REINCARNATE

D1.1 – An ontology for circular management of buildings

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Abstract

Currently, there is no widely agreed-upon set of terms and ideas related to the circular economy within the built environment. This absence of a shared understanding of the language and concepts can result in confusion and difficulties in comprehending and putting circular economy principles into practice. Therefore, there is a need for a well-defined framework that tackles this issue to facilitate the adoption of circular building management practices. This report highlights the significance of a structured framework and the role of knowledge representation in enabling circular economy practices by proposing theReincarnate Ontology (ReOn). We have utilized existing ontologies such as IFC and Circular Economy Ontology Network (CEON) to encompass and structure different concepts within the Reincarnate project. The proposed ontology serves as the backbone of the Reincarnate project, facilitating the efficient management of building data and processes. Implementation of the Reincarnate Ontology (ReOn) involves the integration of various technologies and interoperability solutions. This approach ensures that data related to construction products, materials, and waste management is readily accessible, reliable, and in alignment with circular economy practices. The implementation process, detailed in this report, outlines the integration of ReOn into CPIM, its interaction with external databases for comprehensive data handling. Furthermore, we will present two detailed use cases involving the recycling of windows and concrete. These examples showcase how the IFC schema can be effectively leveraged to construct knowledge graphs and capture the intricate data necessary for informed circular decision-making processes. This work contributes not just to theoretical discussions but provides a tangible tool for advancing circular building management practices.

Keywords:

Circular Economy, Ontology, Building Information Modelling (BIM), Value Chain, Industry Foundation Classes (IFC), Data Flow

Revisions

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Disclaimer

Acronyms and definitions

Acronym	Meaning
CE	Circular Economy
ReOn	Reincarnate Ontology
XD	eXtreme Design
MOMo	Modular Ontology Modelling
C&DW	Construction and Demolition Waste
CP-IM	Circular Potential Information Management
CEON	Circular Economy Ontology Network
IFC	Industry Foundation Classes
GHG	Greenhouse gas
WP	Work Package
BFO	Basic formal ontology
PLM	Product Lifecycle Management
ERP	Enterprise Resource Planning
CRM	Customer Relationship Management
ECI	Environmental Cost Indicator
LCA	Life Cycle Assessment

BIM	Building Information Modeling
IFC	Industry Foundation Classes
EPD	Environmental Product Declaration
ODP	Ontology Design Pattern
OWL	Web Ontology language
RDF	Resource Description Framework
XD	eXtreme Design
WP	Work Package

Reincarnate project

The average lifespan of a building is 39 years[1], and factors such as obsolescence and technical limitations often lead to demolition. Consequently, a significant amount of construction and demolition waste (CDW) is generated. Effectively reducing construction waste requires addressing two key aspects: 1) preventing existing buildings from becoming functionally or financially obsolete, and 2) upgrading buildings and their components to extend their lifetime. Despite good intentions, studies have shown that upgradability as a product lifetime extension strategy is limited and reusing entire buildings, building products, or materials in different settings is challenging. These challenges have resulted in a limited use of secondary materials in the building sector[2]. Despite high recycling rates, CDW recycling often leads to downcycling.

Reincarnate aims to advance circular economy practices in the European construction industry by extending the life cycle of buildings, products, and materials, aiming to reduce CDW by 80%, increase reusability by promoting circular economy principles, and lower sector emissions by 70%.

Through the Circular Potential Information Management (CP-IM) platform and associated innovations, Reincarnate will leverage digital technologies like digital twin representation, artificial intelligence, and robotic automation. Building upon three empirically proven social science insights, the project aims to foster the widespread adoption of reused high-quality construction products and materials. Additionally, it will develop business eco-system frameworks to connect actors within sustainable value chains.

Reincarnate's impact will be demonstrated through eleven real-world projects and value chains. Business process guidelines and an e-learning platform will be developed to facilitate the dissemination and exploitation of Reincarnate's results, ultimately contributing to the advancement of circular economy practices in the European construction industry.

[1] Muresan et al. 2021 - Sustainability through reuse

[2] Van den Berg, Voordijk, Adriaanse (2020). Recovering building elements for reuse (or not) – Ethnographic insights into selective demolition practices. Journal of Cleaner Production, 256.

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1. Introduction

This report is the result of task 1.1, 'Ontologies, information models, and inspection,' which is part of Work Package 1, the 'REINCARNATE CP-IM.' The Circular Potential Information Management platform is one of the key outcomes of the Reincarnate project. It comprises different technologies and processes to centralize the information required to assess the circular potential of assets based on the Reincarnate ontology. The proposed ontology, which is the focus of this report, aims to encompass a wide range of project concepts related to buildings, construction products and materials, waste management, and circular value flows. The structure of this deliverable is designed to first provide a background and emphasize the necessity for such a structured framework. The report then elaborates on the main concepts of knowledge representation and its three pillars, outlining our theoretical view to ontology development. It proceeds with a detailed explanation of our adopted methodology and further explores existing relevant ontologies, describing in detail the most pertinent ones for our project. Subsequently, the report illustrates how the relevant ontologies are utilized to create a core ontology (high-level) for the Reincarnate project. It then follows showcasing a detailed implementation of the ontology to map two specific value streams, namely recycling windows and recycling concrete. Finally, the report concludes by explaining the steps toward practical implementation in the CPIM platform, interfaces to external databases such as Environmental Product Declaration (EPD), and the extension of RE Condition Assessment tool (developed by DMO) to collect, manage, and sort the required data.

1.1. Objectives

Our primary objective was to employ a balanced approach that combines theory and practicality, with a sharp focus on addressing user needs and rendering existing knowledge within industry practices as explicit as possible. Rather than introducing yet another completely new ontology, our aim was to conduct a comprehensive analysis of relevant existing ontologies and explore the potential for utilizing and connecting them. For the identified gaps, we proposed additions, wherever necessary, to enhance interoperability to the maximum extent. In this context, we closely collaborated with similar European initiatives such as Onto-DESIDE[3] and national initiatives such as Trace4Value[4], to ensure alignment and boost the existing synergies. Notably, we intentionally selected the Industry Foundation Classes[5] schema as our starting point since IFC has emerged as a de facto open standard data model and

[3] https://ontodeside.eu/
[4] https://trace4value.se/
5 https://technical.buildingsmart.org/standards/ifc/ifc-schema-specifications/

exchange format in the construction industry. In recent years, substantial efforts have been made to integrate Building Information Modelling and IFC into current construction practices. Leveraging these existing initiatives, we aimed to enhance collaboration between different stakeholders involved (e.g., contractors, designers, waste managers, etc) and improve overall efficiency. Our envisioned workflow and ontology serve as modular building blocks, akin to Lego pieces, to craft a blueprint for diverse circularity processes from which different knowledge graphs can be instantiated.

1.2. Relation To Other Work Packages

As shown in Figure 1, within our project, WP1 plays a central role alongside WP2 and WP3. WP1 comprises four tasks that will benefit from the results produced in this phase. One noteworthy example is *"Task 1.4 Circular Value Flow Planning,"* which focuses on developing methods for integrating the BIM-based information model proposed in the ontology into the existing PLM, ERP, and CRM systems of waste management companies. Our proposed ontology is based on input from several industrial partners, in the form of use cases, each with expertise in recycling, reuse, waste management, or construction management. The outcomes of this task will be instrumental in WP2 and WP3, with emphasis on extending the product life cycle and promoting adaptive reuse respectively, by identifying circular design principles, cataloguing building components, etc. Furthermore, the identified ontology will undergo analysis in WP4 to identify the bottlenecks, map relevant barriers, and propose strategies and actions to enhance its contribution to the transition towards a circular economy in the built environment. Finally, the practical utility of the ontology will be tested in the project's pilots.

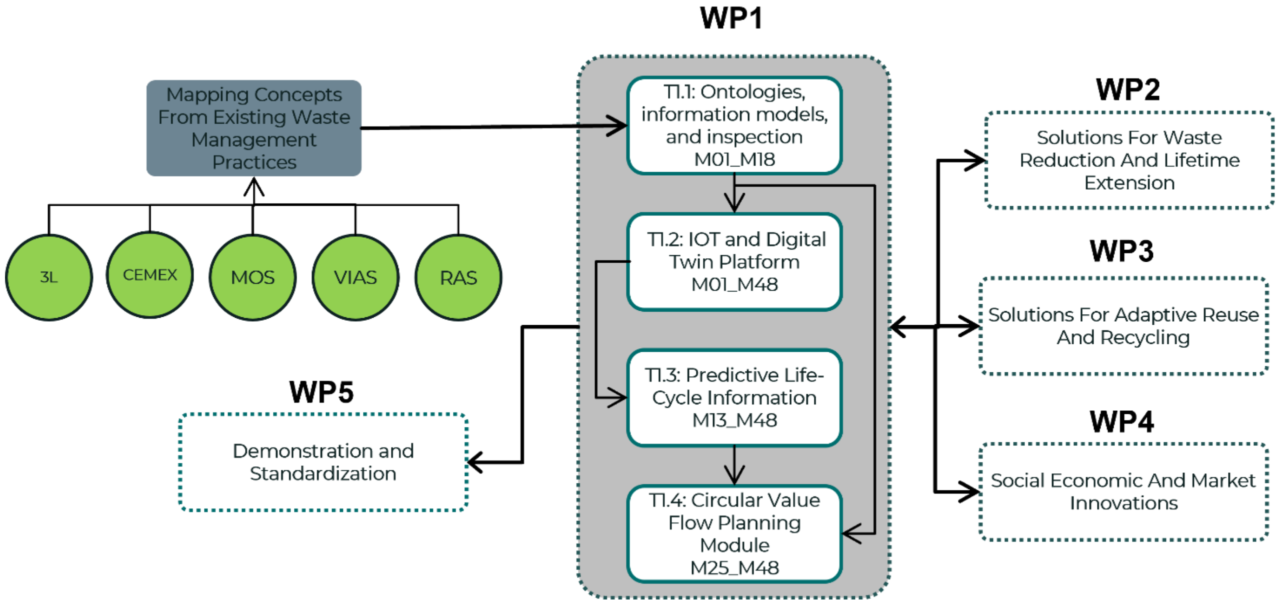

Figure 1: Work package 1 relation with other tasks

2. Background & Motivation

In the face of increasing resource consumption and waste generation, driven by the prospect of doubling material usage by 2050, the need for a circular economy becomes essential. Currently the construction sector, responsible for over 35% of the EU's total waste generation, plays a pivotal role in this global challenge. Greenhouse gas emissions from material extraction, manufacturing of construction products, as well as construction and renovation of buildings are estimated at 5-12% of total national GHG emissions. [1]. The potential for enhanced **material efficiency** to save up to 80% of these emissions underscores the transformative impact of transitioning toward a circular economy [2]. Unarguably, the transition towards a circular economy, characterized by **resource optimization,** and sustainability is a global imperative. Within this paradigm shift, the built environment plays a crucial role due to its substantial resource consumption and waste generation. Conventional construction and building management practices often follow a linear model, resulting in significant resource inefficiency, waste, and environmental impact.

Additionally, as presented by [3], currently, there is a lack of consensus regarding the terminology and concepts associated with the circular economy. This lack of consensus in terminology and concepts can lead to confusion and challenges in understanding and implementing the principles of the circular economy [4]. Importantly, this absence of consensus in terminology and concepts has broader implications, contributing to a deficiency in the formalization of knowledge within the field. This deficiency, in turn, impedes the effective sharing of knowledge among experts, hindering progress in sustainable building practices. Recognizing these challenges, there is an immediate and compelling need for a **structured framework that not only resolves the issues related to terminology and concepts but also facilitates the formalization and sharing of knowledge**. Such a framework is crucial for addressing these challenges and promoting the adoption of circular building management practices on a global scale.

2.1. Shared Conceptualization for Knowledge Sharing

The most effective way to grasp the essence of knowledge representation, as a structured framework, is to consider its purpose. Its primary goal is to render knowledge as clear and explicit as feasible. This is imperative because knowledge is typically held implicitly, residing within individuals' minds, and embedded in social customs within communities, making it unobservable from the outside. To enable the sharing of knowledge, it's essential to articulate it. To facilitate the sharing of knowledge, the transformation of tacit knowledge into explicit forms is essential.

Social agents engage in the exchange of knowledge to broaden their access beyond the information they have individually accumulated. This collective sharing enhances the preparedness of each agent and the community as a whole to make informed decisions. By tapping into a reservoir of knowledge beyond individual experiences, even unfamiliar situations can be effectively addressed. Nevertheless, the exchange of tacit social knowledge is not as efficient. Mechanisms like imitation are constrained within local boundaries, limiting the spread of knowledge across both space and time. To overcome these constraints, certain agents have devised methods to articulate knowledge explicitly and encode it in more enduring formats.

As depicted in Figure 2, tacit knowledge is what an agent (any discerning agent) acquires when it observes its surroundings and internally constructs representations of what it perceives. An agent's choices are derived from its internal representations and conceptual model of the world. This model encapsulates the elements within the environment and their interrelationships, enabling the agent to anticipate the outcomes of its actions or inactions [9].

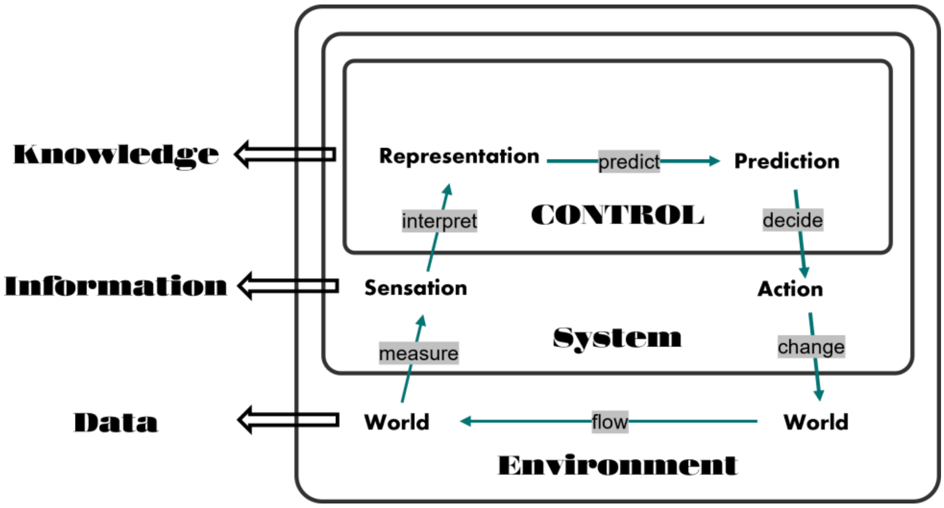

Figure 2: Knowledge viewed from Systems Theory perspective [9].

3. Knowledge Representation

Before elaborating the theoretical underpinnings of our ontology, it is essential to grasp the significance of Knowledge Representation in the context of our work. Knowledge representation is the fundamental process of **structuring and organizing information in a format that computer systems can effectively utilize**. In this report, we aim to elucidate our theoretical view of ontology and its role within knowledge representation. In [6], John Florian Sowa investigates the definition and significance of knowledge representation in great detail. He identifies knowledge representation as a pivotal field that serves as a bridge between the real world or a specific domain and the computational system. He emphasizes that knowledge representation is more than just encoding information or facts; it's about creating structured models that encompass various facets of knowledge. These models play a critical role in facilitating reasoning, problem-solving, and decision-making processes for intelligent systems. As outlined by Sowa, Knowledge Representation is a multidisciplinary subject that seamlessly integrates principles and methodologies from the domains of **ontology**, **logic**, and **computation** (Figure 3):

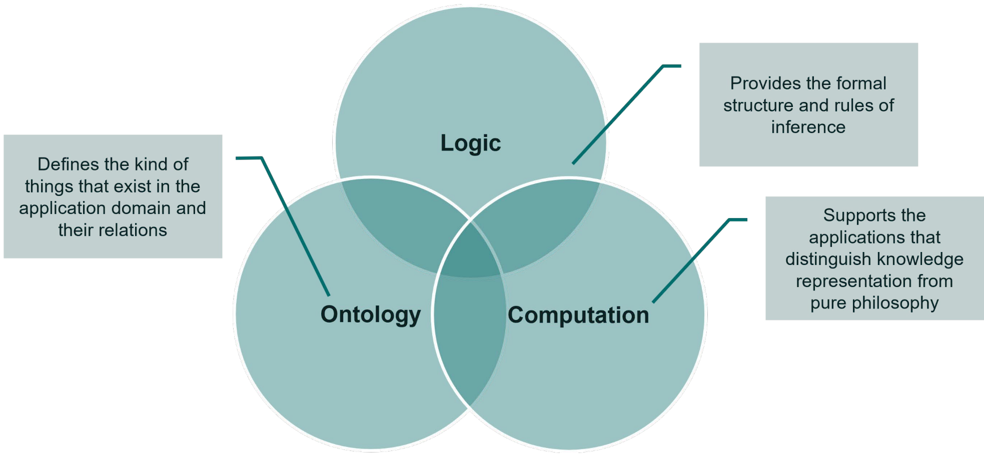

Figure 3: The three main components of knowledge representation; authors illustration according to [6]

Ontology involves the creation of formal structures that define the entities, concepts, and relationships within a specific domain. These structured ontologies serve as the foundational vocabulary for communicating and sharing knowledge. Through ontologies, knowledge representation ensures a common understanding of concepts, enabling both humans and machines to navigate and manipulate information within a particular context.

Logic forms the logical underpinning of knowledge representation. It provides the formal rules and syntax for expressing knowledge in a structured and systematic manner. Logic (e.g., propositional statement) allows for the representation of facts, rules, and inferences, enabling machines to reason and make decisions based on the knowledge encoded. This logical aspect ensures that knowledge is not merely stored but actively processed and utilized.

Computation brings the dynamic aspect to knowledge representation. Computational techniques, including algorithms and inference engines, are employed to harness the knowledge encoded in ontologies and logical structures. These techniques enable machines to perform complex tasks, such as problem-solving and decision-making, by leveraging the knowledge representation. Computation transforms static knowledge into actionable intelligence. (a simplified example is shown in Figure 4).

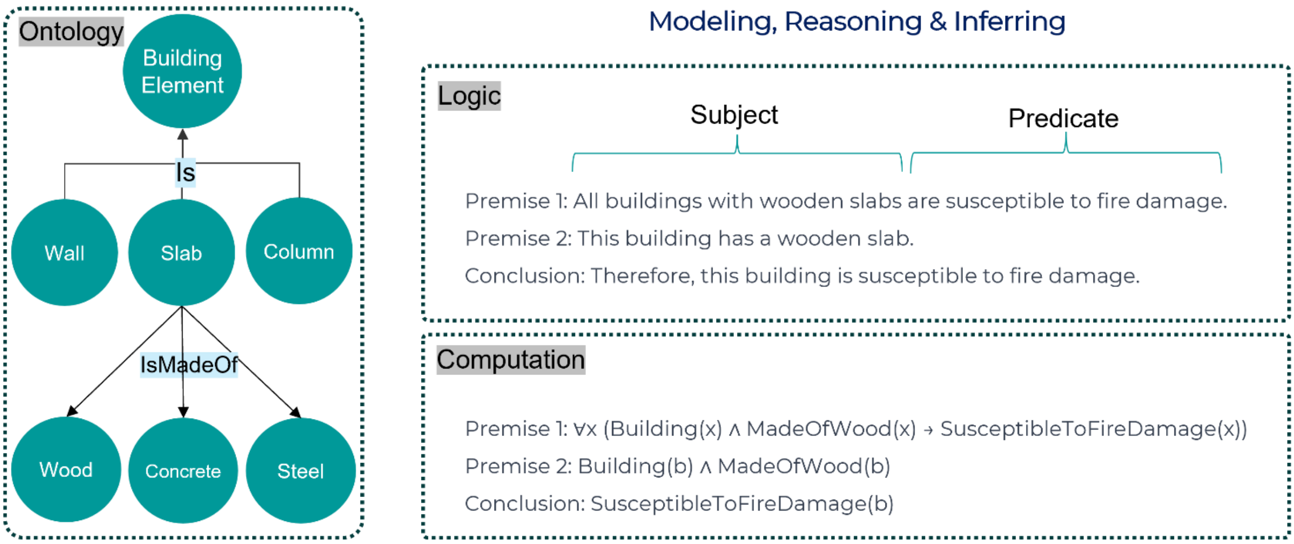

Figure 4: Simplified example showing the three pillars for analysing whether a building is susceptible to fire

Knowledge representation, through the integration of ontology, logic, and computation, provides the structured foundation for understanding, organizing, and applying information, facilitating the transformation of data into knowledge and, ultimately, contributing to the broader goals of knowledge management. Knowledge management goes beyond the mere representation of information and is concerned with the strategic management of an organization's knowledge resources (Figure 5).

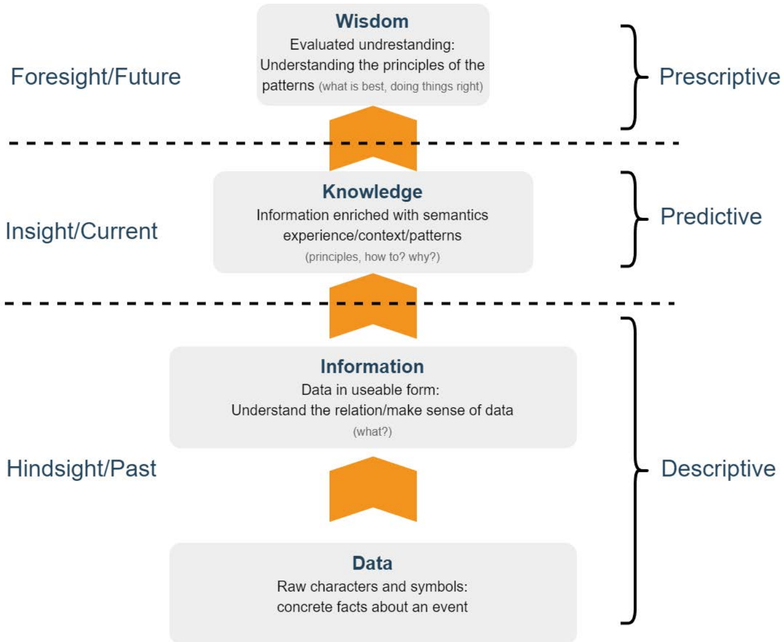

Figure 5: Data, Information, Knowledge, Wisdom (DIK) pyramid according to [7] visualized by authors

3.1. Ontology

According to [8] and depicted in Figure 6, ontology is viewed as a shared and common understanding of a specific domain that can be shared among individuals and diverse, widely scattered application systems.

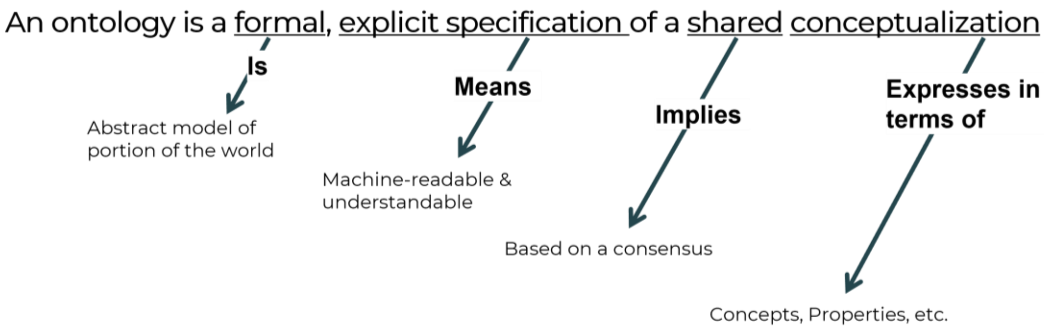

Figure 6: Ontology definition based on [8] visualized by [9]

3.1.1. Upper-Level Ontologies

An upper-level ontology, also known as a top-level ontology or foundation ontology, is an ontology that provides a foundational framework for organizing and categorizing all the concepts, entities, and relationships that are common across all domains. It serves as the highest level of abstraction in an ontology hierarchy and aims to create a common and general vocabulary to support broad semantic interoperability.

Basic Formal Ontology (BFO):

One example of such upper-level ontology is Basic Formal Ontology (BFO) created by Barry Smith and his team. It provides fundamental categories and relationships for representing entities across various domains, promoting interoperability. BFO defines categories and relations that can be employed to build specific ontologies for different fields (see Digital Construction Ontology as an example[6]). The structure of BFO is based on the division of entities into two disjoint categories of *Continuants* and *Occurrent* which are universals and every entity in the world belongs to either of them (see Figure 7). The former consists of objects and spatial regions, the latter contains processes conceived as extended through time [10], [11].

Continuants are entities that exist over time and do not depend on their contexts for their existence. Continuants are further divided into three types: In summary, the main difference between the subcategories is their level of dependence on other entities for their existence or identity.

Occurrents can be contrasted with Continuants. Occurrents are entities that exist in time and have temporal parts and temporal regions. Occurrents are events or processes that

[6] https://digitalconstruction.github.io/v/0.3/index.html

occur or unfold over time and can be observed or measured. BFO distinguishes between two types of Occurrents depending on temporal duration.

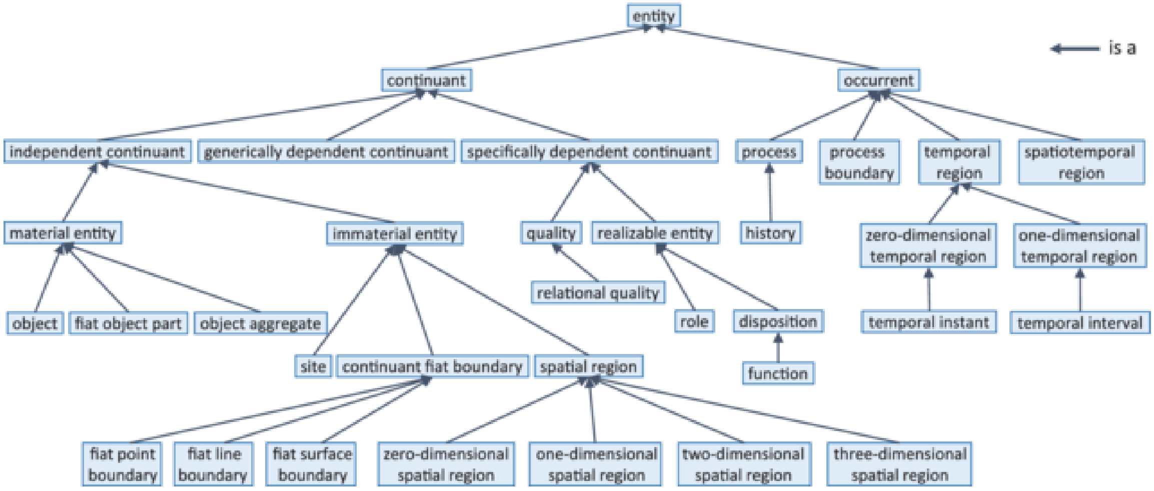

Figure 7: BFO-2020 hierarchy. Source: ISO/IEC 21838-2:2021(en)

3.2. Ontology, Taxonomy, and Knowledge Graphs

The concepts of ontology, knowledge graph, and taxonomy are related but they have different meanings and applications. Taxonomy and ontology are both ways of organizing information, but they differ in their level of specificity and complexity.

- **Taxonomy** is a classification system that organizes information into hierarchical categories based on shared characteristics. It is typically used to categorize objects, organisms, or concepts based on their physical or biological properties [12]. Taxonomies are often represented as trees, with each category branching out from a broader category at the top (as shown in Figure 8).
- **Ontology**, on the other hand, is a more complex way of organizing information that goes beyond simple classification (as shown in Figure 9). Ontology is a formal representation of knowledge that includes not just the hierarchical relationships between concepts, but also the relationships between concepts and the properties and attributes that define them [13], [14], [15]. The are three main components for an ontology:

  Classes: The distinct types of things that exist in the domain in question (nodes)

  Relationships: Properties that connect the two classes (links)

  Attributes: Properties that describe an individual class

While taxonomy is a simple classification system based on shared characteristics, ontology is a more complex representation of knowledge that includes not just hierarchical relationships, but also relationships between concepts and their properties and attributes.

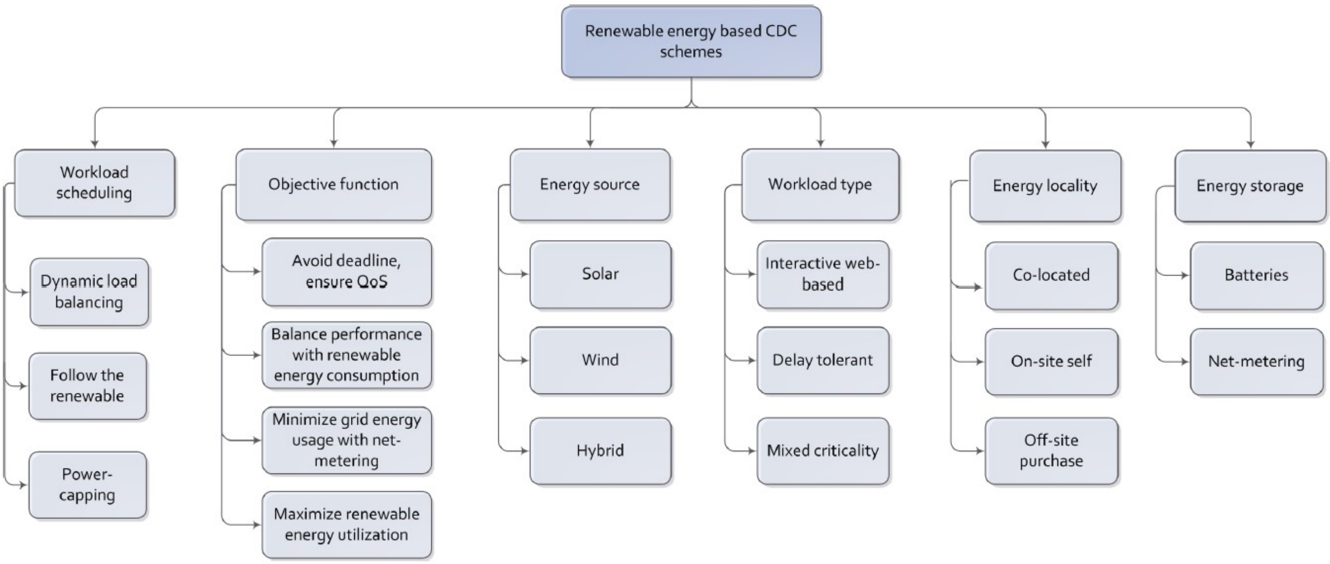

Figure 8: An example of a Taxonomy: renewable energy based proposed by [16]

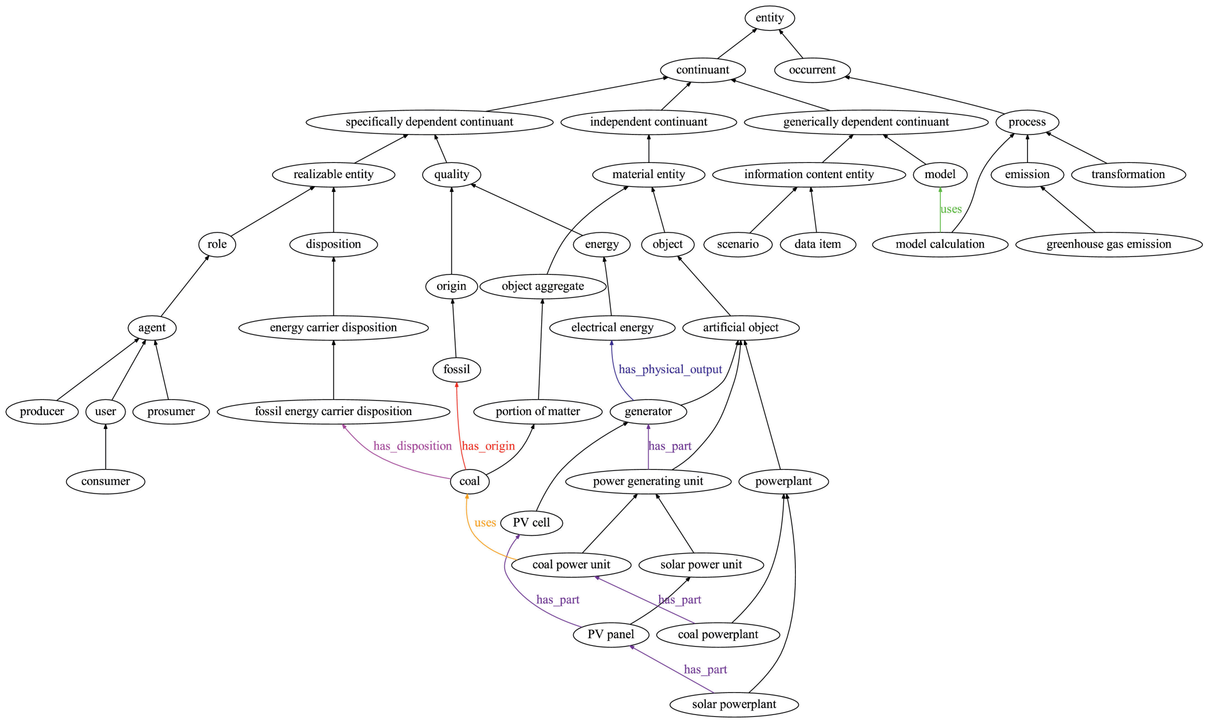

Figure 9: Example of an ontology: Open Energy Ontology, figure from [17]

- **Knowledge graph:** While an ontology defines a vocabulary of concepts and relations and the rules for their usage, a knowledge graph represents actual instances of these concepts and relations in the form of nodes and edges and can be constructed using ontologies [18]. It is designed to provide a rich and structured representation of knowledge, and it can be used to integrate data from multiple sources, perform complex reasoning and inference, and support natural language processing.

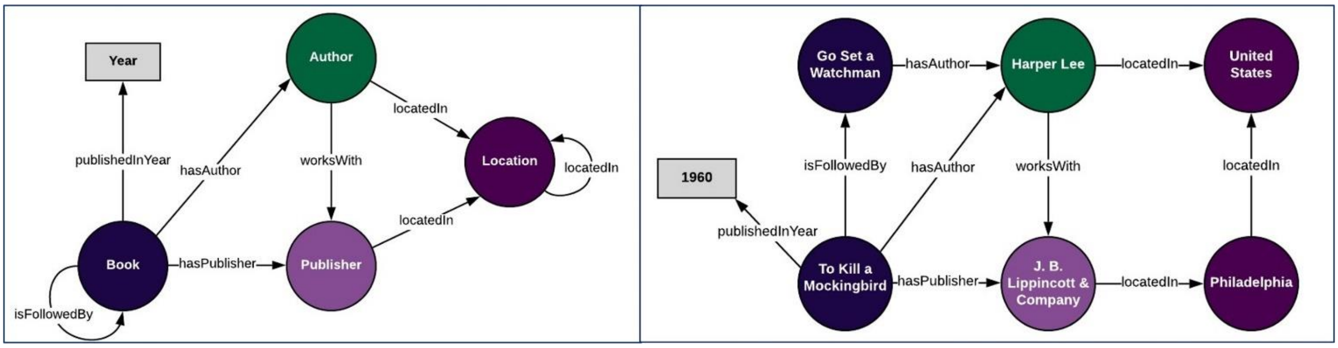

Figure 10: Left: example of an ontology about books, right: an instance [knowledge grap]h constructed using the ontology [18]

Generally speaking, when domain knowledge is concerned, one is not only interested in instances, but also in generalizations and universals. It consists of general terms and those general terms can be used to design scientific experiments. When we do experiments, we are interested in particulars and instances to test assertions about what is general.

3.3. The Significance of Knowledge Representation in Reincarnate

To summarize, within this landscape of pressing challenges and the need for transformative solutions, ontology emerges as a powerful tool for constructing a coherent and rigorous structured framework. It functions as the foundational backbone of knowledge representation, offering a framework for defining, categorizing, and interrelating key concepts and entities within the realm of circular building management. At its core, ontology enables the systematic organization and codification of knowledge, fostering a deeper understanding of complex domains. Through ontology, one can rigorously define the fundamental elements, relationships, and dynamics inherent to circular building management. Formalization and greater clarity in the use of terms and concepts related to the circular economy can facilitate more effective communication and collaboration among researchers, policymakers, and practitioners in the field of sustainability and circular economy. There are different perspectives (e.g., philosophical, information science, interoperability, semantic web, etc.) that pertain to what an ontology is and what it should be. These views help in defining and understanding the nature and purpose of ontologies. Our view toward ontology is similar to [5]. In this research, the authors advocate for a shift in the scientific discourse towards recognizing the importance of engineering knowledge in the development and application of advanced computational methods. They call for explicit formalization of knowledge through ontology and logic, with a focus on purpose and context, to better support engineers in their knowledge-intensive tasks.

In the next sections we elaborate on our approach and adopted methodology in developing the Reincarnate ontology to formalize the exiting knowledge withing the Reincarnate consortium and support their decision-making process.

4. Ontology Development Methodology

We initiated our methodology definition by conducting a literature review to examine existing methodologies. We specifically focused on fundamental ontology engineering methodologies including *METHONTOLOGY* [19], which has a sequence of phases: specification, conceptualisation, formalisation, integration, implementation, and maintenance. However, we concluded that these heavily holistic and hierarchical methodologies were not suitable for our project's scope and nature as it demanded a more flexible and adaptive approach, prompting an exploration of alternative methodologies. In this pursuit, we turned to the NeOn methodology [20], which stood out for its versatility and ability to accommodate the collaborative aspects inherent in ontology development. NeOn supports the collaborative aspects of ontology development, reuse, as well as the dynamic evolution of ontology networks within distributed environments. It offers different pathways for ontology development, including a wide range of possibilities with nine scenarios ranging from developing an ontology from scratch to reusing and re-engineering ontological resources. As shown in Figure 11, this method also allows combination of different scenarios:

1. From specification to implementation
2. Reusing and re-engineering non-ontological resources:
3. Reusing ontological resources:
4. Reusing and re-engineering ontological resources
5. Reusing and merging ontological resources
6. Reusing, merging, and re-engineering ontological resources
7. Reusing ontology design patterns (ODPs)
8. Restructuring ontological resources
9. Localizing ontological resources

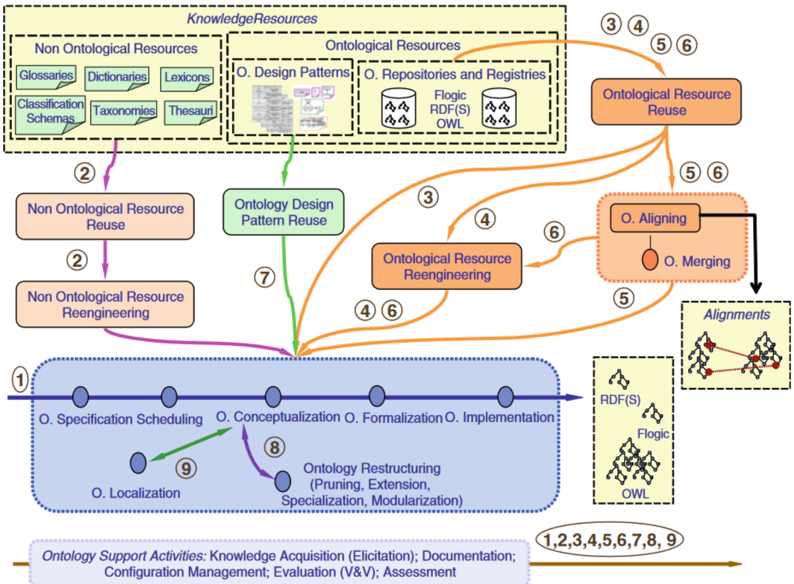

Figure 11: NeOn methodology scenarios for building ontologies

While the Neon methodology provides flexibility, our project also required a more agile and user-centred approach (Figure 12). Given the diverse users and user stories[7] , a more practical implementation was needed. To effectively address these complexities, we recognized the importance of adopting a development methodology which could align closely with the dynamic nature of our users' requirements and the evolving domain knowledge. As a result, we turned our attention to more recent and agile methodologies that could better accommodate our project's unique characteristics. In particular, we explored the eXtreme Design methodology [21], known for its rapid development, iterative cycles, and strong emphasis on collaboration with users. This methodology's principles resonated with our vision of creating an ontology that could quickly evolve and adapt based on user feedback and changing domain requirements. Additionally, we looked into Modular Ontology Modeling Methodology [19], which focus on creating modular and reusable ontology components. By breaking down ontologies into modular components, we aimed to enhance the ontology's scalability and maintainability.

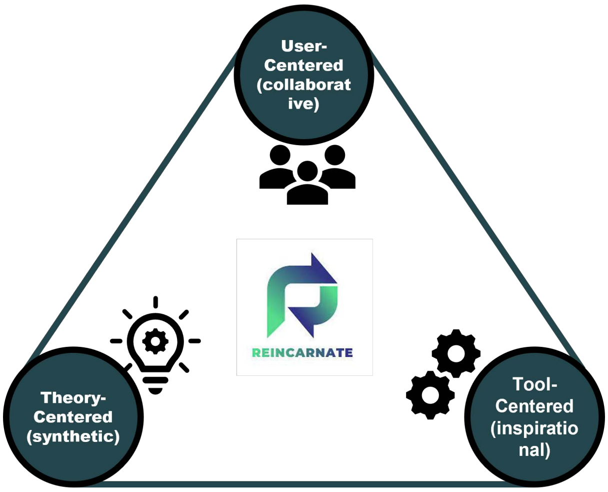

Figure 12: Reincarnate Ontology Development Approach

In the following sections, we will provide a detailed exploration of how these methodologies.

4.1. eXtreme Design Methodology

The eXtreme Design (XD) methodology, was initially proposed as a reaction to the waterfall-like methodologies, introducing a more agile approach. The methodology has certain principles as follows.

- Customer: since ontologies are used as a part of a software or an application, and not in isolation, the involvement of its customers (not necessarily the end users) and the domain experts are important.

[7] Informal descriptions of what users expect from the CPIM

- **Requirements-driven:** the ontology needs to include only the required content, and not more. Therefore, it is important that the development of the ontology is requirements-driven. This was a reaction to the holistic approach in the previous ontology engineering methodologies.
- **Iterative:** the result of an ontology is built throughout an iterative process, by producing tangible results from the early stages, and extension of the results in each iteration.
- **Modular:** the ontology is built piece by piece; therefore, this methodology has a modular approach. The structure of the ontology would be more complex; however, this feature has the advantage of easier partial reuse of the ontology, and possibility to partial use of the ontology for local querying.
- **Test-focused:** it has a focus on testing the ontology against the requirements as its central part of development.
- **Reusable:** an important principle of this methodology, is reusability, particularly through ODPs. Reusing ontologies can be difficult, but at the same time, it has the benefit of utilizing the previous solutions.

The combination of these principles leads to a natural modularisation of both the problem and the solution. This enables a distributed ontology development. The process in this methodology can be summarised as the following steps:

1. Project initiation and scoping
2. Development loop: producing new modules iteratively.
3. Integration loop: adding the increments to the overall solution.

4.2. Modular Ontology Modelling Methodology

Modular Ontology Modelling Methodology (MOMo) is established based on the eXtreme Design methodology. It emphasizes modular development and design pattern reuse and adds the extensive use of graphical schema diagrams.

The main core of this methodology is *modularization*, as a remedy to the issues which prevent reuse in ontologies. For this purpose, it is important to understand the notion of *module* in ontologies. A module refers to a part of the ontology, capturing a key notion in addition to its key attributes. Modules facilitate the divide-and-conquer approach in the development of an ontology; modelling on module at a time and making the connections between them later. This method also makes modifications easier. Another core aspect of this method is the systematic use of Ontology Design Patterns (ODP). ODP is defined as a generic solution or a template for a repeating ontology modelling problem. The workflow of MOMo is summarized as the following steps:

1. **Describe use cases & data sources:** describing the problem, by a set of related use cases, which can also be extended later. Use cases help leading towards a modular ontology development which is extensible and reusable.
2. **Gather competency questions:** competency questions are the queries of interest, for which the ontology will be used later.
3. **Identify key notions:** the key notions can be the modules of the ontology; however, it is also possible to combine multiple key notions into one module.
4. **Identify existing ODPs:** utilizing pattern libraries for reusing in the new ontology.
5. **Create module diagrams:** forming the diagrams, with the goal to find the best patterns suitable to be used as a template, to explain the notions and its key aspects.
6. **Document modules & axioms:** documenting the ontology as an integral part of the modelling process.
7. **Create ontology diagram:** create the schema diagrams from the module schema diagrams.
8. **Review naming & axioms:** the names of entities in an ontology can be helpful to make it understandable, and therefore to increase the possibility of reusing it. Specific conventions on naming can be followed for this purpose.
9. **Create OWL file:** as the last step, formally modelling the ontology in the form of an OWL file. However, the conceptual works of developing the ontology are done using discussions, diagrams, and documentation.

4.3. Existing Ontologies

As the existing ontologies started to be more and more available, the process of ontology development has also turned to a reuse-centric process [20]. Based on this, and to start the process of ontology development for this task, a list of existing ontologies (Table 1) was collected with relevant topics to circular built environment, which were studied for reuse possibilities. For more detailed survey of general ontologies for the cross-industry domain, we refer the readers to [22].

Table 1 List of relevant existing ontologies

Name	URL
Building Topology Ontology, BOT	https://w3c-lbd-cg.github.io/bot/#intro
Building Product Ontology, BPO	https://www.projekt-scope.de/ontologies/bpo/
Digital Construction Ontologies, DiCon:	https://digitalconstruction.github.io/v/0.5/index.html
Ontology for Property Management, OPM	https://w3c-lbd-cg.github.io/opm/
IFCOWL	https://standards.buildingsmart.org/IFC/DEV/IFC4/ADD2_TC1/OWL/index.html
Building Circularity Assessment Ontology, BCAO	https://github.com/linmor-sys/BCAO

Circular Materials and Activities Ontology, CAMO	http://ld-ce.com/vocab/CAMO
Semantic Sensor Network Ontology	https://www.w3.org/TR/vocab-ssn/
SAREF core	https://saref.etsi.org/core/v3.1.1/
SAREF4BLDG	https://saref.etsi.org/saref4bldg/v1.1.2/
Smart Building Ontology for Ambient Intelligence, BOnSAI	https://github.com/BONSAMURAIS/BONSAI-ontology-RDF-framework
The PROV Ontology, PROV-O	https://www.w3.org/TR/prov-o/
Brick Ontology	https://docs.brickschema.org/intro.html
Circular Economy Ontology Network, CEON	https://liusemweb.github.io/CEON/

In the following chapters, we provide a detailed explanation and analysis of two key ontologies: CEON and IFC:
CEON, developed within the ongoing European project Onto-DESIDE[8] (Ontology-based Decentralized Sharing of Industry Data in the European Circular Economy), offers a comprehensive range of vocabularies spanning various domains of the circular economy. This ontology emerged as the most fitting choice for adoption within the Reincarnate project due to its ability to cover diverse concepts and practices. It is important to mention that at the time of writing this report, CEON was still under development, and the report refers to the first version created during this period. Our collaboration with the Onto-DESIDE team was instrumental in this decision, allowing us to explore the practical implementation and usage of CEON in the construction sector. Additionally, we chose to integrate with IFC, a de-facto standard for data exchange and foundational classes in the construction industry.
In the following sections, we elaborate the specifics of these two selected ontologies, elucidating our mapping approach and detailing the reasons behind our choices.

For readers who are familiar with the structure of CEON and IFC Schema structure, we recommend skipping the following chapters and directly start with *Reincarnate Ontology (ReOn)* Development section.

[8] https://ontodeside.eu/

4.3.1. Circular Economy Ontology Network (CEON)

The Circular Economy Ontology Network (CEON) [23] provides a common vocabulary for representing circular economy information, achieved through a network of ontology modules. Figure 13 offers a visual summary of the areas it encompasses, with connecting lines indicating their inherent relationships. This CEON release[9] presents a foundational set of modules that serve as versatile and reusable building blocks for creating ontologes. These modules encompass Circular Value Network, Actor, Process, and Resource (covering both Materials and Products).

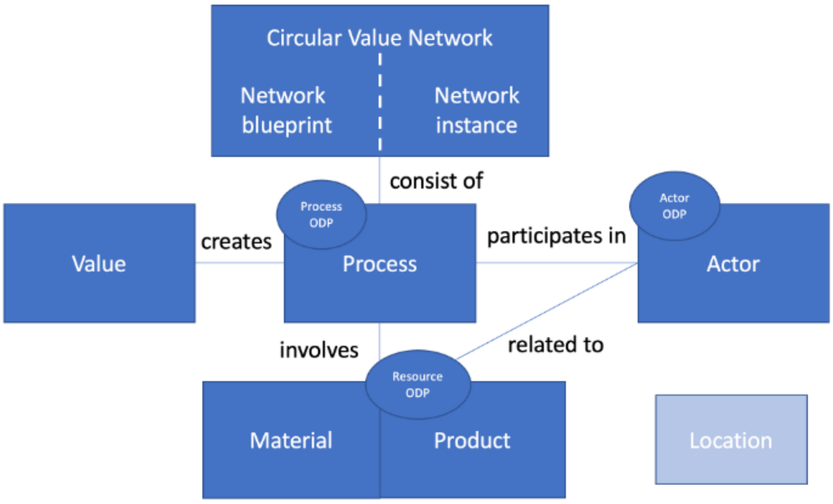

Figure 13: Overview of the CEON ontology pattern or module [23]

In this section, we will begin by conducting a comprehensive analysis of the CEON ontology. Circular Value Network serves as a foundational module of CEON ontology, defining key concepts and relations necessary for modeling aspects of circular value network within circular economy. It provides structured framework for representing information related to circular economy.

Circular Value Network (Blueprint & Network Instance)

A *CVN Blueprint* (Circular Value Network Blueprint) in CEON ontology is essentially a plan or pattern for configuring a Circular Value Network (CVN). It serves as a high-level template that can be used to create specific instances of CVNs. Based on our analysis, the following principles are key:

1. **High-Level Representation:** A CVN Blueprint provides a high-level representation of what a CVN should look like. It defines the structure, components, actors, and possibly the processes that a CVN should involve (a plan or a pattern of a CVN configuration that can be filled with actual actors and processes). "implements blueprint" relationship connects a CVN to the CVN Blueprint as shown in Figure 14.

[9] Version 0.1 which can be found at https://liusemweb.github.io/CEON/

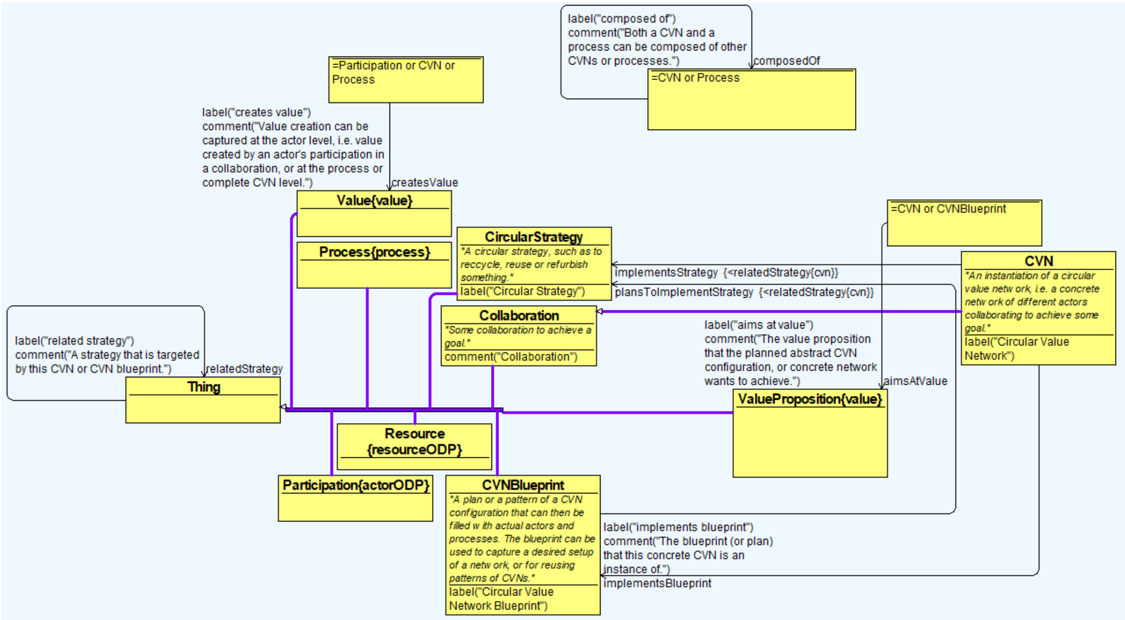

Figure 14: UML visualisation of CVN[24] documentation using OWLGrED

2. **Pattern for Reuse:** One of the key purposes of a CVN Blueprint is to act as a reusable pattern. Instead of defining the entire CVN from scratch each time, one can use a blueprint as a starting point and then modify it as needed to suit the unique characteristics of a specific CVN. This is particularly useful if there are common CVN configurations that are used in different contexts. Here is a simplified example to illustrate how a CVN Blueprint might work:

CVN Blueprint: Recycling Network

- Components: Collection centers, Sorting facilities, Recycling plants
- Actors: Recycling companies, Local governments
- Processes: Collection, Sorting, Recycling
- Circular Strategy: Recycling

Specific CVN: City Recycling Program

- Components: City-owned collection centers, Local sorting facilities, regional recycling plants
- Actors: City Recycling Department, Local waste management companies, Regional recycling consortium
- Processes: Collection by city staff, Sorting by contracted waste management, Recycling by regional plants
- Circular Strategy: Recycling

In this example, the "Recycling Network" CVN Blueprint provides a template for setting up recycling networks. When the "City Recycling Program" is created, it is linked to the "Recycling Network" blueprint, indicating that it implements this blueprint. However, the specific components, actors, and processes can be customized to fit the needs of the city's recycling program.

Process and Process ODP

The *Process Ontology Design Pattern (ODP)* is the core ontology design pattern of CEON ontology (Figure 15) which defines the required aspects of the fundamental concept of *Process* module. *Process ODP* is a more general ontology that introduces foundational classes and properties to describe processes, their executions, types, and relationships. It doesn't go into the specifics of different process types, but rather focuses on the broader aspects of modeling processes within the CEON ontology network. The *Process* Module on the other hand defines specific subclasses of *processODP*: *Transformation* that represents different types of processes within a circular value network. It focuses on providing detailed classes and properties related to those processes such as (e.g., assembling process, buy resource process) and their characteristics (e.g., input, output, energy needs). It represents a series of activities or steps undertaken to achieve a specific goal or outcome within the domain of circular economy practices. These activities may involve actors, resources, and stages that are integral to understanding how material and resources flow within the circular value network.

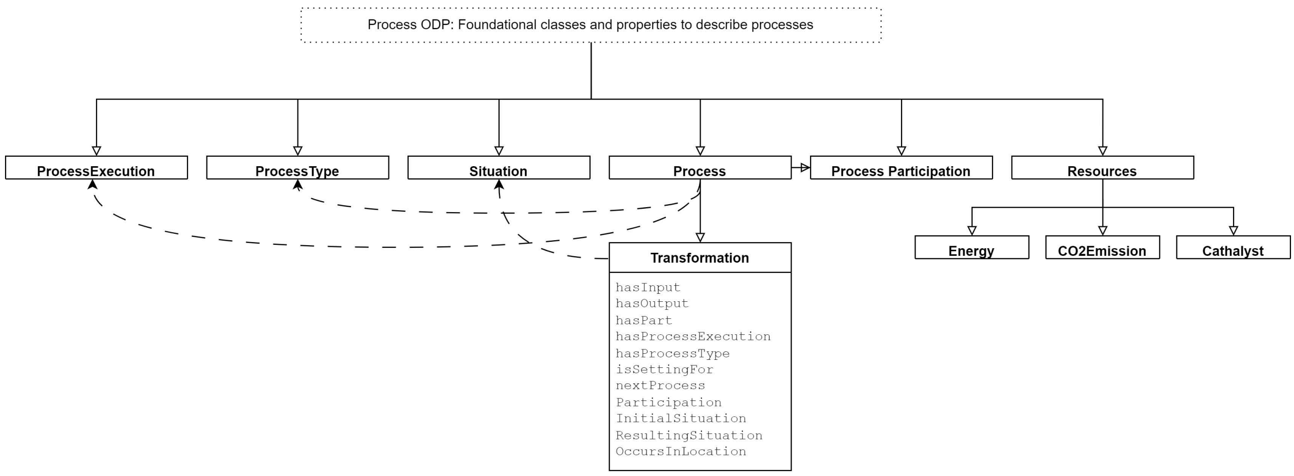

Figure 15: Process ODP structure made by the authors based on Process ODP documentation [25]

Transformation (as shown in Figure 16) refers to a process or activity that converts materials, products, or resources from one state to another within a circular value network. Transformations are central to circular economy practices as they represent key operations like recycling, refurbishing, or converting resources into new products. In the CEON ontology, "input" and "output" are represented as object properties for processes and transformations.

- **hasInput**: Represents the situation before the transformation or process takes place. It can include information about the set of components or resources before they are transformed or processed.
- **hasOutput**: Represents the output situation of a transformation or process. It captures the changes that occur as a result of the process.

Other properties are:

- **needsEnergy**: The energy needed as an input for a certain process.
- **producesCO2**: The CO2 emission produced as an output by the process.
- **resultingProduct**: The resource that is the output or product of a certain process.
- **usesCathalyst**: The catalyst used as an input in a process.

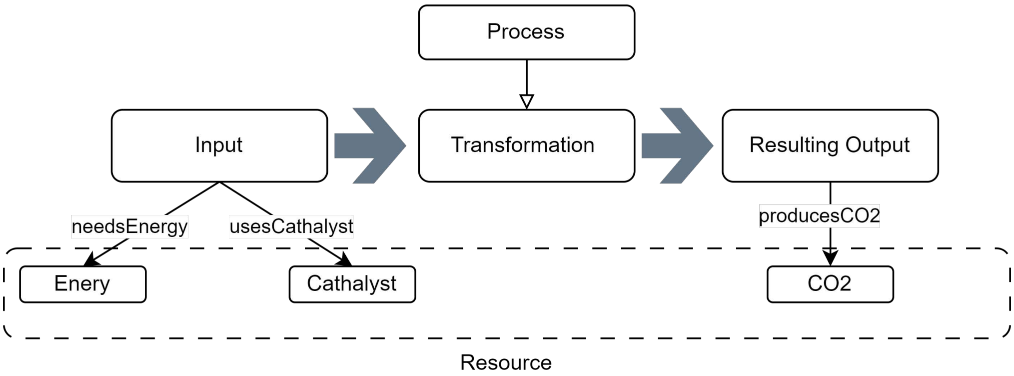

Figure 16: Transformation Process overview

As shown in Figure 17, the provided ontology defines several types of transformation, each represented as a subclass of the *Transformation* class.

Figure 17: Different types of transformation processes based on [26]

Actor and Actor ODP

A circular value network is in essence composed of a set of actors filling certain roles in different phases of the network's flows. Hence, the actors are the ones that actually realise the value network, and perform the work to transform materials, components, and products in the various steps in the value network phases [27]. The *Actor Ontology Design Pattern (ODP)* is a foundational component of the CEON ontology, akin to the *Process ODP. Actor ODP* serves as a generalized framework within CEON, establishing fundamental classes and properties to characterize actors, their roles, capabilities, and interactions in the context of a circular economy. It provides a versatile foundation for modeling actors' attributes and behaviors. This module as shown in Figure 18, defines object properties like capabilityProperty, participantRole, participatingActor, participatingResource, and participationIn. These properties are essential for modeling the capabilities of actors and their participation in different processes, collaborations, or activities within a circular economy.

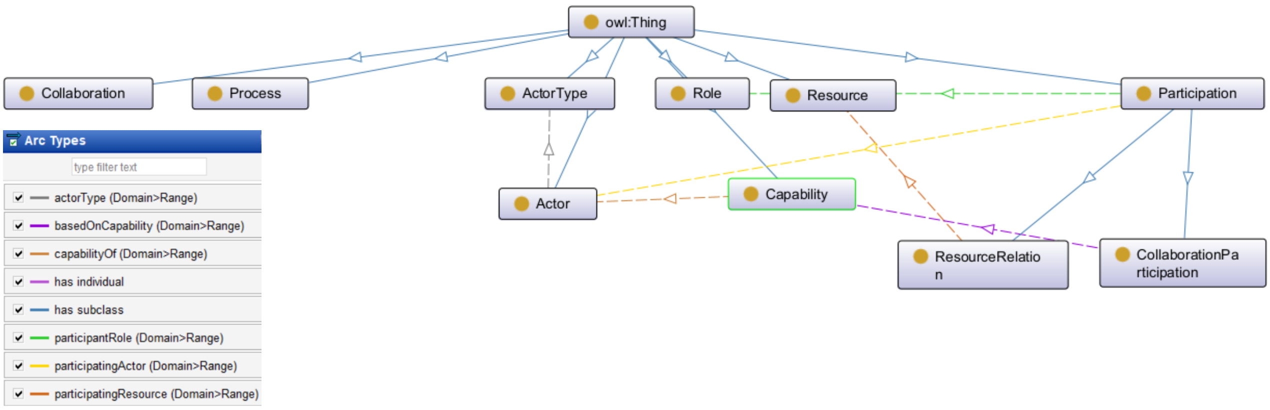

Figure 18: Actor ODP framework based on [28]

Conversely, the *Actor* module extends the *Actor ODP* by offering specialized subclasses, aligning with different actor roles within a circular value network. This module focuses on defining classes representing various actor roles within a circular economy, such as ActorCVNRole, ActorCollaborationRole, ActorProcessRole, and ActorResourceRole. These roles help describe what different actors do within the context of a circular economy. These subclasses encompass actors like buyers, sellers, recyclers, and more, each defined with specific attributes and roles. It defines the roles and characteristics of these actors within the circular economy paradigm, specifying their contributions, resource needs, and collaborative engagements in shaping the flow of materials and resources across the circular value network.

Resource ODP , Product, and Material

Resource ODP provides a generalized framework for modeling various types of resources, including physical objects and information. The Resource ODP can be seen as a broader foundation upon which the Product and Material ontology builds to represent products in the circular economy. As shown in Figure 19, it introduces classes and properties to describe resources, including the concept of "Resource," which encompasses both physical objects and information. It defines relationships like "hasConstituent" and "hasMatter" to represent how physical objects can have components or matter associated with them.

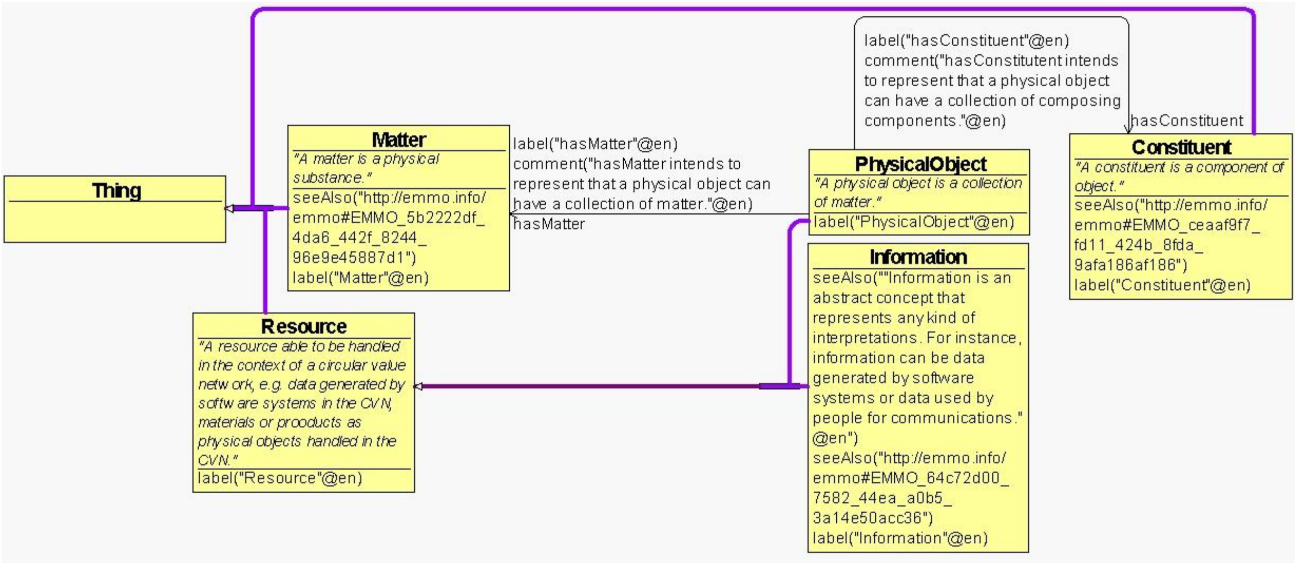

Figure 19: Resource ODP framework

Material and Product modules (Figure 20) are specialized parts of CEON that build upon the Resource ODP. Material is primarily used to model various types of materials, including substances and collections of substances, which are essential components of physical objects. It defines object properties like "hasChemicalEntity" and "hasMaterialComponent" to represent that materials can consist of chemical entities and components. Product focuses on modeling products, which are physical objects put into a market for sale and introduces the "hasProductComponent" property to represent that a product can consist of various components.

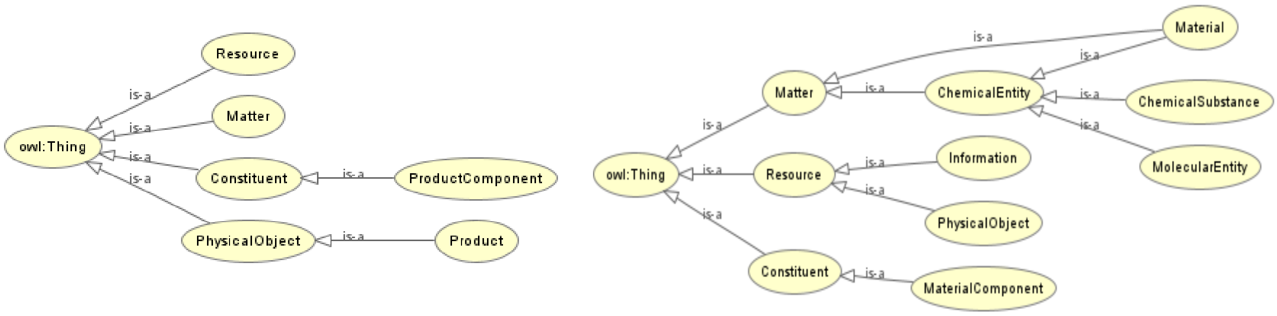

Figure 20: Material (right) and Product (left) modules classes.

4.3.2. IFC Schema

BIM encompasses the entire life cycle of a building, utilizing an information model that comprehensively captures all relevant data. IFC is an industry-wide open data format for the exchange of BIM data that is fast becoming the de-facto standard for rich data exchange. It was designed not only as an open inter-changeable file format but also as an actual **data structure**. In practice, the IFC schema can be considered as an archiving system for organizing and transporting digital data, in order to promote interoperability between different subjects [29]. As shown in Figure 21, the IFC architecture is based on three pillars: Semantics, Relations, and Properties[10].

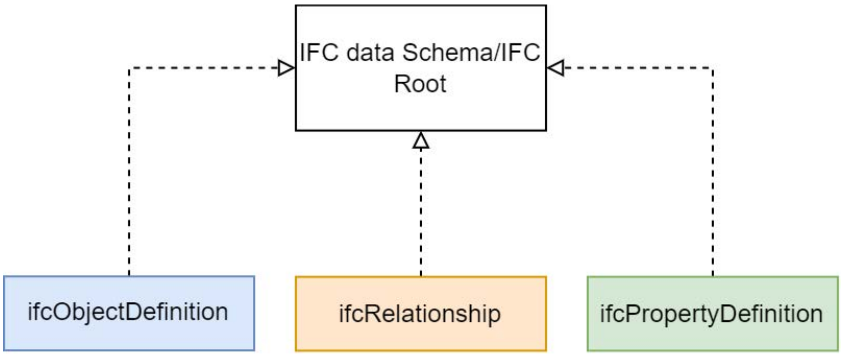

Figure 21: logic of IFC based on 3 fundamental concepts, visualized by authors

1. `IfcObjectDefinition:`

The word **object** is to be understood as an abstract or tangible entity that represents the description of a part of the building that we are digitizing (e.g. window, spaces or processes) [29]. As shown in Figure 22, the scheme outlines six key concepts directly linked to IfcObject:

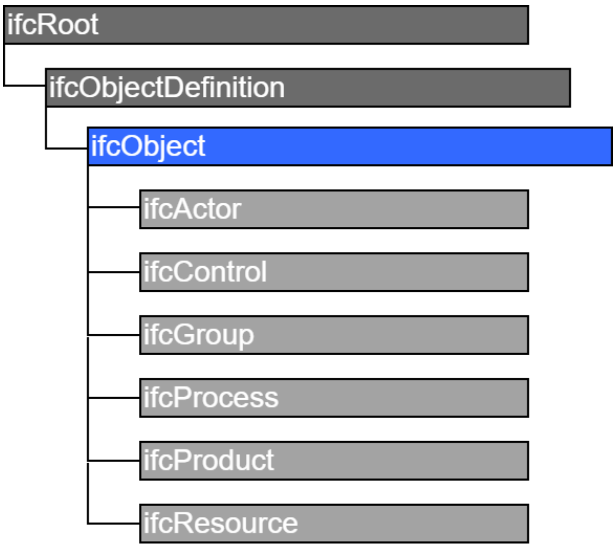

Figure 22: Taxonomy of IfcObject from BuildingSmart

10 Unlike entities in other layers, resource definition data structures cannot exist independently, but can only exist if referenced (directly or indirectly) by one or more entities deriving from IfcRoot.

`IfcActor:` Defines participants in the construction process, storing details like names, addresses, organizations, and roles.

`IfcControl:` Represents design constraints and factors like customer requests, project costs, regulations, and delivery time.

`IfcGroup:` A logical collection of objects without location or shape representation, useful for organizing elements.

`IfcProcess:` Represents time-ordered activities or events that transform inputs into outputs and have sequence relationships.

`IfcResource:` Stores information related to asset costs, scheduling, and impacts, potentially including construction equipment.

`IfcProduct:` Encompasses entities related to geometric or spatial contexts, including physical elements and non-physical items like grids and annotations.

2. **`IFCRelationship:`**

IfcRelationship class encompasses five essential relationship types within the IFC model (as shown in Figure 23, each serving distinct purposes in describing how elements are connected, associated with external information, composed or decomposed, and inherit properties or receive assigned services.

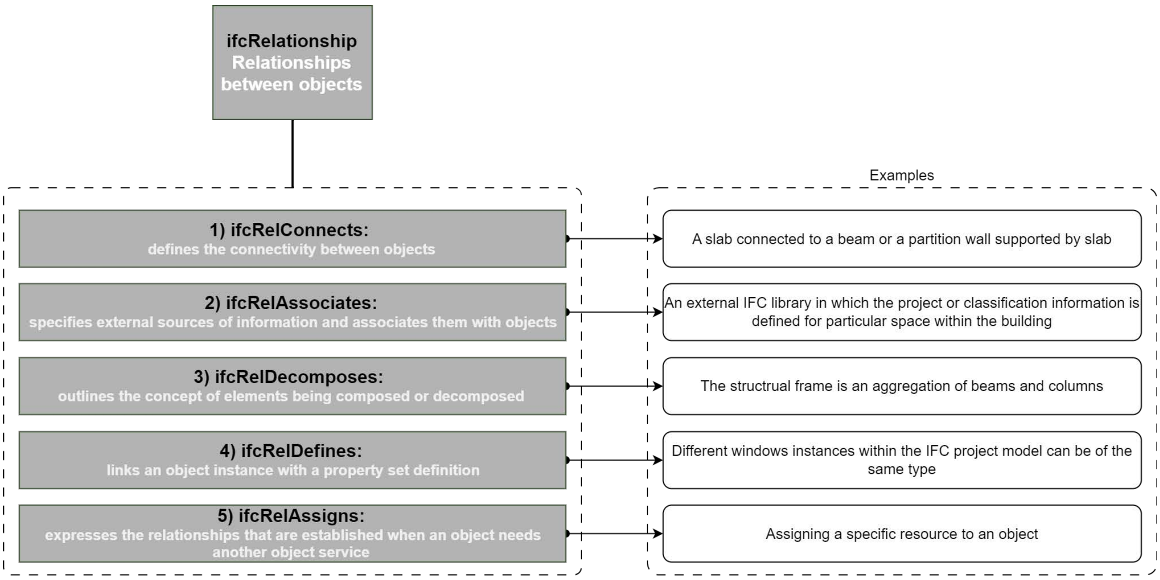

Figure 23: IFC schema describing the IFCRelationship source: https://bim.acca.it/category/ifc-open-bim/

`IfcRelConnect:` Represents a connectivity relationship that links objects based on specific criteria.

`IfcRelAssociates:` Signifies external sources of information and associates them with objects or property definitions. This association is one-way.

`IfcRelDecomposes:` Defines the general concept of elements that are composed or decomposed. Decompositions imply a dependency, meaning that the definition of the whole relies on the definition of its parts, and conversely, the parts rely on the existence of the whole.

`IfcRelDefines:` This relationship allows instances to inherit type properties.

`IfcRelAssigns:` This makes explicit the relationships that arise when one object requires the services of another object.

3. **`IfcPropertyDefinition:`**

This entity serves as a way to categorize all properties that can be assigned to objects (Figure 24). This categorization enables the creation of sets of properties or types of objects (referred to as 'type objects'). These properties define the information that can be shared among multiple instances of objects.

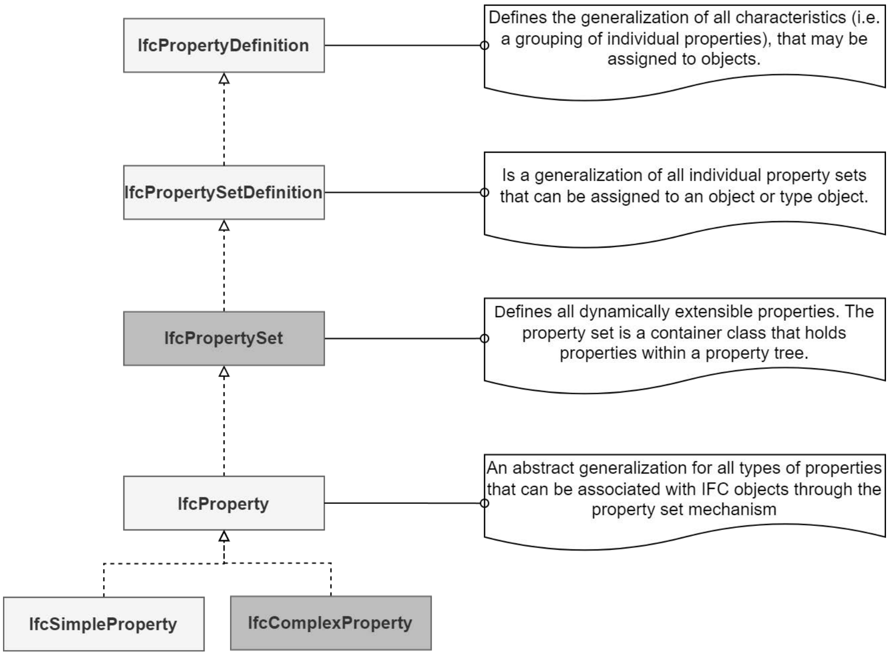

Figure 24: The overview IfcPropertyDefinition; the light grey boxes represent abstract supertype

`IfcPropertySetDefinition:` This allows for the generalization of property sets.

`IfcPropertySet:` It acts as a container that holds various properties, each defined and qualified by a name. Property sets are associated with objects (IfcObject) through the IfcRelDefinedByProperties relationship.

`IfcProperty:` This defines the generalization of property types that can be linked to IFC objects and relies on a set of properties.

5. Reincarnate Ontology (ReOn) Development

Rather than creating an entirely new ontology, our approach was to capitalize on established ontological structures by thoroughly examining existing ontologies for components that could be repurposed for our project. We achieved this by conducting a comprehensive review of existing ontologies, identifying components suitable for adaptation in our project. Building upon the CEON ontology (explained in 4.3.1) as a foundation, we introduce a mapping mechanism utilizing the IFC ontology. This mechanism allows us to encompass fundamental concepts and depict the relationships and interactions among entities associated with the built environment that are integral to the Reincarnate project.

5.1. Utilization of IFC Schema

Our approach of utilizing the IFC schema to map and structure the required concepts for circular concepts is beneficial for several reasons:

- **Practical Implementation:** Rather than proposing a theoretical concept, our approach takes concrete steps to identify where specific data should be incorporated within the IFC framework. This practical implementation approach adds tangible value to industries by facilitating sustainable decision-making for various processes.
- **Focus on Data Requirements:** Our approach centres around identifying the essential data required by different stakeholders for decision-making processes ensuring the ontology will be user based, practical, and valuable.
- **Standardization and Interoperability:** By aligning data within the IFC ontology, we're advocating for a standardized way of representing and sharing information. This promotes interoperability between various stakeholders and software systems.
- **Efficient Data Management:** Our method streamlines data management by eliminating the need for separate databases or systems. This efficiency benefits stakeholders across various industries, making it easier to access and utilize critical information.
- **Enhanced Collaboration & Circular Economy Promotion:** This approach encourages seamless collaboration among professionals in different fields, from architecture and engineering to construction and waste management. They can communicate effectively using a common data framework, improving project coordination. By integrating data essential for circular decision-making into the IFC framework, we demonstrate a commitment to circular economy principles.
- **Scalability and Adaptability:** Our work considers the scalability and adaptability of data representation. As both the IFC schema and circular economy practices

evolve, updates can be made to ensure continued relevance, not just for specific materials but for a wide range of resources.

- Educational Value: Our approach serves as a case study for those seeking to integrate domain-specific data into existing ontologies. It showcases how established frameworks can be extended to encompass diverse and relevant information, promoting circular decision-making across industries.

5.2. Requirements Elicitation

Our data requirements are elicited mainly from the ontology stories, that are produced in collaboration with domain experts and end-users. To achieve this, we employ use case development (Figure 25) as a primary tool. Use cases help identify and document specific scenarios, interactions, and user needs regarding different processes. Through a combination of stakeholder interviews, domain analysis, and real-world examples, these use cases served as practical models to guide the ontology development. This approach promotes a well-informed and adaptable ontology that can support diverse applications and decision-making processes. After collecting the use cases, two sessions of 1-hour workshops were planned to further enhance the requirement elicitation process. These workshops aimed to bring together stakeholders, experts, and the ontology development team to clarify and refine the answers obtained from the use cases. The collaborative workshops encouraged open discussions, allowed for the resolution of any ambiguities. This iterative and participatory approach helped foster a deeper understanding of the specific needs and requirements within the domain, ultimately leading to a more robust and contextually relevant ontology.

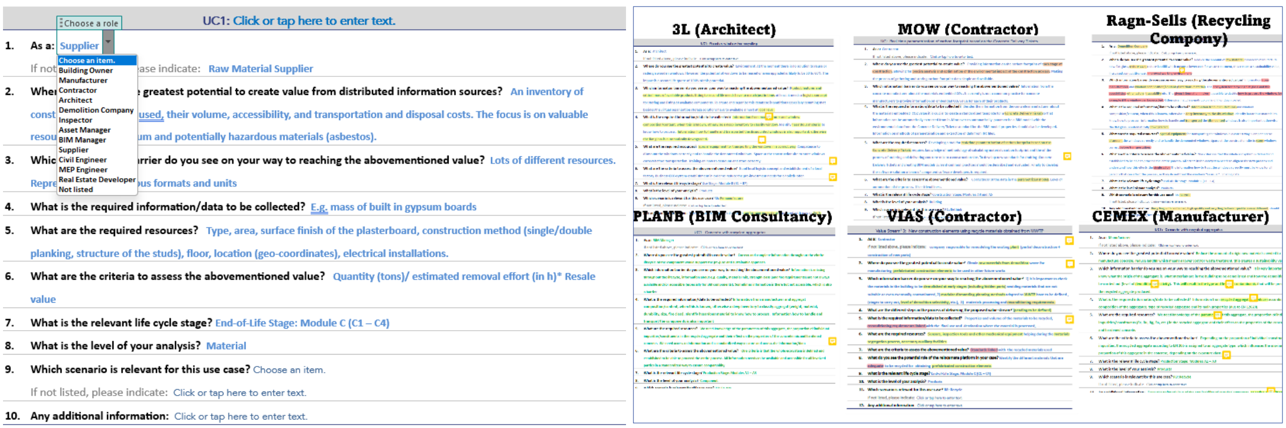

Figure 25: Left: the use case template, Right: examples of the inputs that we received from partners

5.3. Higher Level Ontology

5.3.1. Important Concepts and Terminologies

The higher-level ontology (not to be confused with top-level ontology) within the Reincarnate project serves as a foundational framework encompassing general terms and concepts utilized across various project activities (see Figure 26). Following the terms and definitions defined in *ISO/DIS 59004 Circular Economy – Terminology, Principles and Guidance for Implementation*, the proposed higher-level ontology is designed to align with both the CVN and IFC schema.

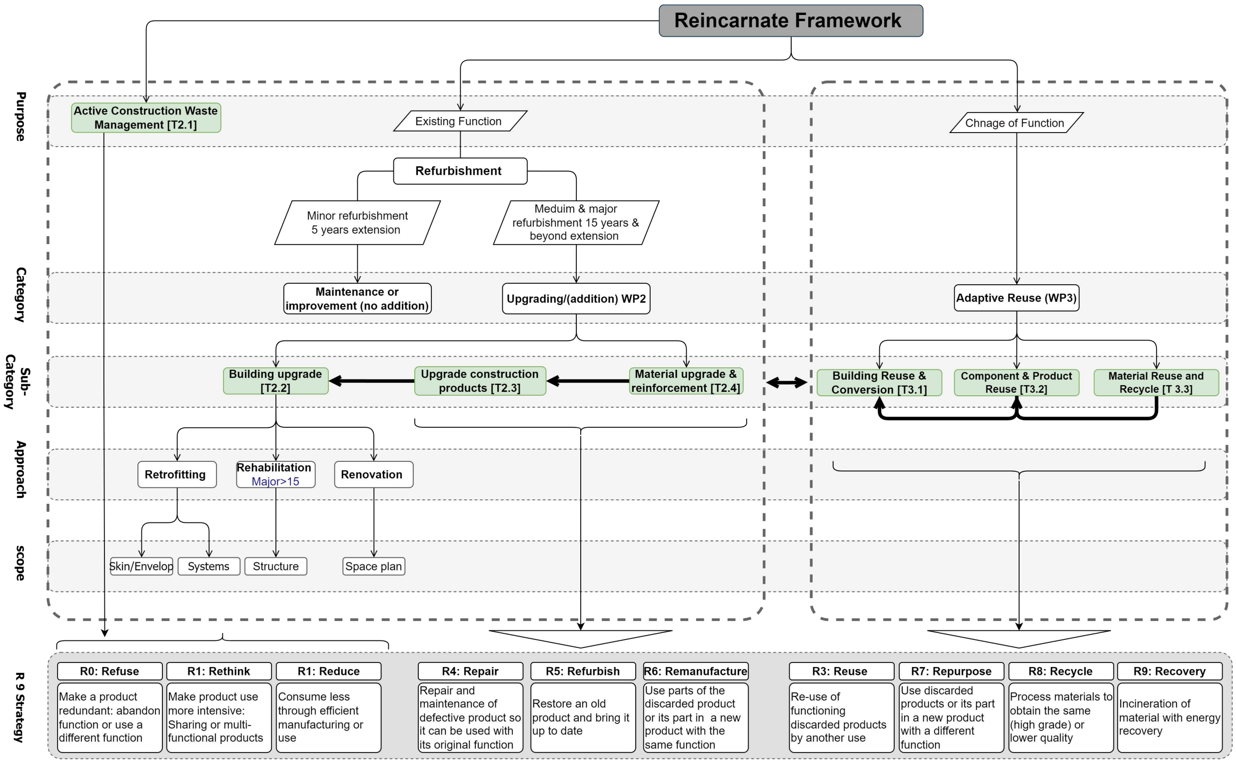

Figure 26: The overview of concepts presented in Reincarnate project

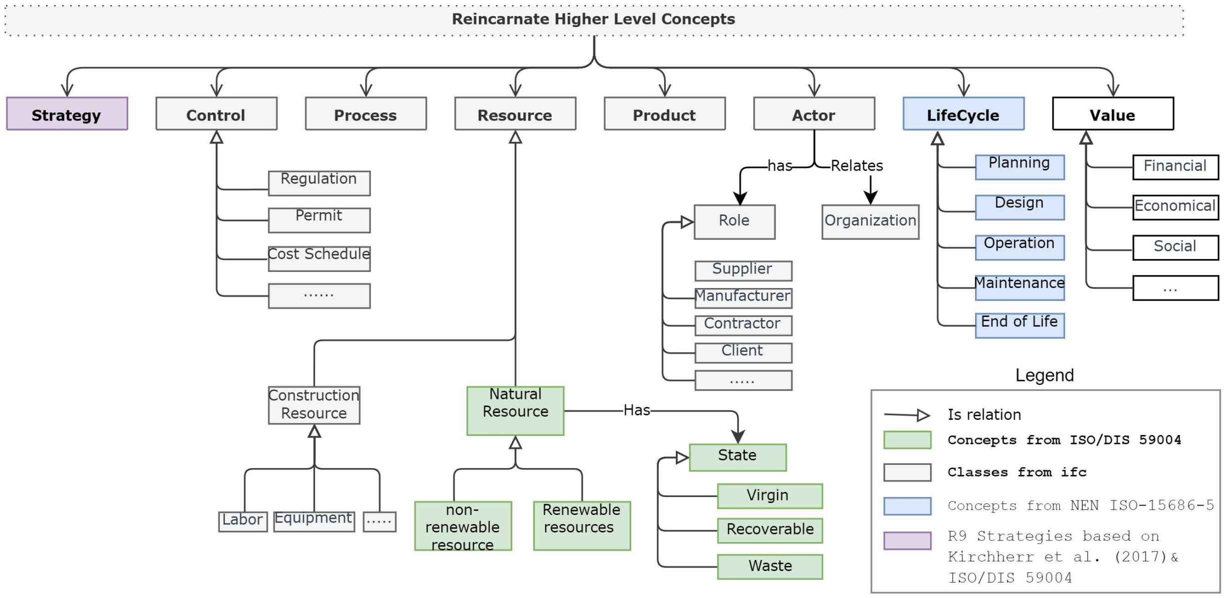

Figure 27: The main concepts and terminologies relevant for Reincarnate project

In this context, as presented in Figure 27, and Table 2, the first step was to identify the key concepts and terms to establish a common language between project partners and facilitate and support the implementation of the proposed processes in the project.

Table 2: Main terms of ReOn concpets and their description

Term	Description
Circular Strategy	*Circular Strategy* or "Resource Management Actions [according to ISO/DIS 59004]" refers to a set of approaches (such as R9) aimed at closing material and resource loops, thus promoting sustainability and minimizing waste. These strategies include activities such as refurbishing, remanufacturing, and repurposing. By implementing these strategies, organizations can contribute to a circular economy by extending the lifecycle of products, reducing resource consumption. Several actions with respect to these strategies are identified as shown in Figure 29.
Control Mechanism	*Control Mechanism* refers to the set of procedures or systems used to manage or regulate various aspects of the processes. Control mechanisms can include quality control procedures, tracking and tracing systems, performance monitoring tools, and regulatory frameworks that help organizations and stakeholders comply with regulations, maintain and improve the efficiency and effectiveness of circular processes.
Process	*Process* is a fundamental concept that transforms <u>input</u> in <u>output</u>, and may connect to other processes through input, output relationships
Resource	*Resource* is a broad concept used to present a wide range of resources utilized within the construction and building industry. The resources encompass not only natural resources but also non-matter things such as labour, machinery, and equipment. Resources are typically classified into various types, including natural resources (raw materials occurring in nature), renewable resources (those that can be naturally regenerated), and non-renewable resources (which are finite and not regenerated at human-relevant timescales). Resources can be in various states, such as virgin resources (unused), recoverable resources (potentially reusable), or waste (no longer providing value) [see Figure Figure 27]. Managing and optimizing the use of resources is a key goal in circular economy strategies to minimize waste, environmental impact, and the depletion of finite resources.
Product	*Product* is a conceptual representation of any object that has a geometric or spatial relevance within the context of a project. These objects can be used as inputs or outputs in various processes. Products can include objects that are manufactured, supplied, or created and are intended for use in Construction/Facility Management projects. An 'element' is a category that encompasses all the individual components that make up an AEC product. Additionally, various property sets such as environmental impact value, service life, etc can be associated with each element
Actor	*Actor* refers to an individual and/or organization playing a distinct role. The circular economy process in construction involves a network of such actors, each with specific roles (as supplier, contractor, manufacturer, etc.[11]) assigned to a specific task.
LifeCycle	*LifeCyle* refers to the phases in which a task/process is being executed.
Value	*Value* pertains to the evaluation of the worth or significance of processes. This assessment is based on their capacity to enhance sustainability, resource efficiency, and reduce environmental impact. It encompasses economic, environmental, and social dimensions and serves as a pivotal element in the assessment of circularity and sustainability within the system.

[11] See ifcRoleEnumaration at https://standards.buildingsmart.org/IFC/RELEASE/IFC2x3/TC1/HTML/ifcactorresource/lexical/ifcroleenum.htm

Figure 28 provides a graphical depiction of how these relationships are structured and the concepts interconnect within the ontology. This structured and interconnected ontology serves as a tool for the project partners to navigate and understand the complexities of the circular economy in the construction and building industry, facilitating their efforts to implement their proposed strategies.

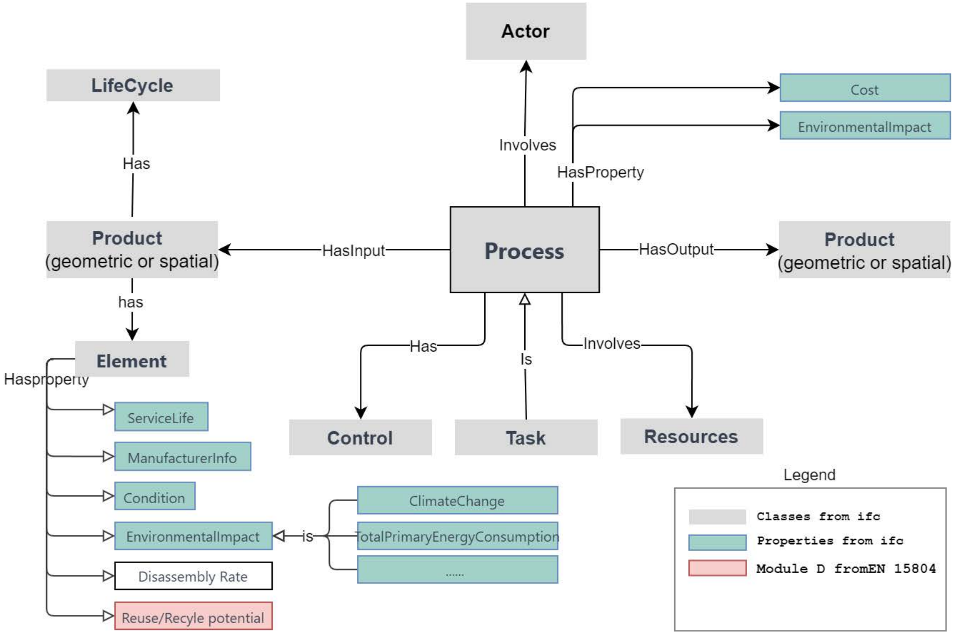

Figure 28: The relations between the main concepts

Several strategies can be adopted to add, retain, and recover value as shown in Figure 29, spanning all stages of the value chain. It's important to note that these measures are not comprehensive, and they may not be entirely separate from one another. Realizing the full potential of these actions for the transition to a circular economy might require innovative thinking.

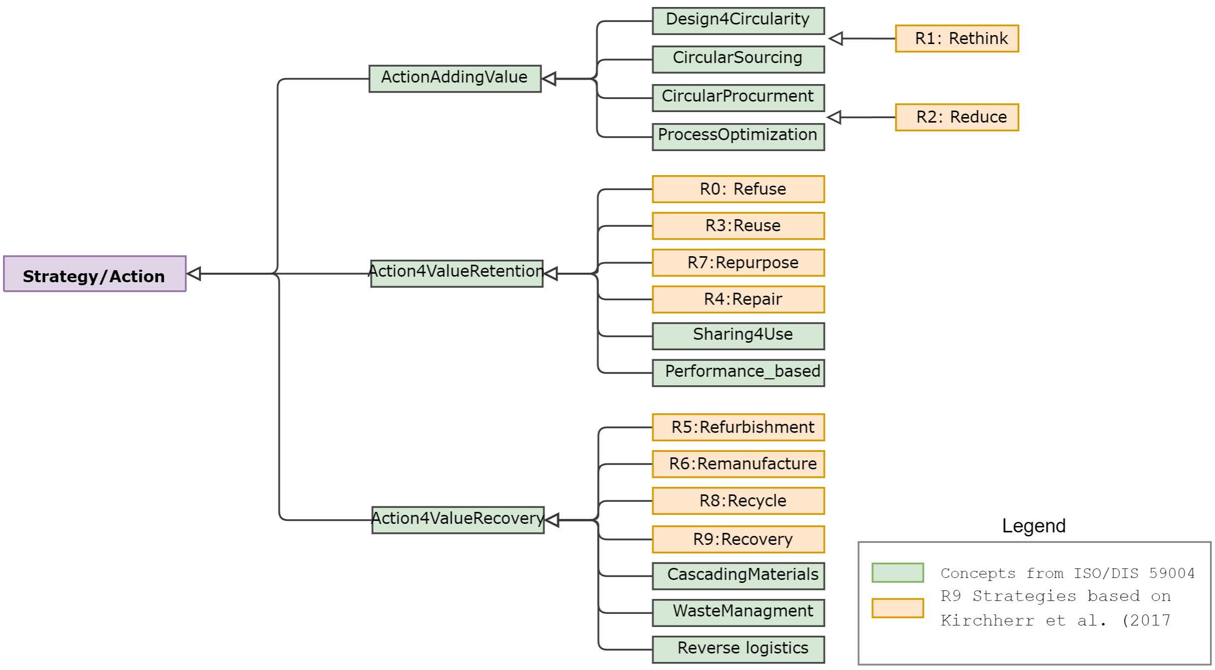

Figure 29: Categorization of actions that can be implemented for circular processes. The list is not exhaustive and can be extended

5.3.2. Mapping Concepts Between CEON and IFC

In our effort to create the higher-level ontology for the Reincarnate project using Circular Economy Ontology Network within the framework of the IFC schema, our approach is rooted in the principle of maximum reuse. As shown in Figure 30, our methodology leverages the rich set of existing concepts and entities provided by the IFC schema to map and represent CEON specific information. Our goal is to minimize redundancy and complexity by aligning CEON concepts with their closest counterparts in the IFC, only resorting to the creation of new entities when required to accurately capture CEON-related data. This strategy ensures seamless integration with existing industry standards, promotes interoperability, and simplifies knowledge representation within the built environment, while also accommodating the unique aspects of circular value networks.

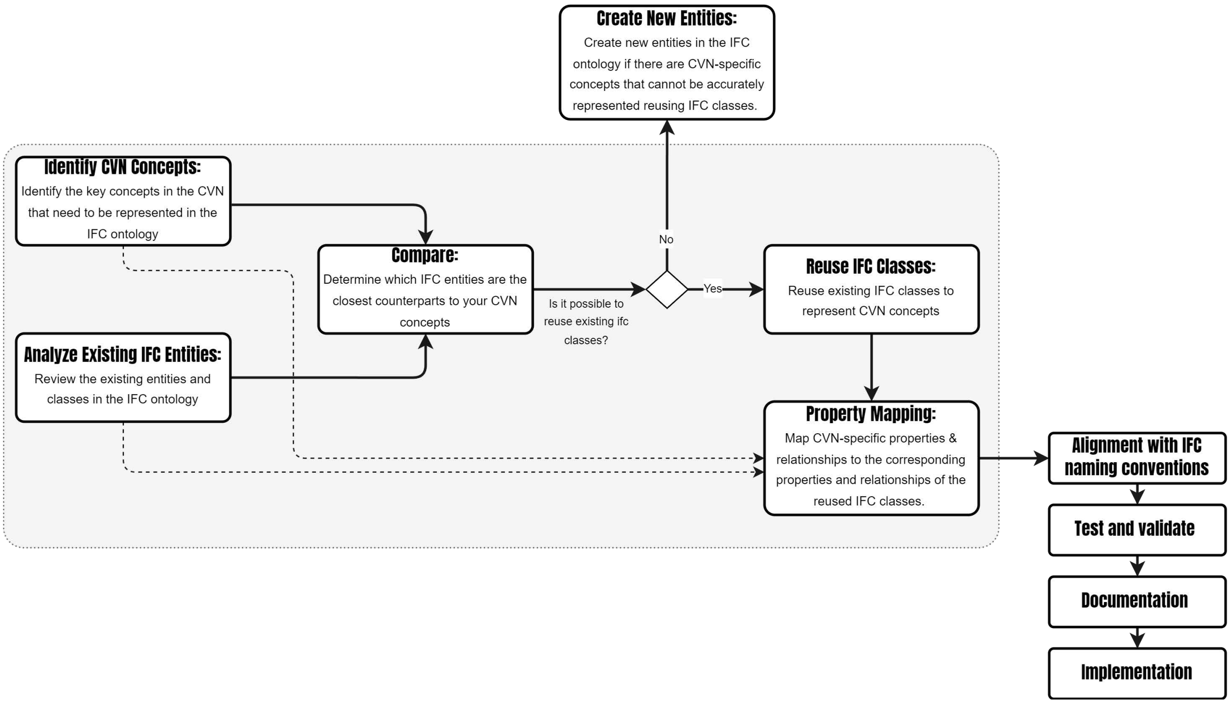

Figure 30: Required steps to map CVN specific information to their closest counterparts in IFC schema

Following the steps explained above, the suitable IFC modules are chosen as the counterparts to present the general topics covered by CEON. As presented in Figure 31, the reused IFC modules are shown with a blue rectangle and the new proposed IFC entities are shown in grey. In the next sections, we analyse two modules in detail.

Circular Value Network Module:

The Circular Value Network (CVN) module is a fundamental concept within CEON. Since we couldn't identify a direct counterpart in the existing IFC schema, we suggest the creation of a new IFC entity named IFCCVN. One practical way forward to achieve this, is cooperation with BuildingSmart International who is maintaining the IFC schema to incorporate essentials from CEON (e.g. CVN module) . This entity can extend the IFC schema and introduces essential properties to capture the essence of CVNs effectively:

- composedOf: Represents a relationship where a CVN or a process can be composed of other CVNs or processes.
- aimsAtValue: Represents a relationship where an abstract CVN configuration or concrete network aims at achieving a specific value proposition.
- implementsBlueprint and implementsStrategy: Describe relationships where a CVN instance implements a blueprint or a circular strategy.
- plansToImplementStrategy: Describes a relationship between a CVN blueprint and a circular strategy it plans to implement.

This new abstract entity, *ifcCircularStrategy*, can be tailored to include specific properties and attributes relevant to circular strategies. These attributes may encompass the strategy's name, description, goals, performance indicators, target values, relevant life cycle stages, and other pertinent details. To maintain consistency, as shown in Figure 32, we propose structuring subclasses around the established R9 strategy [30], allowing for the assignment of impact scores to each strategy. For instance, one can assign an impact score of 10 to R0 (Refuse) and 1 to R9 (Recover), indicating their respective degrees of impact. Regarding the life cycle phases, we recommend adopting the standard phases outlined in [31], which include Planning, Design, Operation, Maintenance, and End of Life.

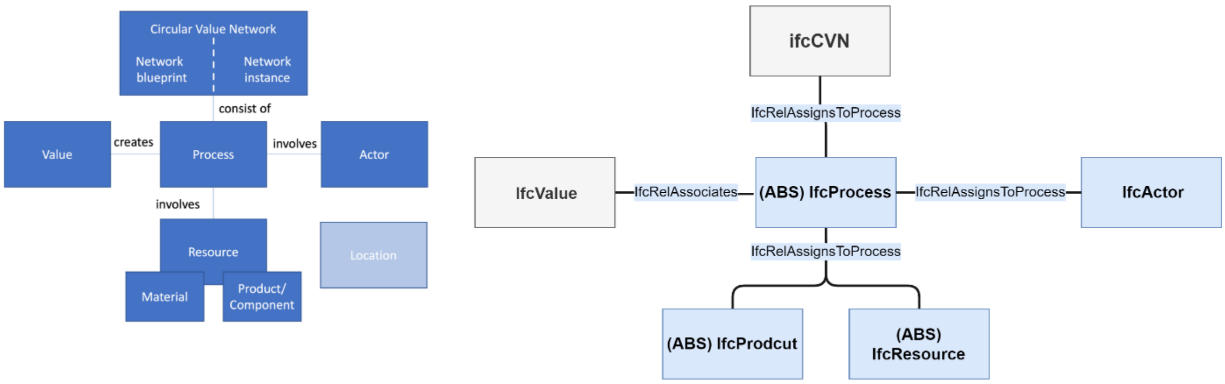

Figure 31: Left: CEON ontology modules, right: The counter parts from the IFC. Existing IFC modules are represented by blue rectangles, while proposed or additional IFC entities are shown in grey.

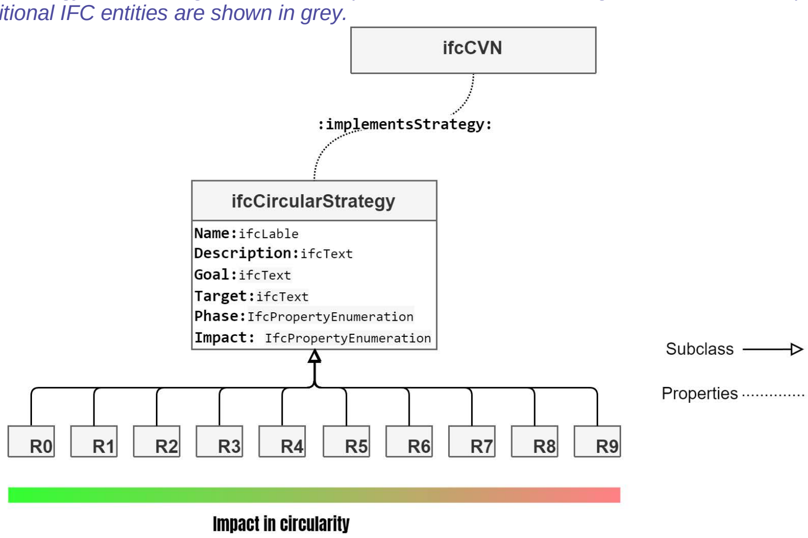

Figure 32: The proposed subclasses for Circular Strategy with an indication of their potential impact in circularity (impact score of 10 to R0 (Refuse) and 1 to R9 (Recover)

Process:

Process module plays a central role in the CEON ontology. The process classes defined in this module serve as a structured way to categorize and represent the diverse activities and operations involved in circular economy practices, making it easier to model, analyze, and manage data and knowledge related to these processes.

According to the Building Smart International, IfcProcess represents an activity or a task that occurs during the lifecycle of a construction project or building operation. It can be used to describe various types of processes, such as construction activities, maintenance tasks, inspections, or any other work process, which transforms input in output (based on the definition of According to ISO9000) and may connect to other processes through input, output relationships. An IfcProcess can be an activity (or task), or an event.

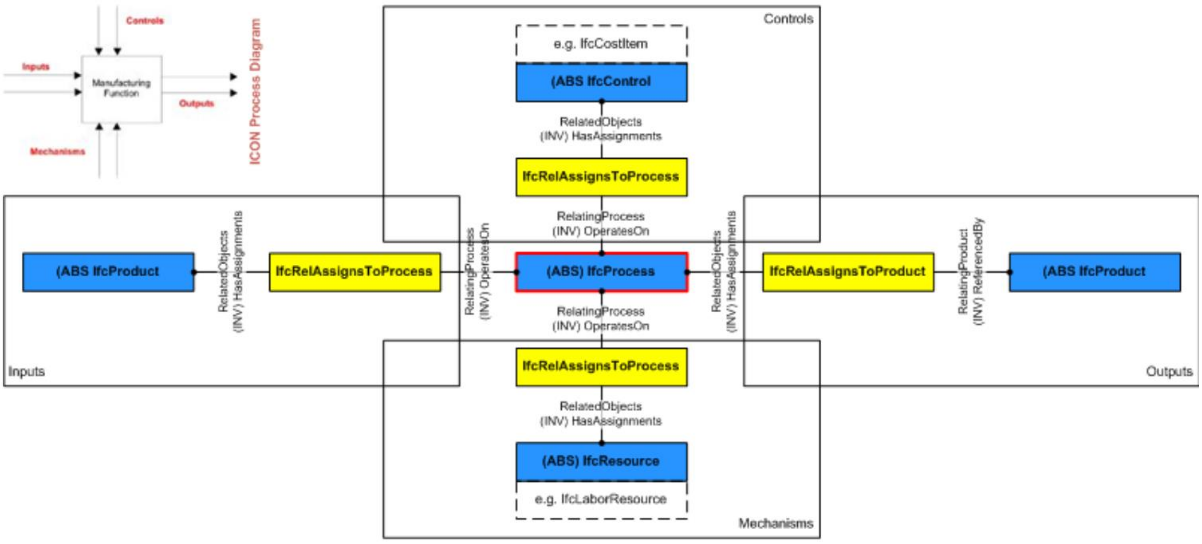

Figure 33: Process diagram as defined by BuildingSmart

The defined subclasses of the abstract IfcProcess are: IfcEvent, IfcProcedure, and IfcTask. The superclass IfcProcess or its subclasses such as IfcTask class are a general-purpose class for representing tasks or activities within a building or construction project. While it can be used to model various types of tasks, including those related to circularity and sustainability, it's important to note that the IFC schema does not provide specific attributes or properties tailored to circularity tasks out-of-the-box. To model tasks and processes related to circularity or sustainability within an IFC-based information model, we suggest using IfcTypeTask as a basis for modeling different tasks (e.g. recycling task) and then use IfcTypeObject to define specific attributes and characteristics for each type of task as explained below:

Create Custom Task:

Use `IfcTypeTask` instances to represent different types of tasks (e.g. from those specified in CEON Tranformation subclasses (Figure 16). These custom types allow to specify specific attributes and characteristics unique to each type of task.

- Create Custom Properties:

Use `IfcPropertySet` to define custom properties or attributes that capture relevant information.

- Assign Properties to the Type

Use `IfcRelDefinesByType` to link the object type definition with the object occurrence. Both may define properties by assigning an IfcPropertySet, including one or many subtypes of IfcProperty to either the object type or object occurrence (Figure 34)

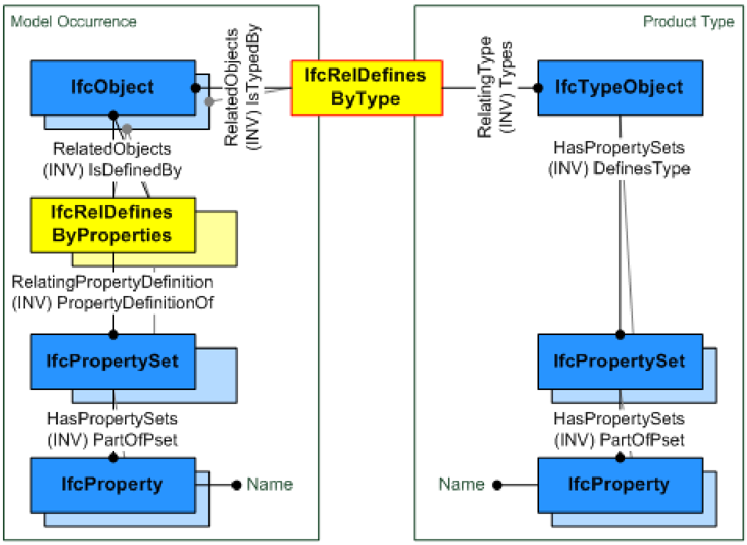

Figure 34: The relation between IFCTypeObject and IIFCObject

Subsequently, in the following chapters, we will present two detailed use cases involving the recycling of windows and concrete. These examples showcase how the IFC schema can be effectively leveraged to construct knowledge graphs and capture the intricate data necessary for informed circular decision-making processes. Using our propsed approach, other use cases can be specified. The primary objective of examining these use cases in detail is twofold: firstly, to ascertain whether the proposed higher-level ontology effectively encompasses the key aspects inherent to this specific domain; and secondly, to assess the feasibility of mapping essential information using the IFC schema within a BIM model. These exercises serve as a critical validation of the broader Reincarnate ontology's applicability and also explores the potential synergy between ontology-driven knowledge representation and the practical implementation of recycling processes within the context of BIM.

5.4. Flat Glass Reincarnation

The construction sector has historically been a prolific generator of construction and demolition (C&D) waste materials. In recent years, there has been a noticeable shift towards sustainable building practices and innovation methods. One noteworthy change is the increasing adoption of sustainable demolition and renovation techniques, potentially leading to more flat glass being separated at its source for recycling [32]. Flat glass typically follows a linear life cycle (Figure 35) and its recyclability potential is not yet fully exploited due to the challenges of collecting it and the quality compatibility challanges with a float furnace[12]. As the drive toward recycling gains momentum, a critical need arises for a structured and efficient approach to managing the diverse array of glass materials generated by construction and renovation activities. This is where the development of an ontology for recycling windows becomes beneficial as it can play an important role in enhancing the sustainable management of glass resources and information.

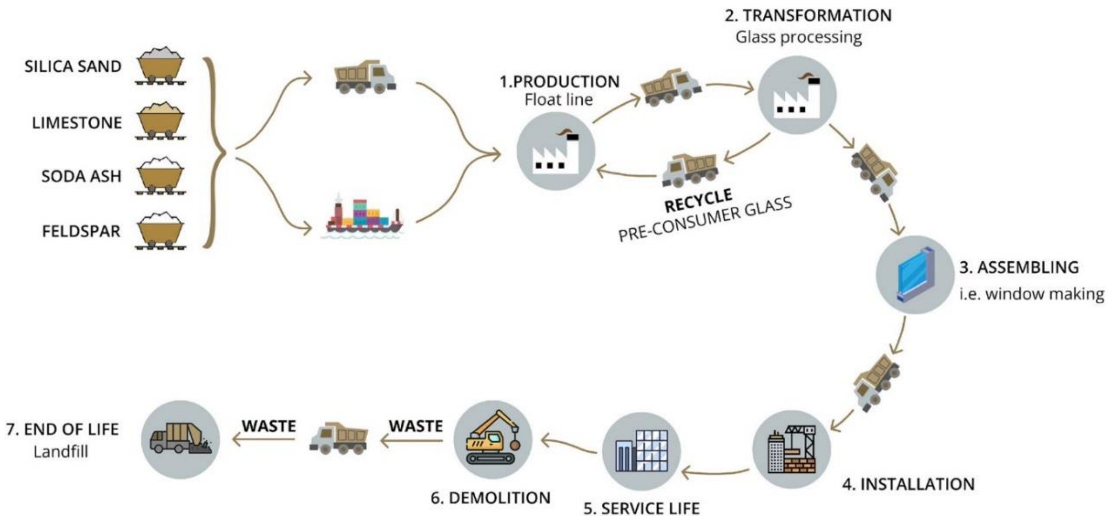

Figure 35: Linear life cycle of flat glass [33]

While the idea of re-using windows is undeniably attractive from an environmental perspective, it often presents practical challenges. These challenges include compatibility issues, energy efficiency concerns, requirements related to building codes and regulatory compliance, liability as well as high costs for installation, labour, separation processes, and processes to ensure the extension of the service life, to name a few. Without such processes in place, the recycling scenario, at the end-of-life cycle, may hold the greatest environmental benefit [40].

Even though, there is ongoing research dedicated for re-using windows (e.g. Ecomatters[13]), the abovementioned challenges have led us to place a primary focus on

[12] See initiatives such as https://www.agc-flattoflat.eu/ (Flat to Flat, a project of AGG Glass of Europe)
[13] https://www.ecomatters.nl/news/will-you-have-circular-windows/

flat glass recycling as a more feasible and scalable solution within the construction industry. The process of developing the ontology for recycling flat glass has been performed in close collaboration with our industrial partner Ragn-Sells. Additionally, while acknowledging the challenges in reuse, we expanded our data requirements to cover scenarios where windows are re-used, incorporating insights from experts at 3L Architekten. The proposed classification supports both usecases.

5.4.1. The Importance of Recycling Flat Glass

Glass is one of the most essential and commonly used materials around the globe. Glass is a sustainable, fully recyclable material which provides great environmental benefits such as contributing to mitigating climate change and saving precious natural resources [34]. After the end use, the waste glass can be screened, sorted and re-melted for the manufacture of new glass products. However, the impurities, multiple type, colour, and lack of screening facilities make barriers to this recovery of the material, and so they usually end up in stockpiles or landfills [35]. The **recycling of glass into new glass products** offers a multitude of benefits, making it a crucial effort within the broader context of sustainability and circular economy principles.

Resource Conservation: Glass is predominantly composed of natural resources such as sand, soda ash, and limestone, all of which are finite resources [36]. Flat glass is produced by the float process, which is classified as an energy intensive industry: 1.2 kg of raw materials produce 1 kg of glass and the corresponding GWP is 1.13 kg CO2-eq due to the manufacturing process, raw material supply and energy consumption [33] . By recycling glass, we conserve these valuable raw materials, reducing the environmental impact associated with their extraction. Recycled glass can be substituted for up to 95% of the raw materials used in the manufacturing process [37].

Energy Savings: The production of glass from raw materials is an energy-intensive process. Recycling glass consumes considerably less energy, lowering greenhouse gas emissions and mitigating climate change (direct energy savings; an increase of 10% cullets by weight leads to an improved energy efficiency of 2.5–3%) [38].

Waste Reduction: Waste glass constitutes a significant proportion of solid waste, the disposal of which is a recognised global problem. Glass is non-biodegradable material and it takes one million years to break down, and its presence in landfills consumes significant space[39]. The estimated volume of landfilled glass worldwide is about 200 million tons per year with very low recycling rate [40]

Preservation of Quality: Glass, unlike some other recyclable materials, can be recycled almost infinitely without loss of quality or purity (if it avoids contamination, including food-waste contamination or cross-colour contamination). It retains its integrity, making it a prime candidate for reincarnation [36].

5.4.2. Flat Glass Recycling Flow

Numerous workshops and interviews were carried out in collaboration with experts from recycling company (Ragn_Sells) to further explore and expand upon the identified use case for flat glass recycling. The primary objective was to comprehensively map the flow of information (Figure 36) within this use case identifying the different actors involved, understand the various processes at play, and determine the minimum data requirements for few critical steps.

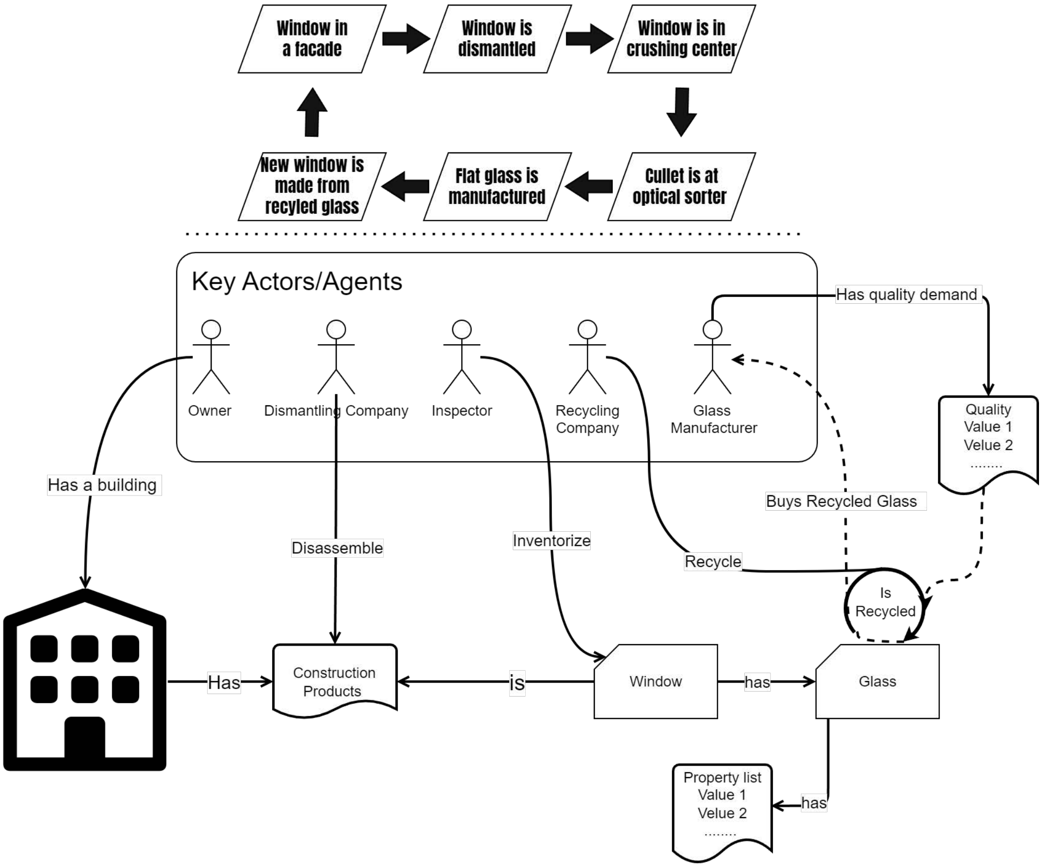

Figure 36: Recycling flat glass stages

As illustrated in Figure 36, the information flow within the flat glass recycling process encompasses several key stages and involves a range of actors, starting from the initial collection phase through processing and ultimately to the reuse or recycling phase. Table 3, maps the actions into four distinct categories of Process, Actor, Input and Output:

Table 3: Key stages in the flat glass recycling

Actions	Actor	Input	Output
1. Window in the Facade	▪ Investors ▪ Property owners ▪ Inspector/ Inventory auditor	▪ Building ▪ BIM model	▪ Decision on reuse, recycle or downcycle ▪ Inventory list of possible material bank (Information about the existing windows, such as dimensions, type of glass, operation type, age, location within the building, the volume of glass, CO2-saving potential, asbestos/ PCB in the window putty[14]
2. Window Dismantling (including sorting, packaging, and transport)	▪ Demolition Company or ▪ Renovation Company	▪ Details about the removal process, including the condition of the glass, and contaminants	▪ Dismantling method based on the decision in step 1 and the purpose (renovation or demolition) ▪ Number of packing for successfully dismantled ones ▪ Detailed inventory and deviation list ▪ Transportation to crushing centre at recycler
3. Window at the Crushing Center	▪ Recycling Company	▪ Supplier quality demand? ▪ Information about the existing windows, such as dimensions, type of glass, operation type, ▪ Volume of glass received ▪ Glass quality assessment	▪ Separated frames ▪ Packing of cullets ▪ Waste generation
4. Cullet at optical Center	▪ Recycling Company	▪ Supplier quality demand? ▪ Cullet quality	▪ Sorted cullet ▪ EoW (End of Waste) When waste becomes a raw material
5. Float glass Manufacturing	▪ Manufacturing Company	▪ Norms and standards ▪ Supplier quality demand?	▪ Float glass
6. Window Manufacturing	▪ Window Producer	▪ Glass with high amount of recycled glass	▪ Windows with low CO2-footprint

[14] It is a pliable material that is applied around the edges of a window to fill any gaps or holes between the window frame and the glass.

The questions and discussions with experts from Ragn_Sellss have led to the identification of key concepts, including "Actor," "Value," "Process," "Information," “Energy”, "Product, Components and Material" (Figure 37). These concepts were aligned with our proposed higher-level Reincarnate ontology, validating that its proposed modules effectively encompass the fundamental concepts inherent to this specific domain.

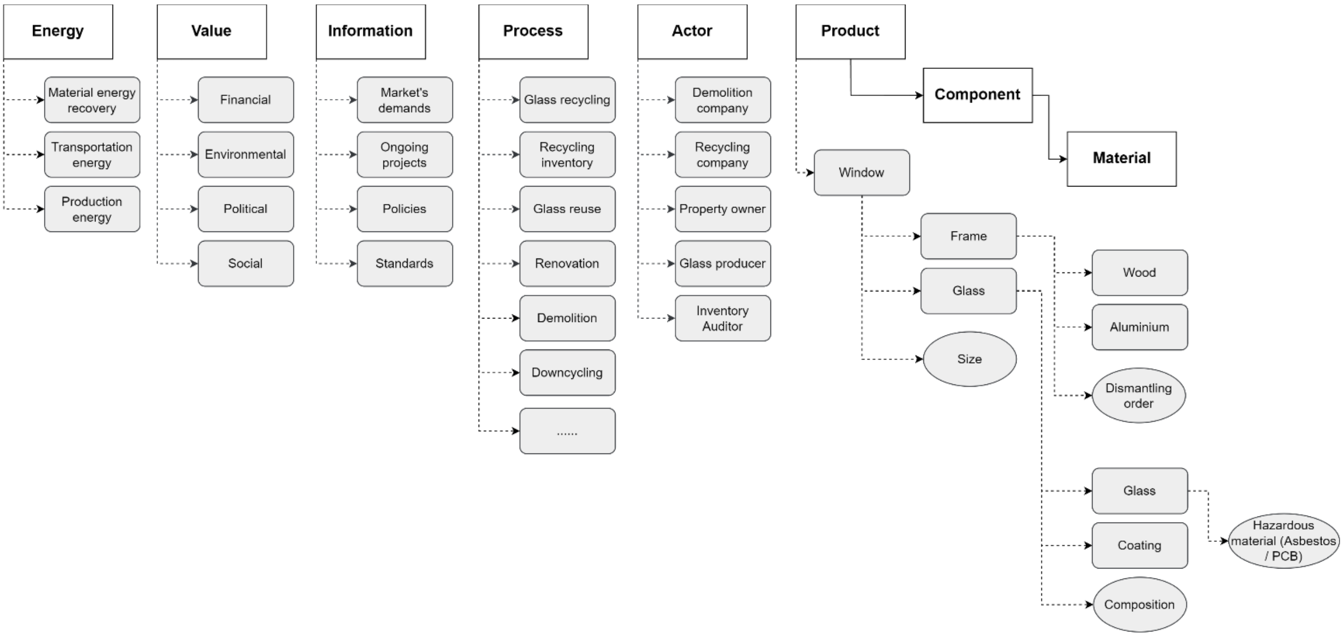

Figure 37: Taxonomy of the key identified concepts for the process of recycling flat glass

After identifying the key concepts essential for flat glass recycling and confirming their alignment with the proposed higher-level, we proceeded to map the relationships between the main concepts of different phases as shown in Figure 38. The interrelation-mapping allowed us to understand the follow of information between the main stakeholders and ascertain the data requirements from the perspective of recycling company. In consultation with industry experts from the field, we highlighted the benefits of a circular information management platform in two keyways: firstly, acting as a central hub for registering demands and the available projects facilitating better connections among the key actors. Secondly it can serve as a tool for decision making process of a glass recycling company. Normally, their decisions about different scenarios of end-life treatments, involve **conditional** statements. For example, $if < laminated\ glass > \rightarrow < downcycling >$ or $if < wired\ glass > \rightarrow < landfill >$. Many of these hypotheses are related to window properties and so leveraging the IFC schema, we structured the required data based on these findings.

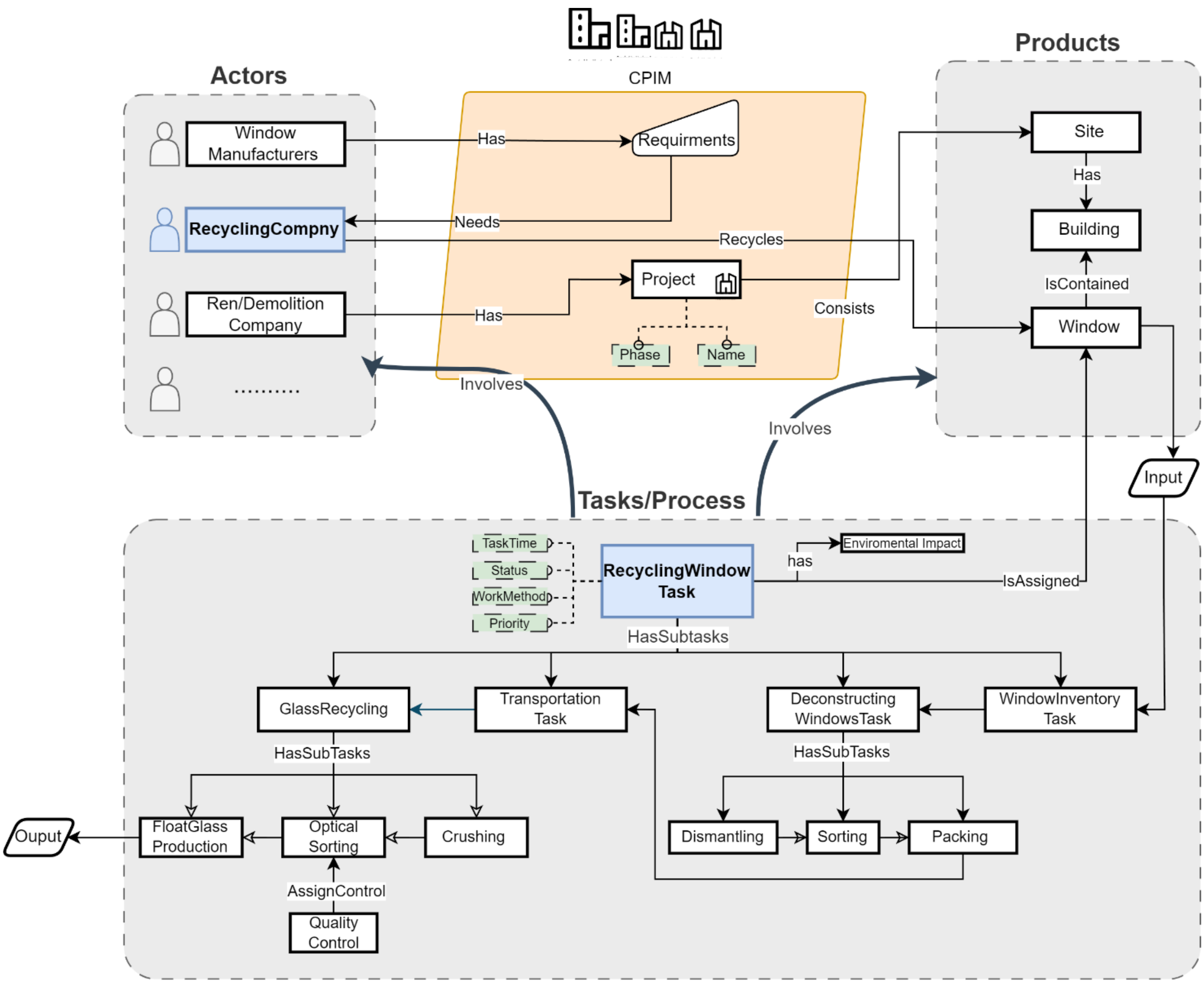

Figure 38: The inter-relations between the main concepts`

5.4.3. Utilization of IFC Schema for Data Capturing

To illustrate the implementation of our proposed methodology (as depicted in Figure 30), we have focused on identifying the essential data needed by recycling company from the “product” module (indicated in Figure 38). This concentrated effort aims to enhance their decision-making processes towards an increased recycling flat glass i.e. processes to recover the flat glass that could fulfil the function of primary material in the next material cycle.

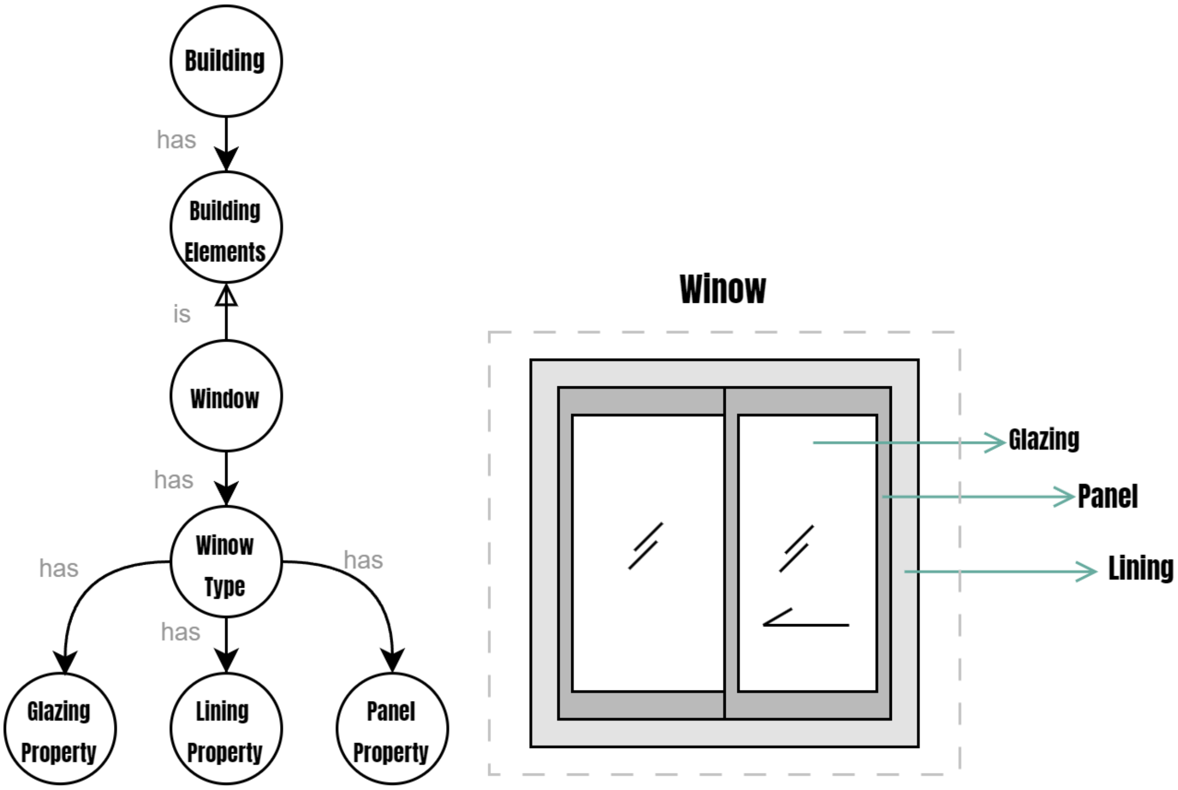

Figure 39:Illustration of IfcWindow and IfcWindowType

As shown in Figure 39, according to the IFC schema, window is composed of glazing, panel and lining. The window lining is the frame which enables the window to be fixed in position. A window panel is a casement, that is, a component, fixed or opening, consisting essentially of a frame and the infilling. The infilling of a window panel is normally glazing. The element type *IfcWindowType* defines commonly shared information:

- common properties within shared property sets
- common material information
- common partitioning of panels
- common operation types of panels
- common shape representations

Through a series of workshops with experts from Ragn_Sells, we pinpointed the crucial properties necessary for informed decision-making. These properties were organized in alignment with the existing *IfcWindow* definition. Subsequently, as depicted in Figure 40, we examined the property set definitions unique to *IfcElement* within the IFC release, identified which of these properties were imperative for window recycling and reuse to create a blueprint.

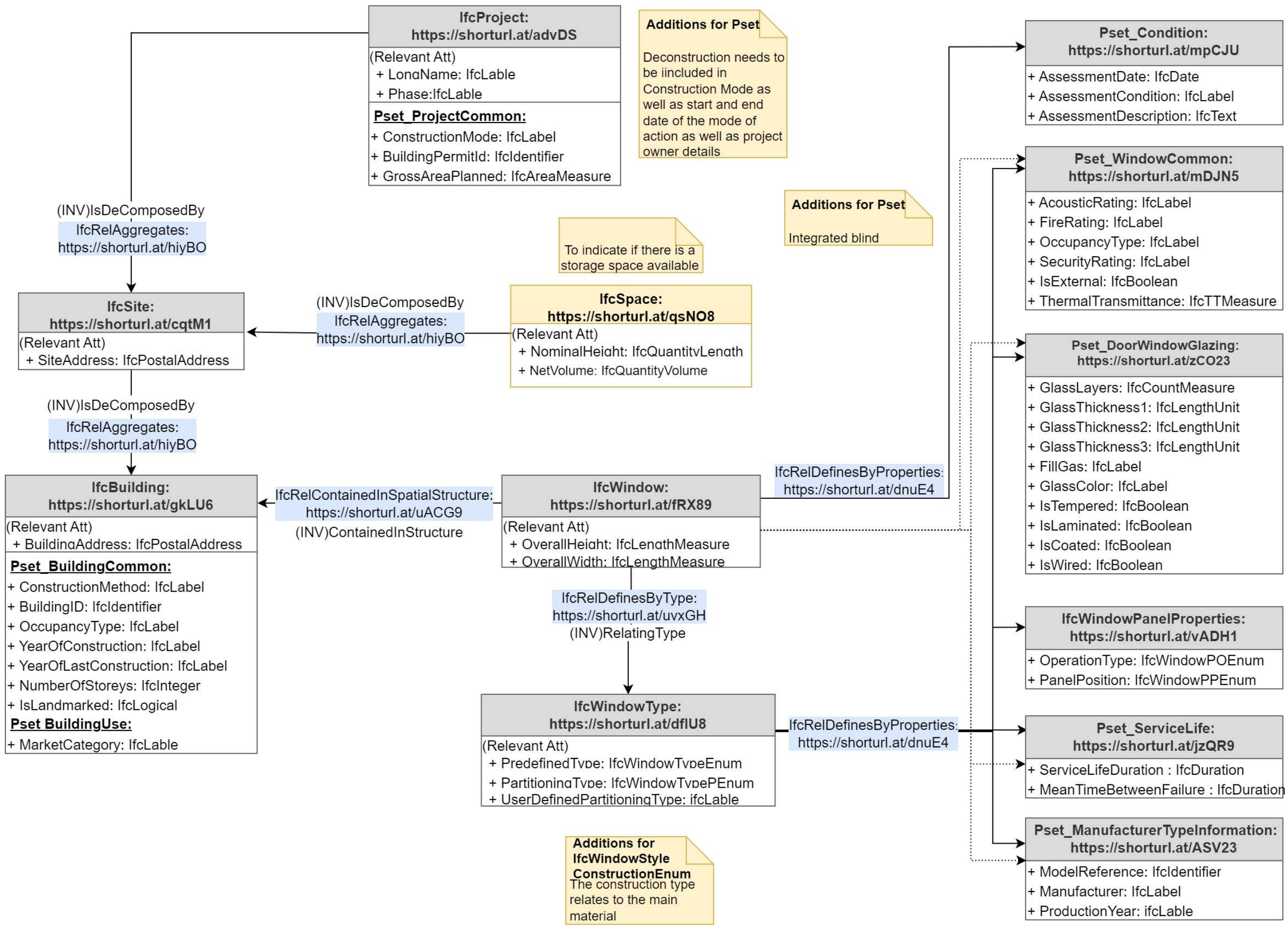

Figure 40: Mapping recycling data requirements using IFC specification

In most cases, the existing properties and attributes sufficed to meet our requirements. However, in a very few instances, we encountered a lack of existing attributes. Even though it is possible to define a custom property sets to encompass any user defined properties, we suggest including such attributes in the property sets that are part of standard IFC schema for better interoperability.

Property sets (Pset_XxxxXxxx) are used to assign groups of individual data fields, or properties, to IFC entities. Property sets can be very specific to an IFC entity, such as *Pset_WallCommon* to *IfcWall*, or more generally applied to any IFC entity, such as *Pset_ManufacturerTypeInformation*. Some property sets and their values are explicitly predefined and listed in the IFC specification; the naming convention *Pset_Xxx* applies to these officially specified property sets.

- *Pset_ProjectCommon*: We suggest including the provisional start and end dates of the project, as this will provide valuable information about when the windows can be disassembled. Regarding the *Construction Model* property, we recommend using a more generic name that encompasses demolition and deconstruction projects as well.

Table 4:Additional properties for ProjectCommon

Name	Property Type	Data Type	Definition
ScheduleStart	IfcPropertySingleValue	IfcDateTime	The date on which the project is scheduled to be started
ScheduleFinish	IfcPropertySingleValue	IfcDateTime	The date on which the project is scheduled to be finished

- *IfcWindowType*: We recommend adding the main material, as suggested below. This addition can provide valuable information for gaining an overview of the different types.

```
TYPE IfcWindowTypeMaterialEnum = ENUMERATION OF
        (ALUMINIUM,
        HIGH_GRADE_STEEL,
        STEEL,s
        WOOD,
        ALUMINIUM_WOOD,
        PLASTIC,
        OTHER_CONSTRUCTION,
        NOTDEFINED);
END_TYPE;
```

- *Pset_DoorWindowGlazingType:* During our investigation, we realized that the existence of three additional attributes is important regarding the end-of-life destination of glass. Therefore, we suggest adding them to the list of parameters.

Table 5: Additional properties for WindowGlazingType

Name	Property Type	Data Type	Definition
IsFilmmed	IfcPropertySingleValue	IfcPositiveLengthMeasure	Indication whether the glass includes a film or not as well as the thickness. If empty, then it is none. The film might be included for different purposes such as for privacy, safety or solar control
IsEnamelled	IfcPropertySingleValue	IfcBoolean	Indication whether the glass has porcelain enamel and fired fuse (TRUE) or not (FALSE).
IsPatterned	IfcPropertySingleValue	IfcBoolean	Indication whether the glass has been etched, sandblasted, or otherwise treated to create a specific pattern design on its surface (TRUE) or not (FALSE).

- *Pset_WindowCommon:* We suggest the addition of blinds in the property set as its existence has implication for the end-of-life scenario. Additionally, the form of installation will determine the dismantling processes and so is an important factor to be included.

Table 6:Additional Property for WindowCommon

Name	Property Type	Data Type	Definition
IntegratedBlind	IfcPropertySingleValue	IfcBoolean	Indication whether the there is Venetian blinds in between two panes (TRUE) or not (FALSE).
InstalledFromInside	IfcPropertySingleValue	IfcBoolean	
InstalledFromOutside	IfcPropertySingleValue	IfcBoolean	
~~FillGas~~ IsIGU?	IfcPropertySingleValue	IfcBoolean	To indidicate whether the unit is sealed (True) or not (False). This can be either gas or air

Additionally, we suggest replacing *FillGas* with insulated glazing unit (IGU). IGU units consists of two (or sometimes more) panes of glass separated by spacer material and sealed together at the edge. In this case the gap is filled by gas or air.

At the same time, building upon on the other pillar of knowledge representation namely "logic", we formulated **decision-making rules** in logical statements, as illustrated below. In Implementation section, we will showcase how these rules can be integrated into the platform, enabling rapid queries from an IFC file.

Table 7: The inference rules table for flat glass recycling

Inference Rules	
Let building be an IFCBuilding **Let project be an IFCProject** **Let windType be an IFCWindowType** Let Object.property denote attribute 'property' in IFCObject 'Object'	
1. If *building.* ***YearOfConstruction*** or if *windowType.****Pset_ManufacturerTypeInformation .ProductionYear***<=2001 *then "PCB is likely in the window insulating unit"* If *"PCB is likely in the window putty"* then ***Combustion Scenario***	Polychlorinated biphenyls are highly carcinogenic chemical compounds, formerly used in industrial and consumer products, whose production was banned in the United States by the Toxic Substances Control Act in 1976 and internationally by the Stockholm Convention on Persistent Organic Pollutants in 2001[15]. If CombustionScenario is observed then the glass can only be used for combustion (burning or incinerating a material, typically to release energy or dispose of waste).
2. If *building.* ***YearOfConstruction*** or if *windowType.****Pset_ManufacturerTypeInformation .ProductionYear***<=2005 *then "Asbestos" is likely in the window putty"* If *"Asbestos is likely in the window putty"* **then** ***Lanadfill Scenario***	As of 1 July 1993 individuals and businesses in the Netherlands are not allowed to use, reuse, store, sell, import, repurpose, treat or give away asbestos. In 2005 a similar ban was introduced across the entire European Union.
3. If *windowType.****PartitioningType***== *'Georgian bar' then* ***Recycling Without Downgrading Scenario***	This enumeration [PartitioningType] defines the basic configuration of the window type in terms of the number of window panels and the subdivision of the total window as shown here. It is also possible to add user defined types. This is helpful when specific types are common in a country and might have specific implication for the end life scenario. Similarly a user can indicate that it is a "connected" type of window which is common in Nordic countries.
4. If *windowType.* ***Pset_WindowCommon.IntegratedBlind*** *==True then* ***Recycling Without Downgrading Scenario***	Interstitial blinds or integrated blinds are high quality aluminum Venetian blinds in between two panes

[15] Refer to this study for measuring PCBs levels in older building

5. *If windowType.**Pset_DoorWindowGlazing.IsLaminated** ==True then **Recycling Downgrading Scenario***	Currently laminated glass is not introduced into the glass furnace. When removing the laminate it is hard to maintain the quality
6. *If windowType.**Pset_DoorWindowGlazing.IsTempered** ==True then **Recycling without Downgrading, Special Treatment scenario***	Tempered glass brakes into small pieces posing challenges to ensure quality. Thus, special treatment is needed.
7. *If windowType.**Pset_DoorWindowGlazing.IsWired** ==True then **Landfill***	It is not possible to recycled wired glass.
8. *If windowType.**Pset_DoorWindowGlazing.IsFilmmed** <= 0.25mm then **Recycling Without Downgrading Scenario;**if higher or none then **Recycling Downgrading Scenario***	A thin film can be accepted into the glass furnace but a film thicker than 0.25mm is treated as laminated glass.
9. *If windowType.**Pset_DoorWindowGlazing.GlassColor** is not null then **Recycling Downgrading Scenario***	The enamel will interfere with the quality and depending on the composition it might or might not be able to use for glass wool. If it is not possible to use for glass wool landfill is the most likely scenario.
10. *If windowType.**Pset_DoorWindowGlazing.IsEnamelled** ==True then **Recycling, Downgrading or Landfill Scenario with further assessment of Enamel composition***	The recycling, downcycling, or disposal of glass depends on the composition of the enamel. If the enamel contains heavy metals beyond a certain threshold, the glass must be sent to a landfill. However, if the enamel contains a low amount or no heavy metals, the glass can be considered for recycling with downgrading. In cases where the glass contains substances that may pose harm or become explosive during the recycling process, it is also directed to a landfill. Therefore, the choice of recycling method is contingent on the enamel's composition, and it may require destructive or other tests to confirm its content
11. *If windowType.**Pset_DoorWindowGlazing.IsPatterned** ==True then **Recycling or Downgrading Scenario***	Small quantities of patterned glass can undergo a recycling process, leading to the upcycling of the material into flat glass. However, when dealing with larger volumes, the upcycling process may not be feasible, and instead, the glass will be downgraded. The decision between upcycling and downgrading is contingent on the volume at hand, necessitating case-by-case evaluation.

5.5. Concrete Reincarnation

5.5.1. The Importance of Recycling Concrete

Concrete is the most widely used material worldwide, yet a substantial portion of it is often landfilled or downcycled as road-base filler in Europe [41]. Improper disposal of concrete poses a significant environmental threat as it has evolved into a global environmental risk. Concrete waste is not perceived a valuable resource by contractors, leading them to opt for landfill over recycling.

In addition to the significant CO2 emissions associated with cement production, a large amount of natural aggregates (NA) are extracted every year. This number was 32 bi tons/year on 2022 [42]. Therefore, using recycled aggregates (RA) from C&DW, can have a substantial positive impact.

The main challenges to concrete recycling can be categorized to four groups [43]:

- Lack of regulation and knowledge
- Low demand for recycled concrete
- Practical challenges, such as lack of sufficient on-site space, and
- Increased costs such as transportation costs

In addition to the aforementioned challenges, and as an input from the project's consortium partners, it is highlighted that the current recycling or reusing practices predominantly occur at a local level, often lacking available markets for material exchange. Moreover, in the analysed cases, lack of digitized processes could be identified.

5.5.2. Recycling Concrete Data Flow

The practical and tacit knowledge held by experts is important sources of knowhow in this field. The primary objective of this task is to capture such knowledge and develop ontologies to encapsulate these practices. These ontologies can then serve as a foundation for digitizing the processes in these practices, ultimately facilitating towards a circular built environment.

Next to the glass recycling, as the first analysed circular value stream in this task, we have investigated a few use cases in the value stream of recycling concrete. The use cases are described as follows.

Use case: concrete delivery ticket - CEMEX

The first use case within the context of concrete recycling, relates to digital concrete delivery tickets. A concrete delivery ticket is a document provided upon the completion of concrete delivery during the construction phase of a project. It contains specific details about the supplied concrete. Certain elements of this information can be useful at the end of a building's lifecycle when considering recycling. Therefore, storing this information in the model can facilitate the exploitation of this circular value. As a result, the primary objective of this use case is to seamlessly integrate this information into the building model.

To achieve this, a comprehensive analysis of the information from the delivery tickets was undertaken, involving discussions with experts from CEMEX. This process aimed to identify the specific information that needs to be imported into the Building Information Model (BIM). To facilitate this integration, an ontology has been developed, which is elaborated upon in the subsequent section.

Use case: recycling aggregates – CEMEX

The second use case relates to the process of recycling aggregates from C&DW for using in new concrete production. The recycling company, CEMEX, purchases aggregates from the demolition companies. The purchases are based on the new concrete's use type and required specifications. In other words, the recycling company, requires information from the demolition company to establish a connection between the quality of the purchased aggregates and the producer's requirements for new concrete manufacturing.

As shown in Figure 41, the information and material flow can be categorized among three main stakeholders: demolition company, recycling company, and the client/ customer of the concrete. As described by CEMEX, their process is project-oriented, implying that the requirements for new concrete come from a specific customer, and the aggregates (for recycling) can be purchased from demolition companies, although not through a centralized marketplace, but rather on a building basis as they undergo demolition. Therefore, the recycling company should match the requirements of new concrete based on the required quality of the client, to the suitable aggregate for recycling. However, the recycling company encounters challenges since the complete information from the demolition companies is not completely available to them, necessitating the recycling company to conduct their own laboratory tests on the aggregates. Analysing the process within CEMEX organization, a potential solution to this issue could involve the establishment of a marketplace for information exchange between demolition companies and recycling companies, where the former can provide the specifications of the available aggregates, and the latter can purchase them based on their own requirements.

Another critical aspect of this process involves the process of selective demolition. The demolition companies conduct an inventory of the building, and subsequently a selective demolition plan is formulated. On the other hand, the quality of the crushed aggregate is influenced by the proportion of the different construction materials within it, including concrete, bricks, wood, etc. For instance, a higher proportion of bricks in the aggregate, can lead to higher water ratio in the new concrete. Therefore, an additional approach to streamline the aggregate recycling process is to extract the information about the building materials, or specific parts for selective demolition, from a BIM. This would enable the demolition company to provide this information to the recycling company. In fewer cases, the process can also be reversed, so that the demolition company plans the selective demolition based on the requirements of the recycling company, and to include the correct proportion of different materials in the final provided aggregate.

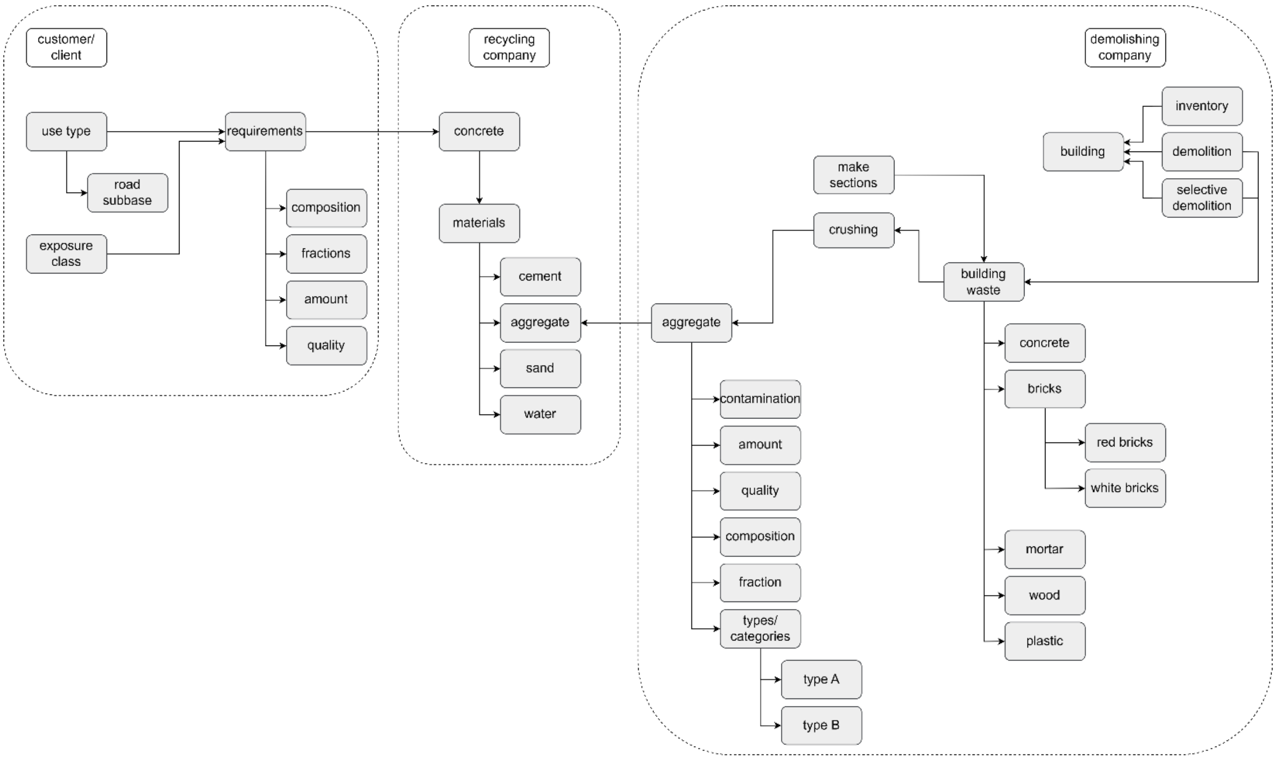

Figure 41: Notions of use case recycling aggregates

In the following sections we demonstrate how IFC can be utilized to capture the required information for the described use cases.

5.5.3. Utilization of IFC Schema for Data Capturing

Use case: concrete delivery ticket - CEMEX

To integrate the information from the delivery tickets into the building models, the main following questions should be addressed:

- Which information are required to be imported from the delivery ticket into the model?
- Where should this information be stored in the model?

The first question was addressed by the experts from CEMEX and MOW, focusing on essential relevant information. The second question, was addressed through the implementation of an ontology, leveraging the existing IFC framework. The initial step is to identify the key notions, and subsequently mapping these concepts to appropriate IFC entities. By doing so, the existing IFC classes are identified that fulfil the requirements for the use case's notions. The following step entails pinpointing the attributes and properties associated with these classes along with their relationships. The last step is to identify the gaps and expand the ontology accordingly. Figure 42 shows the identified notions, divided into three categories of project, element, and material, with the basic mapping of potential IFC classes (depicted in purple boxes) and their properties.

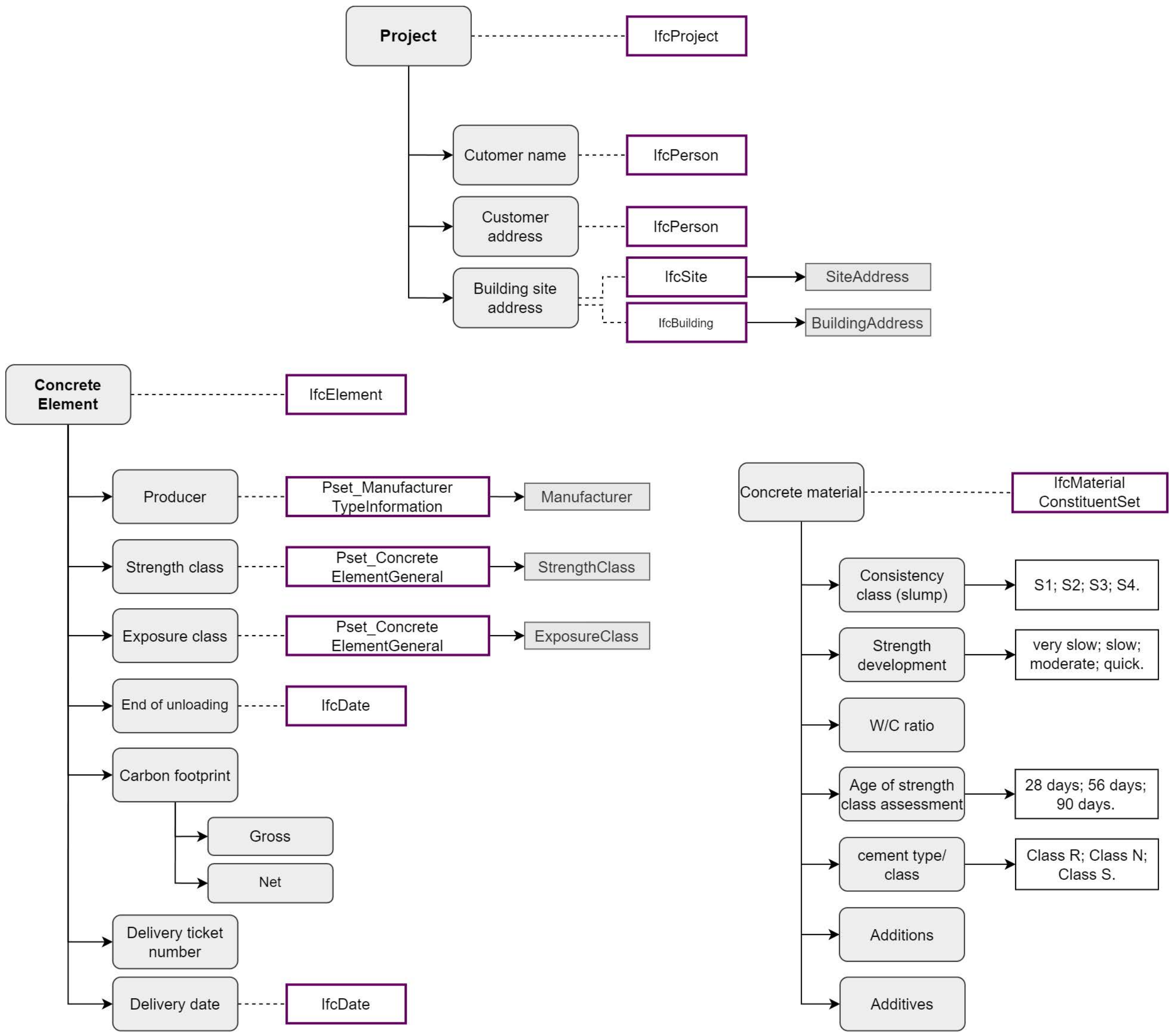

Figure 42: Main notions and IFC counterparts in purple boxes

At this stage, one key consideration is to map concrete both as an element and material within IFC. To accomplish this, the hierarchy of IfcElement, IfcMaterialContituentSet, IfcMaterialContituent, and IfcMaterial are employed. An "element" in this context refers to a physically existent object, such as walls, or floors. On the other hand, a "material constituent set" consists of individual material constituents. A typical usage of it is where a material is made up of mixture of constituents [44]. Therefore, it is well suited to represent concrete, given that concrete is as a mixture of various parts including sand, cement, aggregates, and water, as shown in Figure 43.

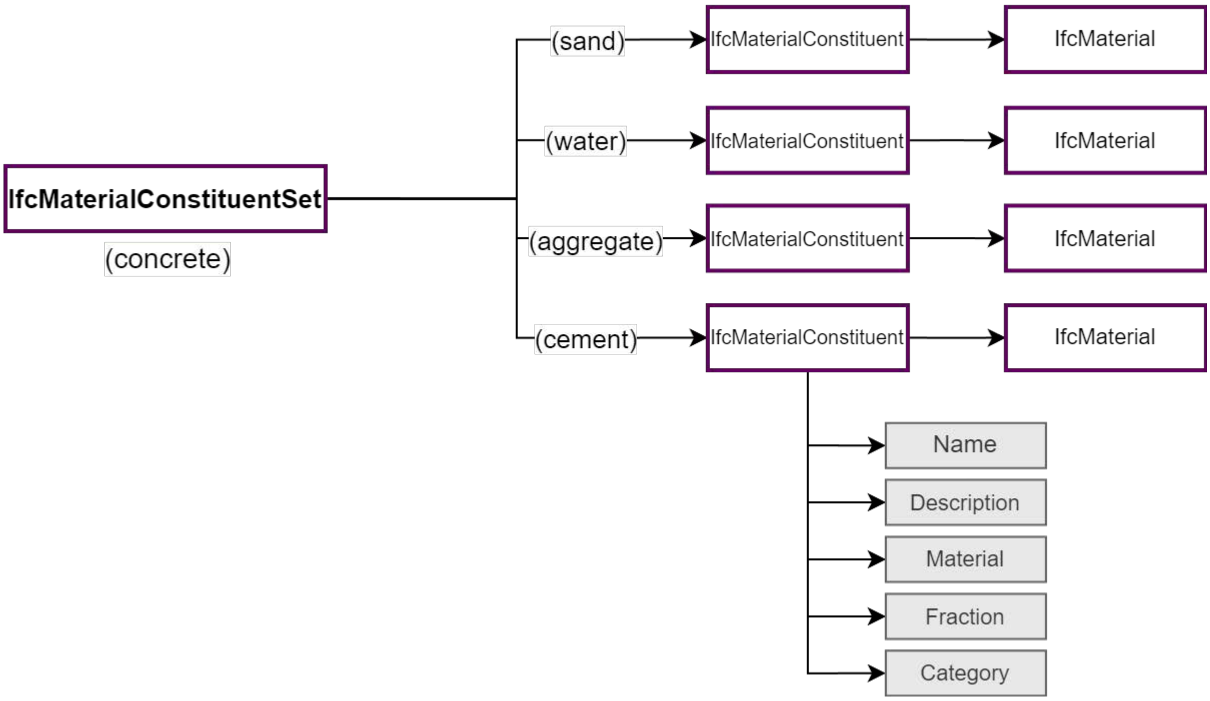

Figure 43: Concrete as IfcMaterialConstituentSet

Figure 44 shows the identified and relevant IFC classes, attributes, properties, and relationships, in addition to two new developed property sets, which are described in Table 8 and Table 9. *Pset_AdditionalConcreteProperties* is defined as a new property set with specific concrete properties, which were not addressed in IFC. An alternative approach could involve integrating these properties as an extension of an existing property set of concrete, such as *Pset_ConcreteElementGeneral*. The second property set *Pset_ConcreteDeliveryTicket* is established as a new property set with needed information of a delivery ticket This property set can be assigned to a concrete element, enabling the incorporation of key details from the ticket into the building model.

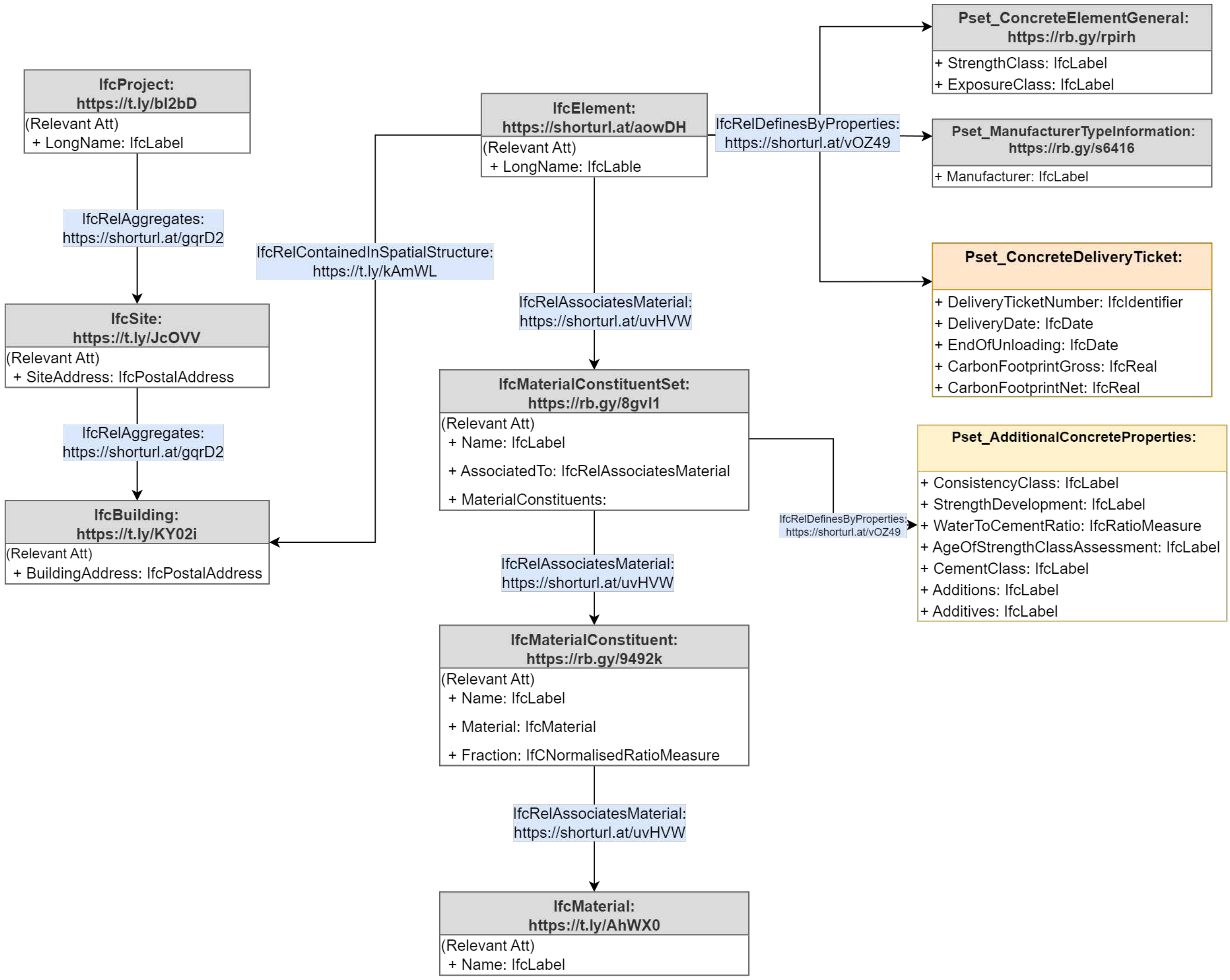

Figure 44: Concrete delivery ticket ontology

Table 8: Pset_AdditionalConcreteProperties

Name	Type	Description
DeliveryTicketNumber	P_SINGLEVALUE / IfcIdentifier	Concrete delivery ticket number
DeliveryDate	P_SINGLEVALUE / IfcDate	The date of the delivery
EndOfUnloading	P_SINGLEVALUE / IfcDate	The date of the end of unloading
CarbonFootprintGross	P_SINGLEVALUE / IfcReal	Gross equivalent CO2 with unit kg
CarbonFootprintNet	P_SINGLEVALUE / IfcReal	Gross equivalent CO2 with unit kg

Table 9 Pset_ConcreteDeliveryTicket

Name	Type	Description
ConsistencyClass	P_ENUMERATEDVALUE / IfcLabel	Slump class of the concrete; values of S1, S2, S3, or S4.
StrengthDevelopment	P_ENUMERATEDVALUE / IfcLabel	The relevant speed of strength development of the concrete, from the values: very slow, slow, moderate, or quick.
WaterToCementRatio	P_SINGLEVALUE / IfcRatioMeasure	The ratio of the mass of water to the mass of cement used in the concrete mix.
AgeOfStrengthClassAssessment	P_ENUMERATEDVALUE / IfcLabel	The age of concrete in time of Strength Class assessment, from the values: 18, 56, or 90 days.

CementClass	P_ENUMERATEDVALUE / IfcLabel	The class of cement, from the values: Class R, Class N, or Class S.
Additions	P_SINGLEVALUE / IfcLabel	List of additions
Additives	P_SINGLEVALUE / IfcLabel	List of additives

This ontology serves the dual purpose of importing information from concrete delivery tickets into a building model during the execution phase, extracting the required data from a model, when recycling concrete at the end-of-a building life cycle.

Further development stages would include automation in enriching a model with methods of reading such information potentially through mechanism such as barcoding. It's important to note that such additional functionality falls outside the current scope of this ontology.

Use case: recycling aggregates – CEMEX

In this use case, the piece of ontology for this use case is designed to enhance the availability of data regarding recycling aggregates from both sides of the supply and demand, facilitating the accurate matching between the two.

As illustrated in Figure 45, the focus is primarily on two key aspects: the requirements of the new concrete, and the specifications of aggregates derived from crushed demolition waste. Consequently, in this ontology, we will only focus on coarse recycled aggregates, rather than natural aggregates, which is produced from C&DW. As shown, the pertinent properties of both sides are identified with properties already available in IFC highlighted in purple boxes.

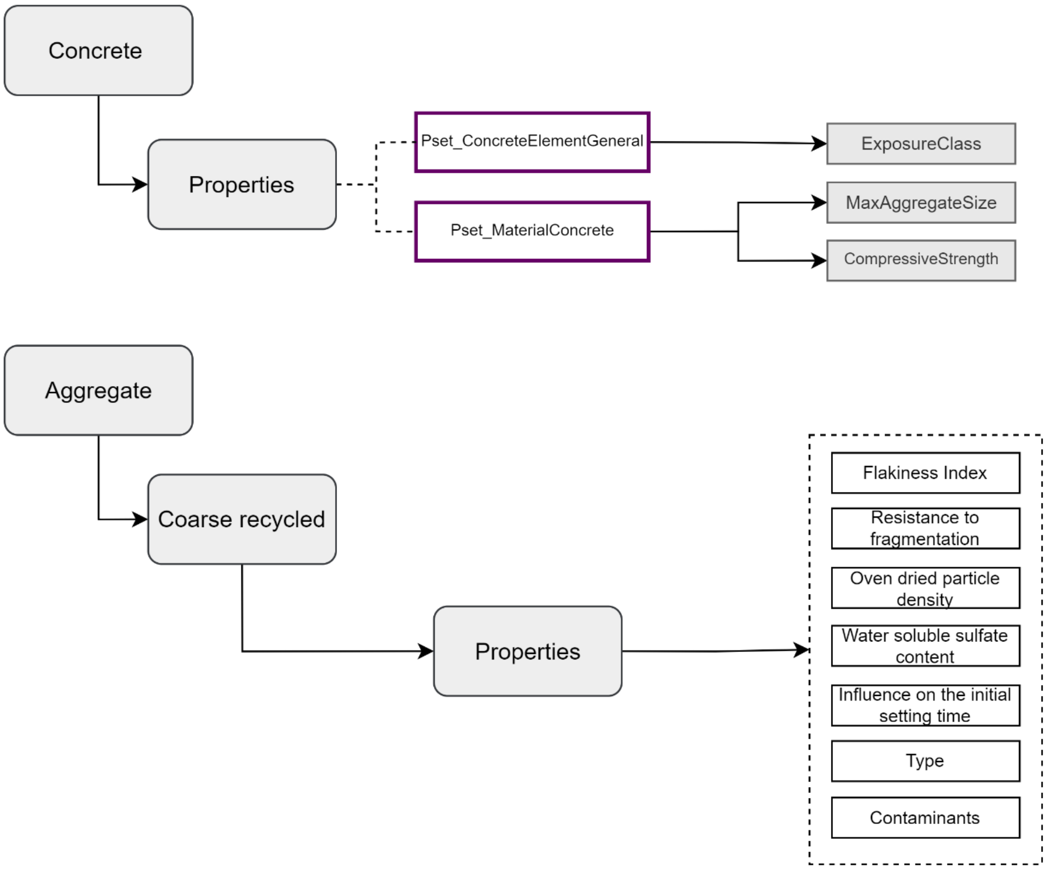

Figure 45: Notions of recycling aggregates and IFC mapping

The ultimate application of this ontology is to implement it in an online marketplace or a platform, where the recycling companies can search for available aggregates provided by demolition companies. The ontology will establish the necessary information and the relationships, to enable users to make queries from such platform.
For this to work effectively, the recycling company must possess the information about the required quality of the new concrete. Key details such as the exposure class of the concrete, can be extracted from a building model. Additional information, such as the site location, can be also extracted and utilized on the platform to identify the nearest demolition sites to the new building's location.

On the other hand, demolition companies should provide the specifications of the aggregates. Additional information regarding location and availability of the aggregates can be also provided by the demolition companies, although this information is not modelled in this ontology. As an illustration, the unit cost of the aggregate is defined as a property of the aggregate. Figure 46 presents this ontology, in two main parts: one for concrete and another for aggregates, with concrete at the top and aggregates at the bottom. An additional challenge encountered in the section 5.5.2 relates to selective demolition planning. To address this, one approach is material quantity take-off, but it is excluded from the scope of this ontology.

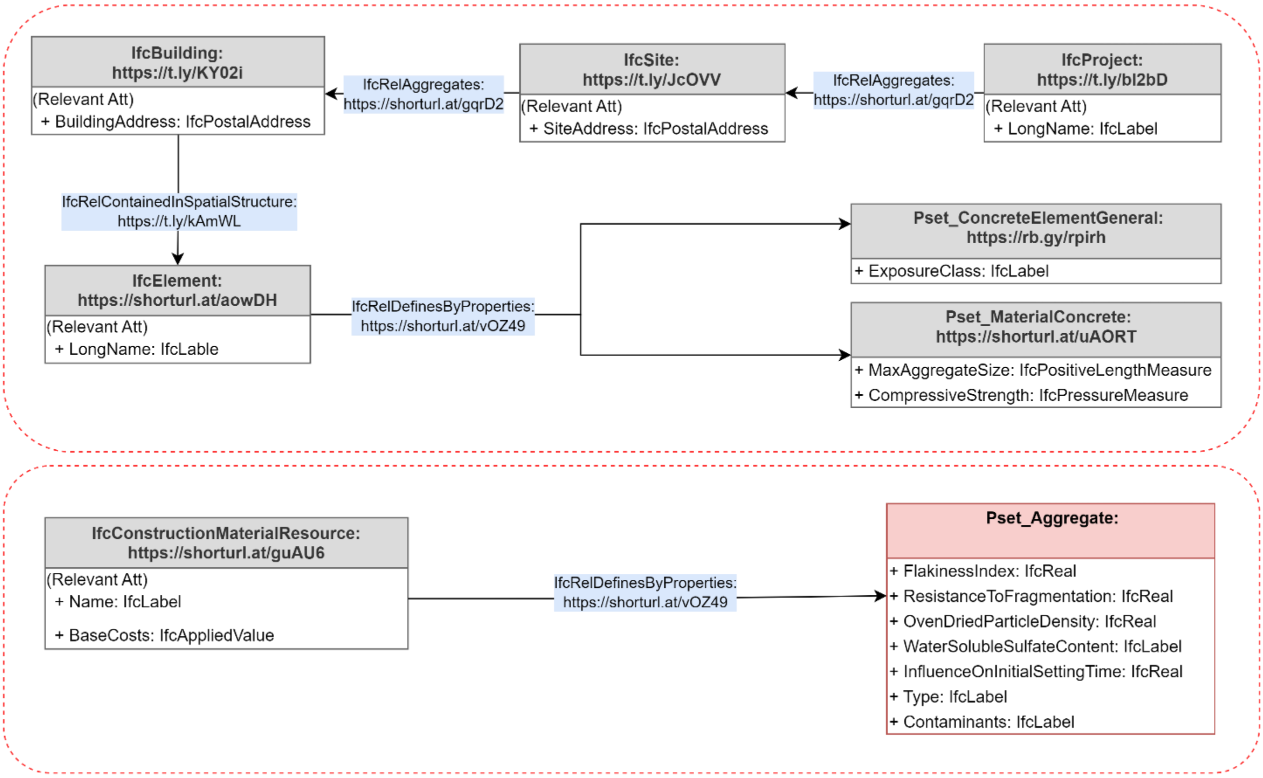

Figure 46: Recycling aggregates ontology

To conduct the relevant queries, the ontology can be augmented with rules governing the matching the two sides of supply and demand. These rules (Table 10) are based on the standard EN 206:2013+A2:2021 (Concrete - Specification, performance, production, and conformity. Two primary inference rules are anticipated to be implemented:

Compliance Rule: This rule will be used to assess whether the aggregate aligns with the recommendations for coarse recycled aggregates as outlined in EN 12620 (Appendix 1)

Replacement Percentage Rule: This rule will be employed to calculate the maximum allowable percentage of coarse aggregate replacement in new concrete. The calculation will be contingent on the type of aggregate and the exposure class of the new concrete. By applying these rules to the ontology, users will be able to query and determine the suitability of available aggregates for their specific concrete requirements.

Table 10: Inference rules for automating decision making processes

Inference Rules	

`1.`
 	
`Compliant=False`
 	
`IF (aggregate.`**`Type`**` == A) AND (`**`aggregate.FlakinessIndex`**` <= 50)`
`AND (`**`aggregate.ResistanceToFragmentation`**` <= 50) AND`
`(`**`aggregate.OvenDriedParticleDensity`**` >= 2100) AND`
`(`**`aggregate.WaterSolubleSulfateContent`**` = 0,2) AND`
	Compliance of the recycled aggregates with the recommendations of EN 12620,

(**aggregate.InfluenceOnInitialSettingTime** <= 40) THEN Compliant=True; print "aggregate is compliant to EN 12620" Else If **(**aggregate.**Type** == B) AND **(aggregate.FlakinessIndex** <= 50) AND (**aggregate.ResistanceToFragmentation** <= 50) AND (**aggregate.OvenDriedParticleDensity** >= 1700) AND **(aggregate.WaterSolubleSulfateContent** = 0,2) AND (**aggregate.InfluenceOnInitialSettingTime** <= 40) THEN Compliant=True; print "aggregate is compliant to EN 12620"	
2. IF Compliant==True IF *(aggregate.Type* == A) IF *(concrete.ExposureClass* == X0) THEN *MaxPercentageAggregate = 0.5;* ELSE IF (*concrete.ExposureClass* == XC1 OR XC2 OR XC3 Or XC4 OR XF1 OR XA1 OR XD1) THEN *MaxPercentageAggregate = 0.3;* Else *MaxPercentageAggregate = 0.0;* ELSE IF *aggregate.Type* == B IF *(concrete.CompressiveStrenghtClass* > C30/37) THEN *MaxPercentageAggregate = 0,0;* ELSE **IF** (**concrete.ExposureClass == X0**) **THEN MaxPercentageAggregate = 0,5;** **ELSE** IF (**concrete.ExposureClass == XC1 OR XC2**) **THEN MaxPercentageAggregate = 0,2;** **ELSE** **THEN MaxPercentageAggregate = 0,0**	Calculating the maximum percentage of replacement of coarse aggregates according to EN 12620.

6. Implementation

In the realm of ontology development, the Reincarnate ontology stands as a repository of formalized knowledge with potential for real-world applications. Beyond the theoretical constructs, formalized knowledge and semantic representations it encapsulates, a fundamental question emerges: how can this ontology be harnessed to enhance the automation of critical processes? This section focuses on the practical implementation and future outlook of the Reincarnate ontology, exploring its capacity to drive automation, address specific project needs, and unlock new possibilities. More specifically in this section we seek to answer the following questions:

- What purposes could the automation serve?
- Which automations serve the project needs?
- What inputs do available automations require?

6.1. Automation Purpose, Process, and Needs

The overall intent in Reincarnate is to facilitate the end-of-life extension and re-use of buildings and building components. This is most easily achieved through automation by facilitating answering questions that currently have no easily available answer. Examples of such questions, as posed through Reincarnate use cases are:

- What re-useable buildings in the portfolio best suit my needs?
- What windows in this to-be-demolished building can be upcycled or re-used?
- What is the surface area of the windows that can be recycled as flat glass?

6.1.1. Requirements for Automation

To automate the process of answering critical questions, several key components must be in place. This includes an accessible data source, a robust search engine, and machine-readable search criteria with precise semantics.

A data source, as an abstract, can be a singular service or a collection of services, warehousing, integrating or referencing data as needed. In practice, relevant data sources, such as building portfolios and architectural data are distributed across various organizations, geographical locations, and systems. More importantly, this data is structured and encoded in a variety of formats.

However, in an ideal scenario for automation data is centralized within a single repository to facilitate the development of a tailored tool. The reality of the data service landscape, does not match this ideal. A potential solution to this distributed data challenge is to encourage each system to align its data model with a common ontology or offer transformation services that enable seamless communication between systems. This approach creates an extensible framework, allowing for the inclusion of additional data sources with the same semantic connectivity. An alternative option to misaligned data sources is to create a new data source (or component) from scratch and advocating broad application of it among various stakeholders. In the design phase an ontology can be taken into consideration, resulting in an exceptionally effective alignment with the ontology and thus unlocking the various benefits this offers. However, these benefits likely do not outweigh the required investment of creating and introducing a new system (component), nor the practicality of advocating this change to a variety of stakeholders.

With regards to requiring a robust search engine, many data sources offer querying possibilities. Alignment of data sources along an ontology means individual data sources can translate ontology-based queries into supported individual formats to provide answers. As such, a plethora of robust search engines is indirectly available. However, even more attractive would be a search engine that can directly operate on the level of the ontology itself as opposed to its distributed implementations in various data sources. This would allow querying the meaning of the data directly and cut out intermediate processing and translation steps.

Finally, regardless of an automation's purpose, any automation requires the ontology to be described in a formal machine-readable language. There are many such languages available. Of particular interest are the widely used Resource Description Framework (RDF)16 and the Web Ontology Language (OWL)17 as an extension of it.

6.1.2. Reincarnate Requirements for Automation

The Reincarnate ontology is an extension of IFC Schema. The ontology IFCOWL provides an OWL representation of IFC Schema. As such many technologies and processes available for IFCOWL may apply to the Reincarnate ontology.

As an example, consider the case of a data source aligned with the Reincarnate ontology. Integrating the Reincarnate ontology with external resources that leverage additional services, such as the Semantic Web (and OWL as its supporting technology), opens the door to the utilization of existing capabilities. The Semantic Web, characterized by its set of technologies and standards, offers a broad spectrum of Internet services. This encompasses search engines, indices, and the integration of available AI, all of which enhance the functionality and value of the ontology.

While acknowledging the benefits of OWL as a powerful language for ontology representation, it may not align perfectly with the unique characteristics and goals of Reincarnate project and questions must be raised regarding the feasibility of

[16] https://www.w3.org/TR/rdf-primer/
[17] https://www.w3.org/TR/owl2-overview/

implementing such a framework. Reusing building components to promote sustainability may be more appealing when considering a local geographical context to minimize factors such as transportation-related environmental impacts. This approach may, in turn, reduce the reliance on global internet-based semantic connectivity. Moreover, the Semantic Web is most influential when dealing with freely available data. Yet, the nature of certain data sources, such as BIM models, material listings, and architectural plans, tends to be proprietary or confidential. As a result, achieving interoperability with the Semantic Web, including its supporting technology OWL, might offer limited advantages for the Reincarnate ontology. In such cases, where data ownership and privacy are paramount, the need for full-scale integration with external Semantic Web resources may not be a necessity. Nevertheless, given that the Reincarnate ontology is grounded in IFC Schema, an extension to embrace the broader capabilities of OWL and the Semantic Web remains a viable prospect for future endeavours via IFC OWL.

6.2. Developing Software from Ontology

6.2.1. Database Creation from Ontology

In the area of software development, bridging the gap between ontology and databases is an important task to allow building shareable and (re)usable data access mechanisms including automated verification and inference mechanisms for knowledge discovery. To facilitate this process, various tools and methodologies have been devised, allowing for the seamless transformation of formal ontology descriptions into relational databases [45]. These solutions often draw from established Computer-Aided Software Engineering (CASE) techniques and leverage translation through the Unified Modeling Language (UML) to create relational structures. [46]. While the direct transformation from ontology to a relational schema is a recognized approach, it is essential to acknowledge that certain challenges may arise. Most notably, some concepts might resist easy transformation, and the pursuit of semantic correctness can sometimes lead to trade-offs in terms of relational database optimization for real-world applications. As a result, ongoing research efforts seek to address these limitations and enhance the efficiency of the ontology-to-database conversion process.

Various tools serve the purpose of generating relational databases from ontology. For instance, Protégé, a widely used OWL tool, provides the OWL2toRDB plugin[18], enabling the creation of relational databases from OWL ontologies (similar scripts with similar capabilities are readily available[19]). This capability allows for a streamlined workflow where both database and programmatic models can be automatically generated.

[18] https://protegewiki.stanford.edu/wiki/OWL2ToRDB
[19] https://protegewiki.stanford.edu/wiki/ConvertToDBScript

6.2.2. Existing Ontology Alignment

If ontology A extends ontology B, it benefits from the software and tools designed for ontology B. In the case of the Reincarnate ontology, which is based on IFCSchema, which in turn is represented in OWL by IFCOWL[20] (an IFC ontology), this relationship brings several advantages. The extension primarily comprises additional constraints and property definitions within IFCOWL's extensible framework, providing a wealth of existing software tool coverage. For instance, conventional IFC viewers can effectively display the relevant properties defined in the Reincarnate ontology. From a software development perspective, this interconnectedness is particularly appealing. Notably, tools like the IFCSharpLibrary[21] and IFCSQL[22] offer ready-made solutions for relational database management and step-file conversion that seamlessly apply to the Reincarnate ontology. However, it's important to acknowledge certain limitations. Existing tooling may not be equipped to validate newly introduced constraints since it lacks an understanding of them.

6.2.3. Connection to Other Data Sources

An ontology provides a clear semantic interface for other systems to align with. As a result, connecting an external data source or consumer becomes more streamlined and less error-prone. When an ontology is related to other widely adopted ontologies, it increases the probability that existing systems are already partially pre-aligned with the CP-IM ontology, reducing the implementation efforts required. Specifically, the extension of IFCOWL and its compatibility with IFC means that any IFC-compatible data source or consumer comes largely pre-aligned. While some effort is still needed to finalize the connection and mapping, the total amount required should significantly decrease through the reuse of existing components.

6.2.4. Search & Queries

An out-of-the-box applicable query language facilitates posing any kind of question to the underlying data without needing anything else. SPARQL, a query language for RDF and applicable to OWL-ontologies, is actively researched for its direct application to IFC. The methodology for applying SPARQL efficiently to IFC is a subject of ongoing research [47]. If the Reincarnate ontology were syntactically specified in RDF or a derivative, SPARQL could be automatically applied. Furthermore, intelligent SPARQL search engines could combine query results from a platform implementing the Reincarnate ontology with other data sources, enriching data and providing more relevant and detailed answers.

[20] https://technical.buildingsmart.org/standards/ifc/ifc-formats/ifcowl/
[21] https://github.com/IfcSharp/IfcSharpLibrary
22 https://github.com/IfcSharp/IfcSQL

6.3. Ontology in the CP-IM

The Circular Potential Information Management (CP-IM) platform is currently in development as part of the project. Considerable progress has already been made in implementing the ontology, and several future prospects have been identified.

6.3.1. Data Exchange and Property Reference

Within the CP-IM, the RE Suite plays a crucial role in facilitating data exchange. Notably, it supports the exchange and referencing of IFC step-files, which is of great interest. Since the Reincarnate ontology is fully compatible with IFCOWL, the data exchange functionality seamlessly extends to IFC step files containing Reincarnate ontology data.

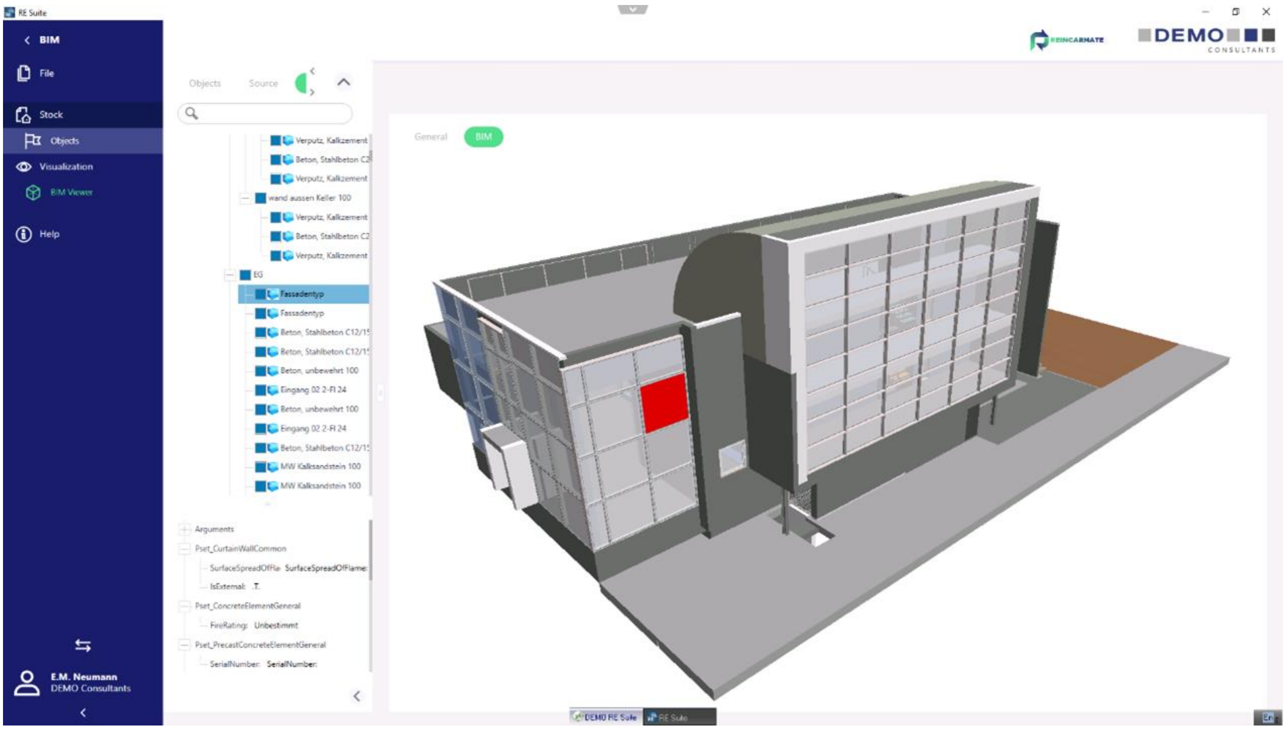

Figure 47: Visualisation of IFC step file, with REINCARNATE-ontology data properties

As shown in Figure 47, BIM models can be easily uploaded, downloaded, and linked to real estate objects for exchange purposes. The existing visualization functionality allows for 3D rendering of the model, while the model navigator enables users to visualize and interact with property values. This means that Reincarnate ontology-compliant data in the step file is readily visible and available for interaction. For instance, one can request the software to highlight all windows in a façade with relevant Reincarnate ontology property values.

6.3.2. Data Extraction

Utilizing RE Suite functionalities, CP-IM can also offer the capability to extract data from IFC files, provided that specific modelling constraints are adhered to. This includes activities such as quantity take-offs, area and volume calculations, and inventory extraction. The functionality relies on recognizable building component code references in IFC properties, aligned with the building component list in RE Suite (NL/SfB[23] compliant). Once imported, this data can be reused, for instance, by importing all inventories as line items in a Life-cycle costing (LCC) analysis. This forms the basis for further extension with relevant attributes as defined in the Reincarnate ontology.

6.3.3. Relating IoT-sensors to IFC Elements

The primary components of CP-IM are RE Suite and Mainflux, serving as a sensor hub and data warehousing solution. These components interact in various ways, including their integration with IFC. In the context of the Reincarnate project, the first work package focused on developing functionality to relate Mainflux sensor definitions to IFC elements or spaces within RE Suite. Notably, the integration of sensors with IFC elements and spaces extends to the incorporation of Reincarnate ontology data. As Mainflux is a versatile IoT hub technology (see Figure 48), it allows for the connection of Reincarnate data to any technology compatible with Mainflux for data collection. This data collection can include information gathered by sensors and non-destructive techniques (Figure 49).

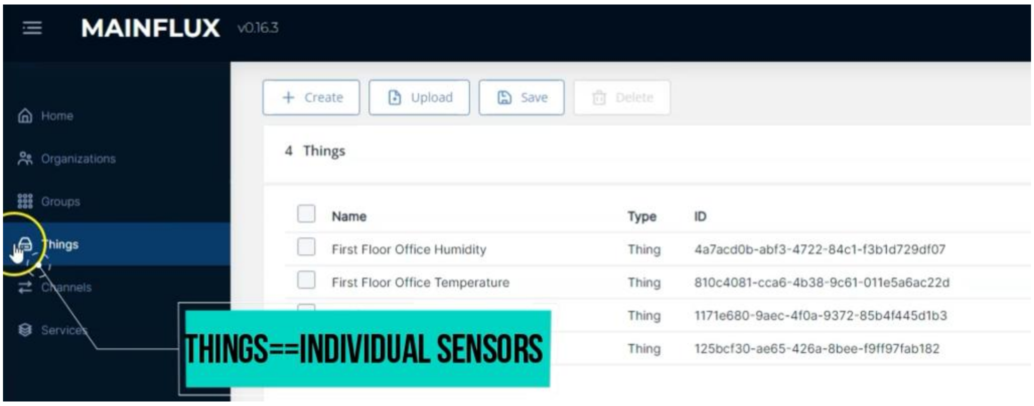

Figure 48: Sensor metadata definition in Mainflux

Figure 49: Left: Importing sensor metadata from Mainflux into RE Suite, Right: Linking sensor to BIM element

[23] https://www.modelleerafspraken.nl/index.php/bijlagen/bijlage-nl-sfb-4-cijfers

6.3.4. Condition Assessment for Lifecyle Extension

To extend the lifetime of a building, the implementation of corrective and predictive maintenance strategies is paramount. As part of the CP-IM platform, RE OnSite plays a crucial role in assisting inspectors to conduct on-site [non-destructive] condition assessments in accordance with the method proposed in Dutch NEN2767[24] standard as depicted in Figure 50. This standard provides an objective evaluation of the physical condition of an asset. The condition classification for each element is determined by the severity, intensity and extent and of defects aggregated into a class number as shown in Figure 51. The condition class can deliver fact-based data to managers, enabling them to distinguish between medium- and long-term maintenance measures in relationship to the desired level of maintenance. This capability serves as a foundational tool for expanding into reclamation audits, incorporating circular-potential-relevant attributes specifically with respect to reuse. This means that inspectors can efficiently gather on-site data for the evaluation of a building's circular potential, focusing on its individual components.

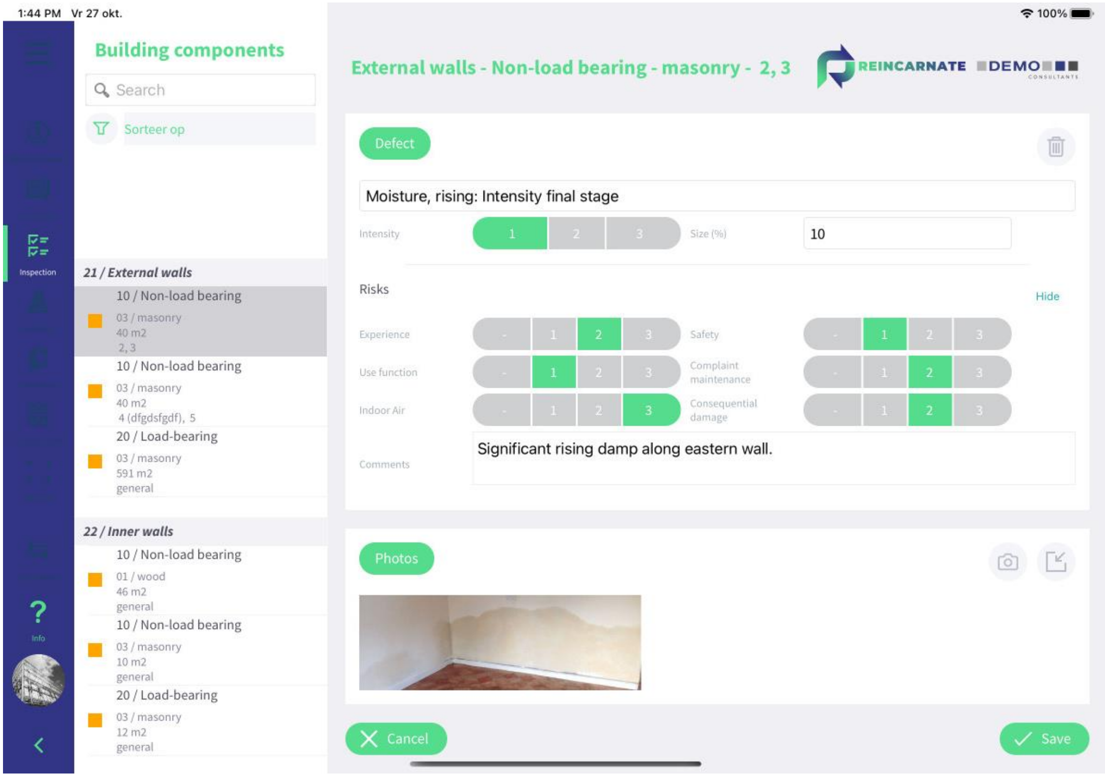

Figure 50: On-site condition assessment

[24] https://www.nen.nl/bouw/beheer-en-onderhoud/conditiemeting/normen-conditiemeting

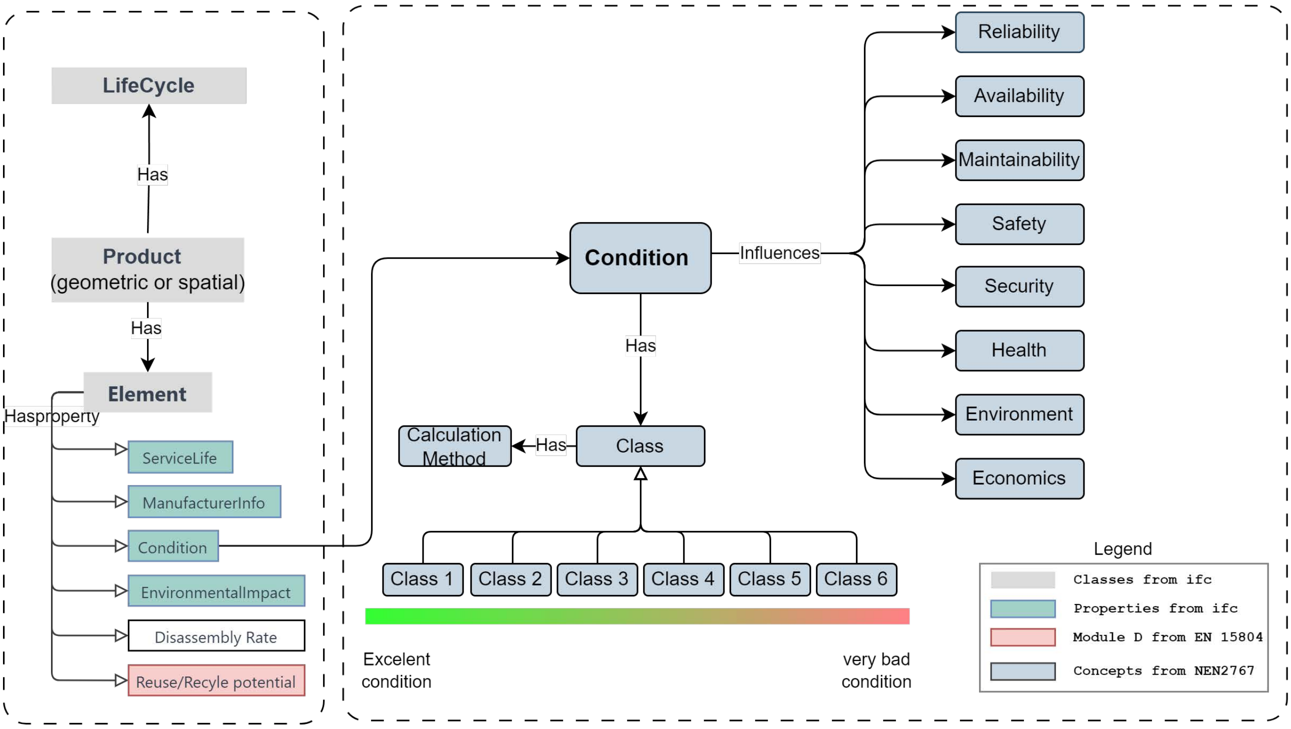

Figure 51: The condition assessment main concepts

6.3.5. External Data Sources

The Reincarnate ontology relies on external data sources to enhance its capabilities and support well-informed decision-making. We have identified several suitable external data sources for integration with our ontology's semantics, aligning with its objectives. As the project advances, we will continuously discover and connect to additional relevant data sources using APIs. This ongoing effort ensures that our ontology remains up-to-date and well-equipped to make data-driven decisions as the project evolves. Currently, the following databases align with parameters in our ontology:

Ökobaudat: [25]As a publicly accessible German national database, Ökobaudat plays a crucial role in ecological building evaluation. By incorporating Ökobaudat, the ontology gains access to a wealth of data that includes environmental impact indicators like Global Warming Potential total (GWP-total). Additionally, we are particularly interested in parameters related to recycling and reuse potential presented in Module D (calculated based on credits, EN 15804), as it aligns closely with our project's objectives. According to the European standard for the assessment of the environmental performance of buildings (EN 15978), potential benefits and loads beyond the building's lifecycle as a consequence of recycling, reuse or energy recovery of building materials can be declared in module D (see Figure 52) . This data is invaluable for assessing and minimizing the ecological footprint of buildings, a fundamental consideration in sustainable construction. According to the second amendment of EN 15804 the declaration of

[25] https://www.oekobaudat.de/en.html

module D will become mandatory on product level. So, in the future the information will be available for evaluations on building level[48].

Ökobaudat is implemented as a soda4LCA[26] application (service-oriented database application for LCA). As such, functionality for export, search and retrieval of datasets is on available. Specifically, the website exposes an archive of the dataset in CSV-format. This is machine readable and could be used for one-time import purposes in the CP-IM. On offer is also a REST API for direct connectivity. Through the API information can be retrieved on-demand and on an as-needed basis.

Indicator	Unit	Production A1-A3	Transport A4	Installation A5	Use B1	Maintenance B2	Repair B3	Replacement B4	Refurbishment B5	Operational energy use B6	Operational water use B7	De-construction C1	Transport C2	Waste processing C3	Disposal C4	Recycling Potential D
Global Warming Potential - total (GWP-total)	kg CO2-Äqv.	21.25	0.0443	0.0404	0	0.00386	0	0	0	0	0	0	0.0017	0.51	0.0231	-0.87

Figure 52: GWP is shown as one of the core environmental impact indicators for flat glass - PRESS GLASS SA - thermally toughened safety glass

Dutch Environmental Database (NMD in Dutch) [27]: NMD offers an invaluable resource for evaluating the environmental performance of structures. It provides LCA-computation results and key environmental impact indicators such as the environmental cost indicator (ECI or MKI in Dutch) for various building components. This is a single-score indicator expressed in Euro (see Figure 53). It unites all relevant environmental impacts into a single score of environmental costs, representing the environmental shadow price of a product or project. This is particularly interesting because the environmental data comes from many different sources, the environmental impacts that are measured vary a lot: They all are measured in different impact categories. For that reason, these numbers can become hard to compare. This is where the Environmental Cost Indicator comes into play: As a single-score indicator, it simplifies and unites different environmental data points into one (monetary) number. The integration of NMD data equips the ontology with the means to make well-informed decisions regarding the environmental sustainability of materials, products, and building components, contributing to greener and more efficient construction practices.

NMD does not expose an API or archive to retrieve machine-readable content. However, as the information is structurally presented on the website a web-scraper can collect the available data points automatically to import in the CP-IM. Should the structure prove static enough on-demand web-scraping is also a possibility.

[26] https://eplca.jrc.ec.europa.eu/LCDN/howto.xhtml
[27] https://milieudatabase.nl

Product name	Isobooster gevelisolatie
Environmental Declaration Number	#nmd_94649
Publication date	11/3/2023
Owner	–
Explanation	De referentiewaarde is berekend voor Isobooster 80, welke is opgebouwd uit 8 lagen bubbelfolie van 10 mm dik afgewisseld met ... Show more...

Unit	m^2
Lifespan	75 year
Category	Categorie 1

Environmental profile	MKI	Scalable
Schaling tbv aluminiumfolie	€0.06	Yes
Schaling tbv bubbelfolie	€0.36	Yes
Total:	**€0.42**	

Figure 53: Environmental cost declaration for floor isolation Isobooster Isobooster 80, which is made up of 8 layers of 10 mm thick bubble film

6.3.6. Inference Rule

Logic, as one of the three pillars of knowledge representation (as explained in 3), plays a pivotal role in formulating rules for inference from the ontology. In the case of the Reincarnate ontology, we have harnessed this logical foundation to generate queries based on the ontology, enabling data-driven decision-making. Within the Reincarnate ontology, numerous properties are defined for IFC elements. Specific combinations of property values enable informed decision-making through inference rules outlined in the Inference Rules Table (Table 7). By querying an IFC file (based on the rules) for specific property value combinations these inferences can be listed. For example, searching for elements that match the property definitions in Rule 3 allows us to identify windows that are recyclable without downgrading.

Inference Rule 1 from the table above (describes the set of all windows of types where a specific property of the type satisfies a condition (*ProductionYear <= 2001*) or a specific ancestor (building) of the window satisfies a condition (*YearOfConstruction <= 2001*).

A possible implementation as a query is illustrated in Table 10. Firstly, the result set should contain only window type elements (1). At least one other condition should also apply denoted by the AND join (2). Either *ProductionYear* suffices (2) or an ancestor should exist (3), namely a building (4) adhering to (5). To denote that the both (4) and (5) are hierarchical ancestor properties a grouping is applied.

Table 11: Query based on inference rule 1

Condition	Group	Join	Identifier	Operator	Value
1			**IFCType**	Equals	IFCWindow
2		**AND**	**PsetManufacturerTypeInformation.ProductionYear**	<=	2001
3		**OR**		ancestor exists	
4	ancestor		**IFCType**	equals	IFCBuilding
5	ancestor	**AND**	**YearOfConstruction**	<=	2001

A flexible query engine, equipped with binary logic operators like “AND” and “OR” and capable of traversing ancestor and descendant relations can efficiently handle queries for various property value combinations. To enhance user experience and streamline usability, frequently used or known queries can be pre-loaded and readily accessible. This approach ensures that users seeking specific information, like "windows suitable for recycling without downgrading," can effortlessly execute queries without the need for manual query construction, although the option to customize queries remains available. This user-friendly design simplifies the process of accessing critical information within the ontology.

A query could be executed on an as-needed basis. A user could upload an IFC file, specify their query arguments and the Reincarnate platform will search the IFC model for the matching elements and produce its answers. This is a workable approach for single models, but the IFC internal file layout is not suitable for a high-performance query engine. To improve efficiency, models can be indexed in a pre-processing stage of the workflow. This would enable fast results for frequently searched models or support searching through entire populations of pre-indexed models in one go.

7. Synergy & Outlook

The findings in this report will be contributing to the development of the CPIM platform, implementing the results of other work packages In parallel to Reincarnate, the Trace4Value and Onto-deside Horizon Europe projects are also dedicated to advancing the field of Circular Economy ontologies, with a particular emphasis on OWL implementations. This concerted effort towards ontology development is significant not only for its potential to amplify the collective knowledge in this domain but also for the practical applications it can unlock. These projects recognize the value of creating cohesive and interconnected ontologies that can collaboratively contribute to addressing the complex challenges of Circular Economy integration. A noteworthy opportunity lies in aligning the resulting ontologies through the established framework of IFCOWL. By doing so, we create a common ground where data exchange and semantic interoperability can thrive. This alignment facilitates the seamless sharing of information between projects, promoting a collaborative environment where insights, best practices, and critical data can be leveraged collectively.

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REINCARNATE

9. Appendix

EN 206:2013+A2:2021 (Annex E) Recommendation for the use of aggregates

Table E.2 — Maximum percentage of replacement of coarse aggregates (% by mass)

Recycled aggregate type	Exposure classes			
	X0	XC1, XC2	XC3, XC4, XF1, XA1, XD1	All other exposure classes [a]
Type A: (Rc_{90}, Rcu_{95}, $Rb_{10\text{-}}$, $Ra_{1\text{-}}$, $FL_{2\text{-}}$, $XRg_{1\text{-}}$)	50 %	30 %	30 %	0 %
Type B [b]: (Rc_{50}, Rcu_{70}, $Rb_{30\text{-}}$, $Ra_{5\text{-}}$, $FL_{2\text{-}}$, $XRg_{2\text{-}}$)	50 %	20 %	0 %	0 %

[a] Type A recycled aggregates from a known source may be used in exposure classes to which the original concrete was designed with a maximum percentage of replacement of 30 %.

[b] Type B recycled aggregates should not be used in concrete with compressive strength classes > C30/37.

Table E.3 — Recommendations for coarse recycled aggregates according to EN 12620

Property [a]	Clause in EN 12620:2002+A1:2008	Type	Category according to EN 12620
Fines content	4.6	A + B	Category or value to be declared
Flakiness Index	4.4	A + B	$\leq FI_{50}$ or $\leq SI_{55}$
Resistance to fragmentation	5.2	A + B	$\leq LA_{50}$ or $\leq SZ_{32}$
Oven dried particle density ρ_{rd}	5.5	A	≥ 2 100 kg/m^3
		B	≥ 1 700 kg/m^3
Water absorption	5.5	A + B	Value to be declared
Constituents [b]	5.8	A	Rc_{90}, Rcu_{95}, $Rb_{10\text{-}}$, $Ra_{1\text{-}}$, $FL_{2\text{-}}$, $XRg_{1\text{-}}$
		B	Rc_{50}, Rcu_{70}, $Rb_{30\text{-}}$, $Ra_{5\text{-}}$, $FL_{2\text{-}}$, $XRg_{2\text{-}}$
Water soluble sulfate content	6.3.3	A + B	$SS_{0,2}$
Acid-soluble chloride ion content	6.2	A + B	Value to be declared
Influence on the initial setting time	6.4.1	A + B	$\leq A_{40}$

[a] Category NR (no requirements) applies for all other properties not stated in this table for which a category NR can be declared according to EN 12620.

[b] For special applications requiring high quality surface finish the constituent FL should be limited to category $FL_{0,2\text{-}}$.