A Product Meta Data Model of Assembly-Related Extreme Data to enable Hybrid Decision Support

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Abstract: Models of Circular Economy introduce circularity strategies like reuse, repair or remanufacture. A significant level of complexity is added when these strategies are applied not only on integrated product level, but on lower levels of assemblies and parts. Therefore, approaches, like Design for Assembly, Disassembly and Reassembly (DfADR) become increasingly important including the consideration of ADR capabilities. To put DfADR into practice, it is necessary to structure ADR-related product data and make it usable for product engineers. For instance, assemblies resulting from disassembly might not be consistent with original assembly structures. Therefore, a Product Meta Data Model (MDM) is required to handle assembly-related data even when it has extreme characteristics. A literature review on related MDMs reveals a range of models for general product data and identifies a gap in consideration of assembly-related data. In an expert workshop, requirements are raised to evaluate existing models and develop ADR-related extensions. The MDM is conceptually modelled and validated by competence questions. The paper presents an approach that makes assembly-related data usable for hybrid decision support and enables engineers to think ahead of ADR processes.

Keywords:
meta data model, product data, assembly, disassembly, re-assembly, extreme data

1 Introduction and Research Question

From the perspective of product creation, Circular Economy means to plan and engineer products in a way that it is economically attractive to circulate all material into new products after decommissioning [1]. Concepts of Circular Economy introduce circularity strategies like reuse, repair, refurbish or remanufacture that keep the original structure of the product and its components [2]. A significant level of complexity is added when these strategies are applied not only on integrated product level, but also on lower levels of assemblies and parts. Enabling Circular Economy requires the economic closing of material flows on highest possible levels. High-level circularity strategy means re-assembly of usable assemblies of parts in complete. Therefore, approaches, like Design for Assembly, Disassembly and Reassembly (DfADR) become increasingly important as well as the consideration of ADR capabilities. Design for Capabilities (DfC) refers to DfADR by considering capabilities: Capabilities comprise machinery, plant, equipment and humans. They must be known and considered in product engineering to ensure later disassembly and re-assembly [3]. Currently, there is a lack of considering human capabilities. The required capabilities of a human highly depend on the product's features. Product specifications such as joining points define which ADR capability the employee needs. For this purpose, assembly-related data of a product must be made usable already during early stages of product creation. Such data concern both, joining and separating different components of a product.

However, disassembly of products leads to processes that differ from assembly and are more complex [4]. In industrial realization, combinations of disassembly processes with inspection and sorting of used

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products in terms of reverse logistics need to be considered [5]. In the realization ADR-process data are directly affected by product data. The ambition to deduct actual capabilities from ADR-process data needs to overcome challenges due to extreme characteristics of such data: the actual ADR-process is only indirectly represented, gaps and errors in data collection cannot be avoided, sensor data needs to be merged with human-generated logs, observation data of human labor is mixed with machine-assisted processing, and granularity spans from MTM-related movements to work process level. Hybrid decision support systems open up potential to process such data efficiently and support early stage decisions based on ADR and capability-related extreme data. A hybrid decision support system combines established engineering methods with methods of Data Science and Artificial Intelligence (DS/AI) like machine learning or ontology-based reasoning. Therefore, it is important that data are machine-readable and stored in a structured way. For this reason, ADR-related product data is structured by an integrative Meta Data Model (MDM) to enable DfADR and support product engineers, coupling ADR-process data that is fed back from actual ADR-processes and engineering data that is created for new products.

The paper at hand proposes an MDM that forms the basis for hybrid decision support to assist engineers by making data interpretable based on knowledge-based DS/AI methods. The focus is on product-related data, while process-related data is focused in parallel work [6]. Therefore, to identify and evaluate models that consider ADR-related product data and can be mapped to ADR capabilities, this article follows the research question: *Which extensions to existing product MDMs enable the link to ADR-capability representations?*

The paper is structured as follows: This introduction and presentation of the research question is followed by a presentation of the methodological approach. In the following chapter, the fundamentals of the topic are presented. Chapter 4 is divided into three sections. First, the systematic literature review is introduced. Secondly, the developed product MDM is presented. And finally, this MDM is validated in the third section. The work concludes with a conclusion and an outlook.

2 Methodological Approach

This research follows a multi-stage methodological approach combining a literature-based scientific approach with the On-To-Knowledge Methodology [9] as an established and often cited ontology engineering methodology. First, an expert workshop with five experts from product creation is conducted to define ADR-related requirements for a product MDM and synthesize them by thematic clustering. Relevance of the range from engineering to ADR process data is investigated. Ten requirements of the MDM are defined, which are transformed into competence questions that the MDM shall answer. In parallel, a systematic literature review is conducted to validate expert statements and to gather related work. The databases Scopus, Web of Science and IEEE Xplore are searched for publications applying a developed search string combining keywords related to product MDMs. In addition, relevant publications from previous research are included into the study. In the next step, the requirements are compared with existing models of product representation identified in the literature review. Relevant partial models form the basis of the envisaged DfC-focused product MDM, which is completed by mapping concepts in terms of semantic similarities and associations. The validation is carried out based on the requirements and competence questions.

3 Fundamentals

Product data in general describe the technical characteristics of a product, such as dimensions or material. Meta data are “data about data”, i. e., structured data that provide desciptive contextual or administrative information about data in focus. By that, meta data support the management and use of data. Product meta data in special provide structural information about the data of a product. Meta data thus enable the efficient management and retrieval of product data without representing primary product characteristics. MDMs form the foundation for managing and analyzing large and heterogeneous data sets by rendering them machine-readable and semantically consistent. They enable the systematic collection of meta data from diverse entities such as products, humans, processes or companies and make this information available in a standardized way. Furthermore, an MDM specifies the properties, constraints, and permissible values of the data it describes. [7]

Beyond data structuring, MDMs can be implemented in ontologies by using languages such as OWL, which provide formal semantics that enable machine-interpretable meaning and automated reasoning over data sets. MDM thus provides an essential prerequisite for knowledge-based DS/AI methods. [8] For validation of such ontologies, competence questions can be used. Competence questions enable to validate semantic models by ensuring that relationships within these models can answer the questions [9]. In addition, competence questions can be applied to meta data models to assess whether the defined metadata elements and their relationships are sufficient to support the intended use cases and information needs [10].

A fundamental, well-established standard to describe product data is the Standard for the Exchange of Product model data (STEP). STEP is a neutral standard for product data that also stores meta data. The standard is written in the data definition language EXPRESS [11]. In addition to geometric data, described by points, surfaces, and curves, STEP also stores meta data like, for example, part numbers, names, and tolerances [12]. The Core Product Model (CPM) and the Open Assembly Model (OAM) are often cited product MDMs. FENVES et al. used the CPM to describe a product using basic elements. The product, referred as an artifact, is the central element that is specified in more detail via function, form, and behavior [13]. The CPM is used to structure product information [13,14]. The OAM, developed by BAYSAL et al., is an extension of the CPM [15]. The OAM focuses on assemblies and enables the storage of information on, for example, assembly or tolerance specifications [15]. CPM as a basis contains functions and behavior of the product and thus describes the product itself. OAM describes ADR relationships and thus the product structure. The representation of ADR capabilities require process logics, which are not considered in CPM and OAM. [14,15]

Extreme data is defined by European Union program Horizon Europe as data whose e.g. volume, speed, variety or complexity reach levels, which make current technologies fail while processing them [16]. PETCU et al. categorize them into the three main dimensions volume, variety and velocity [17]. Human-related data like ADR capabilities are characterized as extreme data due to highly individual characteristics [3].

4 Approach

First, requirements of an ADR-related product MDM are defined. These requirements are identified in an expert workshop with five experts from product creation. The experts were asked to identify product features that are relevant for ADR processes and those are not. Answers were discussed and clustered in iterative rounds of questions followed by a final group discussion. As a result, ten requirements are identified (see table 1). The requirements are subdivided into two main groups. The first group comprises requirements that describe the product itself. These include requirements according to geometry, function, and structural properties of the product (R01–R06). The second group consists of requirements relating product data to the processes and handling of the product. This group deals with requirements according to ADR-processes like implementation of connection and separation processes at the products connection points (R07–R10).

Table 1: identified requirements for the Meta Data Model

ID	Category	Requirement
R01	describing the product	The MDM must represent the geometric shape of the product in a STEP-compliant manner.
R02		The MDM must represent the function of the product.
R03		The MDM must represent the behavior of the product.
R04		The MDM must distinguish between individual parts and assemblies.
R05		The MDM must represent the existing and possible connection points of assemblies.
R06		The MDM must represent the existing and possible separation points of assemblies.
R07	describing product related ADR-processes	The MDM must map the joining processes for all connection points.
R08		The MDM must map the separation processes for all connection points.
R09		The MDM must map product features relevant to assemble and disassemble.
R10		The MDM must map capability-related product features for ADR processes.

Based on the workshop results, competency questions are developed in accordance with the On-To-Knowledge Methodology [9]. To validate the MDM, it must be able to answer these competence questions. The expert's statements from the workshop are converted into such competence questions and it is ensured that these correspond to the product domain of the MDM. Five competence questions are derived:

- What is the {size, mass, form} of the product?
- What is the {surface texture, material} of the product?
- What joints does the product contain?
- Which human capabilities are necessary for (dis- / re-) assembling the product?
- What connection type does the product provide for ADR processes?

This approach ensures that the MDM and the ontology, implementing the MDM, can handle corresponding queries. The competence questions are reference for the validation of the approach.

4.1 Literature Review

A literature review is conducted to identify existing product data MDM. For this purpose, the online platforms *Scopus*, *Web of Science*, and *IEEE Xplore* are searched. In addition to fundamental models, four models are identified and included into further analysis.

OntoSTEP is an ontology that semantically represents STEP concepts as concepts and relationships. It focuses on meta-data elements of STEP, i. e., the semantic description and integration of product data. OntoSTEP describes how the product is specified and provides formal semantics that make the model expandable. With respect to ADR capabilities, an extension is possible. [18,19]

The **Ontology Intelligent Master Model (OntoIMM)** is a formal ontology model for the structured, consistent, and cross-system mapping of product and process knowledge [20]. In order to overcome the arising limitations of CPM at this point, YU ET AL. introduce CPM+ in context of OntoIMM. A significant extension of this approach is the addition of *Parameters* and *ParameterRelationships*, which enable paramerization of products more concretely [20]. The **Common Data Model (CDM)** follows a similar parameter approach. The CDM is a neutral parameter and data model that contains semantic design parameters that are necessary, for example, to link CAD models [21]. However, the CDM not only stores this geometric product data, but also non-geometric functional parameters and constraints [21]. This means that ADR-related capability data, for example, can also be modeled here.

The **Product Semantic Representation Language (PSRL)** by PATIL et al. is an ontology-based, formal representation language that enables semantic interoperability between different systems in product engineering. In PSRL, product information such as objects, assemblies, specifications, and their relationships are modeled in a structured and semantically explicit way. A key feature of PSRL is that product information is formally modeled using description logics. [22]

Further identified publications demonstrate the expandability or use as a basis for these fundamental models. For example, FIORENTINI et al. use CPM and OAM to develop an ontology for representing assemblies with the Web Ontology Language (OWL) [23]. The authors describe CPM as a particularly generic model that forms a basis for further developments [23]. In this context, OAM ensures extensibility to assemblies [23]. In another paper, FIORENTINI et al. also point out the good basis of CPM and emphasize that OAM encompasses both the assembly as a concept and the assembly as a data structure [24]. This multitude of mentions proves the reusability and extensibility of the models.

The models identified in the literature review are evaluated in terms of their requirements fulfillment. In particular, gaps are identified in terms of "describing product related processes". The mapping of joining or separating processes and capabilities is an extension that is insufficiently covered in existing models. At the same time, however, the literature review also showed that a large number of models can be expanded. Existing models can be used to describe products using meta data models or ontologies.

The evaluation reveals that OAM provides the best foundation for the present purpose. It fulfills almost all requirements. The mapping of capability-related product features for ADR processes is fulfilled to a limited extent. At the same time, other approaches only provide partial solutions for R10. Because OAM is essentially based on CPM, these two models are used as the basis for further development. The essential elements, above all the "artifact" concept, are adapted. The following section presents the developed product MDM and explains the parts taken from OAM and CPM.

4.2 The Product MDM

The extended product MDM is based on fundamental literature revealed in the literature review. The model essentially incorporates elements of CPM and OAM. Due to their focus on product data and insufficient mapping of ADR-process-related capabilities, CPM and OAM need to be further developed and linked to other MDMs for process and capability description. Overall, the developed MDM provides answers to the research question. The following Figure 1 shows the entire product MDM using the graphical notation of a class diagram. The classes based on the existing models are highlighted according to the key. According to the CPM, the top-level element is the *artifact* [13]. This can be a complete product, as well as a *subassembly* or a single *part* of it. Various properties can be assigned to the *artifact*, such as *function*, *feature* or *form*. For instance, *form* can in turn be divided into classes such as *material* and *geometry*. Each class of the MDM is described with various attributes. For example, the *material* of the *artifact* is specified in more detail by its density and mass. With regard to linking product data to ADR capabilities, this data is important, for example, to ensure that a person is able to lift the product (artifact) with its mass. The same check is conceivable with regard to the *geometry* class. Here, it must be ensured that, for example, arm spans, i.e., physical body characteristics, are sufficient to grip the product securely. In general, the *artifact* also has additional meta data that is recorded in *specifications*. Assembly and disassembly instructions are particularly relevant with regard to ADR processes, which are subordinated to the *specification* class. The classes *part* (system element) and *assembly* (subassembly) are based on the OAM [15]. The *part* describes the lowest possible level on an *artifact* [15]. Each *assembly* consists of at least one *part*. In the MDM, we adopt the concept of the *OAMFeature* from OAM, which is a subclass of the *feature* from the *artifact*. A feature is a unit of an *artifact's* form that serves a specific function such as assembling [13]. Each *AssemblyFeature* is an *OAMFeature*. The *AssemblyFeature* is defined here as a property of the product (part, (sub-)assembly, or artifact) that is deliberately created by the engineer to connect it to another product (part, (sub-) assembly, or artifact). Accordingly, the link to the *connections* class follows: An assembly feature enables a connection.

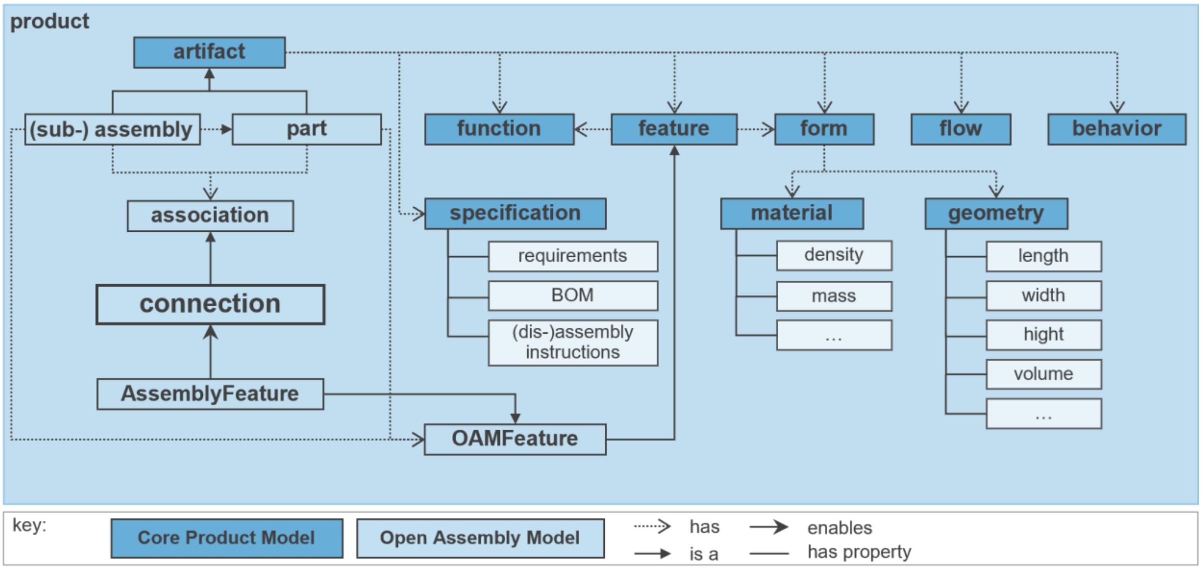

Figure 1: Product MDM based on elements of CPM and OAM with added “connection” concept

Figure 2 shows a detailed excerpt of the developed MDM presented in Figure 1. Exemplary human capabilities describing resources for ADR processes are focused. Different classes within the product MDM require access to resource-related information in order to support their interpretation. The exemplary resources described are various human characteristics from which human ADR capabilities are derived directly or indirectly. Various elements of the product MDM require capability information of resources. An *artifact* can have various *specifications*. In figure 1, for example, assembly and disassembly instructions are listed. In order to understand and implement these, humans need certain *mental capabilities*, which have to be linked to the product model. *OAMFeatures* and its concretization as *AssemblyFeatures* serve to connect two artifacts. When focusing on human capabilities, mental capabilities need to be represented to identify and understand required types of connections.

Accordingly, *mental capabilities* of human are required to understand the type of *connection* and to implement it using the correct joining process. This is especially true when such a connection needs to be properly resolved. Linking the classes of product MDM with *mental capabilities* makes it possible to query whether a person has these capabilities. The *connection* class is directly linked to the *mental capabilities*. The capability model must contain information about the processes that a resource,- including a human - must fulfill. These capabilities also include so-called *domain knowledge*, such as *material knowledge*, which ensures the correct handling of the product and the materials used in the process. In addition to capabilities in the traditional sense, certificates may also be relevant. In industrial field, for legal reasons, the statement “The employee is allowed to do this” must be equated with the statement “The employee is capable of doing this.” In other words, an employee can only do something if he or she is legally authorized to do so. The employee needs necessary certificates and training for machines and equipment for all required joining and separating processes. As an example, the *material* (attribute: mass) is linked to *certifications acquired*, to ensure that the employee is able to handle the mass of the product. Therefore, a capability model must contain such information about certifications of employees.

In addition to these mental and legal capabilities, physical conditions must also be verifiable. As already indicated in the description of the product MDM, this is exemplified by *body characteristics* which is a subpart of the *physical capabilities*. A component with a specific geometry requires corresponding physical characteristics in humans to ensure that this component can be moved. As an example, it must be ensured that a person is able to handle the mass of a artifact. Here, a link to *certifications acquired* is also necessary to ensure that the person is allowed to lift the mass.

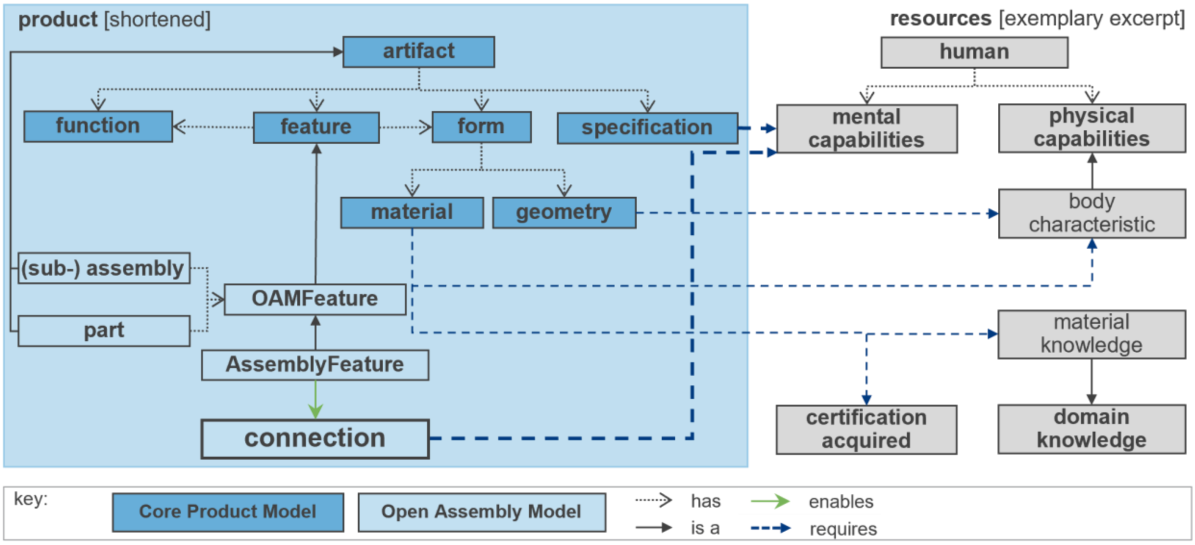

Figure 2: Excerpt from the product MDM, linked to high-level human capability concepts

According to BAYSAL et al., a connection represents a physical connection between two artifacts [15]. A person needs the capabilities and body characteristics to be able to use the connections or the underlying processes and tools. By that, the person is able to understand and handle the artifact. This statement makes it clear that, in addition to the precise description of the product, other aspects must also be considered. These include both the linking of meta data with available capabilities and the ADR-processes for fulfilling the connections within the product.

Figure 3 shows an excerpt of the developed product MDM with the focus on linking the connection to assembly or disassembly processes. There are various ways to join or separate connections. Therefore, joining and separating processes must be analyzed to determine boundary conditions that apply to the processes to be used. For example, the assembly and disassembly processes associated with each connection must be defined. In particular, disassembly cannot be assumed to be the reverse of the assembly process. Therefore, information about assembly, disassembly and re-assembly processes must be linked. The *connection* class enables this link. In line with the ADR capabilities, the process model indicates the *assembly process* and *disassembly process*. The link to a process model via the *connection* class is essential. A process must contain the specifications of assembly and disassembly processes. This includes, for example, the joining or separation process, the necessary tools, the process parameters and the safety requirements.

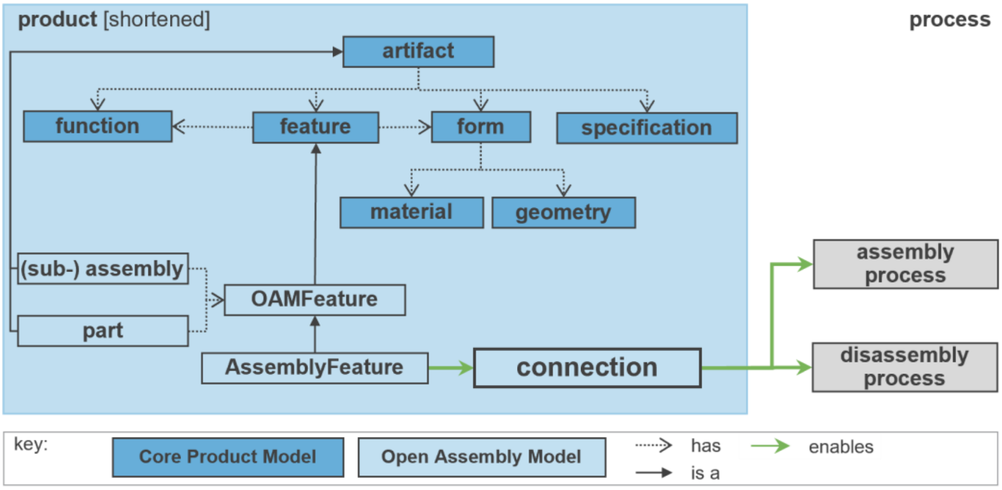

Figure 3: Excerpt from the product MDM, linked to ADR processes

4.3 Validation of the Approach

In an expert workshop, the foundations for requirements and competence questions relating to the MDM were established. The experts were five research associates from the field of product creation. The description of the product MDM and Figure 1 of the MDM shows that the MDM meets requirements R01 – R06. By describing the *connection* class and its ability to be linked to a process model, the requirements R07 and R08 are also verified. The descriptions of *specifications* and *features* showed that the MDM maps product features relevant for assembly, disassembly and capability-related ADR processes (R09, R10). Therefore, the MDM fulfills the prerequisites for validation. To validate the MDM, it must be able to answer these competence questions. Each of the five competence questions is answered based on the MDM:

<u>What is the {size, mass, form} of the product?</u> The size, mass and form of the product (artifact) are specified in the model. Each *artifact* has a *form*, which in turn has a *geometry* and a *material* (c.f. Figure 1). The *geometry* class includes attributes such as maximum length, width, and height. The *material* class has the attribute *mass*. In addition, each material also has the attribute density. Together with the volume, the mass can always be determined. This information is available for queries regarding handling.

<u>What ist the {surface texture, material} of the product?</u> The surface texture and material can also be accessed via the *form* of an *artifact*. The *material* class is subordinate to the artifact. As described above, this class can be linked to, for example, human *material knowledge* with all its associated attributes. If information about surface texture is relevant in the context of handling, information from assembly/disassembly instructions is also recorded in the *specification* class of the *artifact*.

<u>What joints does the product contain?</u> Each part or (sub-)assembly is an *artifact* (product). A part or (sub-)assembly can in turn have an *OAMFeature*. An *OAMFeature* is a joint option purposefully created by the engineer and clarifies how this joint must be created. The *OAMFeature* in an assembly is an *AssemblyFeature* and enables a connection, the type of which is described.

<u>Which human capabilities are required for (dis-) assemble the product?</u> The required human capabilities for (dis-) assemble the product are defined by the joining and separating processes of the product. These are included in the *connections* of the *artifact* (product). In figure 2, for example, the *connection* is linked to the *mental capabilities* of a human.

What connection type does the product provide for ADR processes? Each *artifact* (product) has a *connection* which enables a physical connection to another artifact. This *connection* and their properties enable the link to ADR processes.

The workshop discussion revealed that all required information can be found in documents and models such as (dis-) assembly instructions, CAD models, or system models. This information and their meta data can be mapped to the product MDM that has been developed. For example, meta data from assembly instructions are mapped in the *specifications* class and are found by corresponding queries. This way, the information can be used to ensure the assembly and disassembly of the product and extreme data become usable.

5 Conclusion and Outlook

This paper presents an identification and evaluation of MDMs for product data that contain assembly-related data. The aim is to use this MDM to enable DfADR in product engineering by structuring assembly-related data and enabling engineers to think ahead of ADR tasks and handle extreme data. The literature review reveals a range of established models for general product data and identifies a gap in consideration of ADR process- and -capability-related data within product MDMs. Based on CPM and OAM, this paper proposes mapping concepts enabling retrieval of necessary capabilities to join or separate physical connections between artifacts. A fundamental condition is the existence of the required capabilities for ADR processes. Two fields of action are solved to enable ADR processes in product creation: First, the *connections* of the *artifact* must be linked to the mental and physical capabilities of the employees. These must be separated into assembly and disassembly. Second, each *connection* of the *artifact* must be linked to a (dis-) assembling process. These must be fulfilled to contain and use assembly-related extreme product data in the MDM.

The application-oriented structuring of product data is the first step to enable engineers for DfADR, support them through a hybrid decision support and make the Circular Economy feasible. The developed MDM offers advantages in managing extreme data by creating structured, consistent and contextualized information spaces. It also facilitates hybrid decision support and optimizes data management simultaneously. Looking ahead, the developed MDM will form the basis for the development of an ontology. This will be the foundation for hybrid decision support, which combines methods of DS/AI approaches and classic engineering methods.

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