Enabling Extreme Data by using DS/AI approaches: A Process Metadata Model to link Assembly Features and required Human Capabilities

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Abstract

Design for Assembly, Disassembly and Reassembly (DfADR) prepares for high levels of material circularity in terms of repair and remanufacturing. The intention of reassembling products and their parts implies that inspection and sorting need to be integrated with value-conserving objectives. Further, disassembly and reassembly require higher competence levels of workforce than assembly. To provide the required information during engineering, a metadata model (MDM) is required that links established product models to capability models. Since processes to be carried out for realizing a product largely determine required employees' capabilities, the proposed approach uses the ADR process domain to connect product and capability domains. The research is based on a systematic literature analysis to identify existing approaches regarding MDMs of ADR processes. Based on the results, an integrative MDM is developed that answers defined competence questions. The model enables queries which support engineers by feedback on which skills are required for a product. This builds up a basis to check whether required skills are available in the manufacturing company, either early in product engineering or later in ADR planning.

Keywords:
metadata model, capabilities, reassembly, disassembly

1 Introduction and research questions

Design for Assembly, Disassembly and Reassembly (DfADR) prepares for high levels of material circularity in terms of repair and remanufacturing by recycling products on a higher product hierarchy level. The intention of reassembling products implies that inspection and sorting need to be integrated with a value-conserving objective. Potentially, the originally planned disassembly processes cannot be carried out due to damage, for example, which is why further, partially even improvised processes are carried out. This means that employees need advanced skills to solve the problem. Therefore, it is necessary to know the required capabilities of employees and tools to enable disassembly and reassembly of products and their components [1]. Further the capability based task assignment improves the productivity during the ADR processes. [2,3] Data from engineering is evaluated to provide the necessary information during engineering. ADR relevant data may be extreme due to different sources and applications of data within the production environment. Extreme data is characterized by its origin from distributed sources, heterogeneous formats, high volume, unknown quality, errors and gaps, or different languages to a degree which makes previous technologies fail[4]. The processing of extreme data requires Data Science and Artificial Intelligence (DS/AI). The preprocessing of data to fit specific structures is required in order to analyze the data and extract information by means of DS/AI. In this case, a MDM is required which links an established product MDM based on the Open Assembly Model

International Symposium on Hybrid Intelligence in Product and Production Engineering, March 24–26 2026, Paderborn, Germany

(OAM) [5], to capability MDMs. A MDM for the ADR processes is useful to represent the necessary information, as it is dependent on the product which defines the boundary conditions like, for instance, the product structure or the type of joint. Special employees' capabilities are also required to carry out the processes, which are influenced by the parameters of the processes and the tools used. For this reason, the existing models are analyzed to develop a MDM which meets the required ADR-processes and characteristics. To develop a MDM that links assembly features with required human capabilities, the following research questions needs to be answered: *Which granularity of details needs to be modeled to match assembly features to the capabilities of employees and tools (RQ1)? Which expansions are needed for existing process MDMs to enable the mapping between the product and the resource domain (RQ2)?*

The paper is structured as follos: starting with a description of the research methodology a literature analysis is performed to identify related work. Based on the findings of the literature analysis approaches is proposed. The concept is then verified and validated regarding the fulfillment of the requirements and the related competence question. The results are finally discussed regarding the research questions.

2 Research Methodology

The development process of the MDM is divided into six steps. First, requirements are defined regarding the linkage between capabilities and assembly, disassembly and reassembly (ADR) processes. Within an expert workshop with five experts in the research field of product creation, the defined requirements are validated. The Requirements were used to derive competence questions jointly in the workshop. Existing approaches within the subject area are identified by systematic literature analysis. The identified approaches are analyzed regarding the fulfilment of the defined requirements. Based on identified key elements from existing approaches, a new MDM is developed by analyzing existing approaches and creating the MDM which fulfills the defined requirements. The validation of the MDM is based on competence questions in reference to the validation of the Ontology Engineering Methodology (OEM) [6].

3 Literature analysis

The objective of systematic literature analysis is to identify related work, validate requirements, understand shortcomings and extract applicable contributions regarding RQs. To define targeted search strategy problems and opportunities, stakeholders as well as the focus of later MDM application are detailed in an expert workshop to define a targeted search strategy. Results are documented in the form of requirements (see table 1). The requirements cover the interdependencies of assembly, disassembly and reassembly processes to the required tools and resources. Furthermore, the tools used and the environment must be described to cover the needs of specific certifications or other requirements of the resources like human capabilities. The requirements were used to derive competence questions. The derived competence questions are used to validate the MDM and cover the main groups of requirements (see table 1)

Table 1: Requirements and competence questions of the MDM

Requirements	
ID	**Description**
R1	The MDM must map the joining processes required for assembly activities.
R2	The MDM must represent the interdependence between remanufacturing processes and reassembly processes.
R3	The MDM must map the separation operations required for the disassembly process.
R4	The MDM must map the dependencies between single joining operations.
R5	The MDM must map the constraints from joining operations for separation operations.
R6	The MDM must represent the process characteristics of the joining operations.
R7	The MDM must represent the process characteristics of the separation operations.
R8	The MDM must represent the boundary conditions dependent the assembly system.
R9	The MDM must represent the necessary tools and resources.
R10	The MDM must reflect the necessary workplace safety regulations.
R11	The MDM must represent the interdependence of quality assurance processes and reassembly processes
R12	The MDM must map inspection processes with the necessary checking parameters of the product.
R13	The MDM must map the assembly activities to the relevant product characteristics.
R14	The MDM must map the process characteristics to the capability characteristics.
R15	The MDM represents the interdependence between the processes and the required capabilities of the resources.
R16	The MDM represents the interdependence between processes and mental and physical capabilities.
Competence Questions	
ID	**Question**
CQ1	Which joining processes are required for the joint connection?
CQ2	Which separation process is required for the joint connection?
CQ3	What process parameters must be observed for the joining process?
CQ4	What process parameters must be observed for the separation process?
CQ5	What tools are needed for ADR processes?
CQ6	What quality control processes are needed?

Systematic research is conducted in scientific databases, including Web of Science, IEEE Xplore, and Scopus, to identify related approaches. Therefore, the following search string is derived which is based on keywords of the requirements and got refined using the keywords of publications of the initial analysis.

assembl AND product AND process AND (onto* OR metadata model OR MDM OR taxonomy)*

The search identified 1063 publications. After manual filtering by title and abstract, 35 publications are analyzed, resulting in 9 which are relevant for further evaluation. The analyzed approaches build three clusters. The first cluster contains approaches which represent assembly tasks and the required resources. The approach of LEE et al. [7] describes a MDM that represents the tasks required to assemble a product with regard to capabilities of a collaborative robot. Within the model, the individual assembly tasks are represented as combined tasks based on the assembly features. These are described at the lowest level by atomic actions that correspond to the basic movements of Methods Time Measurement (MTM). The publication of HASAN focuses on the representation of the assembly system to improve the assembly planning process [8]. The focus of the approach is on the representation of necessary manufacturing processes and the required resources. In addition, the processes are differentiated into joining processes and handling processes. The handling processes are to be equated with secondary processes. DAS and SWAIN [9] present an ontology which describes a collection of joining processes. The information of the ontology consists of materials, products, joining processes and requirements of the joining processes. Based on the knowledge a 5-step process to analyze CAD models is described. The identification of the required joining process builds on automated rule-based systems. The approach of CLAEYS et al. [10] represents the manual assembly process by a context model using assembly instructions and further information about the context. The context information contains the locations, the people involved and further objects. The interdependencies between the objects are modeled to represent the influence of the object's condition to process and experience of the employees.

The second cluster contains approaches which represent a mapping of the product, process and resource domain. The focus of the approaches is the representation of required capabilities regarding assembly processes. The publication of GHANJAOUI et al. [12] describes reusable modeling elements from model-based Systems Engineering. The modeling elements are used to link design and assembly concepts. It aims to link the product architecture to required capabilities of the employees. The transfer of the modeling data is enabled using a MDM, which is used to develop ontology. In JÄRVENPÄÄ et al. [13] a approach is presented to model production resources and their capabilities. The capabilities consist of simple capabilities, combined capabilities and competences. The selection of resources is based on the comparison between the requirements and capabilities. Further the approach of FERRER et al. [14] aims to link data of different engineering disciplines. The linked data includes data on processes, products and resources. The developed database is used to configurate automated assembly systems. To configurate the required resources the product and process data is analyzed. Based on the findings the resources are configured to meet the requirements.

The third cluster contains approaches which represent assemblies and their assembly systems. In BAO et al. [11] an approach is described which addresses the development of a ontology to represent the digital twin of assembly workshops. BAO et al. focus on the required resources of assembly processes, for example tools, auxiliary materials and human resources. The developed ontology enables the processing of relevant data. The publication of KIM et al. [15] describes an approach to represent ontology-based assemblies. The ontology is built with a hierarchy of assembly and joining concepts. The approach aims to improve the collaboration during the design of assembly models. The findings are used to model the foundation for the interdependence between processes and the required information of the product structure as well as necessary properties.

The literature analysis reveals existing approaches for MDMs in subject areas like assembly automation, assembly priority graphs and the description of the capabilities of collaborative robots. However, there is a lack of MDMs that link the ADR processes in relation to product features and required capabilities. Both assembly and disassembly processes must be considered to determine whether all the human capabilities required for the necessary ADR processes are available. The evaluation matrix (table 2) reveals that the existing MDMs are not capable to represent the required information to identify the needed capabilities for ADR processes. The requirements R3, R5 and R7 which are in the process category are not fulfilled of any identified approach. As shown in R3 and R5 none of the identified approaches cover the separation operations and their process characteristics. In addition, the interdependencies between joining and separation operations (R5) are missing but are essential to identify required capabilities of the separation operations because there are multiple possible separation operations linked to one joining operation. Further the requirements R10-R12 are not fulfilled by the approaches which show that the required safety regulations of the workplace (R10) and the quality assurance processes are not represented. Therefore, fundamental literature and regulations are analyzed to develop a process MDM which satisfies the requirements.

Table 2: Evaluation matrix of the identified approaches

● - fully addressed ◑- partially addressed ○ - not addressed		BZY+21 [11]	CHS+18 [10]	DS 22 [9]	FAV+16 [14]	GBB+24 [12]	Has 24 [8]	JLL+11 [13]	KMY 06 [15]	LZL 24 [7]
Processes	R1	◑	◑	●	●	●	●	◑	◑	○
	R2	○	○	○	○	○	●	○	○	●
	R3	○	○	○	○	○	○	○	○	○
	R4	○	○	○	○	●	●	○	○	○
	R5	○	○	○	○	○	○	○	○	○
	R6	●	○	●	○	●	●	●	●	○
	R7	○	○	○	○	○	○	○	○	○
Resources	R8	●	◑	○	◑	●	●	◑	◑	●
	R9	●	●	○	○	●	●	●	○	●
	R10	○	○	○	○	○	○	○	○	○
Quality	R11	○	○	○	○	○	○	○	○	○
	R12	○	○	○	○	○	○	○	○	○
Interface	R13	◑	●	●	◑	●	●	●	●	○
	R14	○	●	○	◑	●	○	●	○	●
	R15	○	◑	○	○	◑	○	◑	○	○
	R16	○	◑	○	○	◑	○	○	○	○

4 Concept

Connecting the product domain to the resource domain needs the required ADR processes during the assembly of the product: The process parameters as well as the type of process define the required domain knowledge as well as the physical and mental capability needed. The relationships are based on fundamental assumptions of human-centered assembly planning. [3] The product MDM represents the product structure, features, specifications and the form of the product [5]. The resource MDM represents the capabilities of the resource, in this case the human resource. It includes domain knowledge, physical capabilities and mental capabilities. The process MDM represents a concept which links the product to the resource model (see Figure 1). The matching of the MDMs is based on the required ADR processes which are determined by analyzing the assembly features of joining operations [16] and separations operations [17]. Relationships that are transferable to other classes are not shown in the figures.

On the first level of the mapping MDM, a distinction is made between ADR processes, remanufacturing processes and the environment. The environment describes, for example, the operating resources and the assembly workplace. The ADR process is detailed by the assembly process and the disassembly process. These types of processes are further subdivided to the level of the single operations (see figure 2). The remanufacturing processes [18] instead describe processes which are a subset of different classes like ADR-processes and quality control processes. The additional allocation is used because the processes must fulfill special requirements because of the variation of the initial product quality compared to unused components. For this reason, the class remanufacturing processes has the „contain"-relation to operations for example disassembly processes or inspection. On the lowest level of the ADR processes the processes and the required capabilities are linked. The capabilities in this case are limited to the human capabilities and are differentiated in physical capabilities and mental capabilities. These capabilities must be further subdivided to get matched to specific processes. The processes contain the necessary data which must be queried in case of testing if the resource is capable to carry out the process. Besides the process parameters the processes must contain a description which implies information

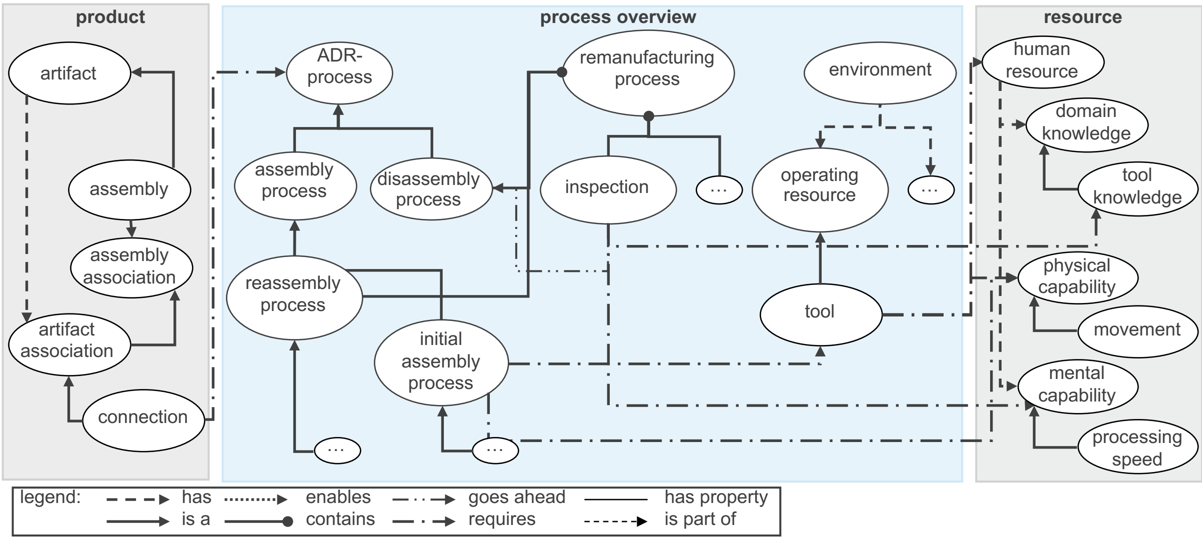

Figure 1: Overview of the process MDM

regarding mental capabilities.

In Figure 2, a focused view on ADR process and the interdependencies between the domains is presented. Based on the connection from the product model, which deploys the information of the used joining technology, the ADR process are determined on the product side via the "requires" relation to the connection. This provides information such as the type of connection and basic parameters. The ADR process of the MDM is subdivided into the assembly and disassembly processes. These are subclasses of the ADR process and are associated with the subclasses "separation operations" in case of the disassembly process. The assembly process needs to be differentiated between the initial assembly and the reassembly, because of varying inspection requirements. The initial assembly process is based on new components which implies less needs for additional quality control processes. The distinction is based on the initial state of the components to be assembled. The reassembly process instead has a different set of linked quality control processes to guarantee a good quality of the products. That means

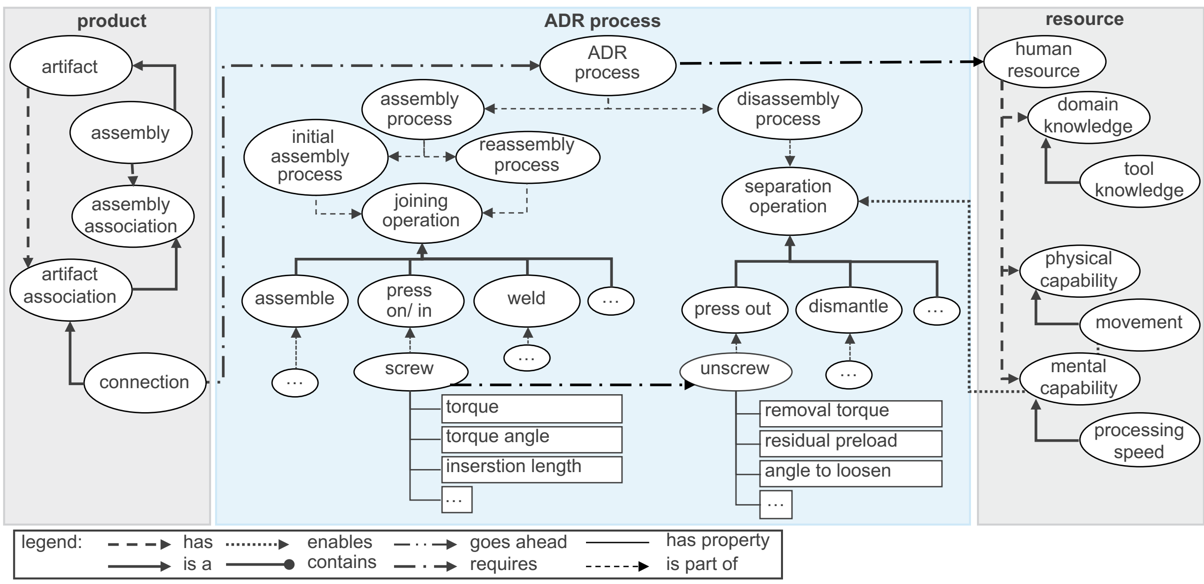

Figure 2: Detailed representation of the ADR-processes of the process MDM

in case of the reassembly processes the identical joining operations must be processed in combination with additional quality control processes.

The assembly process and the disassembly process are divided into joining and separation operations which are individually further subdivided. The individuals of the operations are linked to the required capabilities. The differentiation between manufacturing processes is based on DIN 8580 [16,19], the further differentiation of the assembly processes and the used methods are based on DIN 8593 [16] and the disassembly processes are described by DIN 8588 [17] and DIN 8589 [20]. To identify necessary properties of the joining and separation operations, basic literature from the production domain is analyzed. The screw operation is described by attributes like torque, torque angle and insertion length. Components that have already been used may require additional processes to be carried out to obtain a product of the same initial quality as in the initial assembly.

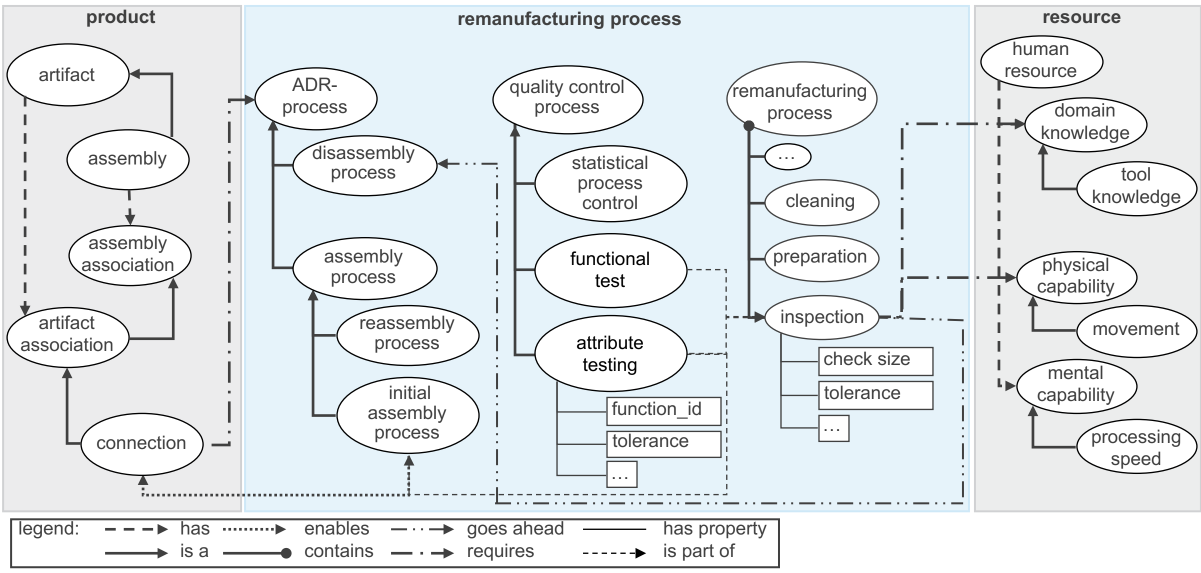

Figure 3: Detailed representation of the remanufacturing processes of the process MDM

The interdependence between the remanufacturing processes to the quality control processes and the ADR process are represented in figure 3. The remanufacturing processes are defined based on CHATTI et al. [18] and are limited to the processes which can be allocated to processes which were defined by the author and reach from the collection of products to the re-commercialization. It consists of ten steps including, for example, sorting, testing, cleaning and inspection. The developed MDM only contains seven of the ten processes, which include the manufacturing processes and excludes logistical and business processes. Each process has its specific requirements to the capabilities of the resources. Besides that, quality control processes are described which subsets are linked to specific ADR-processes. The processes which are linked by the "contains"-relation to the remanufacturing process are a subset of the higher-level classes "quality control processes" and "ADR processes". Contained processes require in this case a differentiation of capabilities than during the manufacturing of regular products. This implies that die employees need to have more developed mental capabilities, because of the high variety of the initial state during the manufacturing process. The identification of the intial state is the reason that the inspection is needed before disassembling the product. The definition of the inspection for this approach is based on the defintion of CHATTI et al. [18].

The inspection is the process to ensure that the product or the process meets the requirements and detect the faults. In the inspection, different kinds of quality control procedures are applied, such as visual analysis or a measurement of the check size. The inspection is central part of the remanufacturing processes and requires specific capabilities of the employees. In addition the subsets of the quality control processes are definied and related to the ispection by the "is part of"-relation. The different processes are also linked to specific ADR processes with the same relation due to the fact that the employees have to control different properties during the process. In figure 4, the environment is illustrated. In addition to the actual processes that require certain employee capabilities, the objects in the process environment also place demands on employee capabilities. The objects in the environment include the tools to be used, but also the actual assembly workplace. In the case of the tools used, the properties of the tool place demand the physical skills of the employees, for example, due to weight. In addition, domain knowledge is required from which the employee recognizes and applies the appropriate tools, but also has the authority to use the tools [21]. The selection and application of tools in disassembly also represent a special requirement. This is because, for example, a connection cannot be loosened due to rust, and the employee must recognize which tool needs to be used instead. As shown in Figure 4, a “requires” relation is used to connect the product structure to the required tool. The specification of the connection defines the properties of the tool. This also specifies central parameters of the tool, such as the tightening torque or the wrench size in the case of a screw connection. Therefore, the class “tool” also is connected by the “requires” relation to the domain knowledge, more specific the tool knowledge. The tool knowledge in this case describes the knowledge about the safety instruction for using the tool as well as the key properties that might have to be adjusted by the employee, for example the tightening torque of the torque wrench. Also, the employee must be capable of using the tool regarding physical capabilities, for example the movement of the tool which depends on the weight.

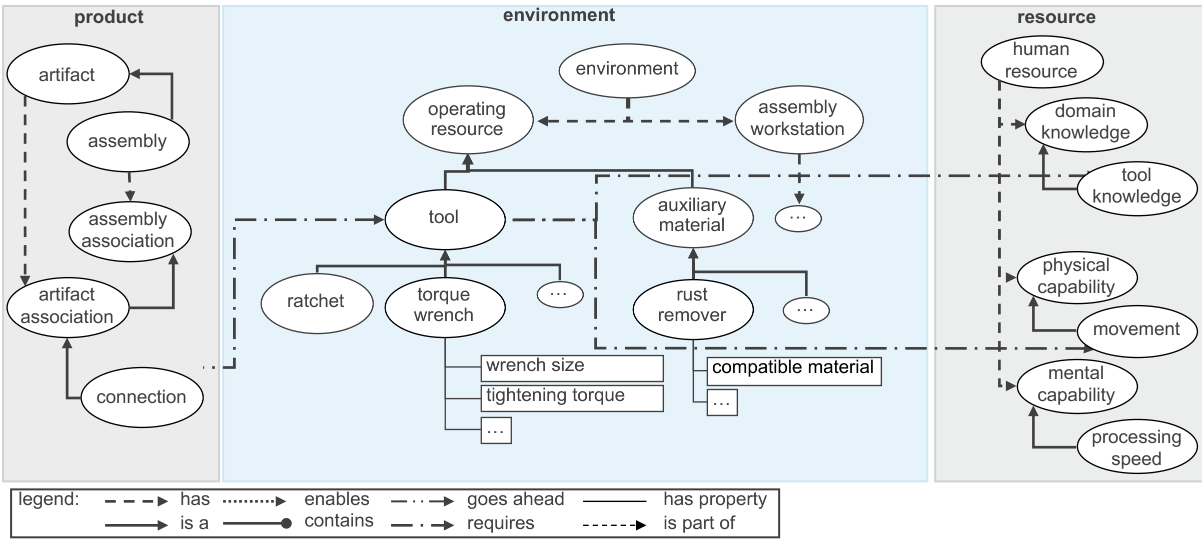

Figure 4: Detailed representation of the assembly system of the process MDM

5 Verification and Validation of the MDM

Based on the requirements, the developed MDM is verified. As shown in Figure 2, the MDM represents the separation processes, their properties and the interdependencies which fulfill the requirements R3 and R5. Also, the quality assurance processes and their properties are represented as shown in Figure 3. The MDM is validated according to the ontology engineering methodology [6] using the competence questions. By answering the competence questions, it becomes clear whether the MDM contains all the necessary information for the use case.

Which joining processes are required for the joint connection? The competence question is answered by the “require“ relation between the class “connection“ and the class “ADR processes” and their subclasses. The class “connection” contains the necessary information within their properties for example the instance of the connection has the property “connection type” with the value “screw” then the class “screw” is connected by the required relation.

Which separation process is required for the joint connection? The competence question is answered by two different queries. The first possible query uses the relation between the joining operation and the associated separation operation using the relation "require" between the classes. The second possible query is the direct path between the class "connection" and the subclasses of "separation operation".

What process parameters must be observed for the joining process? The necessary information is defined on the product domain and are associated with the class "connection". Due to the connection between the instance of class "connection" to the instance of the subclass "joining operation" the necessary is information is accessible.

What process parameters must be observed for the separation process? The necessary information is accessible by two different queries. The first query uses the relation of the class "separation operation" with the class "connection". The second query is possible using the relation between the instance of the subclass of the "joining operation" and "separation operation"

What tools are needed for ADR processes? The competence gets answered by the association between the instance of the subclass of "joining operation" or "separation operation" and the instance of the subclass "tool". The subclasses of ADR-processes are described by the property „tool name" which defines the class of the tool. Further information which defines for example the size of the wrench is associated to the class "connection" and the "ADR process".

What quality control processes are needed? The competence question is answered by the relation of the instances of the subclasses from the "ADR processes". Every Instance of this subclass has specific relation to instances of the class "quality control processes". In addition, in case of the disassembly processes is the inspection associated with the relation "goes ahead".

In summary, the mapping MDM answers the derived competence questions. The MDM contains all information that are necessary to represent the joining and separation operations and their parameters. The combination of the representation of required tools and quality control processes enables queries to identify required resources. Therefore, the mapping MDM is validated based on competence questions.

6 Conclusion

Evaluating needed capabilities to enable ADR processes by analyzing product features requires a connection between the domains. Therefore, approaches are suitable which use the process domain. The development of the mapping MDM is based on requirements, which were validated within an expert workshop. The workshop is also used to define the competence questions which are used to validate the MDM. The systematic literature analysis shows that existing approaches do not cover all processes and interdependencies which are necessary to derive the required capabilities. The identified approaches were expended to fulfill the requirements and answer the competence questions. Regarding RQ2 the needed expansion includes the representation of quality assurance processes, remanufacturing processes and the interdependence to the capabilities of the human resource. The developed MDM represents the ADR process, remanufacturing process and the environment. The modeled granularity in accordance to RQ1 represents the single instance of the required processes to, for example, screw the product. Therefore, the MDM enables a mapping of the product feature with the required process which then maps the capabilities. The resulting mapping MDM builds a logical structure using the underlying rules which was utilized in a created ontology. The links are used to perform queries that allow the required skills to be inferred for specific product features in form of connections. This relation makes it possible to check whether the required employees' capabilities are available within the company. The paper thus lays the foundation for evaluating employees' capabilities using knowledge-based AI methods such as knowledge graphs.

7 Acknowledgement

Funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – project no. 543074930 – as part of the SPP 2443 (Hybrid Decision Support in Product Creation, project no. 521148212, www.spp2443.de).

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