An Ontology to Support Communication in Design-for-Circularity

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Abstract

The urgent need of CO_2-reduction to limit climate change and the potential shortage on raw materials requires the recycling of end-of-life products to regain large portions of the materials invested. This recyclability is already determined by the design of product. Thus in the project *Methods and Technologies for an intelligent Circularity of Materials* (MaTiC-M), we developed a Design-for-Circularity methodology that accounts for recyclability during the design phase of products. To facilitate the necessary knowledge exchange between product designers, recyclers, and other involved stakeholders, we created the Design-for-Circularity Ontology (D4CO). It forms the basis for knowledge graphs that serve as an essential communication tool in the Design-for-Circularity methodology. In this paper, we introduce the Design-for-Circularity Ontology (D4CO) for the improvement of product designs.

Keywords

Circular Economy, Ontology, Knowledge Graph, Life Cycle Assessment, Manufacturing, Recycling

1. Introduction

The urgent need of CO_2 reduction to limit climate change and the potential shortage on raw materials calls for the implementation of an efficient circular economy [1, 2]. This requires the recycling of vast portions of materials at products' end-of-life. However, many valuable resources are still wasted by either downcycling them to materials of lower quality or disposing them altogether.

Comprehensive recycling requires the cooperation of many stakeholders along the entire product life-cycle. The recyclability of a product is already determined during its design. However, improving the recyclability requires knowledge about recycling processes. Vice versa, the optimisation of recycling processes requires detailed knowledge about the end-of-life products at hand. Today, the knowledge exchange between product designers and product recyclers is quite limited. This results in often sub-optimal recycling processes and the loss of a large share of raw materials.

In the project *Methods and Technologies for an intelligent Circularity of Materials* (MaTiC-M)[1], we developed a Design-for-Circularity methodology that accounts for recyclability and criticality as well as economic and environmental factors, obtained from Life Cycle Assessments (LCAs), during the product design phase. To facilitate the necessary communication between product designers, recyclers, and other involved stakeholders, we created the Design-for-Circularity Ontology (D4CO) as basis of knowledge graphs in support of the knowledge exchange.

2. Related Work

A broader overview of ontologies in the circular economy domain is provided by Li et al. [3]. In the following, we discuss the ontologies mentioned by Li et al. that are most relevant to our work:

The ontology BWMD-Domain[2] provides many relevant concepts about manufacturing processes,

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[1]https://www.dlr.de/en/di/research-and-transfer/project/matic-m

[2]https://matportal.org/ontologies/BWMD-DOMAIN

chemical composition and material properties. However, there is a missing separation between the ontology itself and its imported ontologies. This makes reuse difficult from a technical and, due to unclear licensing, a legal point of view.

The Industrial Ontology Foundry (IOF)[3] provides ontologies aiming to support interoperability between suppliers, manufacturers, customers, and other trading partners. It consists of the *IOF core ontology* and several domain specific ontologies. The core ontology is a mid-level ontology providing fundamental concepts for the field of manufacturing and is based on the Basic Formal Ontology (BFO) 2020, the latest major version of the top-level ontology of the Open Biological and Biomedical Ontology Foundry (OBO). The IOF core ontology also adapts concepts of the Information Artifact Ontology (IAO), which is a BFO 2 based ontology that provides concepts for information entities. IAO provides a foundation for the ontological separation between physical entities, like currently running processes or individual exemplars of products, and non-physical entities, like product designs, material specifications, or process plans, which is highly relevant to D4CO. However, IOF core is not fully compatible to IAO, as they are based on different BFO versions. Therefore, BFO 2 and IAO were used as basis for D4CO and selected, relevant concepts from IOF core have been adopted.

The Platform Material Digital Core Ontology (PMDco)[4] [4] is an ontology aiming at semantic interoperability in the field of material science and engineering. Among others, it provides concepts for the description of processes, quantity values, and material identifiers. However, we decided against the reuse of PMDco, due to several design flaws in the ontology until version 2.0.8,[5] (based on PROV Ontology (PROV-O)[6]), e.g., (a) the classification of tools like microscopes or furnaces as `prov:Agent`, which by definition "bears some form of responsibility for an activity", instead of `prov:Entity`, or (b) the modelling of the value interval properties `pmd:fromValue` and `pmd:toValue` as sub-properties of `pmd:value`, which implies that the limits of a value interval are at the same time the exact (single) value. The first significantly revised version 3.0.0-alpha1[7] (now based on BFO 2020 instead of PROV-O) was released too late to be considered for reuse in D4CO.

3. Ontology Requirements

During the development of the ontology, we broadly followed on the Linked Open Terms (LOT) methodology [5]. The first phase of the methodology is the ontology requirements specification. The resulting ontology requirements specification is publicly available [6] and was presented together with a description of the requirements specification activities [7]. This requirements specification consists of 65 Competency Questions (CQs), excluding 32 CQs that have not been published to protect intellectual property rights of project partners. The CQs are categorised into 11 topic. Table 1 shows one example CQ per topic. As already suspected during the requirements specification phase [7], some CQ later turned out to be irrelevant. The main reason being that the Design-for-Circularity methodology, which the ontology is supposed to assist, was under ongoing development at the time. Consequently, the requirements specification activity at the begin of the project was a best effort to approximate the ontology requirements, but the requirements had to be adapted continuously throughout the project.

4. Proposed Ontology

To address the outlined requirements, we developed the Design-for-Circularity Ontology (D4CO) [8].[8] It is based on BFO 2[9] as a top-level ontology. Main reason for this decision was to foster future interoperability with other ontologies German Aerospace Center (DLR) is involved in, as for example

[3] https://github.com/iofoundry/ontology
[4] https://github.com/materialdigital; pmd: <https://w3id.org/pmd/co/>
[5] https://github.com/materialdigital/core-ontology/releases/tag/v2.0.8, released 2024-09-17
[6] https://www.w3.org/TR/prov-o/; prov: <http://www.w3.org/ns/prov#>
[7] https://github.com/materialdigital/core-ontology/releases/tag/v3.0.0-alpha1, released 2025-05-20
[8] https://gitlab.com/dlr-dw/d4co; d4co: <https://w3id.org/d4co/>
[9] https://github.com/BFO-ontology/BFO; obo: <http://purl.obolibrary.org/obo/>

Table 1
Example Competency Question (CQ) for each topic (Table taken from [7]).

ID	Topic	Example CQ
108	material	What **properties** (e.g., **tensile strength**, **thermal conductivity**, **heat capacity**, **density**) does a **material** have?
202	individual part / assembly / product	Which **parts** and **assemblies** does an **assembly** / **product** consist of?
301	connection / joining	Which **connections** of which **connection type** / which **joining method** exist between two **components**?
401	material source	In what **amount** is a **material** available from a primary / secondary **material source**?
503	manufacturing / production	How much **electrical energy** does a **production process** / **manufacturing process** require per **workpiece** or **amount of material**?
601	scrap	What **material** does an amount of **scrap** consist of?
704	collection	What **personnel** is required for the **collection** of the scrap of a **product** or **assembly**?
804	disassembly	Which **disassembly steps** are to be carried out for a **product**?
902	recycling	How much **electrical energy** does a **recycling step** require per **product** or **component** or **amount of material**?
1002	appliance / machine	What is the **lifespan** of a **device**?
1101	personnel requirements	How many **person hours** with which **qualifications** does a **personnel requirement** comprise?

the Open Energy Ontology (OEO)[10] [9] and the Open Transport Ontology (OTO),[11] which are based on BFO, too. Further, we reuse selected concepts of BFO 2020,[12] the Chemical Entities of Biological Interest (ChEBI) ontology,[13] the Environment Ontology (ENVO),[14] the IAO,[15] the IOF Core Ontology and the IOF Annotation Vocabulary,[16] the Ontology of units of Measure (OM) 2 [10],[17] the OBO Relations Ontology (RO),[18] and Wikidata.[19] The Design-for-Circularity Ontology is publicly available and licensed under a permissive CC BY 4.0 license[20], except of some concepts that are kept non-public to protect intellectual property rights of project partners. As already specified in the requirements, the ontology comprises concepts that cover for several topics. In Sections 4.1 to 4.6, we describe the core aspects of the ontology. Dependencies (`owl:import` or soft reuse of selected concepts) between the different ontology modules and reused ontologies is shown in Figure 1.

4.1. Quantities and Quantity Values

Physical quantities are a fundamental aspect for the representation of product designs and is required by most other parts of the ontology. Here, we reuse OM 2.0.46 with some modifications: To simplify SPARQL queries and the addition of further units, we converted implicit typing of units using `owl:oneOf` statements into explicit `rdf:type` statements. To avoid recursive requests and thus enable unit conversion calculations of measurement values at query time, we added a property for the direct

[10]https://github.com/OpenEnergyPlatform/ontology
[11]https://github.com/OpenEnergyPlatform/OpenTransportOntology
[12]https://github.com/BFO-ontology/BFO-2020; obo: <http://purl.obolibrary.org/obo/>
[13]https://www.ebi.ac.uk/chebi/; obo: <http://purl.obolibrary.org/obo/>
[14]https://github.com/EnvironmentOntology/envo; obo: <http://purl.obolibrary.org/obo/>
[15]https://github.com/information-artifact-ontology/IAO; obo: <http://purl.obolibrary.org/obo/>
[16]https://github.com/iofoundry/ontology; iof-core: <https://spec.industrialontologies.org/ontology/core/Core/>; iof-av: <https://spec.industrialontologies.org/ontology/core/meta/AnnotationVocabulary/>
[17]https://github.com/HajoRijgersberg/OM; om: <http://www.ontology-of-units-of-measure.org/resource/om-2/>
[18]https://github.com/oborel/obo-relations; obo: <http://purl.obolibrary.org/obo/>
[19]https://www.wikidata.org/; wd: <http://www.wikidata.org/entity/>
[20]https://creativecommons.org/licenses/by/4.0/

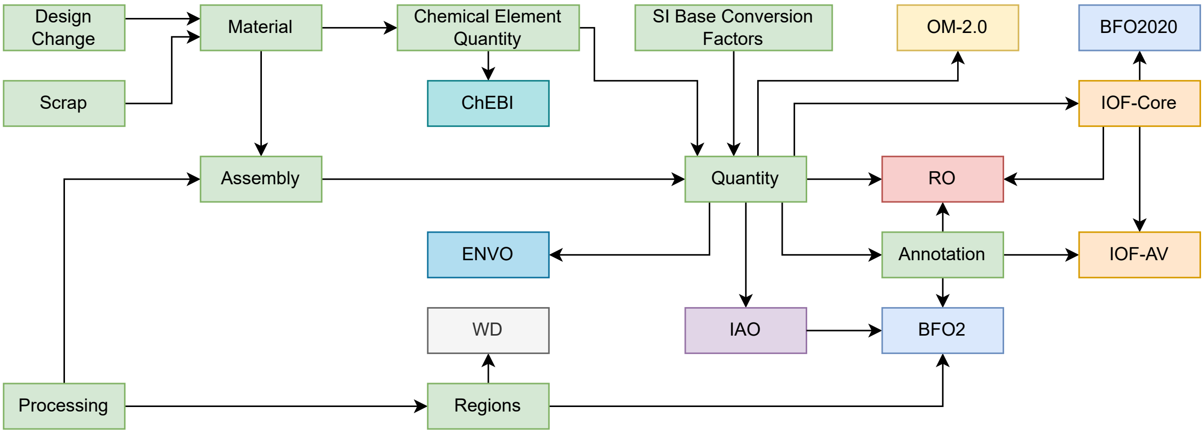

Figure 1: Visualisation of the dependencies between ontology parts and reused ontologies.

conversion factor of a unit to the International System of Units (SI) base unit and pre-computed these factors for all units. In manufacturing, most specifications state ranges of tolerances, so we added properties for upper bound and lower bound of a quantity value to represent them. Both are defined as super-properties of `om:hasNumericalValue` to entail an upper and lower bound equal to the exact value, if an exact (single) value is stated. These properties assign a value or value range to a measure of a quantity, or a point, in case of an temperature quantity. The described additions are visualised in Figure 2. Further, we added required units not present in OM yet, like $\mathrm{s\,kg^{-1}}$ and $\mathrm{kW\,h\,kg^{-1}}$.

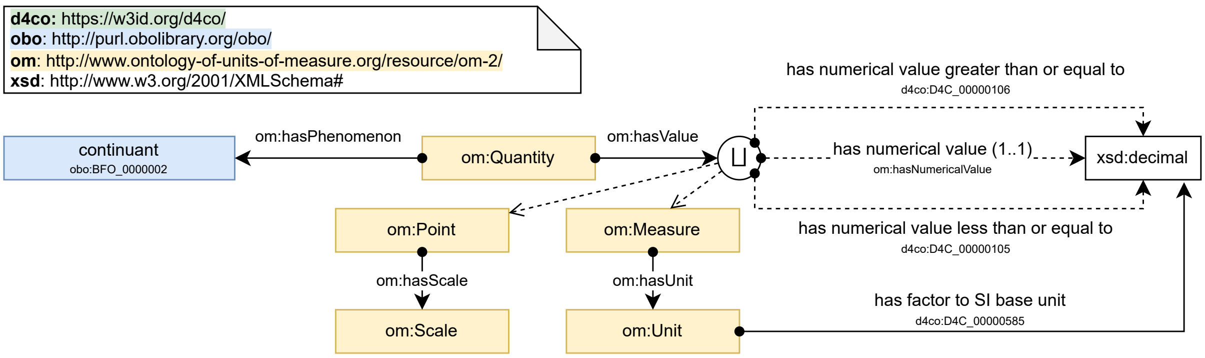

Figure 2: Visualisation of the extended vocabulary for quantities based on OM 2 using Chowlk [11] notation.

4.2. Designs, Assemblies and Components

Product designs are represented in terms of assemblies, which are material entities and consist of other material entities as their components, as shown in Figure 8. Additionally, the relation of components can be detailed by the connection [12]. This structure has been adapted from the Factory of the Future (FoF) ontology [13, 14]. However, we extended the model by distinguishing between (a) actual instances (e.g., the individual car to scrap), (b) descriptions of instances (e.g., the rough resemble of the car's design) and (c) specifications of instances (e.g., the original design of the car). As multiple instances of the same design would be represented in the description or specification by the same resource, additional concepts have been defined to represent multiple applications of components of the same kind to preserve cardinality information. Further, to enable the representation of the location of components or features, i.e. parts of the geometric shape of components, in their context, additional quantity kinds have been defined to represent x, y, and z translation and rotation, as visualised in Figure 3.

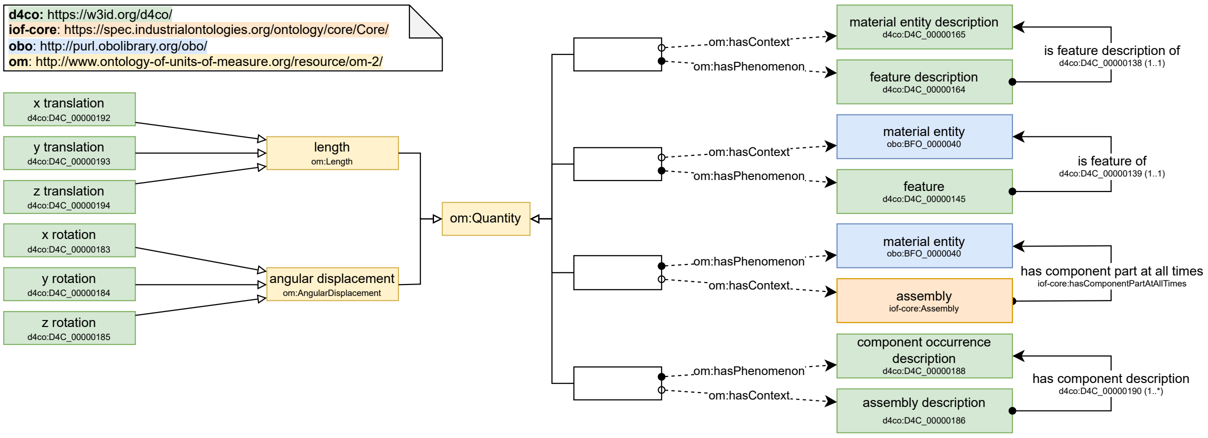

Figure 3: Ontology concepts to represent the location of components in assemblies and features in parts by quantities of the x, y, and z translation and rotation using Chowlk [11] notation.

4.3. Manufacturing Materials and Secondary Raw Material

A key factor for the recyclability of products is the chemical composition of materials in their components. Different materials can be represented by manufacturing material specifications, which describe the physical properties of materials used for manufacturing. They are then referenced by material artifact specifications, as visualised in Figure 4. In the same way, secondary raw material specifications represent the physical properties of compositions of scrap that are suitable for common ways of recycling. The chemical composition of single material entities, manufacturing material specifications, or secondary raw material specifications is represented by mass fraction quantities for the different chemical elements. These quantities are defined as the fraction of (sub-property of `om:hasPhenomenon`) the collection of the corresponding atoms that are the fraction in (sub-property of `om:hasContext`) the described entity. The collection classes again are linked to the according classes of atoms in the ChEBI ontology.

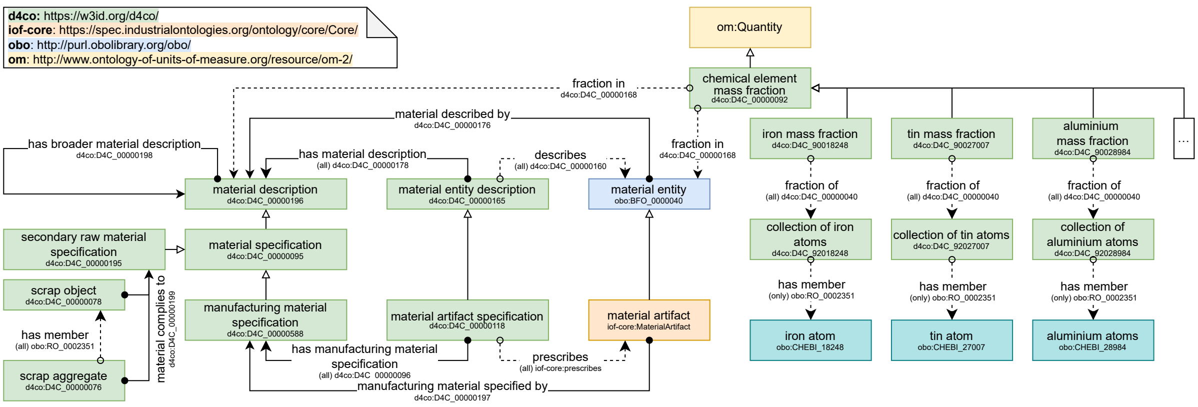

Figure 4: Ontology concepts to represent the chemical composition of manufacturing materials used in design, using Chowlk [11] notation.

4.4. Design Changes

The goal of the Design-for-Circularity methodology is the improvement of designs with a focus on recyclability at the end-of-life of the product. This improvements should be representable with the D4CO, too. We provide necessary concepts to represent the replacement of materials of single components, the complete replacement of components (single components or sub-assemblies), and the replacement of connections between components, as visualised in Figure 5. The affected parts of the design and the intended change are linked with the properties replaces at and replaces with.

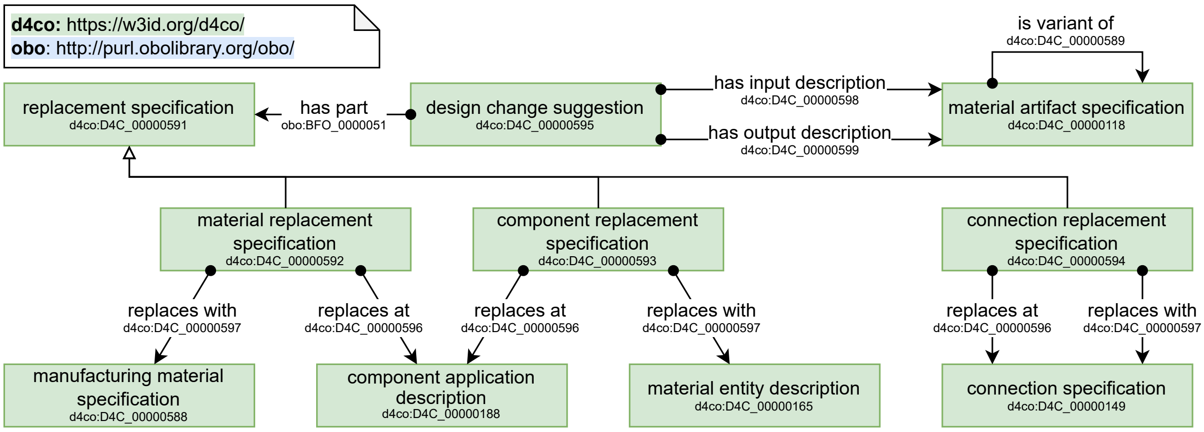

Figure 5: Ontology concepts to represent product design changes, using Chowlk [11] notation.

4.5. Manufacturing and Recycling Processes

Knowledge about manufacturing and recycling processes is necessary to assess economic and environmental factors of a product design for the Design-for-Circularity methodology. We provide concepts for the representation of necessary knowledge about processes either retrospective in form of process observations or prospective in form of plan specifications. Each process might format, breakdown, transport, or utilise material entities, like assemblies, components, raw materials, or machines. These properties represent the actual relation between the process and the material entity, but also imply whether the material entity is input, output, or both to the process.

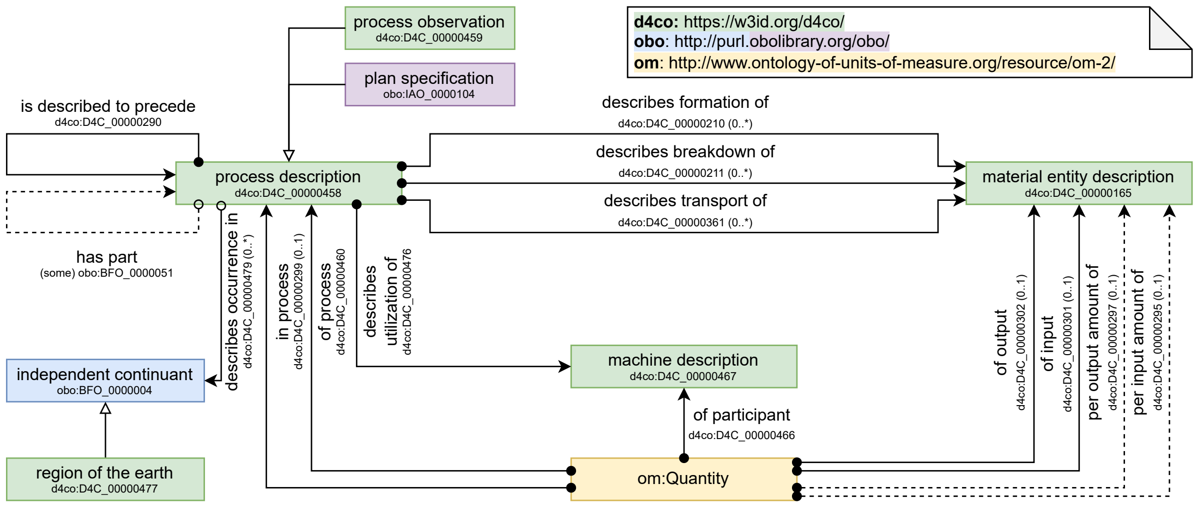

Figure 6: Ontology concepts to represent manufacturing and recycling processes using Chowlk [11] notation.

Quantities are used to characterise processes. A selection of provided quantity sub-classes is shown in Table 2. With a respective sub-property of the generic property `om:hasContext`, these quantities must be set into context to either the amount of an output (e.g., in case of a manufacturing process) or the amount of an input (e.g., in case of a recycling process) and be applied in a specific process. The actually quantified process or material entity is linked with an according sub-property of `om:hasPhenomenon` for inputs, outputs, processes, or participants. Further, the geographical location of process occurrences is often relevant for the LCA execution and can be linked with the property describes occurrence in. Instances of regions of the earth have been adapted from Wikidata. This model is given in Figure 6 and a (greatly simplified) example of a process together with related material entities and quantities is visualised in Figure 9.

Table 2
Selected `om:Quantity` sub-classes for the characterisation of manufacturing or recycling processes.

	per energy	per mass	per unit	per volume
count	d4co:D4C_00000342	d4co:D4C_00000343	d4co:D4C_00000345	d4co:D4C_00000344
cost	d4co:D4C_00000329	d4co:D4C_00000254	d4co:D4C_00000252	d4co:D4C_00000256
emitted CO_2 equivalent (GWP_{100}) mass	d4co:D4C_00000381	d4co:D4C_00000382	d4co:D4C_00000383	d4co:D4C_00000384
required count	d4co:D4C_00000350	d4co:D4C_00000351	d4co:D4C_00000352	d4co:D4C_00000353
required person-time	d4co:D4C_00000314	d4co:D4C_00000237	d4co:D4C_00000238	d4co:D4C_00000310
...of academics or engineers	d4co:D4C_00000316	d4co:D4C_00000247	d4co:D4C_00000244	d4co:D4C_00000311
...of laborers	d4co:D4C_00000318	d4co:D4C_00000249	d4co:D4C_00000246	d4co:D4C_00000313
...of skilled workers	d4co:D4C_00000317	d4co:D4C_00000248	d4co:D4C_00000245	d4co:D4C_00000312
required electrical energy	d4co:D4C_00000323	d4co:D4C_00000280	d4co:D4C_00000281	d4co:D4C_00000282
required mass	d4co:D4C_00000375	d4co:D4C_00000364	d4co:D4C_00000365	d4co:D4C_00000366
required thermal energy	d4co:D4C_00000322	d4co:D4C_00000272	d4co:D4C_00000268	d4co:D4C_00000274
required time	d4co:D4C_00000469	d4co:D4C_00000468	d4co:D4C_00000470	d4co:D4C_00000471
required volume	d4co:D4C_00000346	d4co:D4C_00000347	d4co:D4C_00000348	d4co:D4C_00000349
scope 1 carbon footprint (GWP_{100})	d4co:D4C_00000402	d4co:D4C_00000405	d4co:D4C_00000408	d4co:D4C_00000411
scope 2 carbon footprint (GWP_{100})	d4co:D4C_00000403	d4co:D4C_00000406	d4co:D4C_00000409	d4co:D4C_00000412
scope 3 carbon footprint (GWP_{100})	d4co:D4C_00000404	d4co:D4C_00000407	d4co:D4C_00000410	d4co:D4C_00000413

4.6. Transformation Order

The targeted disassembly of products allows specific components to be removed from an assembly to ease recycling. Similarly, the assembling order of components is relevant for the creation of a product manufacturing plan. Therefore, we provide concepts for the representation of disassembly and assembly sequences. The model uses the same linked list pattern known from `rdf:List` with the properties has first and has rest, but dedicated list node classes for assembly sequences and disassembly sequences that restrict the permitted resources in the list. The model is visualised in Figure 7.

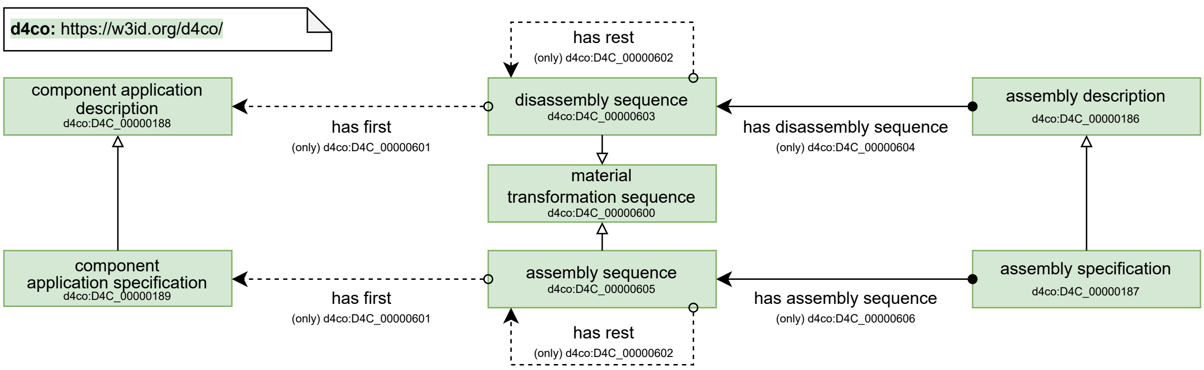

Figure 7: Ontology concepts to represent the order of (dis-)assembly sequences using Chowlk [11] notation.

5. Application and Evaluation

The introduced ontology provides the knowledge graph schema of a prototype software for a Design-for-Circularity assessment. The software retrieves semantically represented product and material knowledge to assess and visually present the suitability for a circular economy for product designs provided as Computer-Aided Design (CAD) assemblies. For that, the software analyses CAD assemblies in terms of their properties (assembly hierarchy, components, materials, connection types) [12]. This information is combined with information from the knowledge graph to perform a traceable circular economy assessment of the proposed design and to analyse the product's recyclability. Here, information is obtained about potentially recoverable components and the classification of their materials into defined secondary raw material categories. This transforms the semantically structured knowledge into a operational decision support tool. A detailed description of this software is beyond the scope of this paper, though. The purpose of the ontology is to avoid ambiguity in the data provided by several stakeholders.

To argue that the ontology is fit for its purpose, we demonstrate the applicability of the ontology by providing SPARQL queries for the CQs shown in Table 1. However, we can not provide queries for all CQs of the requirements specification, as (a) this would exceed the space in this paper, and (b) the ontology only covers 48 of 65 published CQs and 15 of 32 unpublished CQs, due to the reasons mentioned in Section 3. Prefix clauses in the SPARQL queries are skipped for space reasons.

(108) **What properties (e.g., tensile strength, ...) does a material have?** The question is answered by the following query for the ultimate tensile strength as an example. The value is provided as a value range and normalised to the SI base unit.

```
SELECT ?material (?minRaw*?unitFactor AS ?min) (?maxRaw*?unitFactor AS ?max)
WHERE {
  ?material a d4co:D4C_00000588 ; # manufacturing material specification
    ^d4co:D4C_00000168 ?quantity .
  ?quantity a d4co:D4C_00000482 ; # ultimate tensile strength
    om:hasValue [ om:hasUnit/d4co:D4C_00000585 ?unitFactor ;
      d4co:D4C_00000105 ?maxRaw ;
      d4co:D4C_00000106 ?minRaw ] .
}
```

(202) **Which parts and assemblies does an assembly / product consist of?** The question is answered by the following query for an assembly specification. The relation and cardinality is retrieved from a required count per unit quantity.

```
SELECT ?assembly ?component ?count
WHERE {
  ?assembly a d4co:D4C_00000187 ; # assembly specification
    ^d4co:D4C_00000297 ?requiredComponentCount . # per output amount of
  ?requiredComponentCount a d4co:D4C_00000352 ; # required count per unit
    om:hasValue/om:hasNumericalValue ?count ;
    d4co:D4C_00000301 ?component . # of input
}
```

(301) **Which connections of which connection type / which joining method exist between two components?** The question is answered by the following query that provides the connections and connection types of pairs of component applications.

```
SELECT ?application1 ?application2 ?connection ?connectionType
WHERE {
 ?application1 d4co:D4C_00000191 ?component1 . # describes application of
 ?application2 d4co:D4C_00000191 ?component2 . # describes application of
 ?connection a ?connectionType ;
  d4co:D4C_00000158 ?application1 , ?application2 . # connection descr. of
 ?connectionType rdfs:subClassOf* d4co:D4C_00000163 . # connection descr.
 FILTER (?application1 != ?application2)
}
```

(401) **In what amount is a material available from a primary / secondary material source?** The question is answered by the following query for the source of a manufacturing material, represented as production process, with a certain required time per mass of an output. The result is converted into availability in kilogram per day.

```
SELECT ?source ?material (86400/(?valueRaw*?unitFactor) AS ?kgPerDay)
WHERE {
 ?source a d4co:D4C_00000203 ; # material transformation process descr.
  ^d4co:D4C_00000299 ?requiredTimePerMass . # in process
 ?requiredTimePerMass a d4co:D4C_00000468 ; # required time per mass
  d4co:D4C_00000297 ?material ; # per output amount of
  om:hasValue [ om:hasNumericalValue ?valueRaw ;
   om:hasUnit/d4co:D4C_00000585 ?unitFactor ] .
}
```

(503) **How much electrical energy does a production process / manufacturing process require per workpiece or amount of material?** (902) **How much electrical energy does a recycling step require per product or component or amount of material?** Both questions are answered by the following query for the example of the required electrical energy per mass per input amount of a process that breaks down a material entity. In case of a manufacturing processes, these two properties would need to be replaced with the properties per output amount of and describes formation of.

```
SELECT ?product ?process (?valueRaw*?unitFactor AS ?energyNeed)
WHERE {
 ?process d4co:D4C_00000211 ?product ; # describes breakdown of
  ^d4co:D4C_00000299 ?quantity . # in process
 ?quantity a d4co:D4C_00000281 ; # required electrical energy per unit
  d4co:D4C_00000295 ?product ; # per input amount of
  om:hasValue [ om:hasNumericalValue ?valueRaw ;
   om:hasUnit/d4co:D4C_00000585 ?unitFactor ] .
}
```

(601) **What material does an amount of scrap consist of?** The query answering this question would exceed the available space in this paper. Hence, we only outline the approach to a query:

1. Aggregate the chemical element's mass fraction ranges for all scrap parts considering the mass and count of the parts.
2. Find all secondary raw material specifications of that all chemical element mass fraction ranges enclose the according aggregated chemical element's mass fraction range of the scrap.

(704) **What personnel is required for the collection of the scrap of a product or assembly?** (1101) **How many person hours with which qualifications does a personnel requirement comprise?** Both questions are answered together by the following single query that retrieves the normalised value of the required person-time of laborers per unit, the required person-time of skilled workers per unit and the required person-time of academics or engineers per unit quantity.

```
SELECT ?product ?process
 (?laborerRaw*?laborerFactor*3600 AS ?laborerHours)
 (?skilledRaw*?skilledFactor*3600 AS ?skilledHours)
 (?engineerRaw*?engineerFactor*3600 AS ?engineerHours)
WHERE {
 ?process d4co:D4C_00000361 ?product ; # describes transport of
  ^d4co:D4C_00000299 ?laborers , ?skilled , ?engineers . # in process
 ?laborer a d4co:D4C_00000246 ; # required laborer time per unit
  d4co:D4C_00000295 ?product ; # per input amount of
  om:hasValue [ om:hasNumericalValue ?laborerRaw ;
   om:hasUnit/d4co:D4C_00000585 ?laborerFactor ] .
 ?skilled a d4co:D4C_00000245 ; # required skilled worker time per unit
  d4co:D4C_00000295 ?product ; # per input amount of
```

```
  om:hasValue [ om:hasNumericalValue ?skilledRaw ;
   om:hasUnit/d4co:D4C_00000585 ?skilledFactor ] .
 ?engineer a d4co:D4C_00000244 ; # required engineer time per unit
  d4co:D4C_00000295 ?product ; # per input amount of
  om:hasValue [ om:hasNumericalValue ?engineerRaw ;
   om:hasUnit/d4co:D4C_00000585 ?engineerFactor ] .
}
```

(804) **Which disassembly steps are to be carried out for a product?** The question is answered by the following query that provides all parts in the disassembly sequence linked with has disassembly sequence and then counts the sequence nodes traversed via the properties has rest and has first for each part to determine the disassembly order.

```
SELECT (COUNT(?sequenceNode) AS ?disassemblyOrder) ?part
WHERE {
 ?assembly d4co:D4C_00000604/d4co:D4C_00000602*/d4co:D4C_00000601 ?part .
 ?assembly d4co:D4C_00000604/d4co:D4C_00000602* ?sequenceNode .
 ?sequenceNode d4co:D4C_00000602*/d4co:D4C_00000601 ?part .
} GROUP BY ?part ORDER BY ?disassemblyOrder
```

(1002) **What is the lifespan of a device?** The question is answered by the following query that retrieves the normalised value of the design life quantity.

```
SELECT ?product (?valueRaw*?unitFactor*31536000 AS ?designLifeYears)
WHERE {
 ?product a d4co:D4C_00000118 ; # material artifact specification
  ^om:hasPhenomenon ?designLife .
 ?designLife a d4co:D4C_00000251 ; # design life
  om:hasValue [ om:hasNumericalValue ?valueRaw ;
   om:hasUnit/d4co:D4C_00000585 ?unitFactor ] .
}
```

6. Conclusion and Future Work

We have introduced the Design-for-Circularity Ontology (D4CO) that was developed for assessing and improving product designs with regard to a circular economy. The suitability of the developed ontology was substantiated by providing SPARQL queries for a collection of CQs that have been provided and selected in previous work. Further, the ontology provides the basis for a prototype software for product design assessment and improvement. We intend to continue the development of this software to maturity for industrial application for use cases of product design, assembly sequence planning, and recycling-optimised disassembly planning. Most likely, this development will also result in a further extensions of the Design-for-Circularity Ontology.

While timing hindered the reuse of the third version of the PMDco, an alignment of both ontologies might benefit the interoperability of ontology-based software for manufacturing developed in future. Further, a separation of the ontology into smaller and weakly-dependent modules could simplify its reuse. Regardless, we already consider the Design-for-Circularity Ontology a useful basis for describing product designs and manufacturing-related processes.

Declaration on Generative AI

During the preparation of this work, the authors used **DeepL** in order to: **Text Translation**. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the publication's content.

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A. Designs, Assemblies and Components Model Visualisation

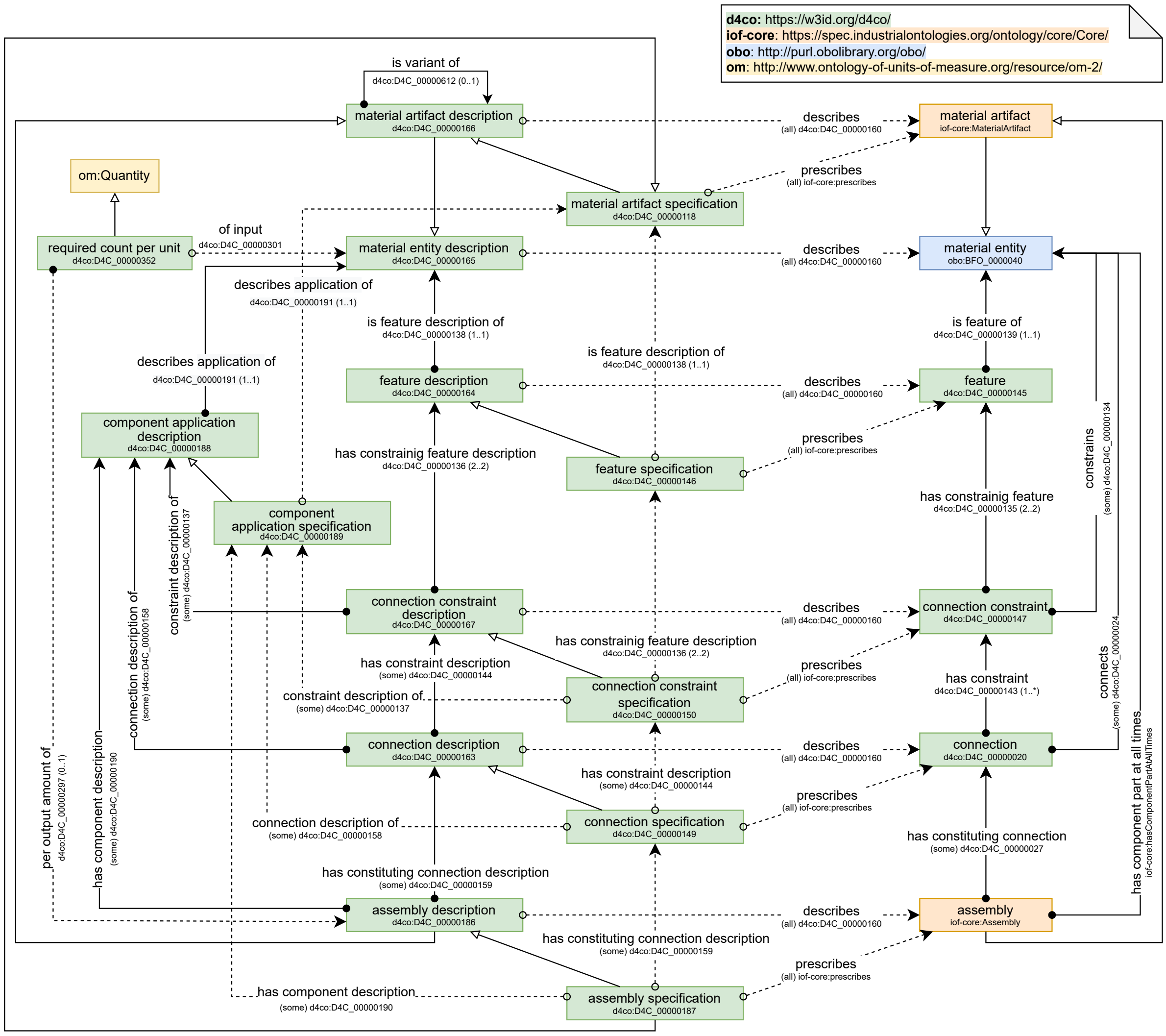

Figure 8: Ontology concepts to represent the design of products, using Chowlk [11] notation.

B. Processing Example Visualisation

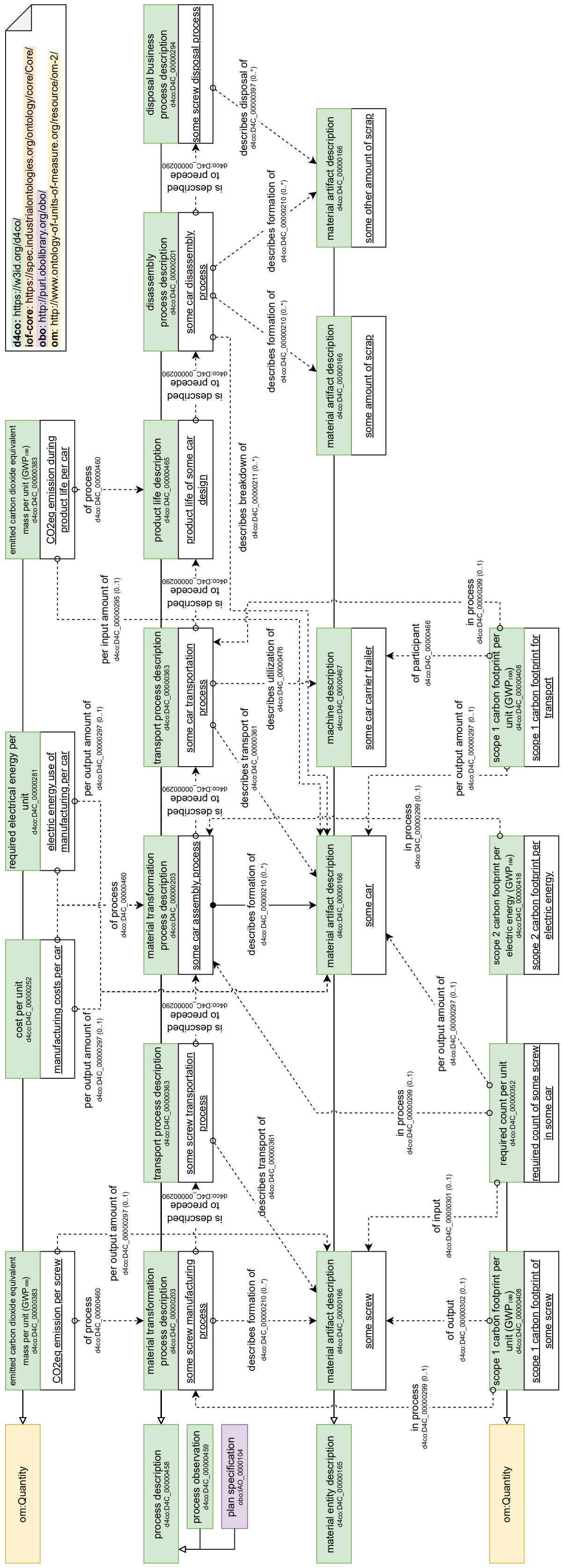

Figure 9: Simplified example to represent a product's manufacturing and life-time processes including selected quantities describing involved processes and material entities, using Chowlk [11] notation.