waste-outlet	World	DK	All waste	Yes, with trade fee	Publicly open	Descriptive by user
EME Excess materials exchange	n/a	NL	Industrial waste and construction materials	No	Organization	Descriptive by user
myWaste (meuResiduo)	World with local domains	BR	Industrial waste	n/a	n/a	Descriptive by user

Integrating BIM with such web solutions in turn can facilitate the process of collecting data with the potential for automation, creating a technology-based marketplace. The concept of information platform for circularity, where the BIM plays a cornerstone role as information center, has already been proposed in research and is shown at Figure 17. Another approach for building demolition services mentions the idea of integration with a trading option to match the CDW supply and demand (Kang et al., 2022).

To make the web data machine readable some, scholars devote their studies to the semantic web, also known as Web 3.0. The proposal of a semantic web-based platform for comprehensive LCA, considering regional market peculiarities, claims to be more applicable for "meta-data-intensive tasks" and web-scale data connection than RDBMS. By developing ontology model and using semantic web, BIM can be integrated with GIS in a web platform, providing interoperable datasets for different optimization purposes (Hor, 2015). However, it is still impossible to justify if semantic solutions will bring better business value (Sobhkhiz et al., 2021).

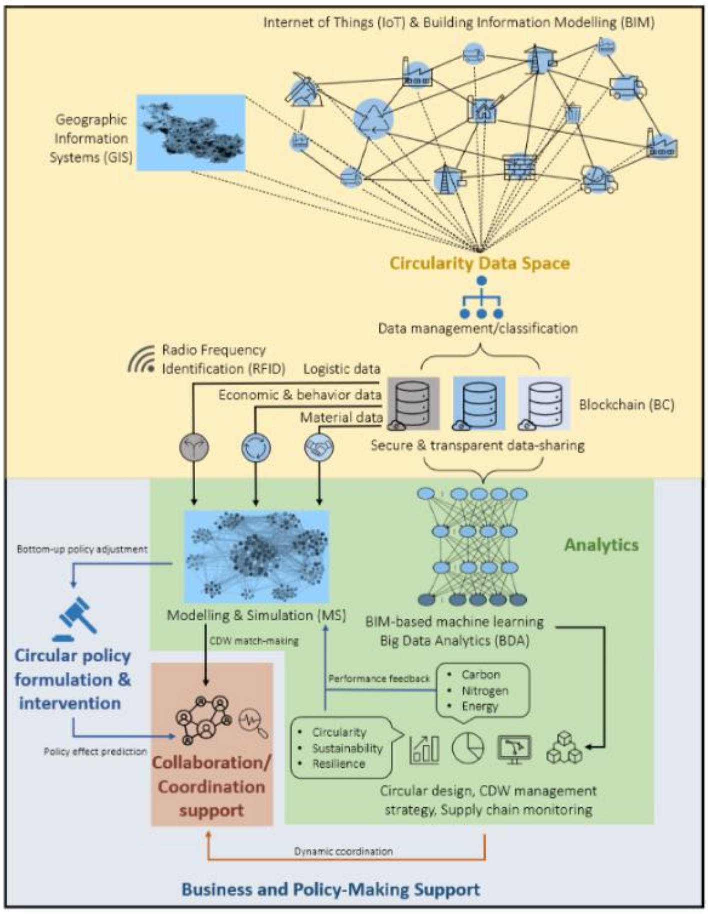

Figure 17 - Concept of information platform with BIM as a centermost technology (Yu et al., 2022)

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3. BPR OF DEMOLITION PRACTICE

3.1. Brief introduction to BPR (Business process reengineering)

A process in ISO 9000:2015 is defined as a “set or interacting activities which transform inputs into outputs”. Processes can be material (inputs and outputs are tangible) or informational (inputs and outputs are presented with information itself, “bits and bytes”). Construction processes can be represented by complex breakdown structures consisting of sub-processes, where information and material processes are integral to each other and the output of one process is an input of another. There should be a distinction between “glue” and “core” processes: the first ones serve as a connector between the core processes and do not add value, while the core processes represent major input transformations (Turk, 2022).

Process when documented enables to plan, perform, and improve the project (ISO/IEC 33001, 2015). To document and represent the process, models are used, providing descriptive, prescriptive, and explanatory information. A business process is a set of activities representing specific organizational goals (Pratt et al., 2022). The purpose of business process management (BPM) is to design, implement, study, analyze, monitor, improve, and redefine the business processes of an enterprise. BPM is a method of efficiently aligning an organization with its needs (Cerovšek, 2022). To measure the process performance, metrics such as KPI (Key Performance Indicator) and KRI (Key Results Indicator) are used. To improve the metrics, there are two methodologies: continuous process improvement (CPI) and business process reengineering (BPR) (Figure 18).

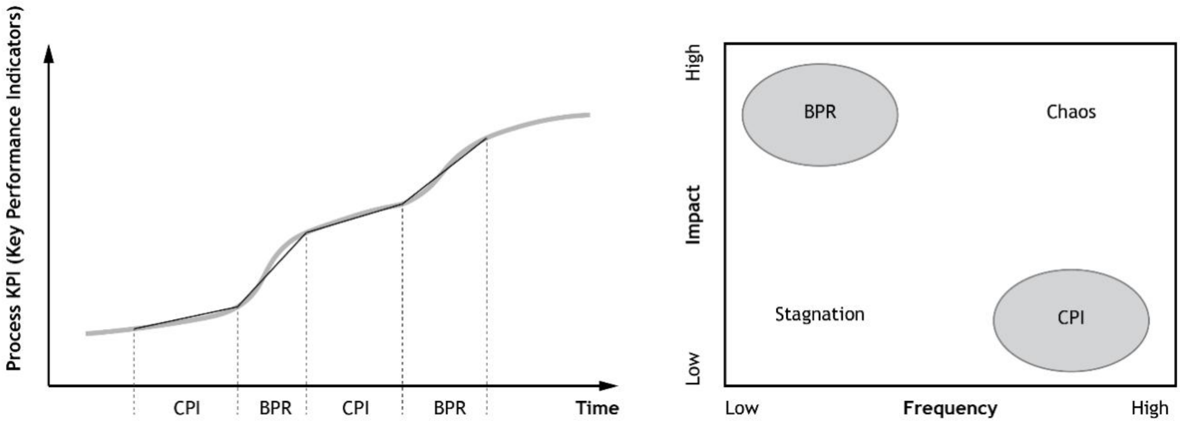


Figure 18 - CPI and BPR effects on KPI and their impact-frequency relation (Cerovšek, 2022)

BPR is “the fundamental rethinking and radical redesign of business processes to achieve dramatic improvements in critical contemporary measures of performance, such as cost, quality, service and speed” (Tønnessen, 2014, origin: Hammer & Champy 1993). Implementation of BPR consists of the following main steps: targeting, examination, gap-analysis, prioritization and implementation. The main activities in BPR are identifying process change, capturing the current business process model, identifying business value, and setting priorities, designing upgraded model, implementing and managing new process (Cerovšek, 2022). To provide high impact and integrate digital transformation to CE model, BPR is required. The main business process models involved in BPR are "AS-IS" and "TO-BE". The first model serves as a baseline for examination and gap analysis.

3.2. AS-IS process model of demolition practice

Based on Chapter 2.2 and the guidelines for CDW management and demolition audit (European Commission, 2018c) the AS-IS process model can be described as shown in Figure 19. The process' actors were put into appointment relations to differentiate the project parties and to provide the same basis for further BIM-driven BPR. Even though BIM-based project delivery is not applicable for this model, some terms were taken to provide a similar framework.

The main process actors are:

1) Property owner (appointing party) – responsible for audit prior to tender invitation to classify waste and detect hazardous materials, as recommended by the Guideline (European Commission, 2018c). As a minimum requirement, a waste audit is performed before permitting;
2) Demolition company or contractor (lead appointed party) - responsible for site activities related to deconstruction and demolition works;
3) Waste manager (appointed party) – responsible for managing the waste flows in accordance with the waste management plan (WMP), facilitating traceability;
4) Auditor (appointed party) – responsible for the pre-demolition audit. The party should be familiar with the construction and demolition techniques, history and state of the local material markets and building types, as well as possess knowledge of waste classification and treatment methods. To investigate and perform assessments for detecting hazardous and harmful materials, legit qualification is required (J. Diven & Shaurette, 2010). It is recommended that this party is not connected to property owner or demolition company to ensure that decisions are unbiased;
5) Recycling facilities and market (third party stakeholders) – parties involved in the process of waste treatment and salvage sales.

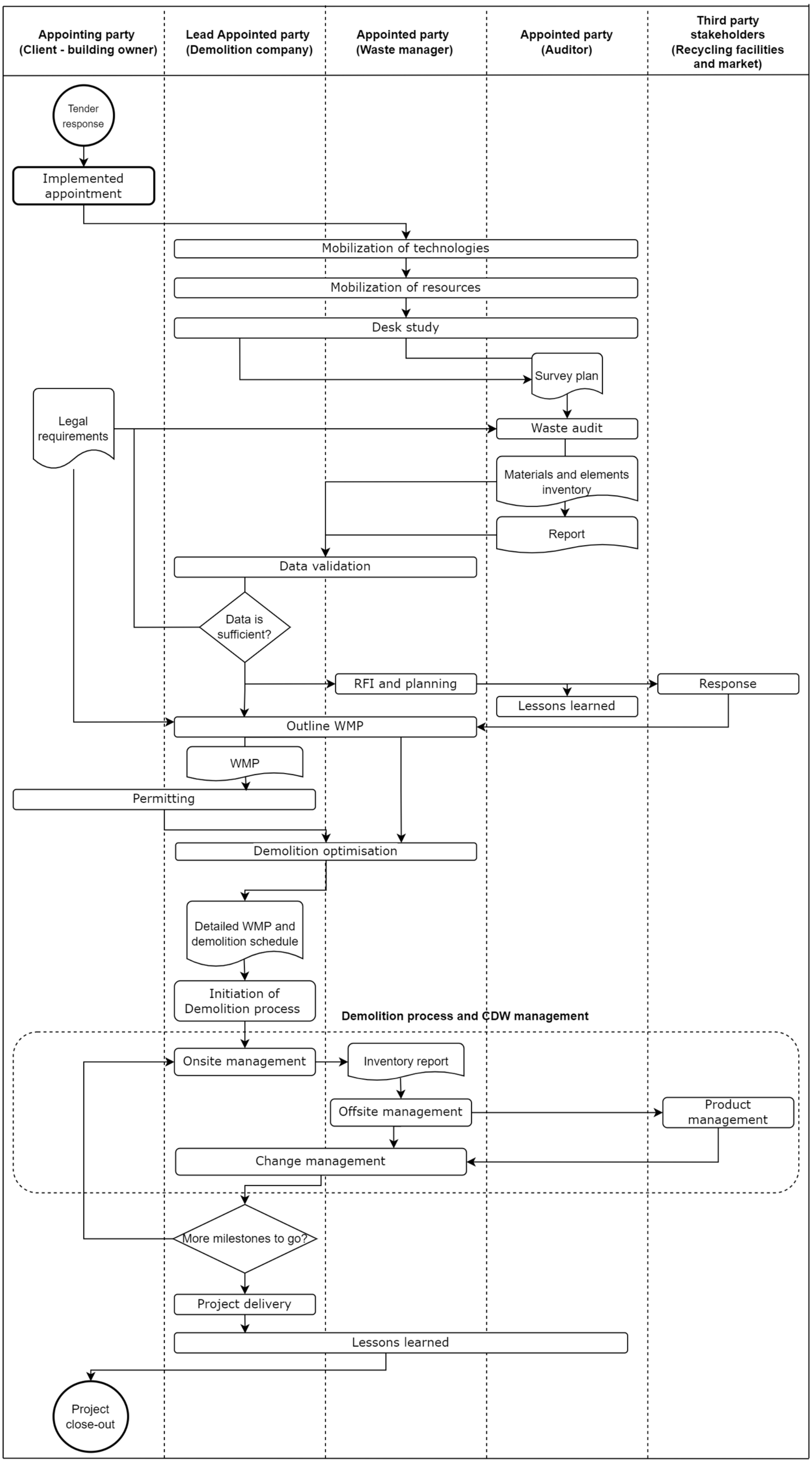


Figure 19 - AS-IS business process model for demolition

The process after the appointment is implemented starts with the mobilization of technologies and resources, when the delivery teams are getting ready to perform the application of required prepared and tested technologies (UK BIM Framework, 2019). During the desk study, the following sets of data are collected: design documents, documentation of use, present dangerous substances (if exists), access to the asset, local facilities. Information generated at this stage provides the first impression of an asset and allows to plan the survey activities. The waste audit includes the site visit, inventory of materials, sample analysis with possible local interventions (opening of ceilings, shafts, coating removal, drilling, dismantling of structures and equipment) and reporting. It is hard to provide a global methodology for the survey, as every building is different; a systematic approach is a key driver of the pre-demolition audit. A report and materials inventory list are the output of an audit and serve as an input for demolition planning. The waste manager with the demolition company formulates the waste management plan in accordance with the influencing factors, such as regulations, local facilities and market demand for salvage sales, available methods, and the work team's machinery and capacity. This waste management plan is required to issue the permit and is the subject of optimization to provide an efficient and effective demolition schedule prior to the site work. After the process is initiated, site management of the demolition company and offsite management (CDW manager) collaborate on project implementation, interacting with local facilities and market to elaborate on the materials disposal strategy.

3.3. Enabling methodologies towards the reengineered process

After defining the AS-IS model, a gap analysis was performed based on the identified business process values and priorities for change. The main priority perceived was to facilitate circularity of materials and products by increasing reuse, recycling, and eliminating landfill without compromising health and safety requirements. The expected value change was optimized schedule, increased income on salvage sales and decreased taxation, which can be a necessity for circularity promotion in the future (European Commission, 2018b; Pacheco-Torgal et al., 2020).

In this way, the gaps in the current process are:

- report and material inventory format (which can be digital or paper based) do not provide data that can be widely used and interpreted, creating a hindrance to information circularity. Even though there are proposed templates, it is a variable subject (not standardized and interoperable data);
- information generated during the audit, even if being digitally recorded (e.g., tables and pdf documents), is not openly used to build parametric models and contribute statistics for future prediction and information reuse (information generated from data is not used for building knowledge and wisdom in other systems – as conceptualized in the "data, information, knowledge, wisdom (DIKW) pyramid";
- the quantities of materials (in tones or cubic meters) depend on the time spent on estimation and the skills of an auditor: uncertainty creates a hindrance for CDW management and requires reactive management during the demolition process;
- a waste manager is responsible for providing information supply on materials for reuse, which in turn depends on onsite management: demand is generated after the site decision is made;
- demolition optimization performed prior to site works is restrained by static information flow. Change management during demolition work is reactive.

To eliminate these gaps, information modelling and management are perceived as viable solutions. Digital progressive methodologies, such as BIM, can provide support in transformation to reengineered process to contribute CE.

3.3.1. Reality capture and demolition audit driven by digital technologies

Even though the demolition of an asset is completely opposite to historical conservation and reconstruction activity, data capture techniques can be potentially adopted but with revision of performance requirements. If the purpose of digital data capture is to generate a cost-effective input for future digital modelling, terrestrial laser scanning can be assessed as the most efficient way due to its processing speed and precision of the generated spatial information, which, as stated previously, is required for estimation of materials' volume. Moreover, today's developments in robotics and grab & go technologies, e.g., handheld laser scanners, significantly reduce the time spent on data acquisition, making the task less labor intensive. It is assumed that, in general, the time required for data capture with a handheld scanner is way less than using the stationary solution, with the acceptance of a difference in output quality. In an example of a product comparison of Leica Geosystems (BLK360 and BLK2GO), this difference in scanning duration was between 4-13 times in favor of the handheld device, depending on the object type (Dlesk et al., 2022). With an average performance of 25 m^2 floor area data capture per minute for an apartment, a house of 300-400 m^2 can be scanned in less than half an hour. On the opposite, stationary TLS, from personal experience, could take at least half a day, which drastically increases with the growing number of partitions and dense planning intrinsic to residential buildings. Another benefit of handheld devices is automatic recognition and elimination of moving objects, allowing to avoid any people within the frames, which in the case of stationary equipment requires non-interrupted operation during the process.

However, the point cloud made by BLK2GO has no panoramic 360° images, since the SLAM (simultaneous localization and mapping) technology does not require fixed positions for data acquisition, making the instrument work during the walkthrough. As assessed from analysis of the point clouds provided by the manufacturer (Leica Geosystems, 2022) and from previous work experience, it is assumed that 360° pictures are complementary to the survey. They facilitate further modelling and provide better object identification. Even with the high precision, "blurred" representation of BLK2GO's clouds (Figure 20) might bring uncertainties, especially when being done in grayscale. On the contrary, this is different for stationary scanners, like BLK360, with better static representation (Figure 21). Moreover, panoramic photos made during the survey can be part of an audit report, as stated previously, revealing the current state of the building's elements. Since existing CDW marketplaces imply identification of products for reuse with images, survey panorama photos might be reused for this purpose as well.

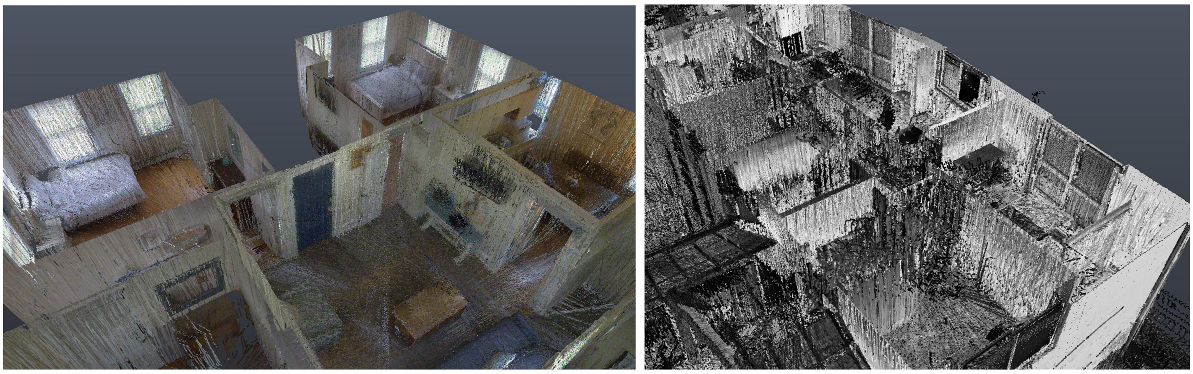


Figure 20 - Example of point clouds made by BLK2GO

Figure 21 - Example of point cloud with panorama made by BLK360

As it was described previously, a demolition auditor is a qualified party responsible for the pre-demolition audit, which includes sample taking, inspection, and partial deconstruction. It is also estimated that the whole audit will require more time in comparison to laser scanning with a handheld device. Therefore, it is assumed that the audit and scanning are subjects to be implemented by different parties. Moreover, the audit should take place before the reality capture is done. This sequence will provide visibility of uncovered elements and local destructions made during the audit, contributing to further modelling. Ideally, reality capture with laser scanning should take place at the end of an audit to provide interaction between the surveyor and the auditor for better informational output. At this point, 360 pictures are supposed to be taken with possible tagging of objects to map the audit report with captured geometry. More common technologies such as audio notes and tablet sketches with well-established information structures can assist the auditor in reporting, providing an organized input for BIM modelling.

3.3.2. PDT as a methodology to improve circularity of construction materials

As it was disclosed in Chapter 2, material and building passports are needed for waste management improvement (Giorgi et al., 2018; Mêda et al., 2021). When there is no available data regarding the asset to be demolished, which is a study of this work, there is a necessity to establish a set of information requirements to promote circularity. When the digital model already exists, this dataset can be used for a digital twin, since the idea of an incremental building passport is to be upgraded with time (Groh & Dubik, 2018).

To identify the structure and a set of circularity related properties, the following information sources were studied: Level(s) framework, EPD and ISO 22057:2022, ISO 23386:2020 and ISO 23387:2020, EC guidelines for the waste audit and reclamation audit (Interreg Europe, 2020), IFC property sets, sustainability related properties from NBS data templates, proposal of product circularity data sheet and BAMB material passport report. The definition of PDT's sub-set of information related to recycle and reuse potential can be represented as shown in Figure 22. From both perspectives, product (adopted from Cobuilder) and material (adopted from BAMB), reuse and recycle potential can be defined with the set of specific properties characterized in specific information source (IFC and EPD as legal base, waste/reclamation audit, Level(s) as industry recognized documents). User-specific requirements can be complementary to product definition to enable specific business processes, e.g., to provide application functionality or to identify and classify products with organizational standards.

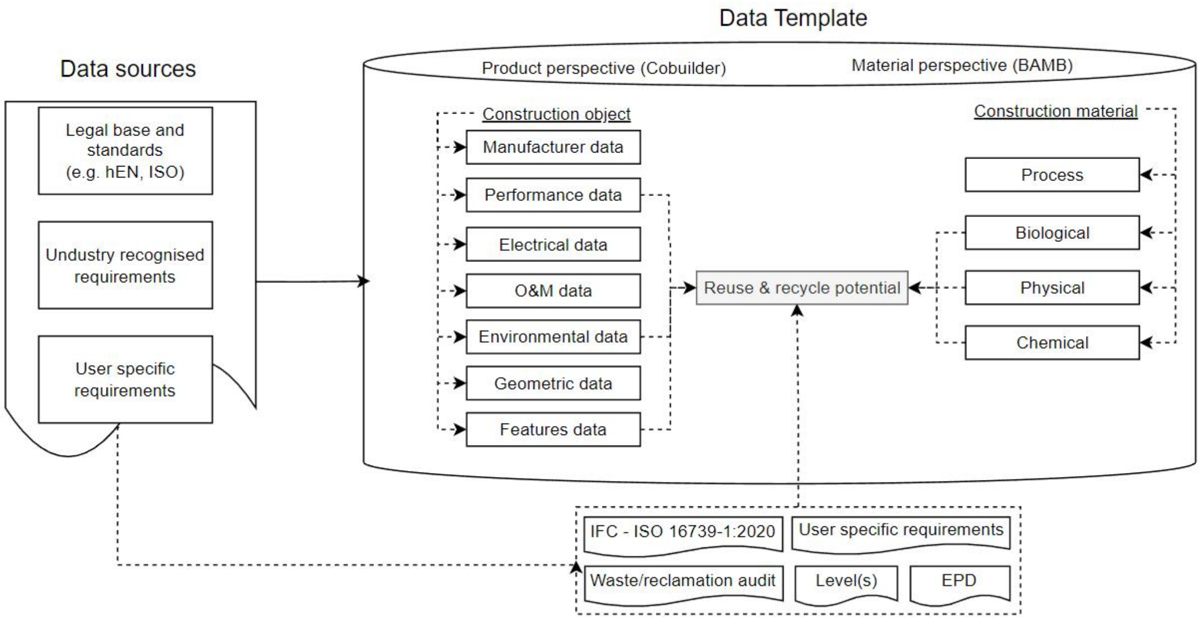


Figure 22 - Data template definition. Adopted and modified from (BAMB, 2020; Cobuilder, 2021)

In the case of new products and design, data templates, after being filled with the required information, become product data sheets, serving as a product's digital passport. In the case of existent building assets, where such information is not available, this data can be developed using parametric models of existent construction products. These parametric models, called archetypes, were proposed by the Circular EcoBIM project (Circular EcoBIM, 2021) for sustainability and circularity assessment. Using BIM as a methodology for data management allows us to reuse this information, creating incremental database with the potential for prediction models' development.

The process of data sheet definition for both cases—new product and existing without document references—is shown in Figure 23, and it starts with domain determination (material, component, product, or system). Since the focus is made on recycling and reuse potential, the search for related properties is implemented in correspondent documents, specifying data for this information container.

In the case of an existing object that has no references (e.g., declaration of performance or EPD), this information can be obtained by on-site investigations with a conclusion on specific characteristics. When these conclusions are documented, they can be used to create a database for future use when the same or similar elements occur. After mapping the real characteristics of an object with corresponding properties defined in a data template, the product data sheet is ready.

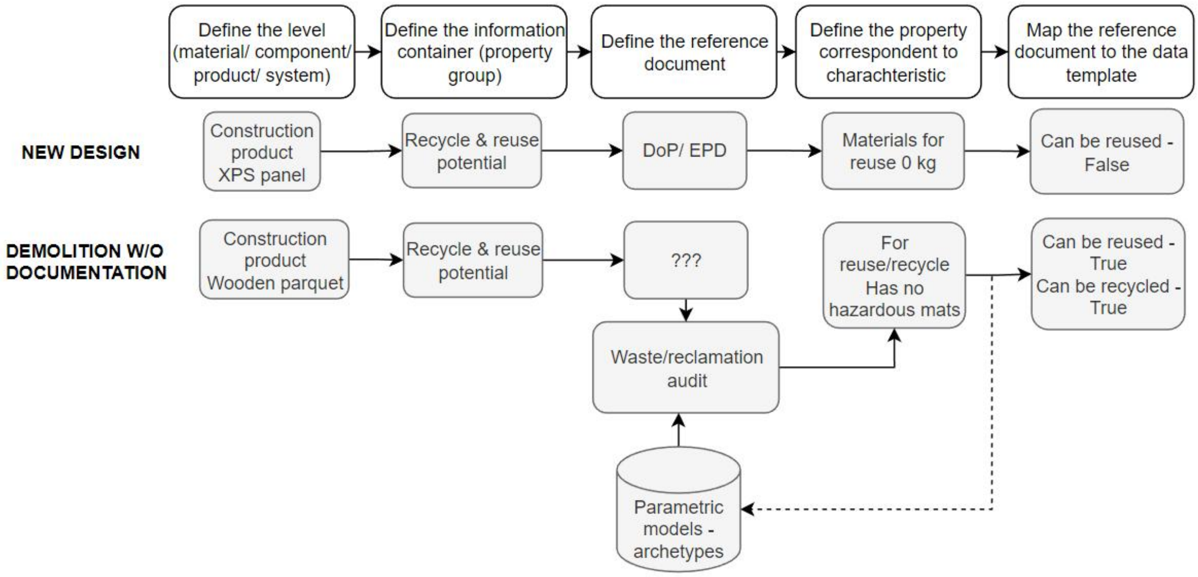


Figure 23 - Generic product data sheet definition process

As it was assumed that the main purpose of using digital modelling in BPR for CDW management is to provide a cost-effective and time-efficient process, closing the gaps of the AS-IS model, the sub-set of information for reuse and recycling should be established in a way to enable traceability and provide all the necessary input for the waste manager's decision-making process. The configuration of information containers shall enable automatic generation of output that can be sent to the marketplace for recycling, reuse, and reclamation. For this purpose, the following minimum PDT sub-set was defined as shown in Table 3.

Object class, defined by the IFC entity, is required since the BIM model handover is done in an open data format, according to the IFC schema. It is needed to identify the product in accordance with the bSDD and clearly represent the product's concept. Level(s)' tiers classification and European waste codes (EWC) are asked to generate automatic reports defined by the Level(s) framework, which is currently represented in a spreadsheet format with manual input of CDW estimated quantities. The presence of Uniclass classification code is conditioned by more granular product identification in a market. Declared unit represents the primary quantity taken for product assessment and is asked to provide correct automatic quantification from a BIM model. Declared quantity per unit represents the quantity of product that is used in its assessment, e.g., for EPD. I.e., if the product is a ceramic tile 60x60 cm with m^2 as the declared unit, and one tile was taken as a sample for environmental impact assessment, the declared quantity per unit (or declared quantity per EPD unit) will be a numeric value of 0.36, acting as a scale factor. Material compound and quantities of embedded materials per declared unit define the product composition of materials in kg of weight and are represented with an array property. This data can be applied in the Level(s) report and helps to represent the BIM model as a bank of materials.

Information on the possibility of reuse and recycling identifies the potential for product circularity. Type of joints is user-specific requirement created to provide the product context and analyze its deconstruction possibilities. At the current stage, it is proposed to identify it simply as a numeric value on a scale from 1 to 3, which can be elaborated with more complex classification to enable demolition sequence optimization. Information on potential danger identifies the presence of any conditions that affect the demolition process and require EHS inspection, e.g., hazardous substances, damaged load-bearing constructions, etc., and is aimed to attract attention of the waste manager, since EHS aspects can drastically affect the project's costs. An image is asked as an optional property with a correspondent attached document to visually assess the current state of a product and its potential for reuse.

Table 3 - PDT information sub-set for reuse and recycle potential

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"

* 1- fully dismountable mechanical joints (designed for deconstruction - DfD) without use of wet processes / relatively easy to dismantle for reuse and recycling; 2 - dismountable joints that requires extra human effort for being disassembled / wet connections are present but do not drastically affect the process; 3 - element is attached/ welded / walled up and requires machinery or extra human effort for being disassembled / element is casted or installed completely with wet processes

3.3.3. Level of information need framework for the demolition use case

As disclosed in Chapter 2, the level of information need defines the information required for a specific milestone in terms of geometry, alphanumerical information and documentation, as well as its purpose, actors and object content. The framework allows us to set a systematic approach for information exchange and ensure the absence of information waste. In relation to the demolition and CDW management process improved by digital technologies (point cloud survey and BIM modelling), the following key milestones of information exchange were defined: 1) input from appointing party providing available asset's information; 2) waste/reclamation audit report handover for modelling and outlining waste management plan; 3) point cloud data handover for modelling and outlining waste management plan; 4) BIM model handover for demolition optimization and planning. The information content for defined milestones is shown in Table 4 - Table 8. Since the level of information need defines the content of a BIM driven project deliveries, it can be applied for all subjects of information exchange.

As an input for the desk study (Table 4) prior to the survey and audit, the information about an asset is mostly defined by existing documents. If any project's model exists (BIM model, 2D drawings), representing the spatial relations of building elements, it is given with the required location specification to facilitate asset's geometry identification. In the absence of an existing model, a schematic layout is required to plan the survey.

Information delivery of laser scanning and reality capture (Table 5) as an input for modelling is defined directly by the point cloud data set as a spatial representation of an asset and by documents specifying the registration results for precision assessment. The set of documents includes images of specific elements defined by the auditor to provide a better identification of the current state of an object. Comprehensive information on the current state of building elements, their material compounds and characteristics is provided in the deliverables of an audit report, specified by the set of documents required for further modelling (Table 6).

Information content for BIM model is defined by requirements for its objects (Table 7, Table 8) and is specified from all three aspects: geometry, alphanumeric information, and documentation. When this content is satisfied for all elements of a BIM model, we could talk about specific model representation specified in accordance with information requirements—model view definition (MVD) for deconstruction.

Table 4 - Information content for the input for desk study

Purpose:	Input for the desk study
Actors:	Appointing party to lead appointed party
Object:	Building asset's information – construction information
Geometrical Information:	
Dimensionality	If available, in order of priority: 3D BIM model / 2D drawings / scheme of the building
Location	Closest georeferenced point if referencing is required and GPS coordinates
Documentation	
Set of documents	Pictures of the asset. Authorization of access if needed. Age of the building. Design documents and specifications. Documentation of use. Possible EHS restrictions and list of hazardous materials.

Table 5 - Information content for the modelling input from digital survey (laser scanning)

Purpose:	Input for modelling
Actors:	Appointed party (survey) and lead appointed party to appointed party (modeler)

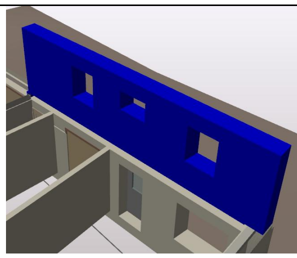
Continuation of Table 5

Object:	Point cloud
Geometrical Information:	
Detail	DPI enough to identify the elements (e.g., full point density for BLK2GO/ standard density for BLK360 - benchmarks)
Dimensionality	3D set of spatial data in proprietary software format coordinated with the BIM modeler (such as rcp/rcs) and one of the following formats (e57, ply, xyz)
Location	Registered point cloud w/o georeferencing (with georeferencing if requested)
Appearance	Set of points with colors. Grayscale is possible if 360 high quality color images (not less than 6 MP cameras) are available to unambiguously identify the objects
Documentation	
Set of documents	Registration data report Focused pictures, showing the current state of building elements (support joints where possible, cracks if present, deflection, and other related pictures that potentially can influence demolition process, incl. EHS aspects)

Table 6 - Information content for the modelling input from demolition/reclamation audit

Purpose:	Input for modelling
Actors:	Appointed party (auditor) and lead appointed party to appointed party (modeler)
Object:	Materials and elements inventory report
Documentation	
Set of documents	Materials and inventory report in defined form. Sketches, denoting the layers of multilayer materials with approximate thicknesses. Notes if hazardous materials are present within the layers. DB with present archetype characteristics. Voice recordings and pictures of building elements (support joints where possible, cracks if present, deflection, and other related pictures that potentially can influence demolition process, incl. EHS aspects) to provide better input for modelling

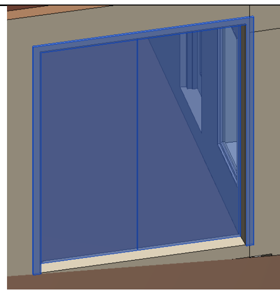
Table 7 - Information content for DIM – BIM model for demolition (on example of a wall)

Purpose:	BIM model for demolition, schedule optimization and waste management	
Actor:	Appointed party (BIM modeler) to Lead appointed party	
Object:	Building's element – construction result (on the example of wall)	
Geometrical Information:		
Detail	Simplified shape representing the volume (rectangular parallelepiped for the simple rectangular wall) without compromising the QTO properties (volume, height, etc.). If openings are absent due to IFC export, QTO should not be compromised.	
Dimensionality	3D object	
Location	Positioned relative to the building levels and other load-bearing elements	
Appearance	Single-color fill to visually distinguish between different types and materials	
Parametric behavior	Explicit geometry	
Alphanumeric Information:		

Continuation of Table 7

Identification:	Correctly defined object class and IFC entity corresponding to the object class which most clearly describes the concept of the element
Information content	Properties, defined within reuse and recycle PDT sub-set, quantity sets required for specific class, object class and type name, related building levels
Documentation	
Set of documents	Reference to information container (preferably within project CDE) with pictures, showing the current state (support joints where possible, cracks if present, inclines, etc.), data from waste audit report, sketches with wall layers and any other related information given by the auditor

Table 8 - Information content for DIM – BIM model for demolition (on example of a door)

Purpose:	BIM model for demolition, schedule optimization and waste management	
Actor:	Appointed party (BIM modeler) to lead appointed party	
Object:	Building's element – construction result (on the example of wall)	
Geometrical Information:		
Detail	Simplified geometry representing the frame and a door leaves if information content is well defined. If the DB of archetypes exists, allowing to define material content basing on quantities with certain accuracy, object can be complex. In this case the quantities should be machine readable and automatically extracted from the object of specific entity (e.g., glass panel in a door – IfcPlate with calculated area)	 DeclaredUnit: pcs DeclaredQuantityPerUnit: 1.000000 MaterialCompoundPerDeclaredUnit: wood,steel MaterialQuantityPerDeclaredUnit: 130, 50
Dimensionality	3D object	
Location	Positioned relative to the building levels and host elements (walls)	
Appearance	No color in case of simplified geometry, different colors for modelled geometry to distinguish different materials	
Parametric behavior	Explicit geometry	
Alphanumeric Information:		
Identification:	Correctly defined object class and classification (IfcDoor)	
Information content	Properties, defined within reuse and recycle PDT sub-set, quantity sets required for specific class, object class and type name, related building levels and host element/parent element	
Documentation		
Set of documents	Reference to information container (preferably within project CDE) with pictures, showing the current state (support joints where possible, cracks if present, inclines, etc.), data from waste audit report, sketches with wall layers and any other related information given by the auditor	

To provide a framework for demolition/reclamation audit, based on the defined level of information need and existent guidelines (European Commission, 2018c; Interreg Europe, 2020), the following inventory report is proposed with the sample layout location tags (Figure 24, Table 9).

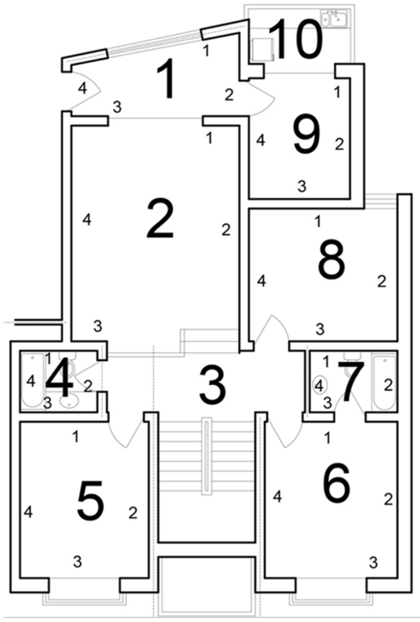


Figure 24 – Building layout notation for inventory report template

Table 9 - Inventory report template with examples

Item	Location (room/ wall)	Reuse & recycle potential	Waste codes and materials	Declared unit		Mass (kg) per declared unit		Has potential danger	Precautions to take during deconstruction	Notes
				unit	qt	kg/ unit	qt tot			
Wall	1/1 - entrance	-+	17 01 02 brick 380 mm with 17 08 02 plaster 30 mm	m3		1750		yes	Load bearing, holds the roof	Partially covered with mold
Window	1/1	++	17 02 01/ 17 02 02 Wood and glass	pcs	1		30/ 15	no	For reuse requires careful dismantling	Carved antique wood
Arch frame	1/3	++	17 02 01 wood	pcs			75	-	Careful dismantling	Carved antique wood
Staircase	2	++	17 02 01 wood	pcs	1		45	-	-	-

3.4. TO-BE model of demolition process and CDW management

After the gaps were defined, the TO-BE process model was elaborated based on the opportunities of digital technologies (Figure 25). The workflow was put into the information management framework defined by ISO (ISO 19650-2, 2018). In comparison to the current process, new roles were introduced: digital survey and modelling company (appointed party) and VDC (Virtual Design and Construction) specialist (appointed party), perceived as an advisory side related to the demolition company. For simplification purposes, digital survey and modelling are performed by the same party, which is in line with current practice, even though these tasks can be done by different participants. In contrast, a VDC specialist is defined separately to demonstrate BIM-specific activities associated with reengineered processes. The new actors' responsibilities are:

1) Digital survey and modelling company (appointed party) – responsible for digital survey (laser scanning) of a building asset to be demolished and provides processed point cloud data and 360 images, serving as an input for modelling. It oversees BIM model creation in accordance with the information requirements and guarantees its quality. This party interacts closely with the auditor and VDC specialist.
2) VDC specialist (appointed party) – responsible for BIM model validation and updating of information on the building asset (including digital model and other project related data) in a publicly open platform for trade of CDW and products for recycle, reuse and restoration. The party contributes to information sharing and facilitates the waste manager's decision making

Another significant change proposed in the new process model is the way communication with third-party stakeholders is done. Instead of a reactive way when the supply of dismantled and demolished products depends on onsite management, a more active workflow was introduced with the materials bank concept. Since information becomes available in early stages prior to demolition works and is represented in an open digital way for the public, the demolition schedule and WMP can be influenced by the market's demand, promoting more careful deconstruction and reuse as well as potentially increasing income on salvage sales. A web platform for this purpose was proposed (see Chapter 4). It provides automatic input for the marketplace and facilitates model validation to ensure trustworthy and correct informational input, based on quantities retrieved from a digital model.

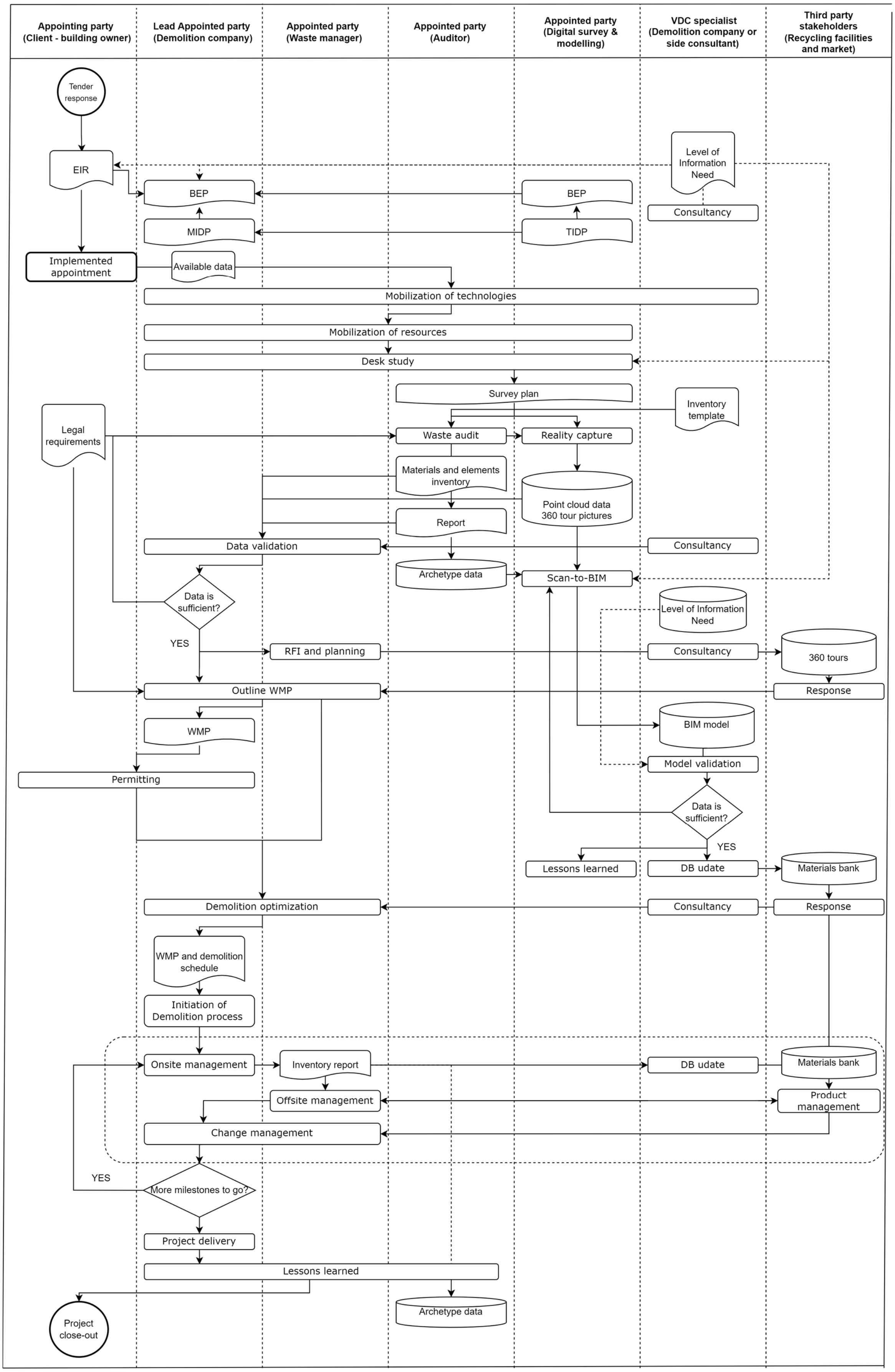


Figure 25 - TO-BE business process model

The process after the appointment is implemented starts with the mobilization of technologies and resources, by analogy with the AS-IS process. The first change introduced in the reengineered process is the establishing of information management related documents: EIR, BEP, information delivery plans (MIDP and TIDP). The EIR for the client can be set by the VDC specialist, as a consultant of the lead appointed party, and is complemented by the level of information need defined for each delivery milestone. Desk study becomes a step required for the digital survey to plan on-site activities for data acquisition. During the audit, reality capture is implemented in collaboration with the auditor to ensure that the current state of an object was recorded to the right extent and provides all the data defined by the level of information need. Survey output is a subject of data validation and can be used for designing WMP outline for permitting, as in the AS-IS process, to avoid time delays caused by digital modelling (even though it is assumed that this period is relatively short). The outline WMP, in fact, can be done with more precise data from the model after it is done. Another assumption considered is that the demand for materials can start to be generated after uploading the survey 360 pictures to the marketplace, thereby making information available earlier. The survey and audit data, after being validated, serve as an input for the scan-to-BIM workflow. The digital model created for demolition planning is also a subject of validation, which is performed by VDC specialist with the help of the digital platform. This platform parses the model and provides automatic generation of a database of objects and materials (constituting a materials bank) for the marketplace. This marketplace serves as a platform for interaction between waste manager and third parties for demolition and product management (waste and deconstructed objects for recycling facilities and restorers are treated as products). In this way, the WMP can be optimized using digital modelling and simulation tools, basing not only on time and cost efficiency, but also on required rates of reuse and recycling, thereby facilitating the circular economy. After the demolition process is initiated, collaboration between the demolition company, waste manager, and 3rd parties becomes data driven and is based on information sharing for a better disposal strategy.

Some problematic points in the reengineered process model, however, remain. One of them is the information completeness, generated during the audit and survey: regardless of the chosen methodology (as-is audit or upgraded with a digital survey), utilities and any hidden objects, such as MEP elements and inaccessible building areas, remain unknown. It diminishes the value of an elaborated digital twin. To compensate this shortcoming, the archetype database plays a huge role for better characterization and definition of building's objects. This data, ideally, should be available for the demolition auditors and be open for new contributions, facilitating better quality of the process and its outputs, outcomes, and impact. The same can be inferred for the BIM objects' database: by inheriting the archetypes' data in the product data sheets and providing geometry close to real representation, the objects might constitute the database of existent construction products, making the information about them traceable and reusable. This could be especially useful for objects and products of high value for restoration and with high reuse potential.

4. WEB-BASED PLATFORM FOR IFC VALIDATION AND PROCESSING

4.1. Assumptions, principles, and performance requirements

In the reengineered process, mentioned in Chapter 3.4, the notion of a web-based platform was introduced. The intended purpose of this service is to promote the circularity of construction materials and products. It is assumed that this can be done by providing an automated input for the marketplace with relatively precise information on quantities generated from the digital model in early project stages. As it was defined in Chapter 2, currently existing marketplaces operate mostly based on human input, therefore, the information is not standardized and requires extra processing to be shared. Another implied contributing factor for CE is that the platform is a subject of open use and operates with open data formats. It is built based on open-source libraries and developments (also see Chapter 4.3) and can be publicly upgraded to customize the service and spread the technologies.

It is assumed that in a real-world scenario, the platform can be hosted in a public web-domain and linked to the marketplace. Since the marketplace platform itself was not considered as a subject to be developed in this work, the platform's functionality ends in preparing the data derived from the BIM model for the marketplace population. The marketplace functionality can be obtained by using existing templates, free or commercial and customized (e.g., available in ThemeForest - Figure 26), introducing the CDW trading option.

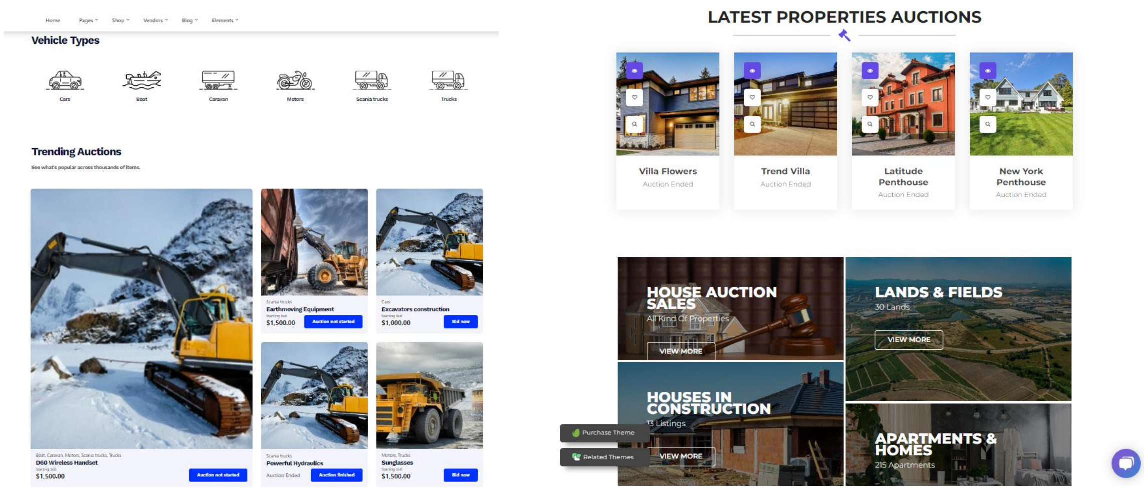


Figure 26 - Auction templates' examples (ThemeForest, 2022)

Connection between the platform and a marketplace can potentially be implemented in a responsive two-way workflow, so generated demand will be put into an information structure that can be read by any BIM software and the platform itself, providing shared data space and facilitating decision making. However, only the upstream process was elaborated in this work, demonstrating the concept of machine-readable informational input and an example of automatized validation in accordance with information requirements. The working principle of a platform can be outlined as shown in Figure 27. It starts with registration and model upload, continues with model processing, including validation, report generation, and finishes with BIM model parsing and preparing project specifications.

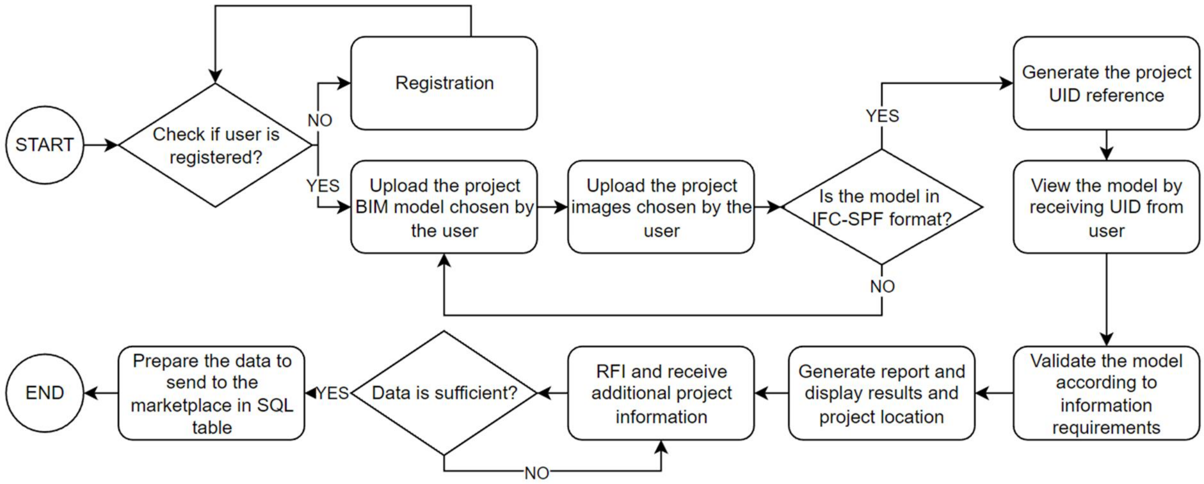


Figure 27 - Platform's workflow to validate and parse a BIM model

Even though open data formats today do not necessarily provide full interoperability and the full spectrum of information transferred, it is assumed that IFC-SPF (.ifc) is the most applicable to transfer circularity-related data to the full extent defined by information requirements. It is supposed that the data provided in the IFC file is not a subject of consistency checking. This procedure implies inspection of the file on the subject of user intervention, resulting information tampering and unreliable object quantities. The way the IFC was generated was not assessed with different authoring software; only one of the most common applications was applied to illustrate a case study. Every demolition project implies one generated BIM model as an input for the platform; a federation strategy was not considered, and it is expected that only one model file will contain all the project related data. Another requirement for the input is that the IFC schema shall be of version 4 (IFC 4 ADD2 TC1 - ISO 16739-1:2018) as the most up-to-date standard complied with ISO.

The reason for using web-based technology was to provide “thin” client service that would not require high-performance computational capacity and could be used with portable devices for instant information sharing. However, possible drawbacks can be related to application and domain maintenance, as well as to the threat of data loss caused by hacker attacks or server crashes. These statements lead to the necessity of data governance and adoption by regulatory institutions if the platform is a subject of open public use. Another possible scenario is to adopt the business models of existent marketplaces (advertising as a service or information as a product), so potential benefits can attract organizations to manage the platform operation. However, data protection, data ownership, and legal aspects were not considered in this work.

Because of the absence of previous knowledge and experience in domains related to software and web application development, all the skills regarding the platform design and coding were developed during the dissertation period. The main objective was to provide an MVP (Minimum viable product) that could be used as a tool to promote circularity in the demolition process.

4.2. Platform structure as an MVP and description of business logic

The web platform was elaborated using a local server on one machine with Apache and MySQL modules of XAMPP. However, after being deployed in a real-world scenario, the application could be described as a three-tier architecture (Figure 28). The business logic depicted in the sequence diagram is shown in Figure 29 (also see Appendix 1).

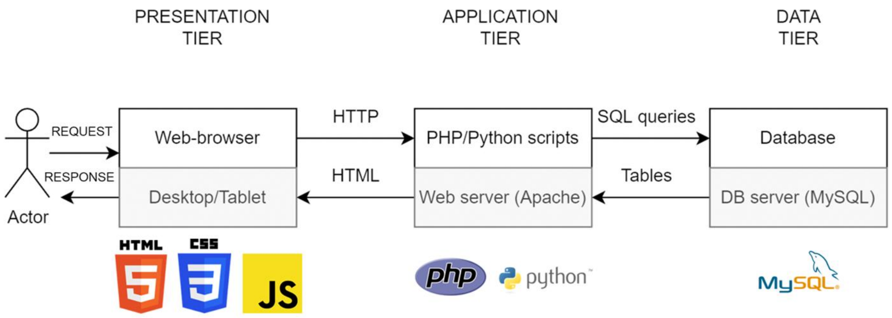


Figure 28 - Platform's 3-tier architecture representation

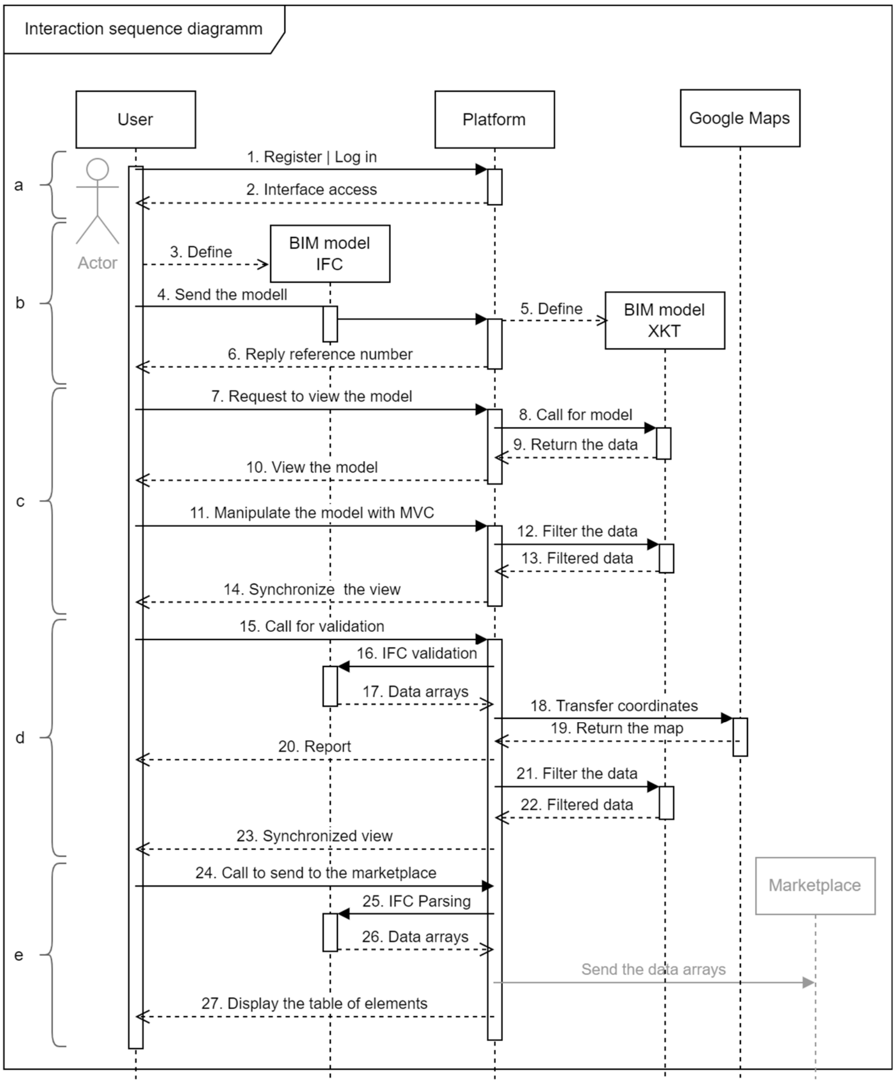
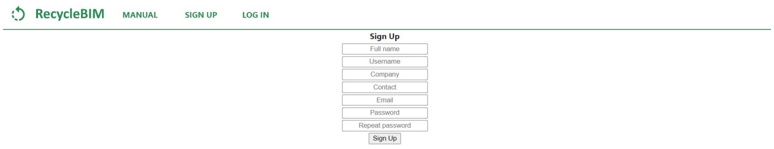
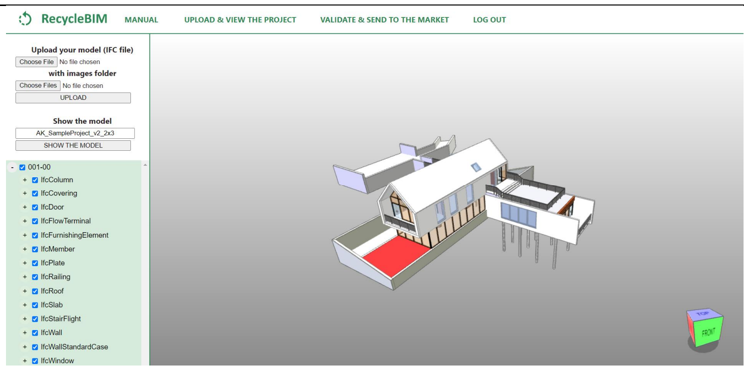
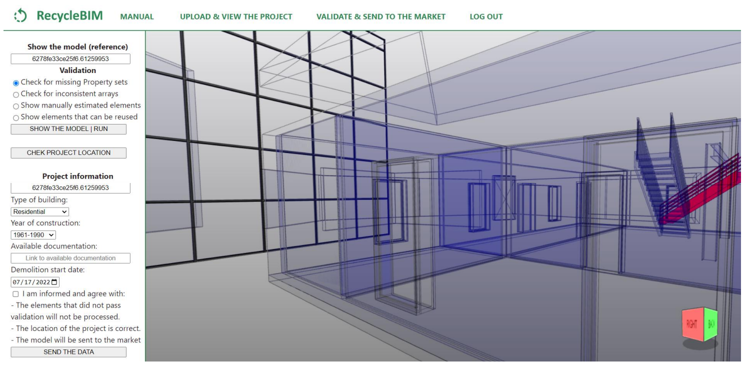
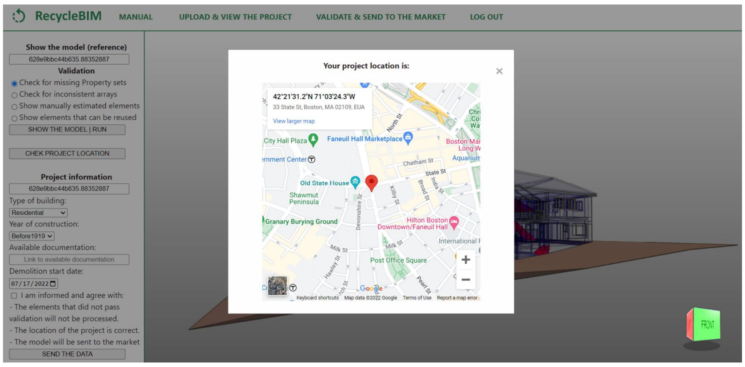


Figure 29 – UML sequence diagram of the developed platform

The developed platform provides the following functionalities, defined as a minimum set to outline the concept of use of a digital model as an automated input for the marketplace (Table 10):

Table 10 – Functionalities of the elaborated web platform

User registration system to ensure authorized access (Figure 29 a)	
Uploading a BIM model with images of objects and displaying it (Figure 29 b, c)	
BIM model validation and generation of reports (Figure 29 d)	
Display of project location in Google Maps (Figure 29 d)	
Parsing of a BIM model for generation of list of objects for reuse and recycle (Figure 29 e)	

The user registration system (Figure 29 a) allows us to establish authorship of BIM models and implies that accounts are created by waste managers. The uploading module (Figure 29 b) receives the model with documentation from the registered user and sends it to the DB tier, assigning a unique identifier, so the objects can be addressed in an unambiguous way and then showed in a browser. The viewer (Figure 29 c) allows to filter displayed object classes, rotate the model, and visually assess its quality. Validation is performed with predefined scripts in the application tier that take the model from the DB tier (Figure 29 d). Currently, the procedure is predefined within the scripts, so the information requirements are constant. This can be improved by storing the level of information need in a DB format, so it can be addressed with the set of variables within the validation scripts, making the platform more flexible and scalable. The connection of a project to Google Maps is perceived as a requirement to provide the local context, since the profitability of CDW recycling and reuse is mostly related to local conditions (European Commission, 2018b). Potentially, this data can be used to calculate the distances and estimate logistic related decisions, including environmental impacts, such as GHG emissions, caused by transportation. The parsing of the model allows to represent the data on elements for reuse and recycle in an SQL table, making it ready to be sent to any marketplace (Figure 29 e). The purpose of the marketplace is to make information on materials and products included in the building available in early stages, before the demolition starts. Based on various reuse and recycling perspectives and potentials, generated purchasing requests or bids for specific lots could make a difference in project scheduling and waste management plan, providing a comprehensive foundation for project optimization.

The platform represents the project information in such a way that it can contribute to and be used in the future for:

1) Demolition and deconstruction planning;
2) Generation of justified quantities of materials and building elements for reuse and recycling;
3) Providing traceable information and business transparency;
4) Open market for CDW trade;
5) Free public use and CE promotion;
6) Creation of prediction models and use of AI for better decision making.

All the platform's source code can be accessed on GitHub (https://github.com/ArturKuzminykh/Masters).

4.3. Applied libraries and SDK

To build up the interface (front end), HTML, CSS and JavaScript were used, allowing to represent the application on the client's side in a web-browser. To provide the model interpretation in a web page, the Xeokit SDK (software development kit) was deployed in application tier. Before displaying the model in a browser, the IFC-SPF file, after being uploaded by the user, was converted to XKT format. The native XKT file, containing geometry (representation of 3D models saved in the GL Transmission Format -glTF) and connected metadata model (in JSON), then could be displayed for user interaction, as shown in Figure 30. According to the update, in the upcoming 2.3 release, this process will be simplified, "*passing the output of IfcConvert straight to convert2xkt, as a binary glTF file*" (Xeolabs, 2022). There are other options to display IFC directly in a browser (e.g., by using the free IFC.js library) without conversion. However, due to the availability of documentation and a variety of examples for Xeokit SDK, this workflow was assessed as more efficient with an acceptable entry threshold.

Moreover, Xeokit supports conversion not only of IFC files but also CityJSON, glTF, LAZ, and LAS (Xeolabs, 2022), which can be used for potential scalability of the developed platform to provide, e.g., point cloud data or site geometry from open street maps referenced to the model.

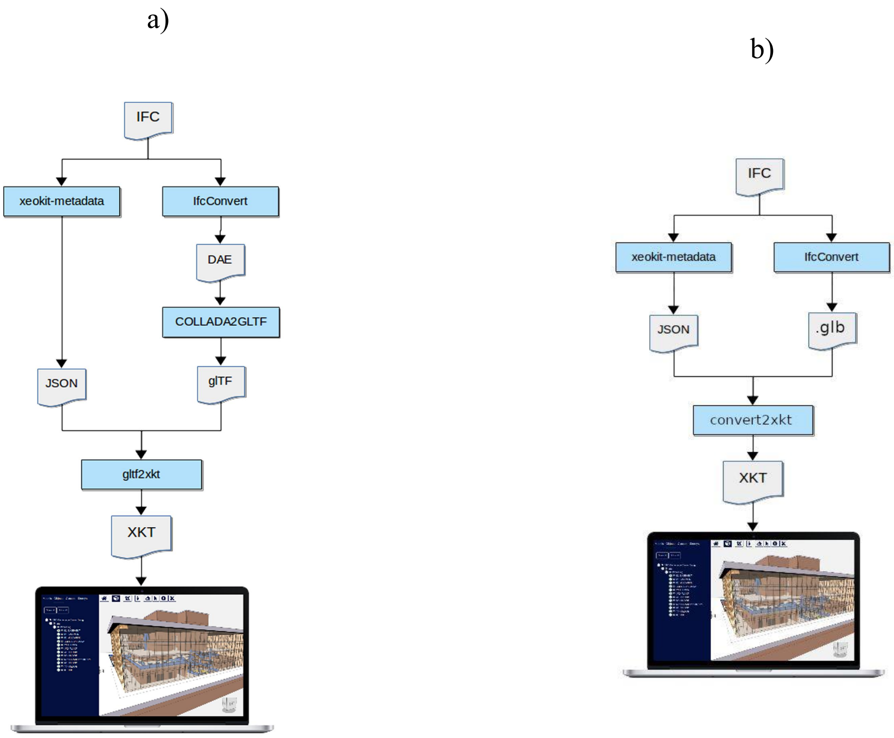


Figure 30 –IFC to XKT conversion procedure (a- existing, b- updated in release 2.3) (Xeolabs, 2022)

Analysis and validation of a BIM model were performed with the use of the “IfcOpenShell” python library. By addressing python scripts with PHP calls, the IFC models are taken from the server and processed in a python shell in the application tier. The scripts parse the IFC files and return the output in accordance with predefined check procedures, defined by information requirements. The python library "MySQLdb" was used to connect to the MySQL database on the server side, the "sys" library was used to pass variables from PHP to scripts, and "json" was used to compactly encode the python output and pass the arrays back, for example, to the JS libraries of Xeokit to filter and display the BIM objects in a specific way.

4.4. Database structure

On the back end, in the data tier, the MySQL database was deployed. The entity relationship (ER) diagram of the current state of the platform can be described as shown in Figure 31. Every registered user is defined by a unique ID, email and username with company name and contact. Users’ passwords are hashed and cannot be accessed by third parties. After being registered, users can upload, view, validate, and parse BIM model that represents the project. Each project in turn is connected to a specific user and is defined by location, BIM model, unique ID, type of building (residential, commercial, industrial, infrastructure, agricultural, public institution), year of construction (adopted years range for archetypes from Circular EcoBIM), available documentation link (ideally, related to project CDE) and demolition start date. Within every project (BIM model), each element is defined by the set of alphanumerical information, which was determined by the level of information need. Basically, the table of objects represents the specification of elements for reuse and recycling.

Figure 31 - ER diagram of current platform development

When the marketplace functionality is installed, the ER diagram can be conceptually described as shown in Figure 32 (also see Appendix 2). It is an extension of the currently developed concept with demand-related entities, connected to the marketplace DB. The main feature implied for the marketplace is providing the best outcome for building elements. For instance, if an element (a building object) can be reused and recycled, the marketplace algorithms should give priority to the reuse strategy instead of representing it as a material aggregate. Customers, being the users, can create orders for the materials or products. Therefore, demolition operators can make decisions on deconstruction strategy.

Relations between entities of elements for reuse and materials for recycling can be shown schematically as depicted in Figure 33. The elements have a more discrete nature and represent a higher class; they contain different materials that can be or cannot be recycled (colored and empty cells, respectively). However, every material belongs to a specific element that can be reused or not. Elements' entity is just intersecting with materials' entity, since some of the elements can only be reused, even when containing materials for recycling (e.g., when being produced in a way that makes it hard to separate different materials, or when containing hazardous substances). The project can be estimated from different perspectives, building up the basis for more comprehensive and complex analysis in the future, which would include optimization in terms of economic and environmental indicators. Another expected function of the marketplace is the mechanism of price building based on supply and demand, with the possibility of auction trades for items of significant value (e.g., antiques).

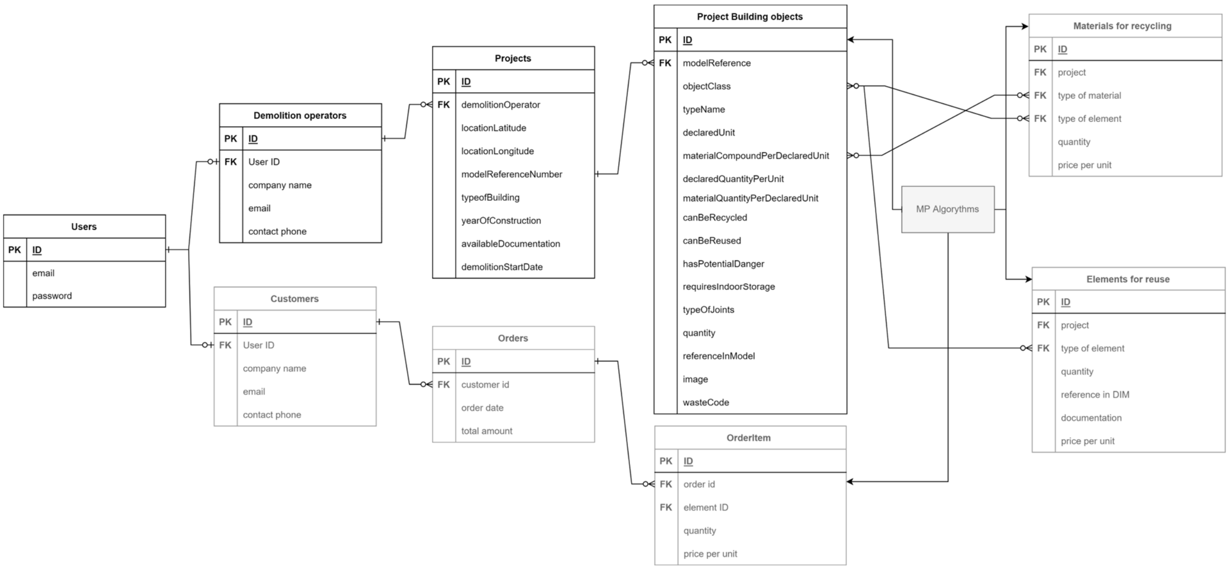


Figure 32 - Conceptual ER diagram with marketplace realization

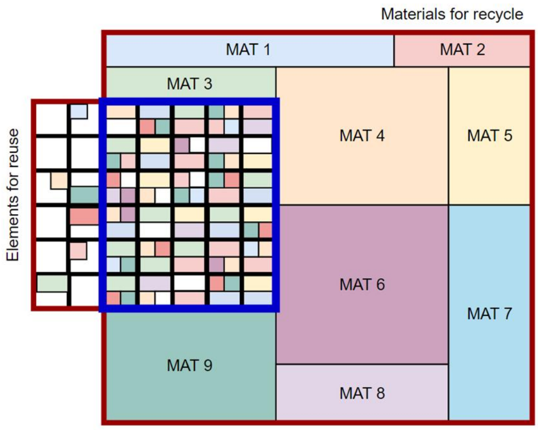


Figure 33 – Entities' relation between building components and materials

4.5. BIM model validation procedure

Currently, the platform allows users to perform 2 check procedures and 2 analyses to display elements for visual assessment. As it was described previously, the model is parsed with the python "IfcOpenShell" library within the scripts which pass arrays with elements' GUIDs to the JS code parts of PHP pages.

The first validation script checks for missing properties, defined by the level of information need (specified in Chapter 3.3.3). The algorithm defines all IFC building elements' classes present in the model and then checks all elements in the generated lists for present property sets. Since BIM objects can be compound, i.e., having a parent-child structure with nested BIM objects, the script first checks all the elements at the lowest level, and then, if properties are missing, the same procedure is done for parent elements, if applicable. For example, in the case of a curtain wall created in Revit, when being exported with default settings, the parent element will be defined as “IfcCurtainWall”, having nested elements of panels (“IfcPlate”) and mullions (“IfcMember”). If children do not have the required properties, the code will perform the search for the parent data set. At the end, the arrays of GUIDs and notes will be generated and passed to the PHP pages generating the text report, as shown in Figure 34. The algorithm can be described as shown in Figure 35.

```
"IfcStairFlight - 3 element(s). Circularity properties are filled: 0%"
"NOTE: For the class IfcStairFlight 3 elements (100% ) have parent elements, 34% of them have Circularity properties"


"IfcWall - 32 element(s). Circularity properties are filled: 72%"


"IfcWindow - 10 element(s). Circularity properties are filled: 100%"


"IfcStair - 3 element(s). Circularity properties are filled: 34%"


The list of questioned elements:

"1$hyjxWWz9YAXRWMjtwBLJ","1$hyjxWWz9YAXRWMjtwBLJ","1$hyjxWWz9YAXRWMjtwBLI","1$hyjxWWz9YAXRWMjtwBLH","1$hyjxWWz9YAXRWMjtwBLG","1$hyjx
WWz9YAXRWMjtwBKl","1$hyjxWWz9YAXRWMjtwBKk","1$hyjxWWz9YAXRWMjtwBKj","1$hyjxWWz9YAXRWMjtwBKi","1$hyjxWWz9YAXRWMjtwBKh","1$hyjxWWz9YAX
RWMjtwBKg","1$hyjxWWz9YAXRWMjtwBKf","1$hyjxWWz9YAXRWMjtwBKe","1$hyjxWWz9YAXRWMjtwBKd","1$hyjxWWz9YAXRWMjtwBKR","1$hyjxWWz9YAXRWMjtwB
KQ","1$hyjxWWz9YAXRWMjtwBKP","1$hyjxWWz9YAXRWMjtwBKO","1$hyjxWWz9YAXRWMjtwBKN","1$hyjxWWz9YAXRWMjtwBKM","1$hyjxWWz9YAXRWMjtwBKL","1$
```

Figure 34 - Example of report for missing properties

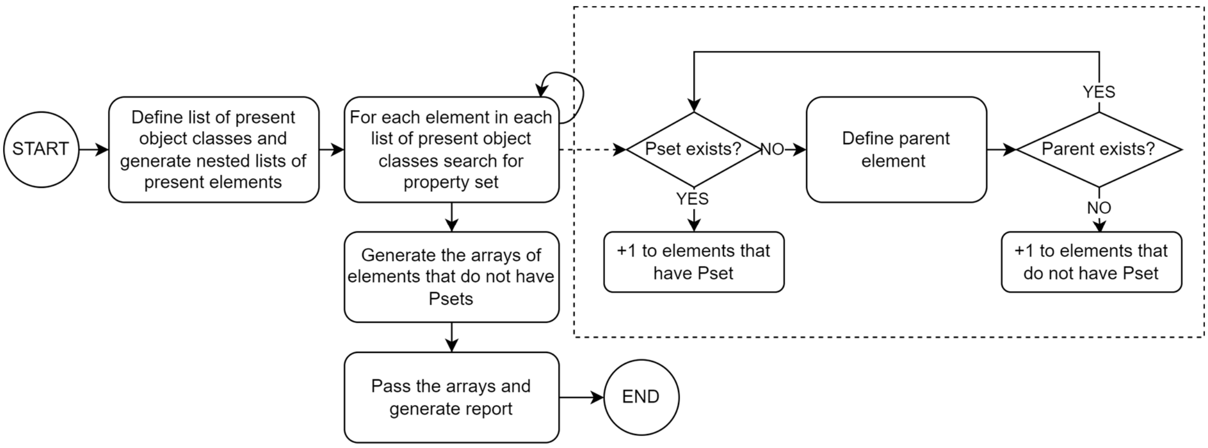


Figure 35 - Search for property sets – process flow

The second checking procedure identifies inconsistencies in array properties. As it was defined in Chapter 3.3, three properties are constituted by arrays (material compound per unit, its quantity, and waste code). If elements have the required set of alphanumeric data, checked in the same way it was described before, the search for 3 array properties is implemented. The results are inspected for the array lengths, and if they are not consistent, the IDs of these elements are reported.

The last two designed options for analysis allow us to distinguish two entities of elements. The first one identifies components that were quantified by the user manually. Manually estimated elements can be referred to complex objects that would require considerable time to model to be estimated correctly (e.g., handrails and staircases), so identifying their quantity by alphanumeric data would be more time efficient and can be re-checked at this stage. However, this methodology is expected to be less applicable with the growth of the BIM objects’ database. The second analysis displays and reports elements for reuse (Figure 36), allowing users to ensure the right assessment of reuse potential and examine visually what elements were taken into consideration, since the marketplace's priority is to promote them for a new use cycle.

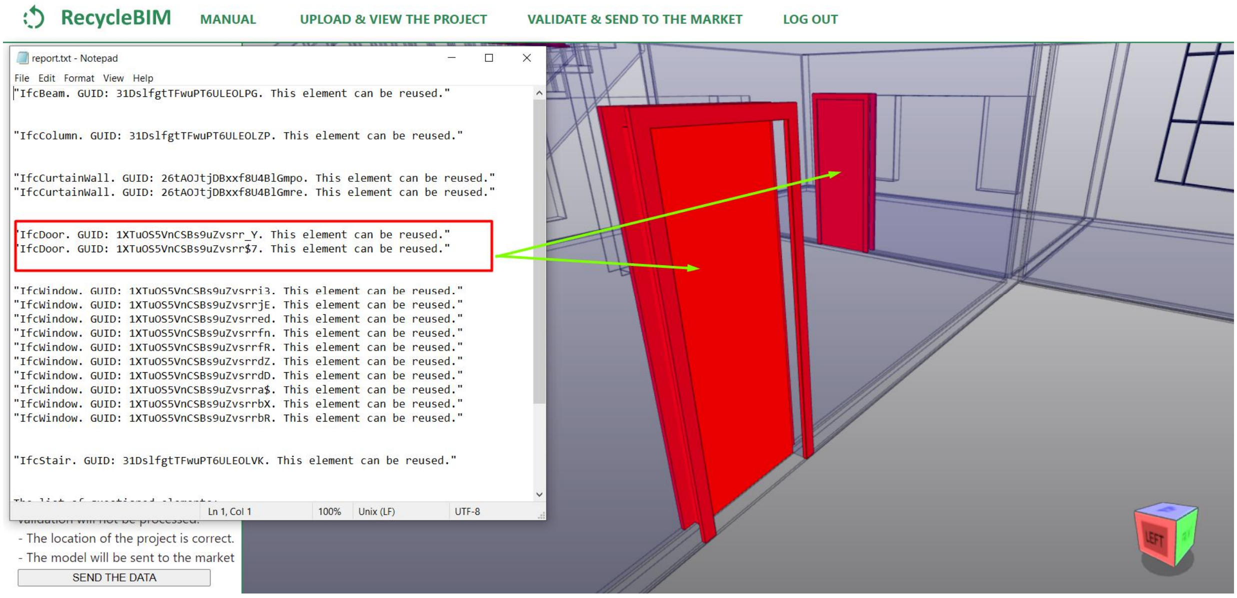


Figure 36 - Displaying the elements for reuse with generated report

4.6. Potential for development

This subchapter describes a conceptual possible platform's upgrades and serves as a starting point for future development and inspiration. Firstly, as stated previously, integration with the marketplace is a paramount step for application deployment aimed at providing a bidirectional link between the model and the market's supply and demand requests. The model, ideally, should be updated constantly and shown on a web page, based on the trade and waste manager's decisions. Therefore, the model could be represented from different perspectives, as conceptually already proposed by some authors (Figure 37). Moreover, a marketplace with business analytics would allow us to estimate the project's benefits from the salvage sales based on the current prices of materials and elements.

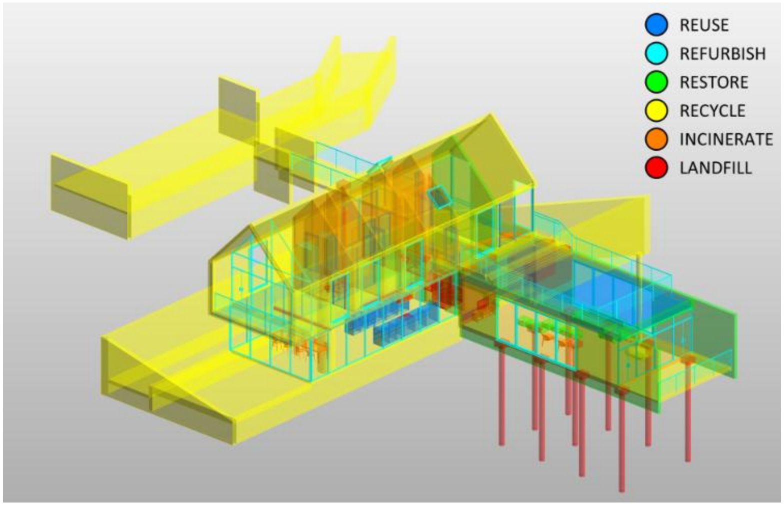


Figure 37 - Use of BIM model to represent is from different perspectives (Groh & Dubik, 2018)

Another potential for development is calculating the transportation routes and their optimization. Knowing the weights of materials, it is possible to estimate the economic benefits and environmental impacts of various options, based on the projects' locations. Adding information about the positions of recycling infrastructure, warehouses and storage, decision-making in disposal strategy could be supported by this type of information. The platform could perform LCA assessments of different disposal strategies, providing optimization functionality. In general, when information requirements are set with a purpose, data analysis can be implemented for any data subsets contained in a digital model.

Since today's web-developments allow users to connect schedules with models in a browser, constituting 4D BIM (e.g., Sigma viewer), the platform could provide time tracking for demolition projects. In this way, the information for all involved parties becomes available from portable devices with web browsers and the internet. The schedule might be built based on different aspects, e.g., market demand, available facilities and machinery, giving a basis for better decisions.

As stated previously, using parametric models for undefined building areas allows one to roughly estimate present materials and their quantities. After gathering the data on completed projects, the platform could provide an option for preliminary project assessment, based on previous statistics. For example, any involved party could use the platform knowledge base to predict contained materials per square meter, average raised earnings on salvage sales, demolition duration, etc., based on input of the project's location, age, and area. Therefore, even prior to the project's tendering, the platform could serve as a support in bidding.

Since Xeokit allows generating BCF-based viewpoints, the items sent to the marketplace could contain the link to the element in a model. Therefore, when checked in the marketplace, the item can be shown in a model context, which can be complemented with point cloud data and panorama images of the correspondent space. This could give a better perspective on the project and make it more transparent for public review.

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5. CASE STUDY DEMONSTRATION

5.1. General description

Proposed methodology with the use of digital modelling was tested in a case study. The asset is located in Portugal, Vermoim, Maia (Figure 38). The building is residential and consists of several compartments which were built with different materials. It has two stories with elevations that follow the terrain and about 400 m^2 of plot projection. The eastern block was renovated in the 1960's with a brick and concrete second floor and is adjacent to other parts mainly built with granite walls. The insulated sloped roof is supported by wooden beams and is finished with clay tile. The floors are performed with concrete and wooden structures.

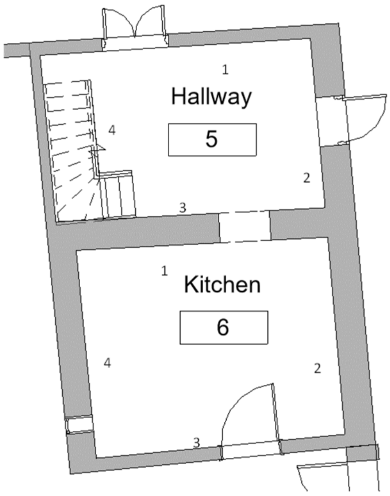
Figure 38 - Project location and outside view

The building is perceived as a typical project for to-be demolished assets, even though the real demolition was not planned. The case study was applied to this property due to its accessibility for surveys and investigations. Appointment relations were applied only for the digital survey (laser scanning), which was performed by a specialized company with available equipment. The rest of the reengineered process in the part from survey to use of the digital platform for BIM models was performed to demonstrate the application of the proposed workflow methodology. Some assumptions and simplifications were made regarding individual steps, such as an audit, since the main goal was to demonstrate the approach rather than complete implementation of the process itself.

5.2. Survey methodology and data capture

The redesigned process implies a digital-driven survey to enable further BIM modelling and includes pre-demolition audit and laser scanning for spatial data acquisition. The audit was carried out during the site visit and included photo-recording and inspection of structures. Since this procedure is subject to being performed by a qualified specialist, it can be said that the audit in this case study was simplified, including the assumptions in the audit report. The data regarding material compounds and their relative weights and waste codes was obtained from existent EPDs of similar products. Part of the audit report is shown in Figure 39. The item referred to an inspected element, its location was defined by the room number and closest wall (counted clockwise). Reuse and recycling potentials were marked with a yes

(+) or no (-) option. Waste codes and materials were defined in accordance with the EWC as array properties. The declared unit was taken from an existing similar EPD. The mass was also specified as an array of constituting materials and identified either based on existent documentation or on average values of weight distribution per primary quantity (linear, area, volume density).



Item	Location (room/wall)	Reuse & recycle potential	Waste codes and materials	Declared unit		Mass (kg) per declared unit		Has potential danger	Precautions to take during deconstruction	Notes
				unit	qt	kg/unit	qt tot			
Wall	5/1	+ +	17_05_04 granite av.240 mm, 17_01_07 mortars	m3		2700,50			Load bearing	Reuse as blocks and aggregates
Door	5/1	+ +	17_02_03, 17_02_02,17_04_05 - PVC door	pcs	1	55 (7,40,8)				Reuse if deconstructed carefully
Wall	5/2	+ +	17_05_04 granite av.540 mm, 17_01_07 mortars	m3		2700,50			Load bearing	Reuse as aggregates
Door	5/2	+ +	17_02_03, 17_02_02,17_04_05 - PVC door	pcs	1	40 (6,28,6)			-	Reuse if deconstructed carefully. Entrance to building
Wall	5/3	+ +	17_05_04 granite av.540 mm, 17_01_07 mortars	m3		2700,50			Load bearing	Reuse as aggregates
Opening frame	5/3	+ +	17_05_04 marble	pcs	1	150			-	Reuse if deconstructed carefully. For opening 930x2000
Wall	5/4	+ +	17_05_04 granite av.180 mm, 17_01_07 mortars	m3		2700,50			Load bearing	Reuse as aggregates
Staircase	5/4	+ +	17_02_01 wood	pcs	1	250			-	With pocket door. Good condition. Heigh 2.6 m
Floor	5	- +	17_01_03 ceramic tile 8mm	m2		20				

Figure 39 - Part of the filled template for the audit report

As it had been proposed, expeditious reality capture was implemented with a handheld laser scanner. However, the outside context was surveyed with TLS providing georeferenced point cloud data since the client had a specific request. Therefore, the point cloud data was obtained by 2 scanners: stationary with panoramas and handheld. The survey with a handheld scanner took about 30-40 minutes and 6 exterior stations were scanned in around 20 minutes, making the survey a 1-hour activity. The point cloud was transmitted in the e57 vendor-neutral format for modelling. The given file was preprocessed in ReCap to prepare the data for use in Revit, since it was chosen as one of the most common BIM authoring software. Audit report, point cloud and photos were generated as an output from the survey (Figure 40).

Figure 40 – Point cloud and photos obtained during the survey

5.3. Level of information need specification

The next step was the creation of a BIM model of the asset in accordance with the specifications of the level of information need stated in Chapter 3.3.

5.3.1. Established modelling rules and implementation of geometry related requirements

To provide the requirements specified for geometry, the following modelling rules were established in the case study:

1) The project's information shall include GPS coordinates (latitude and longitude). The site name shall clearly identify the location;
2) If there is no available object in the library with the required geometry, representing the volumes of materials close to reality, elements from the graphical point of view should be modelled as simply as possible (with 3D dimensional representation) following the level of information need specification and without compromising the quality of alphanumeric data;
3) The elements shall be modelled within correspondent levels representing the building structure. The minimum set of levels is defined by the minimum quantity of the building's elevated stories + 2 (ground level at entrance and roof bottom level). Each storey should be related to the finish floor level (FFL). When it is possible to define and it is needed from a practical point of view, more levels can be introduced, representing the levels for structural elements (e.g., STL/SBL – structure top/bottom level). When due to large deflections it is impossible to determine the plane of the level, its elevation should be taken as an average and in a way to provide as precise quantities as possible;
4) If data regarding the buried element of a building is not available, this part is not a subject of modelling. Therefore, the building volume in a BIM model ends at ground level. If the data of

inaccessible areas, e.g., roof, is absent, parametric models of archetypes should be used: the objects are modelled simplified with the required set of alphanumeric data;

5) Objects shall be defined in space and belong to the specific level they are located on with the use of displacement when needed (for example, with an average floor height of 3 m, the window on Level 3 shall be assigned to Level 3 in the project structure with a required displacement, e.g., of 1,5 m, rather than to Level 1 with a displacement of 7,5 m);
6) Bearing and non-bearing elements must be modeled with separate BIM-objects;
7) If elements have a clear difference in reuse and recycling potential, they must be modeled by separate objects (e.g., tiling on plaster or screed layers are to be modelled separately);
8) BIM objects must define the concept of the building element they represent unambiguously (for example, the wall object class cannot be used to model columns). Refer to the bSDD (buildingSMART Data Dictionary) for clarification;
9) BIM objects with the same purpose and representing the same concept shall be referred to the same object class;
10) Object's geometry shouldn't overlap. If this is unavoidable, the quantities automatically retrieved from those objects must remain unaffected. Alternatively, they should be specified in the alphanumeric dataset for the correspondent property. Generally, geometry should be joined and cut when it is needed;
11) The project's naming convention must be consistent, provided with reference documentation, and specified in BEP;
12) The BIM model shall include rooms and spaces with necessary information, defined by the level of information need;
13) When an object includes nested objects, either only the parent element is responsible for having all the requested information (with comma separated array properties) or all the nested objects. When both are present, only the parent element will be considered, so the extra definition is not required.

Since the building is erected on sloped terrain, several levels were created, distinguishing between two dominant parts of the building. The ground level was set at the minimum terrain point on the building's perimeter (Figure 41).

Figure 41 - Eastern facade with defined levels

To simplify and due to the lack of a real database of BIM objects representing construction products from the past century, standard software libraries were used. The quantification based on real geometry was applied only to the elements that do not need complex modelling, e.g., walls, slabs, roof; the rest of the objects were quantified based on the data from the audit report but without compromising dimensions. For example, as shown in Figure 42, facades were completely built with the use of standard library, even though some details, e.g., railings and door frames, seemed different. Appearance was not redacted, the main requirements referred to correct overall dimensions, level assignation and correspondent hosting element (e.g., in the case of a door, hosting in a load-bearing wall).

Figure 42 – Northern and eastern facades - photos and views from the BIM model

During the modeling and definition of the level of information required for roof girder systems, an intricate question arose. The main beams were modelled assuming probability of reuse, while secondary structures were left for alphanumeric definition of materials per square meter (Figure 43). Overall strategy perceived was to reduce modelling time focusing on major elements that could provide most valuable changes in the deconstruction process. The whole geometry modelling part took 2 working days. The results are shown in Figure 44. Based on the work completed, it can be inferred that more case studies will contribute to a better definition of the level of information need to avoid uncertainty for BIM modelers, as demonstrated by the roof system example. The major principle formulated is that the effort invested for BIM model should not overcome the possible benefits of the work itself. Potentially, semi-automated scan-to-BIM workflows with point cloud segmentation and procedural modelling with machine learning algorithms could speed up the process of geometry definition, but these methodologies were not considered in this work.

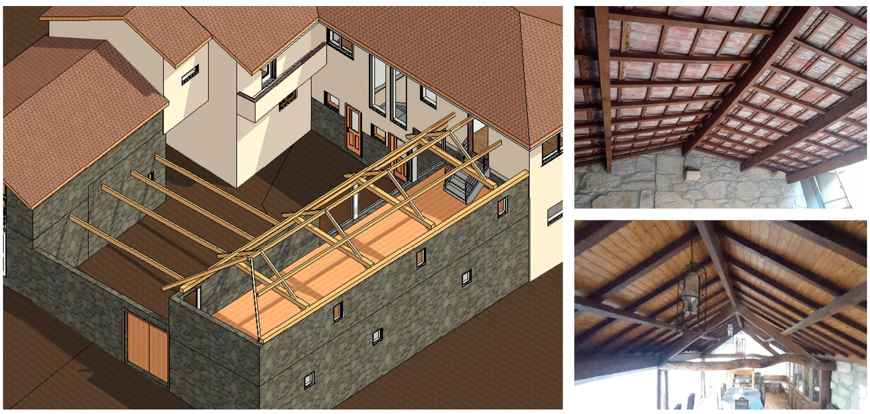


Figure 43 - Definition of roof structures' geometry

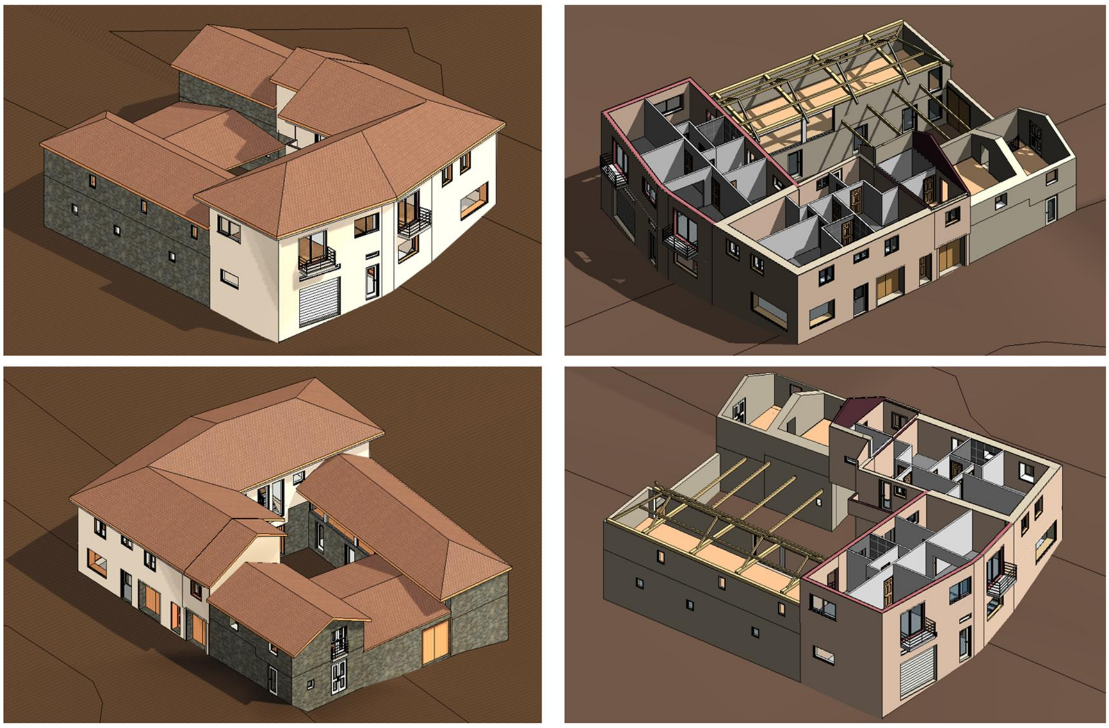


Figure 44 - Geometry of elaborated BIM model for deconstruction

5.3.2. Implementation of requirements for alphanumeric information

The set of alphanumeric information was provided in accordance with the requirements specified in Chapter 3.3. Property values were filled using the data synthesized from the audit report, existent EPDs of similar products, and Level(s) framework. The naming convention adopted for object identification was generalized to the following structure: "AK (User's prefix)_Type_Subtype (if applicable)_Main dimensions". "AK" denotes Artur Kuzminykh, "Type" and "Subtype" define distinctive object's description, e.g., "ExteriorFinish_Plaster". "Main dimensions" for walls, floors, and roofs, for example, would be thickness; for doors and windows—overall dimensions; for beams—cross section profile; for railings—height, etc.

All requested properties were defined within project parameters taken from the shared parameter file and put into "Identity data". Even though the model was later exported to open data format (IFC-SPF) when it was possible to redefine the property names and their grouping, the organization of information containers was also done in Revit to facilitate and structure the process. The building's "tiers", defined by the Level(s) framework, with the Uniclass2015 product definition were put into the objects' classification.

After information content had been filled, BIM objects were identified in terms of alphanumeric requirements (Figure 45). The whole procedure took half a day, with the rare use of simple scripts created in Dynamo for faster data filling. With the availability of existent databases, it is estimated that this process would require much less time.

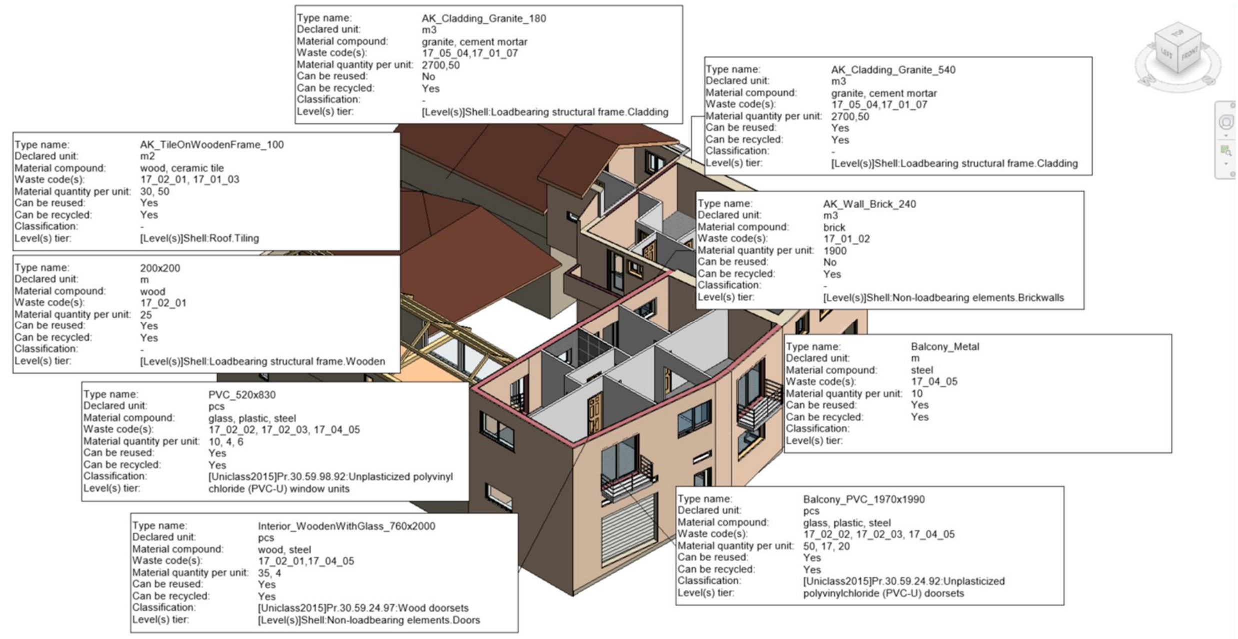


Figure 45 - Part of alphanumeric content of BIM objects

5.3.3. Ensuring documentation requirements

A set of documents, defined by the level of information need, is expected to be stored within project CDE and managed by a VDC specialist as an appointed party. This set of documents includes all project-related requested data. As for BIM objects, this data is mostly connected to photos of products to generate an automatic input for the marketplace population. Since model's elements have alphanumeric identification of images, the files' names are mapped with the correspondent photos after being uploaded to the web platform. Photos made during the survey were connected to some objects with potential for reuse in Revit, as it allows attaching images as properties, generating the link to the files and displaying them (Figure 46).

When matching the pictures with elements in the case study, the following proposal had been made: sometimes due to the high density of objects, attaching 360 images as an attribute to spaces may be more beneficial. These images could be displayed with the use of the web application in a browser, eliminating the necessity to connect the same image to many objects, thereby saving memory space and time. Since one of the platform's development goals is to include point cloud data and BCF, mapping the spaces with panorama images and generating viewpoints within point cloud is considered a reasonable objective to create a better user experience.

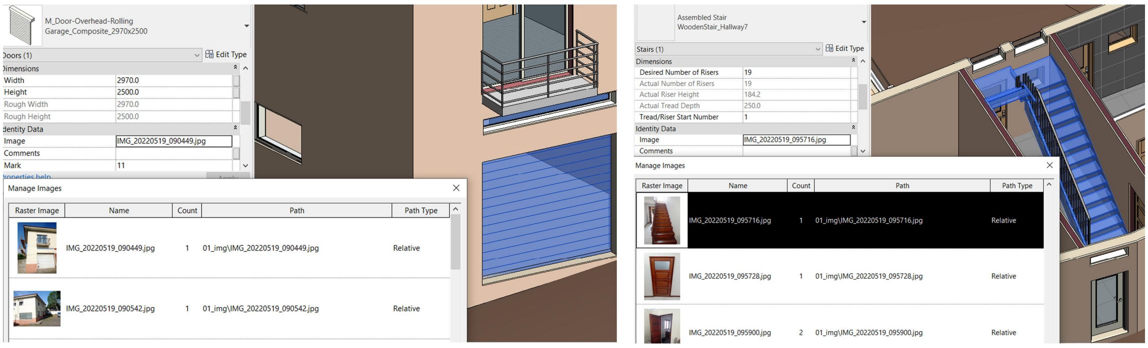


Figure 46 - BIM objects with attached photos of real objects

For simplicity and cost savings, project-related documents may be kept on free public web drives if security measures are not defined, and retention period is sufficient until the project is completed. With full deployment of web-platform service project documents could be reserved within its own database.

5.4. BEP for the described use-case

ISO 19650 Guidance establishes asset information requirements (AIR) not only for new design and construction, but also for demolition of a built asset (UK BIM Framework, 2019). Therefore, in BIM driven project delivery, the BIM execution plan (BEP) is a compulsory document aimed at responding to exchange information requirements (EIR), which in turn are set in accordance with the AIR. Since the reengineered process implies BIM-based project delivery, the outline of the pre-appointment BEP was elaborated. It is assumed that this document includes a synthesized content of all appointed parties' BEPs, and the web-platform functionality is fully deployed with all stated potential developments. The document's structure is shown in Table 11.

Table 11 – Outline of pre-appointment BIM execution plan for the case study

Issue date:	01-03-2022 (March 1st, 2022)
Review date:	29-06-2022 (June 29th, 2022)
Current version:	1.0
Authorized by:	Artur Kuzminykh
Position:	VDC specialist. Lead appointed party's consultant
Project information	
Project number:	PT_BIMAPLUS_2022
Owner:	University of Minho
Lead appointed party:	Demolition operator ABC
Project name:	Vermoim_house
Project location:	Vermoim, Maia
Contract type:	Lump Sum Contract
Brief description:	Residential 2-storey building with several compartments.400 m^2 of plot projection. The 1st floor is represented by granite walls with plaster finishing on the eastern building block; the 2nd floor is constituted by granite walls on the northern façade and brick with plaster on the eastern side. Slabs are mostly concrete in the renovated area and wooden in the old parts of the building. The insulated sloped roof is supported by wooden beams and is finished with clay tile.

Project key stages:

Mobilization	Survey and audit	Outline WMP and permitting	BIM model elaboration	Scheduling and site works
03.2022	03-04.2022	04.2022	04.2022	04-07.2022

Appointing p. EIR: Available within project CDE: https://BimBoomBamDrive360/PT_BIMAPLUS_2022/EIR.php

Project contacts:

Client	Demolition company	Project VDC specialist	Surveyor	Auditor	BIM modeler	Waste manager
Name Surname	Name Surname	Name Surname	Name Surname	Name Surname	Name Surname	Name Surname
email, tel.	email, tel.	email, tel.	email, tel.	email, tel.	email, tel.	email, tel.

Project goals

Digital modelling driven goals: To provide precise enough quantities derived from the digital model and represent the asset as a bank of materials for reuse and recycling. The model should act as a communication tool in the project and serve as the basis for demolition and deconstruction decisions. Automatically extracted project specification shall serve as in input for CDW marketplace and assist to manage the project disposal strategy optimization.

BIM Uses

Project BIM Uses:

1) Capture existent conditions to provide an input for BIM modelling
2) Design authoring for model elaboration
3) Coordinate design models to provide reliable data of as-built asset
4) Author 4D model to plan demolition activities
5) Author construction site logistics model
6) Monitor model to ensure constant information update
7) Analyze sustainability performance of different disposal strategies

BIM roles:

- Project BIM manager/Information manager/BIM Lead –VDC consultant *Name Surname*
- Project BIM coordinator(s) - VDC consultant *Name Surname,* BIM modeling company's coordinator *Name Surname*
- CDE Manager - VDC consultant *Name Surname*
- Project Manager – Waste manager *Name Surname*
- Modeler/BIM specialist - *BIM* modeling company's specialist *Name Surname*

All project participants related to BIM driven project delivery have stated their capability and capacity to perform taken responsibilities.

Processes

Project meetings:

Meeting	Project Stage	Frequency	Participants	Location
Set up meeting	Mobilization	Tu, Fr	Delivery team	online
BEP update, MIDP update	Mobilization, BIM model handover	Tu, Fr	Delivery team	online
Desk study discussion	Mobilization	TBD	Demolition company, surveyor, auditor, modeler, waste manager	online
Survey plan	Survey and audit	TBD	Survey company, auditor, client	TBD
Reality capture	Survey and audit	TBD	Survey company, auditor, client	Project location
Survey data quality discussion	Survey and audit	TBD	Demolition company, surveyor, auditor, modeler, VDC specialist	online
Outline WMP	Outline WMP and permitting	2 days a week	Demolition company, waste manager, client	online

BIM model coordination	BIM model elaboration	TBD	Modeling appointed party, VDC consultant	online
BIM model validation and handover	BIM model elaboration	TBD	Modeling appointed party, VDC consultant	online
Demolition optimization	Scheduling and site works	Tu, Fr	VDC consultant, waste manager, demolition company	online
Offsite management	Scheduling and site works	TBD	VDC consultant, waste manager	online
Onsite management	Scheduling and site works	Every day	Waste manager, demolition company	TBD

Deliverables:

All BIM based deliverables should follow established level of information need, specified in EIR

Stage	Deliverables / file formats
Mobilization	Updated post-appointment BEP / pdf Survey plan / pdf
Survey and audit	Point cloud data / e57 and rcp Point cloud data registration report / pdf Survey pictures / jpeg, png, jpg Audit report / pdf, mp3, jpg (zipped)
Outline WMP and permitting	Outline waste management plan / pdf Permit for demolition / pdf
BIM model elaboration	Model in authoring software / rvt Model in open data format / ifc Images that were used as documentation / jpg, png (zipped)
Scheduling and site works	Demolition schedule / pdf Detailed waste management plan / pdf 4D model for deconstruction / pdf, ifc

Deliveries' milestones:

TBD in accordance with project stages

RACI matrix:

BIM Use	Demolition company	Project VDC specialist	Surveyor	Auditor	BIM modeler	Waste manager
Capture existent conditions	A	-	R	R	I	C
Design authoring	I	C/I	C	C	A	-
Coordinate design models	I	A	-	-	R	-
Author 4D model	A	C		C	-	R
Author construction site logistics	C/I	C	-	-	-	A
Monitor model	I	A/R	-	-	-	C/I
Analyze sustainability performance	C/I	C	-	-	-	A

Collaboration procedures:

Collaboration between project members is implemented within the project's CDE, provided by the Lead Appointed Party. CDE's structure, organization, and management are the Lead Appointed Party's responsibility and are supported by the VDC consultant, assuming the obligations of the lead appointed party. Collaboration is supported by regular meetings and mutual understanding of delivery milestones by all involved parties. The main facilitators of successful collaboration in BIM-driven delivery are: (i) well established responsibilities and project relationships, (ii) structured information containers, (iii) information sharing in right amount and at the right time.

	Check	Definition	Responsible	Software	Frequency
Model quality control:	Visual	Ensure there are no unintended model Components and visual representation satisfy information requirements in terms of geometry	BIM modeling company	BCF manager, IFC viewer	Continuously
	Clash	Detect object clashes that affect quantities	BIM modeling company	TBD	Continuously
	Information requirements	Validate the model for the use in web-platform	VDC consultant	Web-based platform	Handover
	Integrity	Ensure that requests from marketplace and demolition schedule are synchronized with model representation.	VDC consultant	Web-based platform	Continuously

Standardization

	Units	Format
Project units:	Length	mm
	Area	m^2
	Volume	m^3
	Degree	^{0}
	Currency	EUR
	Time	day
	Temperature	^{0}C
	Speed	km/h
	Force	kN

Project coordinates:	Project coordinates shall correspond to the real location. Minimum requirements are GPS coordinates, contained in BIM model: 41°14'32, -8°-36'-22"
Project BIM standards:	ISO 19650 Series for information management ISO 17412-1 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 European guidelines for demolition and reclamation audits
Information containers' structure	Documents' structure: refer to BS EN ISO 19650-2:2018 National Annex: Project-Originator-Functional breakdown-Spatial breakdown-Form-Discipline-Number Level naming convention: Discipline_Elevation_Name ("FFL_0,000_1 Floor") Object classes naming convention: User's prefix_Type_Subtype (if applicable) _Main dimensions
Modelling rules	As stated in Chapter 5.3.1

Technologies

	BIM Use	Software
Software applied:	Capture existent conditions	Cyclone 3D, Ricoh Theta
	Design authoring	Revit
	Coordinate design models	Revit, Web-platform "RecycleBIM"
	Author 4D model	Web-platform "RecycleBIM"
	Author construction site logistics	Web-platform "RecycleBIM", Microsoft Office
	Monitor model	Web-platform "RecycleBIM"
	Analyze sustainability performance	Web-platform "RecycleBIM"

CDE:	TBD
Data security and information authorship	
Security measures and privacy:	CDE rights should be adjusted by the responsible party in accordance with the roles of all project stakeholders. If the project contains data that is not subject to disclosure, additional measures need to be discussed. Information contained in a BIM model that is uploaded to the web-platform is specified in information requirements and will be available for public use and dissemination. Point cloud data and taken images during the survey will be checked for the presence of any vulnerable information content that is going to be treated correspondingly.
IPR, data ownership and information dissemination	All information generated in the project belongs to the appointing party after it is completed. The data regarding the audit report, project location, year of construction, contained materials, applied disposal strategy, and duration is subject to open public availability and is going to be used to build the statistics and archetype database. No client's personal data is to be disclosed openly and its content is defined prior to the beginning of every project stage. Reality capture's content requirements can be adjusted in accordance with the client's requests. During the project implementation, the digital model of an asset is owned and managed by the lead appointed party with shared responsibilities with involved subcontractors and consultants.

5.5. BIM model in open data format

As defined in information requirements, the model from authoring software was exported to the open data format – IFC-SPF. To provide the correct output and amount of information, the following settings and steps were applied, using the Revit IFC Manual 2.0:

1) A separate 3D view was created to include only the objects that are necessary for export;
2) Object classes were checked for correct entity definitions in the standard export mapping table. When required, specific elements were exported to different entities in accordance with bSDD (buildingSMART Data Dictionary). For example, the flooring created as a slab in Revit was redefined to be exported as "IfcCovering.FLOORING" instead of "IfcSlab". The same was done for the wall tiling – "IfcCovering.CLADDING" instead of "IfcWall". The element-based mapping was achieved by identifying the instance parameter "IfcExportAs" (Figure 47 a);
3) IFC version and MVD: IFC 4 Reference view (buildingSMART 2022);
4) Exported property sets: IFC common property sets, base quantities, and user-defined property sets with mapping table (Figure 47 b). User specific properties were referred to established information container for circularity – "RecycleBIM";
5) IFC GUID was stored after the export for further correction of inconsistencies, if there were any during the model validation.

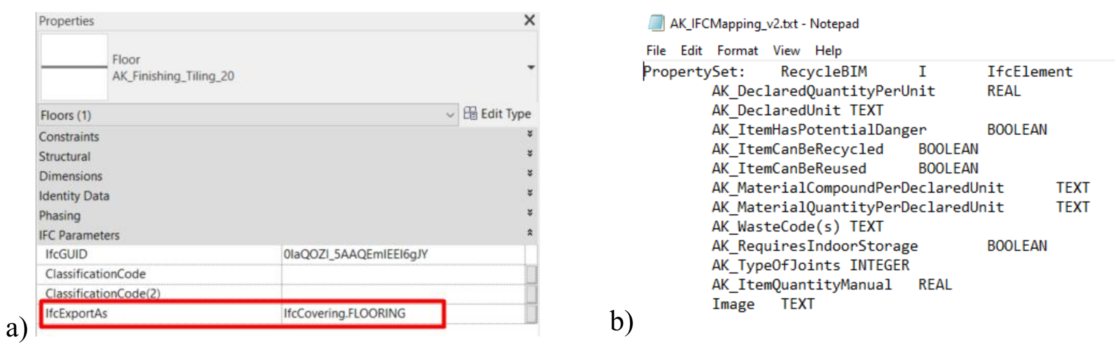


Figure 47 - Element-based entity mapping and custom properties' mapping

Prior to file upload to the platform, a model check was performed in the IFC viewer (BIMvision). Firstly, the project's properties were explored for having the correct location based on the site's latitude and longitude properties, since these values were used later for project identification in Google Maps (Figure 48). Secondly, the elements were checked for correct visual representations and quantities, by comparing them in authoring software and in the IFC viewer. Even though sometimes due to the IFC export geometry was distorted, exported quantities seemed to be identified correctly (Figure 49: the wall has a different representation but the same quantities). Then, the presence of requested alphanumeric data was examined in accordance with the defined level of information need (Figure 50).

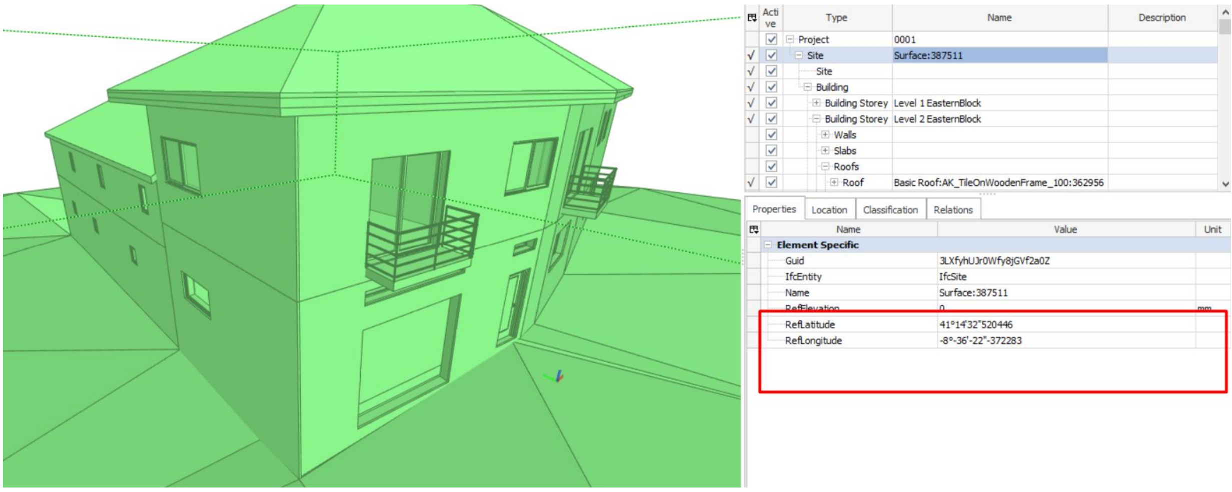


Figure 48 - Project location in IFC file

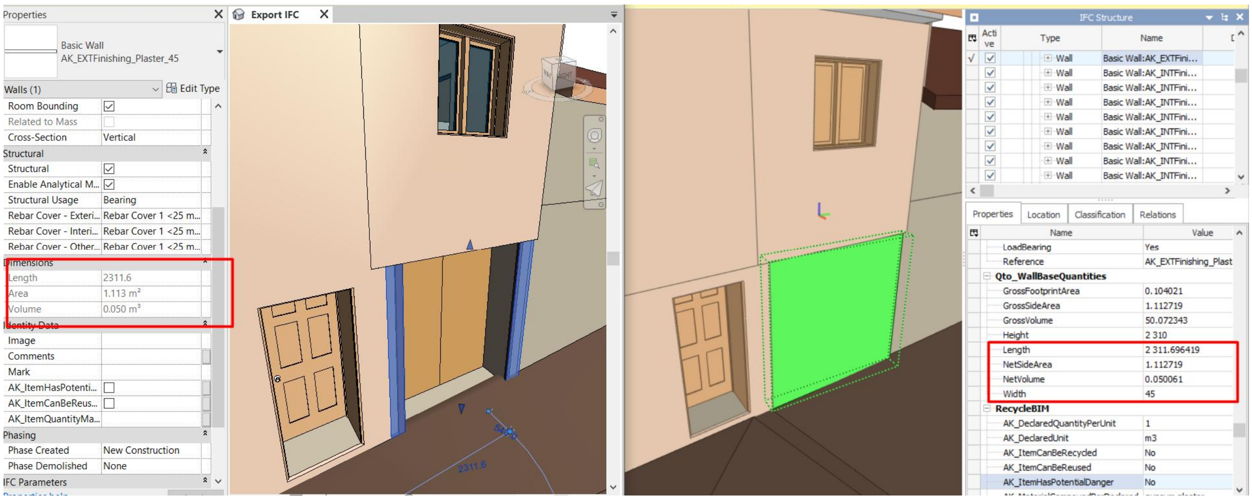


Figure 49 – Comparison of elements' geometry and alphanumeric information

Property	Data type
Object class	text
Tier 1 building aspect	text
Tier 2 building aspect	text
Classification	text
Declared Unit	text
DeclaredQuantityPerUnit	float
MaterialCompoundPerDeclaredUnit	text array
MaterialQuantityPerDeclaredUnit	float array
ItemCanBeReused	bool
ItemCanBeRecycled	bool
WasteCode(s)	text array
ItemTypeOfJoints*	integer
ItemHasPotentialDanger	bool
Quantity	float
Image	text

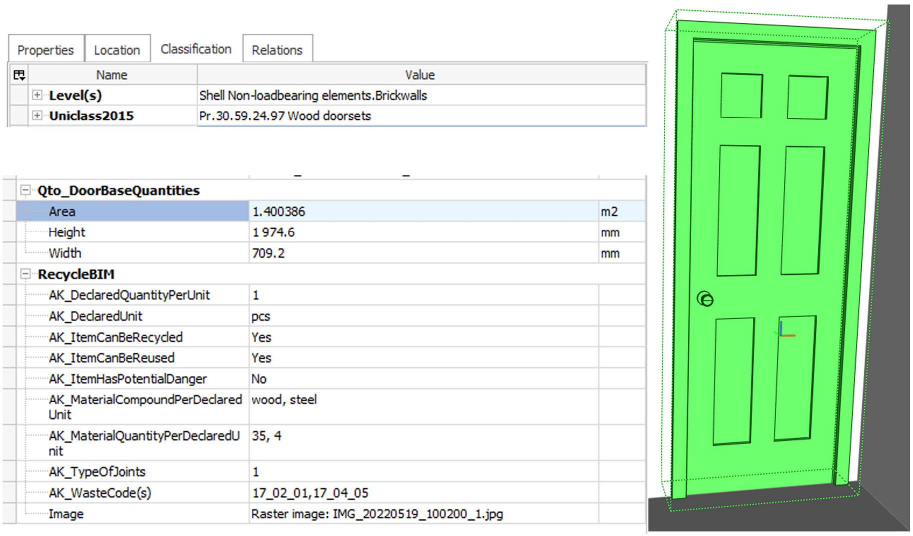


Figure 50 - Checking for required alphanumeric information for circularity-related properties

After the "manual" model check was performed, the file was ready to be uploaded to the web-platform for parsing, validation, and generation of automatic input for the marketplace.

5.6. Application of the web platform to the case study

After the registration and log in procedure, the model and folder containing the object's photos were uploaded. The platform generated a unique ID for the project "62bb0c97c4d452.15018739" which was used as a reference to access all the files. In simulated server on the local machine, they could be seen under this unique name (Figure 51). This unique identification was designed based on embedded programming algorithms and was used for unique referencing and file depersonalization. However, based on the previously described DB structure, this name could be simplified for a better user experience, e.g., to a combination of primary keys – user's ID and project's ID. It was perceived as a future development.

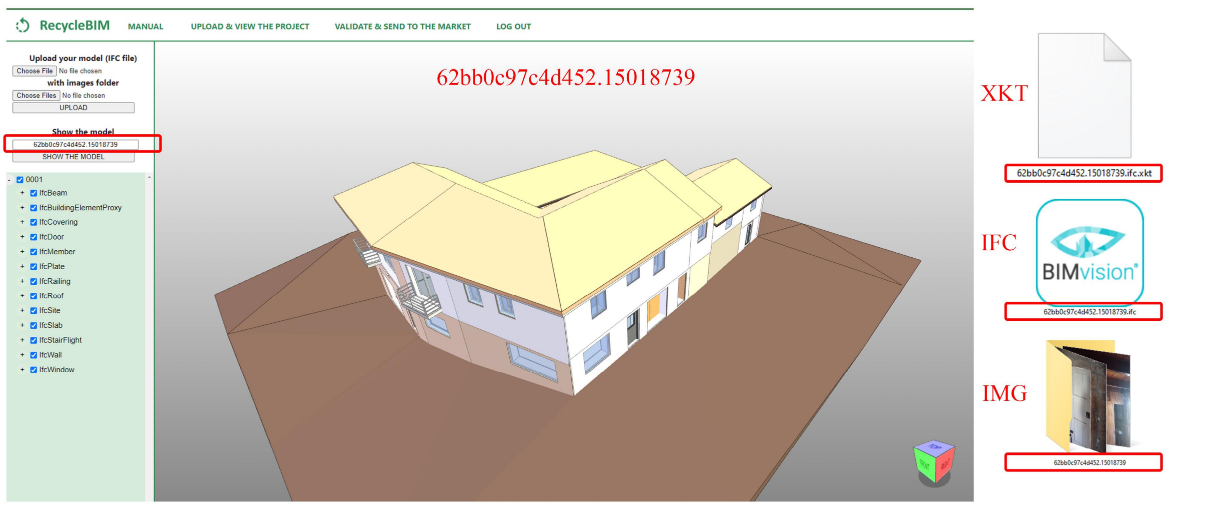


Figure 51 - Model displayed on the web platform and uploaded reference files on the server

As described in business logic (Chapter 4.2), after uploading the model with documents, its validation can be performed. All designed options were tested, starting with the search for missing property sets. The report and visual representation of the model identified that all the objects had requested alphanumeric information (no generated GUIDs and highlighted elements - Figure 52). Even though some elements did not have requested information, their parent elements did.

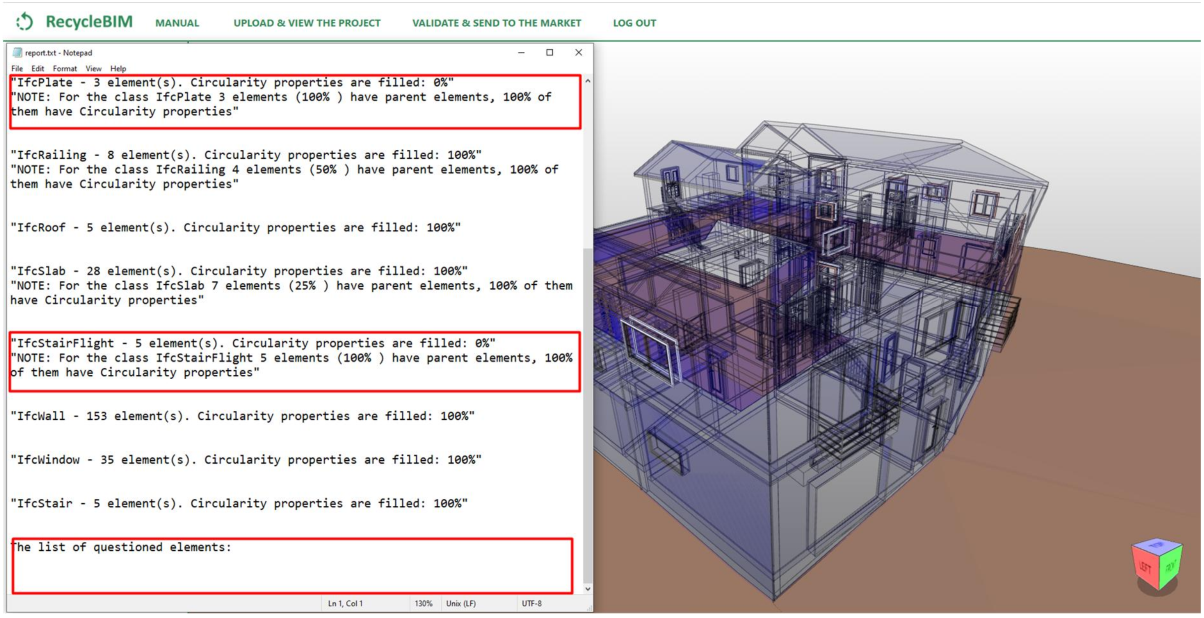


Figure 52 - Results of checking for missing property sets. Report and visual representation

The second check was performed for inconsistent array properties (array lengths), which identified one element with an issue: when describing component materials, a dot was applied as a separator instead of a comma, causing the result of different array lengths (Figure 53). This option allowed to identify an element in authoring software and correct the property. Currently, the platform's logic is not designed to overwrite the files to avoid data duplication. If any error occurs at the validation step, users are expected to upload new corrected files as a new project with a new generated ID. As a future development, the logic is supposed to be redesigned so the users create the project with a unique ID first, and only after that they can manage all related files (creating, sharing, redacting, deleting).

The check for manually estimated elements, i.e., when the user identified quantity by typing the numeric value to the correspondent property "ItemQuantityManual", showed that no items were identified in that way. Therefore, all the quantities taken were defined by objects' geometry directly by the authoring software. In the case study manual definition of quantities could be applied to the roof girder system, specifying roughly estimated total lengths of beams and allowing less precise modelling. But since the girders were referred to the roof objects with approximate values of weight per square meter, it was not applied.

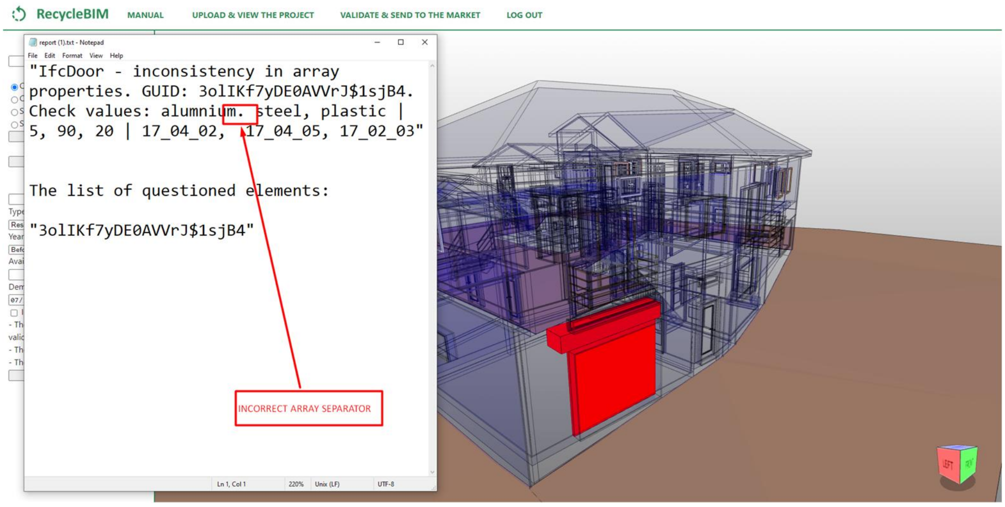


Figure 53 - Identified element with inconsistent array properties

The last option was inspection for elements that could be reused. The list of objects mostly consisted of windows, doors, load-bearing beams, and granite walls (Figure 54). It is implied that this functionality could help to understand better the possibilities of salvage sales and the necessity of careful deconstruction, as well as to double check the output of BIM modelling and its matching with the audit report; the 3D model in this process becomes a mean of communication between the demolition company and the waste manager. As a potential for development, average market prices could be displayed on top of elements when the model is being explored.

Before parsing the file for transferring the data to an SQL table for marketplace, the platform requested additional information about the project: type, year of construction, link to available documentation, and start date of demolition work. After checking the location and filling in the required fields (Figure 55), the project was submitted for generation of the specification. The platform identified that 90% of elements were perceived as available for reuse or recycling. At this step, it was possible to check the photos of objects to see if they had any documents attached (Figure 56).

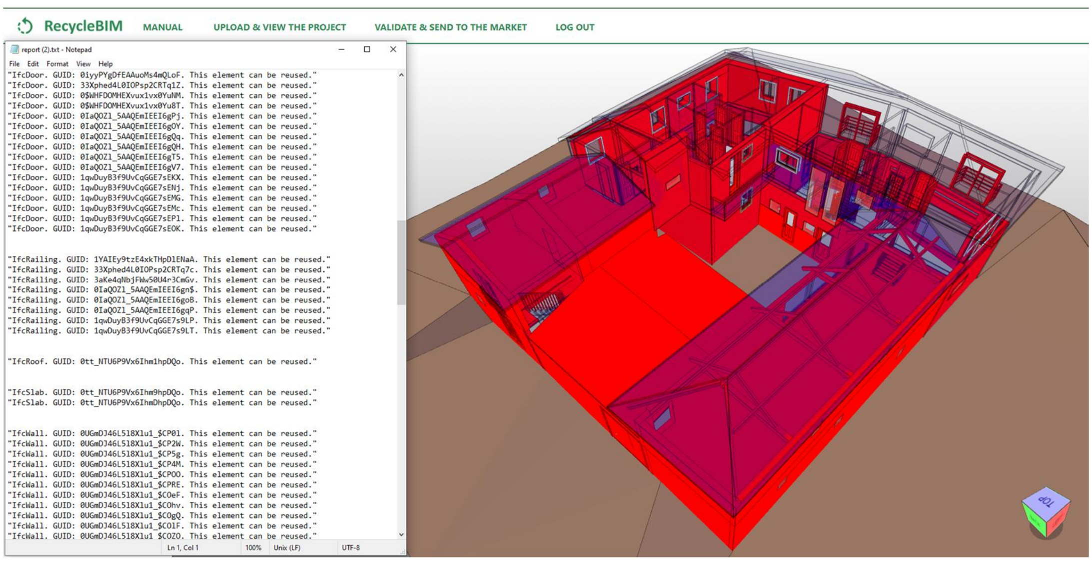


Figure 54 - Identified elements for reuse. Report and visual representation

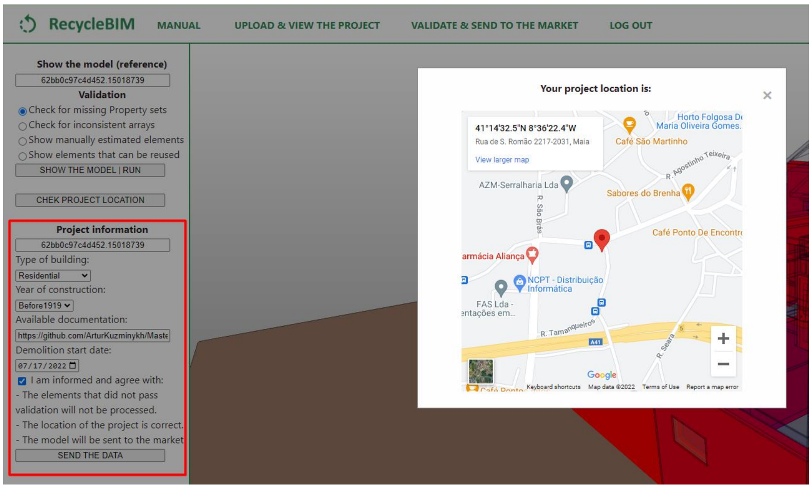


Figure 55 – Identified location and filled requested information

Figure 56 - Generated specification and display of attached images in the platform's interface

Basing on the provided demonstration, it can be concluded that the designed platform's functionalities were tested successfully. Some options and interface features still need to be optimized for a better user experience and more comfortable operation. However, the objective of providing an MVP that could be developed as a tool to promote circularity in the demolition process can be assessed as achieved.

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6. CONCLUSIONS

6.1. General conclusions

The construction industry is one of the main environmental contaminators where material processes cause major impacts. Therefore, their efficient management and planning play a huge role in making the industry more sustainable. At this work, the focus was on asset demolition, as currently generated waste rates indicate that more effective process is needed to enable circularity of construction materials since most of them have potential to be reused or recycled. The state of the existent legislation base, guidelines, and current CDW management were studied to implement the analysis of potential integration of information management and modelling methodologies for better process performance.

Based on existent practice and recommendations for demolition workflow and preparation procedures, a business process model was defined with further gap analysis. Using the business process reengineering approach, a new upgraded process model was proposed with digitally driven methodologies, including BIM-based project delivery. These methodologies refer to: 1) expeditious reality capture with a handheld laser scanner, enabling fast generation of precise spatial representation of an asset, and a digitally supported standardized demolition/reclamation audit; 2) building information modelling and management in accordance with established information requirements and content, identified in the level of information need specification; 3) use of open data formats, open-source approach, and web applications for information sharing and dissemination of new technologies.

For the new reconsidered business process, reality capture and pre-demolition audit were suggested to complement each other and to be elaborated with the end use in mind – qualitative input for BIM modelling. The role of product data templates was discussed to establish information requirements for demolition project deliverables. The minimum set of properties in PDT's circularity-related sub-set was defined, constituting alphanumeric requirements for BIM objects. Following the level of information need framework, ensuring that no "information waste" will be produced in the process, causing extra time and project costs, geometry and documentation related requirements were also set. These requirements were aimed to provide an output that would be used for comprehensive demolition and disposal strategy planning with the use of a digital model and a web-based platform.

The roles of open data formats, open-source approaches, and web-based applications in promoting circular economy in the construction sector and providing affordable technologies for widespread public use were discussed. Basing on identified potential and advantages, the MVP of a web-based platform for IFC BIM model processing was proposed, including a description of its concept, business logic, database structure, and intended workflow. The objective of the elaborated application, as demonstrated, was to provide a comprehensive basis for waste manager's decision making and to generate an automatic input for the marketplace for reuse and recycling and CDW trade, thereby enabling demand generation before the actual demolition.

Proposed methodologies were demonstrated on a case study of a real building in Portugal. As an example of an information management related document, a pre-appointment BEP was elaborated. To ensure the level of information need specification, modelling rules were established for the BIM modelling procedure with demonstration of examples. The workflow of the implementation of alphanumeric information and documentation requirements was also shown using one of the common authoring software. The exported model in an open data format, IFC-SPF (.ifc), was inspected on the subject of correct data transfer and then was sent to the elaborated web-platform for further processing. Examples of validation reports were shown, denoting the model's quality. As it was estimated by the platform, based on data provided in the BIM model, about 90% of the building's elements had the potential to be reused or recycled.

The main conclusions are:

Drawbacks of the current process, as identified, include: 1) not standardized and not interoperable data of inventory report of pre-demolition/reclamation audit that cannot be easily reused and applied in other projects; 2) the preciseness of quantitative assessment of construction materials that can be extracted from a building highly depends on time spent on estimate and the auditor's skills; 3) waste management is reactive and depends on onsite decisions, therefore, disposal strategy design is usually limited by tight time frames and supply is dependent on site operations; 4) demolition planning and schedule optimization if being defined are restrained by static information flow.

With no major change in the audit procedure, complementary point cloud data generated in a cost-effective way would provide a relatively precise asset's spatial representation, enabling BIM modelling with automatic quantification. The time spent on the field survey with a handheld scanner in the case study can be estimated as little, since it took only 1 hour for the whole building of 430 m^2, making the scanning application reasonable.

To enable circularity of construction materials with the use of digital modelling, information on the products should also become circular, which cannot be done without standardized and interoperable product data sheets. Parametric models, derived from the audit and demolition experience, are also perceived as being of high importance to facilitate the whole reengineered process. These models and data sheets should be available for open use in the industry to build a knowledge base and to unify the effort in the creation of a sustainable future.

Automatically retrieved specifications, derived from the BIM model and supported with visual representation in the web-based platform, can eliminate the hindrance related to human-input interface of existent marketplaces for CDW and products for reuse. The developed web platform allows to provide traceable information flow and business transparency, to create an open free market for CDW trade, promoting circular economy, and serves as a base for building prediction models using accumulated data. It has been demonstrated that the designed web application successfully uploaded, displayed, validated the model, and then parsed it to generate a project specification.

All the processes of modelling and providing the requested level of information need took 2.5 days, which, as explained, will tend to decrease with the development of databases of BIM objects with correctly defined data sheets. Generally, since the proposed methodology is a BIM-driven project delivery, the difference with traditional demolition practice can be described by MacLeamy's curve, when the time spent additionally in the beginning will lead to more comprehensive analysis in early stages and better output quality. Even though extra effort as well as expenses are needed to deploy the proposed approach, potential benefits can not only make a difference for a more sustainable future but also be economically justified by income from CDW trade, since waste in the circular economy model is treated as a product.

6.2. Future development

The potential for the future development of the proposed methodology can be outlined as follows:

1) Testing of an automated procedural modelling workflow, allowing generation of BIM objects' geometry based on segmented point cloud data with the use of neural networks and artificial intelligence algorithms;
2) Developing an archetypes' information database that would allow us to identify the alphanumeric content of BIM objects in accordance with the level of information need;
3) Elaboration of plugins for different authoring software that would use the database of archetypes to automatically assign requested properties;
4) Providing a more user-friendly platform interface and implementing mobile versions and applications;
5) Storing the level of information need in a more flexible way (e.g., generation of JSON files that would transmit the variables in validation procedures) instead of using them directly defined within validation scripts;
6) Adding the marketplace functionality to the developed platform, including bidirectional link and synchronization with the marketplace's database;
7) Enabling logistics optimization based on project location and performing 4D BIM workflow in the platform without any use of proprietary software;
8) Establishing a comprehensive base to enable LCA/LCC assessment with revision of information requirements and platform functionalities;
9) Supporting point cloud data visualization in the designed application, as well as BCF compatibility and automatically generated 3D tours;
10) Establishing a knowledge base of archetypes within the web-platform database and providing statistics of similar projects to support decision making in tendering.

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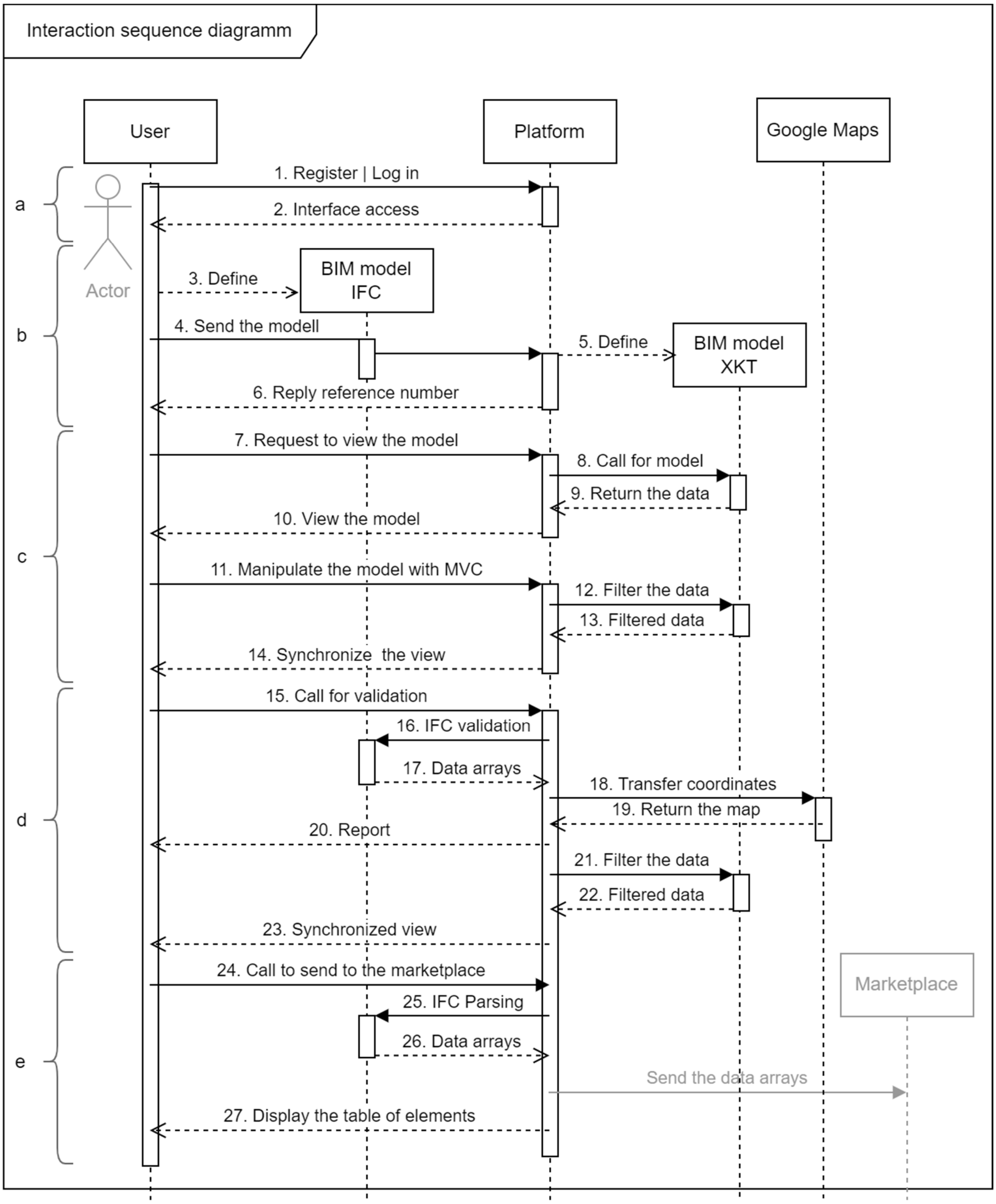
LIST OF ACRONYMS AND ABBREVIATIONS

AEC	Architecture, Engineering and Construction
AI	Artificial Intelligence
API	Application Programming Interface
B2B	Business to Business
B2C	Business to Customer
BCF	BIM Collaboration Format
BEP	BIM Execution Plan
BIM	Building Information Modelling
BPM	Business Process Management
BPR	Business Process Reengineering
bSDD	buildingSMART Data Dictionary
CDW	Construction and Demolition Waste
CE	Circular Economy
CPI	Continuous Process Improvement
CPR	Construction Product Regulation
DB	Database
DBL	Digital Building Logbook
EC	European Commission
EHS	Environmental Health Safety
EIR	Exchange Information Requirements
EPD	Environmental Product Declaration
ER (ERD)	Entity Relationship (diagram)
EU	European Union
EWC	European Waste Codes
GHG	Greenhouse Gas
GIS	Geographic Information System
GPS	Global Positioning System
GUID	Globally Unique Identifier
ICT	Information and Communication Technologies
IDM	Information Delivery Manual
IFC	Industry Foundation Classes
IT	Information Technologies
KPI	Key Performance Indicator
KRI	Key Result Indicator
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
MIDP	Master Information Delivery Plan
MVD	Model View Definition
MVP	Minimum Viable Product
PDT	Product Data Template
RDBMS	Relational Database Management System

RFID	Radio Frequency Identification
SDG	Sustainable Development Goals
SDK	Software Development Kit
TIDP	Task Information Delivery Plan
TLS	Terrestrial Laser Scanning
UN	United Nations
VDC	Virtual Design and Construction
WMP	Waste Management Plan

APPENDICES

APPENDIX 1: UML SEQUENCE DIAGRAMM OF THE DEVELOPED PLATFORM



APPENDIX 2: CONCEPTUAL ER DIAGRAMM WITH THE MARKETPLACE REALIZATION