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Development of a Domain-Specific Ontology to Support Research Data Management for the Tailored Forming Technology

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Abstract

The global trend towards the comprehensive digitisation of technologies in product manufacturing is leading to radical changes in engineering processes and requires a new extended understanding of data handling. The amounts of data to be considered are becoming larger and more complex. Data can originate from process simulations, machines used or subsequent analyses, which together with the resulting components serve as a complete and reproducible description of the process. Within the Collaborative Research Centre "Process Chain for Manufacturing of Hybrid High Performance Components by Tailored Forming", interdisciplinary work is being carried out on the development of process chains for the production of hybrid components. The management of the generated data and descriptive metadata, the support of the process steps and preliminary and subsequent data analysis are fundamental challenges. The objective is a continuous, standardised data management according to the FAIR Data Principles so that process-specific data and parameters can be transferred together with the components or samples to subsequent processes, individual process designs can take place and processes of machine learning can be accelerated. A central element is the collaborative development of a domain-specific ontology for a semantic description of data and processes of the entire process chain.

Keywords: Manufacturing Process Chains; Digitisation of Scientific Data; Ontology Development; FAIR Data Principles; Research Data Management;

1. Introduction

The work on complex scientific research questions demands interdisciplinary and inter-institutional projects. At the same time, the ongoing digitisation of almost all steps in research and manufacturing is generating increasingly large and diverse quantity of data, leading to radical changes in the research process and the handling of data. In the engineering sciences with their plethora of sub-disciplines a wide variety of data are generated from experiments, observations, process simulations, the machines used, or subsequent analysis [1]. Additionally, data is gathered in various heterogeneous formats and volumes, ranging from plain text to proprietary formats and from kilobytes to gigabytes. Together with the resulting components data serve as a complete and reproducible description of a research or manufacturing process. The efficient management of data and information, generated in research processes, and the acquisition of knowledge is a critical success factor for large, collaborative projects [2]. When developing multi-step process chains, a large number of process steps have to be considered, which differentiate by individual research activities, applied methods, characteristics of the data, and guidelines on how to handle data. For the successful interdisciplinary development of process chains, it is crucial how well individual research activities are interlinked and data as well as information flows optimised. For a time and material-efficient organisation of the whole manufacturing process it is relevant to access all the key data used for process configuration and the data subsequently generated within the individual process steps. The availability of comprehensible data throughout the process chain from the upstream and downstream steps enables all stakeholders to make more precise process-related decisions. The development of research and knowledge management systems is designed to process and store data, descriptive metadata and semi-structured information and make it available in a suitable way.

In many cases there are no common standards for the description of the data and the documentation of the data generation. The FAIR Data Principles provide a set of guiding principles for successful research data management (RDM) in order to make data findable, accessible, interoperable and reusable [3]. The principles state, that each data set should be described

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with detailed metadata providing context information how the data set was generated and who collected or edited it. Metadata thus provide the necessary context information for the correct interpretation of research data. The F refers to the findability of data. Data and metadata should be easy to locate, both by humans and by computer systems. Basic machine-readable data and descriptive metadata enable the discovery of needed data sets. Ontologies play in many ways an important role in representing metadata to describe both data and processes. Ontologies can establish the interlinking of relationships between research data and contextual data within process documentations. The development of ontologies for the description of data and research activities requires a close cooperation between domain experts who can describe the knowledge of a domain or technology and ontology experts who can describe this knowledge in a structured and formalised way. The knowledge about technology is also subject to constant changes, so that the development of an ontology must be open for such necessary adaptations. The paper [4] presents an overview of several prominent RDM platforms which can be put in place by an institution to support RDM workflows. One such a system for storing research data is the Comprehensive Knowledge Archive Network (CKAN, ckan.org). Major advantages of the CKAN compared to proprietary commercial systems are the connectivity via open-configurable interfaces (APIs) and the extensibility of the services via plugins and implementation of subject-specific vocabularies. Wikis like MediaWiki, Semantic MediaWiki or OntoWiki have established themselves as Knowledge Management Systems (KMS) for semi-structured information in companies and in research [5], [6]. Semantic MediaWiki is able to store semantically annotated data and semi-structured information using a machine-readable vocabulary.

This paper describes an approach how an ontology can support an advised RDM system for manufacturing processes within Tailored Forming Technology. These processes are characterised by complex, multistage process chains with various research activities of numerous researchers in individual research projects producing a large variety of research data. For this purpose, selected process chains of Tailored Forming Technology in the Collaborative Research Centre (CRC) ”Process Chain for Manufacturing of Hybrid High Performance Components by Tailored Forming” are being investigated [7]. Research data will be stored in a data repository. Further data and information on individual process steps and the process chain as well as contextual information about the data generation will be stored in a KMS. For the semantically description of the research data and process information a domain-specific ontology will be developed. This ontology enables linking relationships between data and context information in both systems.

2. Problem Setting

Some of the main challenges of the RDM system are the standardisation of processes for working with data of various types and formats, the organisation of information flows and the recording of its significance for technological process steps. Basic objects and functions of the RDM system are depicted in Figure 1 at the example of a Tailored Forming demonstrator (see section 4).

At the beginning of the process chain, two mono material workpieces are joined together by friction welding, ultrasonic aided laser beam welding or lateral angular co-extrusion. Subsequently, the semi-finished workpieces are shaped by metal forming either by cross-wedge rolling, extrusion or die forging. After that, the hybrid solid workpieces are heat-treated and the geometry is finished in a cutting process. Resulting, a high-performance demonstrator with locally adapted properties is available.

The RDM system stores data about research objects like raw materials, semi-finished workpieces, demonstrators and operating resources. Contextual information is stored in the RDM system as technical documentation of various types like simulation protocols, planning or experiment documentation. The development of a RDM system requires the identification of project-specific research data types, involved workflows as well as the analysis and interpretation of research protocols and report structures are necessary. Most of the research data already gathered are stored in an unstructured text-based or semi-structured table-based formats. These data structures can generally be interpreted by humans, but are not suitable for machine processing. To eliminate the heterogeneity of the revealed data structures and make them machine-readable, it is necessary to define characteristic parameters describing the research objects, processes and activities and to establish interconnections between them. Development and implementation of such relationships are possible by creating a domain specific ontology.

As indicated above, RDM is based on two systems: a Data Management System (DMS) which enables the storage and the access to research data and a KMS that supports generating and storage of research documentations. The two parts are to be realised by means of the open source software CKAN and Semantic MediaWiki. A Tailored Forming specific ontology builds the knowledge basis for these two part systems. It enables to annotate research data filed in RDM and establishes thus the interlinking between them.

The domain knowledge is expressed in ontology by a set of central concepts, which denote the real-world physical objects, processes and activities within the relevant research domain. The concepts involved are semantically interlinked by relations, creating a complex knowledge structure. The ontology is modelled by a computational logic based language, so that it can be reasoned and processed by a machine for different proposes [8]. Due to this feature ontology is increasingly used in data and knowledge management either as a knowledge model or as descriptive metadata [9]. Metadata management provides improved access to structured data and the mapping of their relationships to other information tables and can optimise or meaningfully recognise the stored data through identification and comparison. An overview of general approaches to domain-specific ontology development is provided in section 3 of this article. A basic description of the process model and description of the semantic definition of formalised production process elements are given in section 4.

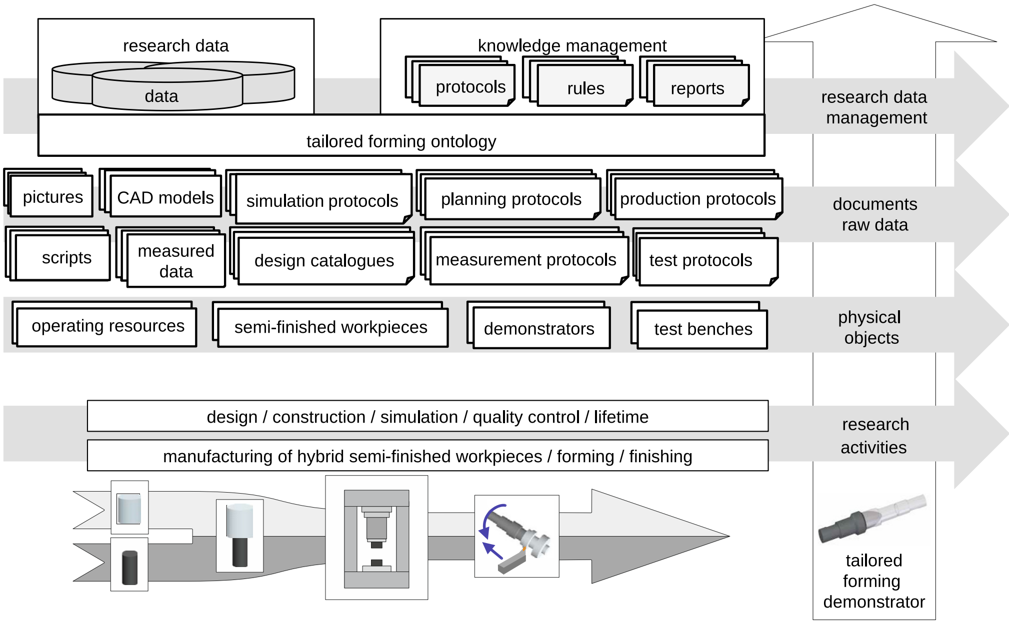

Fig. 1. Basic objects of a research data management system.

3. Related Work

There are several preliminary works and approaches handling the usage of semantic description in the technical field. The Asset Administration Shell is the result of the major initiative for the standardisation of the system component description within the Industry 4.0. The key findings of this initiative affect such aspects as product properties, process variable, references to data sources, data files and property collections, libraries, lists, and tables [10]. El Kadiri and Kiritsis [11] describe the role of ontologies within the product life cycle management with the focus on product modelling and applications. Negri, Fumagalli and Garetti [12] give an overview of requirements and languages for the semantic representation of manufacturing systems. The most important research issues to be considered by planned ontology development are manufacturing process modelling and formal representation of properties. The Process Ontology of [13], the Manufacturing Core Ontology [14] and MASON [15] provide the main generic terms, properties and relationship for the core process components, that can be partly reused in the planned ontology development. The usage of properties for semantic description of technical components in the area of the industry 4.0 is described in [16] and [17]. Heeg [18] focuses on a method for the analysis and development of data models for metric and non-metric product data within the process control engineering. This method covers such issues as cross-system property identification, property scaling based on its information content (e.g. dimensions, types of measured values, units of measurements). Some findings concerning the handling of properties can be applied in the ontology development. Furthermore, there are several international and national standards providing the core terminology for manufacturing processes like DIN 8580 [19], DIN EN 10079 [20], DIN 8582 [21].

4. Ontology Development

4.1. Description of Tailored Forming specific manufacturing process model

The process model is developed by the analysis of manufacturing processes. This is achieved in close cooperation between domain experts and ontology experts, to capture all requirements for the domain knowledge to be included in the ontology. The core content elements needed to be analysed are semi-finished workpieces, demonstrators, research activities, and setting parameters. The manufacturing process within the Tailored Forming Technology is represented by complex process chains consisting of three main steps. In the first step, the two mono-material semi-finished workpieces are joined to one hybrid semi-finished workpiece using an appropriate joining procedure [22]. In the second process step, the joined hybrid semi-finished workpiece is changed in its shape by applying a specific forming procedure [21]. Depending on particular workpiece characteristics and external/internal process conditions this step can be complemented by one or more upstream and downstream process stages like preheating or cooling. In the third step, the finishing ends the process chain resulting in the end product, called demonstrator.

Based on this description the following basic concepts are identified as relevant for the ontology development:

- *manufacturing process* represents a generic production activity, which aims the production of a demonstrator;
- *manufacturing process chain* stands for a complex manufacturing process involving three or more process steps;
- *joining* stands for a subcategory of the manufacturing process, which connects two or more semi-finished workpieces to one hybrid semi-finished workpiece;
- *forming* represents the subcategory of the manufacturing process that transforms the joined hybrid semi-finished workpiece to the required shape;
- *finishing* stands for a subcategory of the manufacturing process that brings the processed demonstrator into compliance with the required specification;
- *semi-finished workpiece* represents a generic geometrically defined body which is objective of manufacturing activities;
- *mono-material semi-finished workpiece* represents the first subcategory of the super-ordinate category semi-finished workpiece and is objective of the joining process;
- *hybrid semi-finished workpiece* represents the second subcategory of the super-ordinate category semi-finished workpiece and is objective of the forming process;
- *demonstrator* is the end-product of a manufacturing process chain.

Based on these findings, the formalised process chain model is established, as shown in Fig. 2. It is then transferred into a formalised structure applying an appropriate ontology development environment.

4.2. Semantic definition of manufacturing process elements

In the next step, the identified Tailored Forming specific concepts are semantically described by a set of properties essential for performing and tracking of the relevant manufacturing processes. The designations of properties are chosen in compliance with the standardised designations of corresponding concepts from technical standards of National, European or International Organisations for Standardisation, such as DIN, EN or ISO. This ensures full conceptual accordance between the formalised manufacturing system model, as shown in Fig. 2, and the performed manufacturing processes. Initial property sets vary in their structure and content depending on appropriate concept they semantically define. Property sets can have a particular complex (non-)hierarchical structure and involve different property types. The typical property set structure can be described based on the concept *semi-finished workpiece*.

As illustrated in Fig. 3, the property set of the semi-finished workpiece has a complex structure and is divided into intrinsic and assigned property categories. Intrinsic properties represent in general distinguishing features of a concrete real existing physical product which is an objective of a real manufacturing process step. The analysis of the semi-structured manufacturing data reveals three essential intrinsic properties of the semi-finished workpiece: length, diameter and material that it is made of. Assigned properties are normally not characteristic features of a real existing product. They are mostly added to the property set of the appropriate product by defining them in formalised data structures. This kind of properties enables to make the product distinguishable within a given application system. As shown in the Fig. 3, the typical assigned properties of the semi-finished workpiece are, for example, probe number and charge.

Another distinguishing feature between intrinsic and assigned properties is, that the concrete values of intrinsic properties are changing depending on which manufacturing step the appropriate semi-finished workpiece is actually being processed. Values can also change depending on how the workpiece is being influenced by specific process and environmental conditions like pressure or temperature. The diameter or the length of the semi-finished workpiece may, for example, change during the joining or forming process. In contrast to intrinsic property values, the assigned property values do generally not change during the manufacturing process. Once assigned, the charge or the probe number of the semi-finished workpiece remains unchanged. All property sets of the Tailored Forming specific concepts are created in the form of an extensible structure, which enables the inclusion of one or several new properties or removal of no longer needed properties over the further development of the KMS. This characteristic is marked in Fig. 3 by using of a dashed line to indicate the semantic borders of initial property sets. Furthermore the given property structure does not exclude the possibility to transform initial properties into autonomous elements and to define their own property sets, as it is the case with the material property set from Fig. 3.

The manufacturing process model and the property sets form the basis for the ontology developed to establish the cross-project KMS. The manufacturing model provides the basic formalised conceptual knowledge about the manufacturing process chains specific for the Tailored Forming Technology. The transfer of this knowledge into a machine-readable ontology representation enables to define the frame in which the research data and contextual data are structured and interlinked with each other. Using the presented property classification approach, the ontology is enriched with all required elements needed to annotate research data and contextual data semantically. Annotated data become unified and interoperable and support a standardised information exchange between the intended DMS and KMS.

The Knowledge Management is based on the Semantic MediaWiki system. The developed ontology is used to enter, annotate and organise data gathered in manufacturing processes

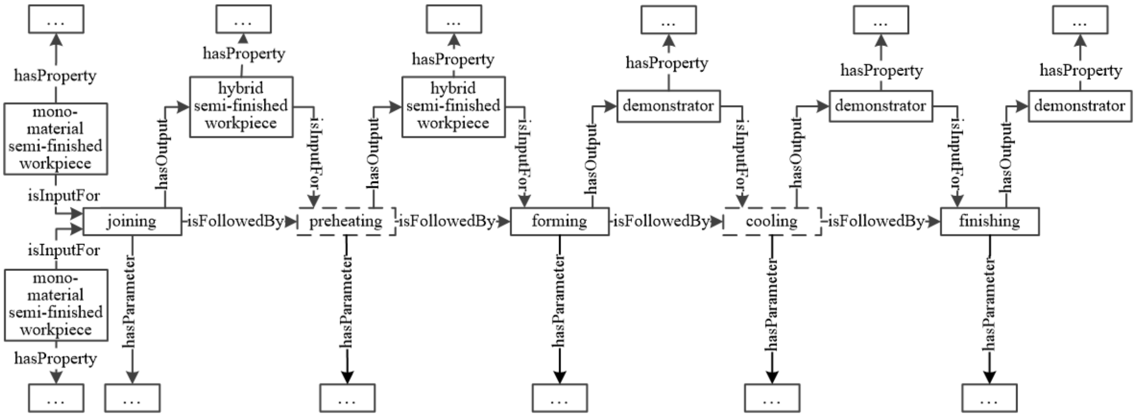

Fig. 2. Formalised manufacturing process chain.

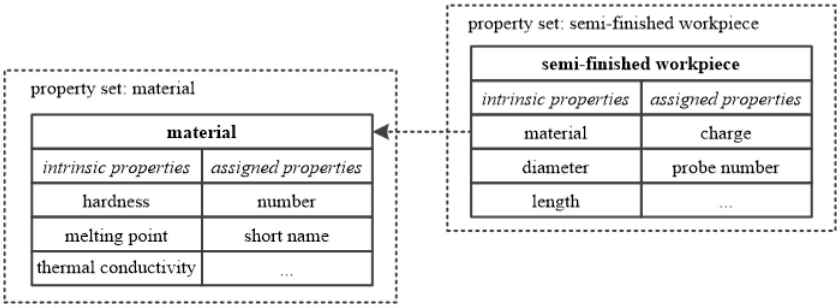

Fig. 3. Property classification within the Tailored Forming specific manufacturing process.

using the feature page properties. For example, a semi-finished workpiece is represented by a Semantic MediaWiki page, the corresponding property set of the workpiece is stored in the page properties. The Semantic MediaWiki system provides user-friendly form-based data input routines. These input forms reflect the semantically representation of an element. Each property of a property set is represented by a input field of the form. The label of the input field represents the property name. This way data like process parameters and experiment documentation can easily be entered by researchers without detailed knowledge about the MediaWiki Markup Language. Within the knowledge management of the CRC, several template types of the input forms are generated. Each template type focuses on specific content that corresponds to the key elements of the manufacturing process model presented here. Thus, the input forms are developed for components such as mono-material semi-finished workpieces, hybrid semi-finished workpieces, and demonstrators. In addition, more complex form templates are used to enter manufacturing processes and merge several input forms for entering the data of different information content. For example, a complex template for the joining process involves in addition to input forms for parameter-related data also such as input forms for workpiece-related data gained before and after the joining has been carried out. The semantically annotated data can be queried and filtered by the underlying properties defined in the ontology. This feature can be used to generated complex reports and overviews of process chain data over multiple projects, increasing data availability and transparency over all projects of the CRC.

5. Conclusion and Future Work

The presented approach for Tailored Forming specific manufacturing processes demonstrates how a technology-specific ontology can be developed from the various, heterogeneous data and process information in an interdisciplinary research environment of a CRC and how this ontology can be used as a foundation for semantic annotation of data from different project sources. Using a Semantic MediaWiki as KMS the ontology supports the transformation of protocols and other documentation from research activities of the individual projects into semantically annotated information and data, which can be queried and organised for automatic reporting. Corresponding research data will be stored in a data repository based on CKAN. The ontology can semantically link the content of the DMS and the KMS. Data from different projects along a process chain can thus be described uniformly; their data linked more closely, analysed and interpreted in the overall context of the process chain. All projects can access data from upstream and downstream process steps. The ontology thus enables the development of a common understanding of the data within the interdisciplinary, collaborative research project. The semantic annotation using the underlying ontology further supports and enables the adaption of the FAIR Data Principles. Data are made available in a machine-readable format and can be further processed. Based on the results of the analysis and modelling of first process chains gained, future work focuses on the adaptation and extension of the ontology for Tailored Forming. As manufacturing process chains are continuously being improved by ongoing research, the ontology representing the process chains, their steps, and parameter settings needs to be adapted as well. The implementation of this continuous ontology development process will be reported in the future. Another focus will be the support of ontology in the development process of process chains for new demonstrators.

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