Structuring and Provision of Manufacturing knowledge through the Manufacturing Resource Ontology

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Abstract

One challenge in manufacturing-integrated product development is the accessibility of the required manufacturing knowledge. Here, ontologies offer the possibility to structure and formalize information in the form of a knowledge base in order to act as a generic interface to the manufacturing and design specific systems. This paper describes the development of a generic knowledge base called MARON (MAnufacturing Restriction ONtology) for the structured representation of manufacturing restrictions via formalized manufacturing capabilities. Using the example of an expert system for process element-oriented manufacturability analysis, it is shown how MARON contributes to automated decision support in the context of manufacturing-oriented design.

Keywords

design for manufacturing, ontology, manufacturing knowledge, manufacturing resource, computer aided engineering

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1. Motivation

A production-optimized design includes thinking ahead about the manufacturing process, the necessary machines and tools [1]. Due to the increasing requirements and the manufacturing alternatives, the designers are no longer able to think ahead in detail about various manufacturing processes, although these have a very high influence on the manufacturing efforts and thus ultimately on the costs [2]. As product specification increases, so does the level of detail of the required manufacturing knowledge. Reasons for this include the lack of accessibility to the necessary knowledge, which provides a sufficient description of the manufacturing potentials and restrictions, as well as the difficult access due to different formats of the information and sources [3]. In reality, manufacturing potentials and constraints are usually taken into account by experience from previous designs, which means that novel manufacturing possibilities are not considered. In addition, different perceptions of a technical component as well as its characteristics by all parties involved complicate the exchange of knowledge. This is due to inconsistencies in the semantic and syntactic description of product models and different ways of thinking (product function-oriented and manufacturing process-oriented) [4]. To overcome this problem, knowledge-based systems represent an interesting approach to feeding manufacturing knowledge back into product development. These systems basically consist of two components: a knowledge base and a problem-solving component that can use formalized knowledge to conclude specific problems [5]. In the context of production-oriented design, manufacturing knowledge is formalized within the knowledge base. This makes it possible, for example, to set up expert systems for analyzing the manufacturability of products, which can identify manufacturing conflicts and provide information on more favorable product designs. In order to make these knowledge-based systems accessible to the designers, common semantics is required.

Ontologies offer the possibility to structure and formalize such information in the form of a knowledge base to act as a generic interface to the manufacturing and design specific systems. Furthermore, ontologies have the advantage to represent dependencies and information of different characteristics and to represent a robust and consistent knowledge base of existing resources. In this context, the links between different manufacturing artifacts are created manually, making maintainability and extensibility difficult.

This paper describes the development of a generic knowledge base called MARON (MAnufacturing Restriction ONtology) for the structured representation of manufacturing constraints via formalized and automated links of manufacturing capabilities. The knowledge base is modeled over an ontology and has a SPARQL interface to query required manufacturing information for design activities and decisions. Using a Process Chain Constraint Network (PCCN) as an example, the integration of MARON to initialize available manufacturing capabilities is described.

2. Theoretical Background and Related Work

Knowledge-based systems are programs that represent knowledge of a particular domain in a knowledge base and use it to solve problems. The structure of a knowledge-based system fundamentally consists of the knowledge base and the problem-solving component [6]. Such systems can support the user in decision-making or situational knowledge provision. Even if the two areas are considered separately, the two are related to each other and provide the framework of the respective component attached to them [7].

An automated adaptation of a product design based on this is also possible with knowledge-based systems [8, 9]. The setup of such systems requires the linking of information and knowledge about manufacturability with product models [10]. A causal linkage is provided by manufacturing induction, which describes the realisation of product characteristics and properties by suitable manufacturing processes [11]. This manufacturing induction is subject to certain limitations, which are, among others, due to the specific manufacturing capabilities of deployable manufacturing resources. This knowledge of manufacturing constraints must be effectively made available to engineers for efficient manufacturing-oriented design. There is a need to include the available resources in the form of machines and tools and their manufacturing capabilities in the process development to design manufacturable products.

In the context of manufacturing technology, there are many developed ontologies for structuring and representing different concepts of these domains. Thereby, the structure of such ontologies strongly depends on their field of application [12]. Thus, ontologies are used for the collection and consideration of resources in the enterprise up to the specific modeling of certain manufacturing systems.

One approach of an ontology-based manufacturing model is provided by the MASON ontology of Lemaignan et al. [13]. The ontology aims at designing a common semantic network for the manufacturing domain. The basis of the structure of the ontology is the concept of integration of products and processes created by Martin et al. [14], which understands manufacturing as the sum of product, process, and resource. The MSDL ontology developed by Ameri and Dutta [15] is used to represent manufacturing services and provides the building blocks to describe a wide range of these services. A manufacturing service is defined as "a set of manufacturing capabilities offered by a supplier". In their work, Sarkar and Sormaz [16] present an ontology model to describe capabilities of machine tools in manufacturing at the process level. The capability of a manufacturing resource is usually stated in terms of the function of the resource. Thus, in this work, the capability notion of a resource, specifically a machine, is not used as a measure of feature dispersion, as is the case in manufacturing engineering. Therefore, in these works, the concept of capability is mostly considered with the basic executability of manufacturing processes of machines or companies and descriptions of executions on the part of robots [17]. An integration of manufacturing restrictions is not considered further or structurally enabled.

In addition, Anjum et al. [4] use ontologies to analyze the manufacturability of engineering components in the early design phases. This is done by developing shape feature-based ontological models of these components and linking manufacturability knowledge to these models. To achieve this, an ontological modeling technique is proposed that uses shape feature-based geometric models of engineering components as building blocks. Furthermore, Li et al. [18] present an ontology-based product design framework for manufacturability verification and knowledge reuse that supports the sharing and reuse of design and manufacturing knowledge. To this purpose, in the previous two papers, a rule base was built into the ontology using SWRL (Semantic Web Rule Language), which allows internal inference for the selection of manufacturing processes. SWRL enables high interoperability, reusability, extensibility, computational scalability, and ease of implementation [19]. The rule base stores two main types of rules, namely inference rules and constraint rules.

3. Problem Analysis and Research Aim

Tailored Forming is a novel manufacturing technology for the production of solid multi-material components. This technology combines joining, forming, and cutting processes in a process chain to produce multi-material components with locally adapted properties. From a lightweight construction perspective, these components are more efficient than monomaterial components [20]. These process chains are characterized by a strongly reciprocal behavior between the individual processes. For the design of tailored forming components, knowledge of these interactions must be taken into account [9]. In addition, knowledge about tailored forming technology is not yet widespread in the industry due to its novelty. To support industrial knowledge transfer, research is being conducted into knowledge-based assistance systems that bundle this knowledge and make it available to users. In the context of Design for Manufacturing, a PCCN is used that enables automated manufacturability assessment of tailored forming components. For this purpose, the tailored forming process chains are considered as configurable design objects. The PCCN maps the manufacturing stages required for the manufacturability evaluation via design features and links these via constraints. On the one hand, this describes the geometric transformations of the manufacturing stages, on the other hand, constraints are used to formally represent material- and resource-related manufacturing restrictions and link them to the models of the manufacturing stages. The consideration of all manufacturing stages necessary for production enables a holistic process chain view, whereby cross-process manufacturing constraints can also be identified and checked [9].

For the development of a PCCN, the interrelationships within a multi-stage tailored forming process chain leading to a specific component shape must be captured and formalized. Due to the complex process chains, the planning and verification of deployable manufacturing resources is more complex than for mono-material process chains. This requires a structured annotation of manufacturing resources within a knowledge base, as this is not possible with the PCCN. This leads to the following research questions:

1. How can manufacturing resources be structured with the help of an ontology to enable a machine-readable formalization?
2. How can the usability of manufacturing resources be identified in relation to concrete manufacturing issues in an automated way?
3. How can deployable manufacturing resources be made accessible for development-supporting CAE environments?

4. Development of the MARON ontology

The MARON ontology is to be used to formally describe and structure existing resources and processes by given properties. With the developed ontology, manufacturing knowledge about existing tools and machines should be integrated into the process development. It should be possible to formally describe the contents and characteristics of manufacturing processes that influence the manufacturing methods. Through the formal description and rule integration, a possible applicability of machines and tools for the realisation of defined process elements is to be concluded and a knowledge base of the available manufacturing resources is to be built up. In doing so, a differentiated consideration of the manufacturing restrictions is aimed. Machines and tools are examined individually for their usability, regardless of their possible configurations. This is followed by a review of an operational machine-tool composition. In this way, process elements that cannot be implemented can be considered in a differentiated manner.

For the development of the MARON ontology, the method according to Noy and McGuinness [21] is used concerning the research questions posed. The ontology development is carried out based on defined steps. Due to the manufacturing-specific restrictions and characteristics for the description of the processes and resources, the methodology is divided into the development of a generic ontology structure and the development of manufacturing-specific content. In this way, a continuous expansion of the ontology and knowledge base is made possible based on a defined ontology structure. Thereby, the manufacturing-specific elaboration of the ontology provides for the instantiation of resources and process elements and the embedding of manufacturing constraints in the form of rules. This is the basis for identifying operational machine-tool compositions for defined process elements. This results in competency questions, which are to be answered with the knowledge base based on the ontology:

- Which resources can be used for which manufacturing processes?
- What properties does a particular resource have?
- Which machines and tools can realize a certain process element?

4.1. Development of the generic ontology structure

Based on the competence questions, the basic structure of the ontology is developed. Here, the ontology must contain information about the characteristics of resources, processes, and classifications of manufacturing processes that are necessary for the description and selection of existing resources in manufacturing processes. The structure of the ontology is based on the product, process, and resource representation of Martin et al. [14], a much-cited basic structure in the field of manufacturing engineering. Based on this, existing components of the Mason ontology by Lemaignan et al. [13] are reused. This includes the basic class concepts of machines, tools and the workpiece representation. The components are extended by the upper concept for the representation and integration of manufacturing capabilities and the processual representation through parameters. The upper concept resource contains the sub-concepts of machine, tool, and also workpiece. The product concept is represented via the workpiece concept as part of the resource concept, as this can be represented as the initial workpiece of a final process step. These three objects thus describe the physical objects that are used in a process element and are therefore related to the associated process elements. The upper concept process consists of the two main elements process chain and process element, for the integration of defined process elements. The process elements are defined in more detail via the resources involved in the form of workpieces and parameter descriptions. A process element is a single element of the process chain and describes an operation to be carried out, such as the forming of a workpiece. The upper concept operation defines all realizable operations that are realized within a process chain. In the context of this work, we will limit ourselves to the manufacturing processes as the basic operation for realizing the process steps. The upper concept of Technology Parameters (cf. [22]) enables a formal parameter description of the resources and processes. Each parameter serves as information for the description of a characteristic of an element and thus for the formal description of the process elements, the capabilities of the machines and tools, as well as the geometric characteristics of the workpieces. The resource-oriented parameters are referred to in the following as system parameters (cf. [22, 23]). The three resource types are also considered separately and described with different parameter types. Thus, the geometry parameters of the physical objects are necessary for the interaction of the active partners between the tool/machine and the workpiece. For the applicability and description of machine tools, the manufacturer data contain important characteristics. In addition, process-dependent parameters are used to describe the process elements. For the process description, process parameters that occur during the process and limit the resource selection must be defined. Furthermore, in addition to the process parameters, the process-dependent control parameters also serve the description. To develop a coherent ontology, the properties of the classes are defined based on the class concepts, from which the coherent structure of the ontology results. The properties include relationships between the classes and basic data properties, such as the manufacturer name of a machine. The data properties are directly attributed to the classes. Figure 1 shows the developed overall concept of the ontology with the basic structure and the main classes: technology parameter, process, operation, and resource.

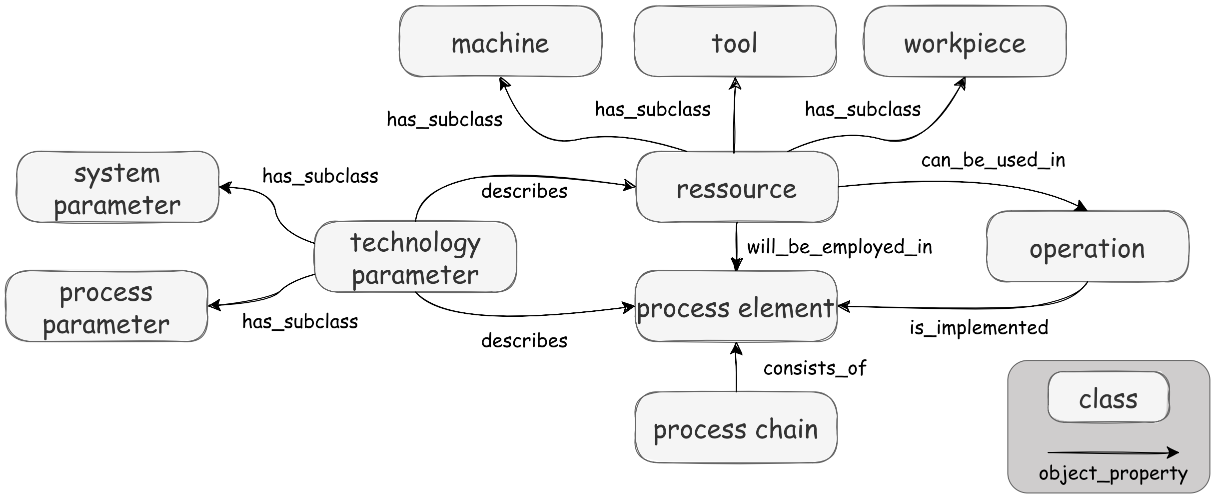

Figure 1.: Representation of the basic structure of the developed MRO ontology

4.2. Manufacturing-specific extension

For the integration of manufacturing constraints into the ontology and to provide resource recommendations for the use of machines and tools in present process elements, the ontology is extended by corresponding manufacturing-specific properties within the parameter classes. Using the example of forward full extrusion, the related punch force, the extrusion force, the stroke, and the internal pressure are defined as data properties of the process parameters. These properties are assigned to the parameter classes and form the basis for the parameter-based inference of deployable machine-tool compositions. For the identification of operational machines and tools in defined process elements, a rule base with manufacturing constraints based on expert manufacturing knowledge is integrated into the ontology. This rule base is based on SWRL, which can be defined directly in the ontology. These are constraint rules of properties or inference rules to derive new information. Based on this, inferences of operational machine-tool compositions can be identified and the consistency of the knowledge base can be checked. For example, for full forward impact extrusion, the comparison of the geometry of the initial workpiece with the die geometry of the extrusion tool is carried out, or, as shown in rule (1), that a machine (?M) must be able to execute a process-specific stroke and execute a required extrusion force to potentially be used for a process element (?PE).

- Rule (1): enablesRealisationOf(?M, Full Forward Impact Extrusion) ^ hasMachineParameter(?M, ?MP) ^ hasOperation(?PE, Full Forward Impact Extrusion) ^ hasProcessParameter(?PE, ?PEPP) ^ hasSettingParameter(?PE, ?PESP) Impact Force(?P, ?FP) ^ Nominal Impact Force(?MP, ?NP) ^ swrlb:greaterThanOrEqual(?NP, ?FP) ^ Stroke(?PESP, ?H) ^ MaxHub(?MP, ?MH) ^ swrlb:greaterThanOrEqual(?MH, ?H) -> canRealiseProcessElement(?M, ?PE)

4.3. Instantiation

After the basic structure has been built and the manufacturing characteristics have been determined in the form of further properties and defined rules, the prevailing resources and processes must be created in the ontology in the form of instances. The creation of an individual instance requires the selection of a class and the determination of the associated data properties and object properties. In addition to the instances for the realizable production processes, instances of the individual resources and processes are created with the associated parameter instances. The instances of the resources are linked to other instances via defined relations and their capabilities are described in terms of production technology with parameter specifications in the data properties, which are entered in the associated parameter instances. In addition, the timeliness of the information on temporary usability must be ensured about current use in existing processes or repair work. Based on this, a virtual machine park is created in which all prevailing machines and tools are formally described by production-specific parameters. Example instances of existing press tools and associated parameter instances are shown in Figure 2. The parameter instances are subclasses of the system parameter class. The tools are arranged in a class hierarchy oriented to the production processes. This results in a knowledge base of prevailing machines and tools, which can be used to determine usable machine-tool compositions for defined process elements when executing a reasoner.

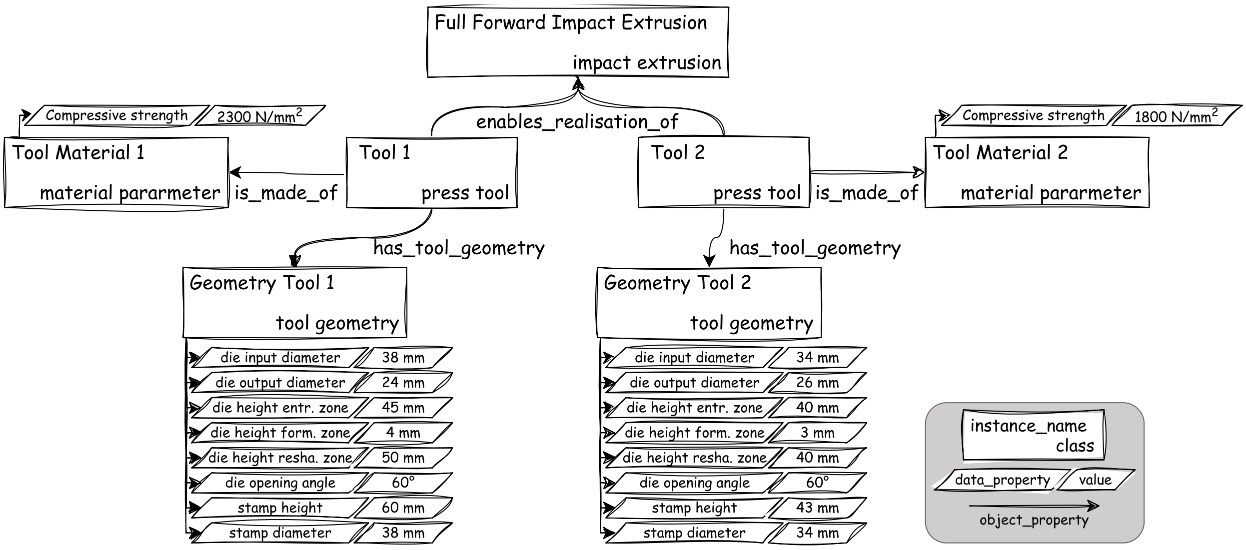

Figure 2.: Implemented instances of press tools

5. Application

In this chapter, the example of a full forward impact extrusion process for forming tailored forming components is used to show how MARON can be used together with the PCCN to enable the manufacturability of a component design. In addition to the general availability of resources (resources are available in the company), MARON can also take into account actualities such as capacity utilization or repair intervals. The manufacturability assessment starts with the PCCN. There, a component design to be examined is loaded as a CAD model and read out via feature recognition. The result of the feature recognition is a feature-based description of the component design. Within the PCCN, these features are linked to features of upstream manufacturing stages according to transformation rules of manufacturing processes to be performed via constraints. The characteristics are mapped in the PCCN as variables with a defined domain (definition range). The resulting constraint network is a formal representation of the manufacturing process and allows the configuration of the manufacturing stages required for manufacturing. If a valid configuration can be found, no constraints are violated and general manufacturability can be established. The PCCN considers manufacturing resources, but the resources are described over several domains, which can be configured independently. Therefore, there is the problem that specific manufacturing resources cannot be mapped because, for example, the specific diameter and a specific length can be assigned to a specific tool together. In this case, linking via constraints is very time-consuming and not efficient. However, this specific tool linkage can be represented by MARON. In addition, MARON can also link tools with associated machines. Therefore, the advantages of the PCCN and MARON can be combined. The PCCN analyzes the general manufacturability and MARON can filter the result by adding relevant information about the availability of manufacturing resources as restrictions. The PCCN provides important information that MARON needs for the specification of tool-machine configurations. This concerns in particular the geometries of the input and output workpieces from a manufacturing process (see figure 3).

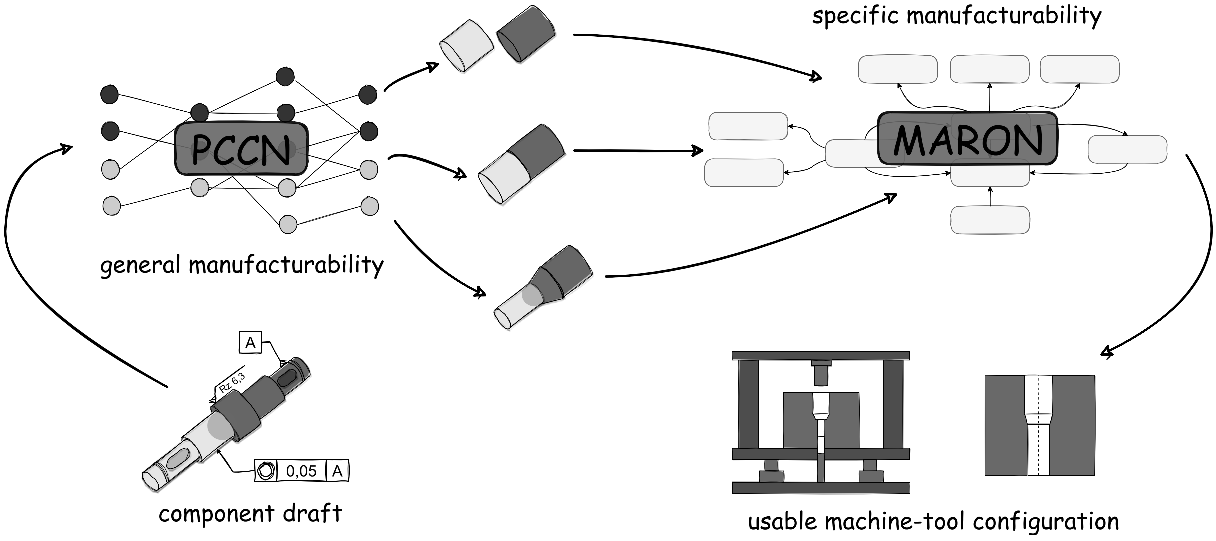

Figure 3.: Integration of MARON

This workpiece information is transferred to MARON via the data properties defined in Chapter 4.2. This process is automated via a Python interface. For this purpose, the library Owlready2 [24] is inserted. If all input parameters are set, the Pellet Reasoner is started. This executes the defined SWRL rules and thus determines the usability of the machines and tools for the implementation of the process element under consideration. The check is multi-stage and within each stage, if there is consistency, new object properties are automatically created between the respective instances. The rules partially build on each other, as inferred object properties are included within the other rules. During the execution of the reasoner, all axioms and facts are automatically checked, and based on this, consequences are derived, such as inferred object properties or errors in case of irregularities are output. Specifically, operational machines and tools are linked to the inferred object properties. In the first check, tools are determined that are operational with regard to the initial workpiece to be manufactured and the process element under consideration. The corresponding manufacturing restrictions are entered in the SWRL rules. If the check is positive, the result is reflected in the linking of the tools with the initial workpiece via the *canPotentiallyProduce* relation and the linking with the process element via the *canBeUsedInProcessElement* relation. Here, the actualities of the production environment, such as maintenance or capacities, are also taken into account. In addition, the stored production restrictions, such as the permissible compressive strength of the tool, are also taken into account at this point. Machines declared as ready for use for the realisation of the process elements are linked with the *canRealiseProcessElement* relation according to the SWRL rule. In addition, analogous to the tools, a machine is linked with an initial workpiece via the *canPotentiallyProduce* relation if this can be produced independently of the process element. Here, too, the rules for manufacturing restrictions are observed. In the case of impact extrusion, among other things, the required press force is compared with the nominal press force of the machines. The next step is to check the design of usable machine-tool configurations. In accordance with the SWRL rule, only previously declared serviceable machines and tools are considered, which were determined based on the checks already described. In this check, machine-tool configurations are formed, which means that in addition to the individual usability of the machines and tools, the compatibility of the machines and tools is also checked. Since within a relation, only one subject is related to an object at a time, the tools and machines are individual via the *PermittedMachineToolCombinationFor* relation with the process element. Accordingly, the affiliation of the machines and tools is still determined in the query via the *canUseTool* relation. All checks can be started via a cascading SPARQL query.

```
PREFIX owl: http://www.w3.org/2002/07/owl#>
PREFIX ref: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX rafs: <http://www.w3.org/2000/01/rdf-schema#>
PREFIX sd: <http://www.w3.org/2001/XMLSchema#>
PREFIX mro: <http://www.semanticweb.org/MARON#>

SELECT ?machine ?process_element ?tool
WHERE{
?machine mro:PermittedMachineToolCombinationFor ?process_element.
?tool mro:PermittedMachineToolCombinationFor ?process_element.
?machine mro:canUseTool ?tool.
}
```

Using several example impact extrusion presses, it was validated that the corresponding inferred object properties are created via the queries and that a machine-tool configuration is finally output. With this method, it is thus possible to select operational machines and tools based on the data and rules entered. Used machine-tool configurations for the realisation of a process element are then linked to the process element via the corresponding object properties. In this way, the ontology develops into a growing knowledge base that can be actively used.

6. Summary and Outlook

In this work, the MARON ontology was used to present a generic ontology structure for the formal description and structuring of predominant resources and process elements in manufacturing technology. Based on this, the ontology was extended by manufacturing knowledge in the form of manufacturing constraints using a forward-full flow process. In this way, ontology-internal conclusions can be used to identify usable machine-tool configurations. The ontology thus enables a building knowledge base on the manufacturing capabilities of existing machines and tools concerning the potential realisation of defined process elements. In the described application, the ontology serves as an interface in a CAE environment and, by integrating formally described process elements, provides potentially deployable machine-tool configurations that influence manufacturability. This enables adjustments to be made in the design process if no resources could be identified and an investment is too large. On the other hand, targeted enhancements in the production environment can also be identified. Furthermore, the knowledge base of the ontology that is being built up can be used for process planning purposes and supplemented by relevant features of these. Thus, the use of machines and tools in complex process planning can be controlled. In the future, an interface to CAPP and ERP systems can be created to automate the maintenance of the ontology.

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References

[1] Ehrlenspiel, Klaus et al.: Kostengünstig Entwickeln und Konstruieren. Berlin, Heidelberg: Springer Berlin Heidelberg, 2014.

[2] Doellken, Markus; Zimmerer, Christoph; Matthiesen, Sven: Challenges Faced By Design Engineers When Considering Manufacturing In Design – An Interview Study. In: Proceedings of the Design Society: DESIGN Conference 1 (2020), S. 837–846.

[3] Ferrer, Ines et al.: Methodology for capturing and formalizing DFM Knowledge. In: Robotics and Computer-Integrated Manufacturing 26 (2010), Nr. 5, S. 420–429.

[4] Anjum, Najam et al.: Manufacturability verification through feature-based ontological product models. In: Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 226 (2012), Nr. 6, S. 1086–1098.

[5] Beierle, Christoph; Kern-Isberner, Gabriele: Methoden wissensbasierter Systeme. Wiesbaden: Springer Fachmedien Wiesbaden, 2014.

[6] Hopgood, Adrian A.: Intelligent Systems for Engineers and Scientists. Boca Raton: CRC Press, 2021.

[7] Giarratano, Joseph C.: Expert systems: Principles and programming. 4. ed. Boston, Mass.: Thomson Course Technology, 2005.

[8] Plappert, Stefan et al.: Feasibility Evaluation of Milling Designs Using Multi-Agent Systems. In: Proceedings of the Design Society 2 (2022), S. 763–772.

[9] Herrmann, Kevin et al.: Process Chain-Oriented Design Evaluation of Multi-Material Components by Knowledge-Based Engineering. In: Algorithms 16 (2023), Nr. 5, S. 247.

[10] Li, Wei D.; Ong, Soh. K.; Nee, Andrew Y.C.: Recognizing manufacturing features from a design-by-feature model. In: Computer-Aided Design 34 (2002), Nr. 11, S. 849–868.

[11] Groche, Peter; Bruder, Enrico; Gramlich, Sebastian: Manufacturing Integrated Design. Cham: Springer International Publishing, 2017.

[12] Sheveleva, Tatyana et al.: Ontology-Based Documentation of Quality Assurance Measures Using the Example of a Visual Inspection, Bd. 546. In: Valle, Maurizio et al. (Hrsg.): Advances in System-Integrated Intelligence. Cham: Springer International Publishing, 2023 (Lecture Notes in Networks and Systems), S. 415–424.

[13] Lemaignan, Séverin: MASON: A Proposal for an Ontology of Manufacturing Domain. In: IEEE Workshop on Distributed Intelligent Systems: Collective Intelligence and Its Applications (DIS'06): IEEE, 2006, S. 195–200.

[14] Martin, Patrick: Some Aspects of Integrated Product and Manufacturing Process. In: Bramley, Alan et al. (Hrsg.): Advances in Integrated Design and Manufacturing in Mechanical Engineering. Berlin/Heidelberg: Springer-Verlag, 2005, S. 215–226.

[15] Ameri, Farhad; Dutta, Debasish: An Upper Ontology for Manufacturing Service Description. In: Volume 3: 26th Computers and Information in Engineering Conference: ASMEDC, 2006, S. 651–661.

[16] Sarkar, Arkopaul; Šormaz, Dušan: Ontology Model for Process Level Capabilities of Manufacturing Resources. In: Procedia Manufacturing 39 (2019), S. 1889–1898.

[17] Järvenpää, Eeva et al.: The development of an ontology for describing the capabilities of manufacturing resources. In: Journal of Intelligent Manufacturing 30 (2019), Nr. 2, S. 959–978.

[18] Li, Zhi: An ontology-based product design framework for manufacturability verification and knowledge reuse. In: The International Journal of Advanced Manufacturing Technology 99 (2018), 9-12, S. 2121–2135.

[19] Horrocks, Ian: SWRL: A semantic web rule language combining OWL and ruleml. In: W3C Member submission 21 (2004), Nr. 79, S. 1–31.

[20] Herrmann, Kevin et al.: Quantification of the material-related environmental impact of topology-optimized multi-material components. In: DS 119: Proceedings of the 33rd Symposium Design for X (DFX2022) : The Design Society, 22 and 2022, S. 10.

[21] Noy, Natalya F.; McGuinness, Deborah: Ontology Development 101: A Guide to Creating Your First Ontology. In: Knowledge Systems Laboratory 32 (2001).

[22] Albrecht, Katharina; Anderl, Reiner: Information Model for the Integration of Manufacturing Restrictions into the Algorithm Based Product Development Process. In: Procedia CIRP 50 (2016), S. 819–824.

[23] Wegner, Hagen: Ein System zum fertigungstechnologischen Wissensmanagement. Zugl.: Aachen, Techn. Hochsch., Diss., 2007. Aachen: Shaker, 2007 (Berichte aus der Produktionstechnik Bd. 2007,30).

[24] Lamy, Jean-Baptiste: owlready2. GitHub, Bitbucket, 2019. URL: https://github.com/pwin/owlready2. Accessed 16.07.2023.