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Structured Product Engineering: Ontology-based Advanced Product Quality Planning

Uppili Srinivasan [a], Dominik Mittel [a]*, Daniel Lemberger[b], Alexander Perzylo [a]

[a]fortiss – Research Institute of the Free State of Bavaria associated with Technical University Munich, Guerickestr. 25, 80805 Munich, Germany
[b]IBO GmbH, Ammerthalstr. 9, 85551 Kirchheim, Germany

* Corresponding author. Tel.: +49 (89) 3603522 263; fax: +49 (89) 3603522 50. *E-mail address:* mittel@fortiss.org

Abstract

Increasingly complex products make it difficult to efficiently meet customer requirements and underline the need for structured product engineering. Ontologies enable the combination of heterogeneous data sources and linking of existing knowledge to automatically derive further insights. In this work, an ontology-based approach for a structured product engineering process is introduced. We develop an ontology for Advanced Product Quality Planning (APQP)-guided product development and combine it with semantic models regarding production knowledge, ontology-based geometric representations, and a graphical user interface. As a result, an assistance system that provides support from customer inquiry to product design is developed.

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1. Introduction

Product development is getting more and more complex [1]. Furthermore, products are developed involving a dynamic collaboration across various fields, including design, engineering, and manufacturing [2]. In particular, small and medium-sized enterprises (SMEs) have numerous financial and human resource constraints [3]. Therefore, the application and use of a structured product engineering process needs to be simplified.

Product engineering investigates the development phase of a product, from the design, to manufacturing, to delivery and to after-sales support. Product engineering combines design, development, testing, and optimization. Thus, systematizing and structuring the product engineering process to ensure a timely and cost-effective product delivery becomes crucial.

Whenever a customer inquiry needs to be answered, the product design engineer requires diverse information regarding the product functionality, utilization, design, the manufacturing processes, and the resources required. Thus, interlinking different product and process parameters and identifying the interdependencies becomes crucial for the product engineering process. Once the initial customer queries are answered, the company gets a confirmation for prototyping or manufacturing. Afterwards, the design engineer creates a geometric representation and product functionalities. The manufacturing engineer develops the processes and defines the required manufacturing parameters.

In this work, a product engineering process of a radial bearing is considered as an example. Currently, the process runs on the knowledge of subject matter experts in the company. This leads to complete reliance on them for tasks and manufacturing processes, thus leading to a more manual

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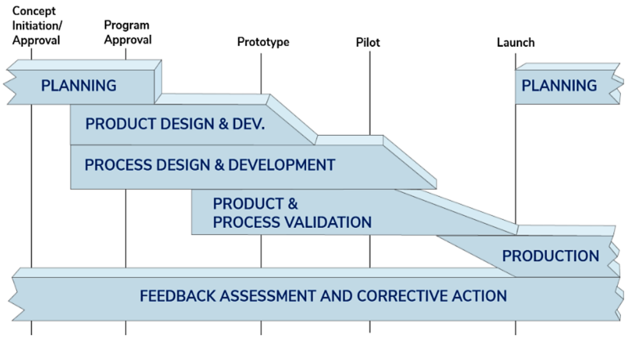

Fig. 1. Five phases of the APQP process [4]

documentation process rather than an automated one. An assistance system is required to support the stakeholders and ease the complicated tasks in the product engineering process. To handle these complicated tasks, different structured approaches are well-known and described in literature. In this context, the Advanced Product Quality Planning (APQP) process is used. The approach of APQP is chosen as it serves as a framework to guide cross-functional teams effectively throughout the product development lifecycle [4]. APQP is described in detail in the following sections.

The assistance system needs to store and link heterogenous data from various departments. To identify interdependencies and enhance collaboration, an ontology is developed to model production and APQP knowledge regarding product engineering. The ontology also includes geometric representations of the different components following the OntoBREP representation [5]. These allow to link production knowledge with geometric entities and visualize components in the self-developed graphical user interface called OntoBREP Viewer.

2. Background & Literature Review

2.1. Advanced Product Quality Planning

Before the 1980s, manufacturing industries heavily relied on reactive quality management methods such as inspection and correction after production. These methods were often inefficient, costly, and resulted in high rates of defects and customer dissatisfaction. Hence, during the 1980s, APQP was developed as a joint effort between major automotive manufacturers such as Chrysler, Ford, and General Motors along with their suppliers. Through a proactive approach, cross-functional integration, standardization, and continuous improvement APQP addressed the issues to enhance product quality and reduce defects during production [4].

APQP is not just a quality methodology. Currently, organizations use the APQP process to meet customer requirements and on-time delivery within budget. The five phases of the APQP process for product engineering are shown in Fig. 1. Furthermore, it is done in combination with other quality management tools, e.g., the Failure Mode and Effects Analysis (FMEA) [4]. Typically, the process involves several documents that are in Word or plain-text format, tabular spreadsheets, or in recent times as software applications. Technological improvements like computer-aided design (CAD), simulation software, real-time monitoring, and data and predictive analytics have enhanced the efficacy of the APQP process [4]. Common challenges with APQP include complexity, resource intensiveness, lack of alignment across organizational functions, inadequate utilization of emerging technologies, and difficulty in adapting to rapidly changing market demands.

2.2. Ontologies in General

Ontologies can be described as structured frameworks for organizing and representing knowledge within a specific domain. They facilitate effective information management and semantic understanding via the Web Ontology Language (OWL) and in this case OWL 2 [1]. Concepts, entities, and relationships between them are formally described using OWL 2. This is achieved by modeling class hierarchies, property restrictions, cardinality constraints, and logical axioms. The formal representations not only capture domain semantics but also provide a shared and standard vocabulary promoting interoperability and knowledge sharing. Logic-based reasoning and Semantic Web standards allow the realization of implicit knowledge and empower automated systems to perform complex tasks like data integration, knowledge search, and decision support. Querying via the SPARQL Protocol and RDF Query Language (SPARQL) [2] results in improved information retrieval, enhanced data interoperability, and knowledge reuse.

2.3. Ontologies for Product Engineering

As APQP includes the integration of quality information from several product development stages, manufacturing processes, and industrial departments, trying to construct a semantic representation for the APQP process seems profoundly valuable. Ontologies for different phases of product engineering have been widely investigated in recent years. For example, the main idea of Product ONTOlogy (PRONTO) [6] is to represent product-related concepts in different abstraction levels. This kind of multi-level formal representation helps deal with heterogenous data and enables systems to perform product-related tasks like planning actions. The Product Semantic Representation Language (PSRL) [7] ontology uses mathematical logic along with a standards-based approach to determine semantic equivalence between application ontologies. This allows seamless communication between product development systems. Other existing ontologies enhance the performance of a product engineering process specific to a certain manufacturing domain. Process Specification Ontology (PSL) [8], Supply Chain Operations Reference Ontology (SCOR) [9], Manufacturing System

[1] https://www.w3.org/TR/owl2-primer/

[2] https://www.w3.org/TR/sparql11-query/

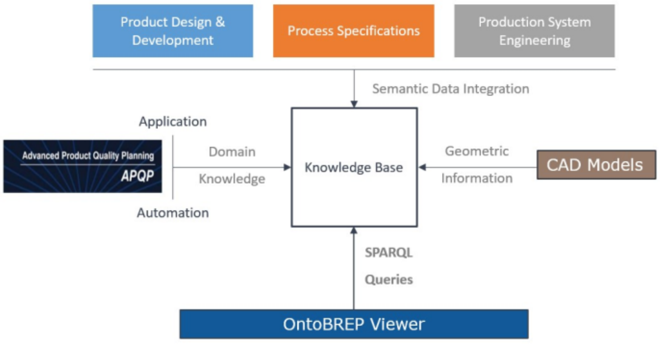

Fig. 2. Architecture of the implemented semantic models and the connection to the OntoBREP Viewer, adapted from [16].

Engineering (MSE) [10], and Manufacturing's Semantics Ontology (MASON) [11] are some of the examples.

Most of the ontologies mentioned above are application and task oriented. Otherwise, they provide general product and process information. The APQP process contains detailed knowledge regarding product and process parameters, which are seldom addressed. Hence, ontologies with an approach for the APQP process are developed. Chhim et. al [12] focused on the reuse of knowledge resulting from Design FMEA (DFMEA) and Process FMEA (PFMEA) to formalize manufacturing process failures. Even the ontologies existing for the APQP process focus more on addressing failures and lack connection to upstream design knowledge and information required for different stakeholders during production. This information is part of the APQP process.

Similarly, [13] introduces a part-focused manufacturing process ontology covering the gaps from product specifications to manufacturing processes where the specific process requirements can be selected based on desired features and attributes. Also, Schlegel et al. [14] introduce an ontology for future robust product portfolio evolution. The authors highlight the importance of a consistent terminology to enhance communication and efficiency in product development processes. The developed ontology is stated as a first basis and will be further developed in the future by the authors.

In this work, the production knowledge is enhanced by APQP-related knowledge for product development and integrated with semantic geometrical representations for interactive visualizations.

3. Architecture & Use Case

The backbone of the assistance system is the semantic knowledge base (KB) storing ontologies about different manufacturing knowledge. Fig. 2 shows the architecture of the assistance system and sources for the semantic data models. The system includes the semantic models of APQP knowledge and CAD data and stores them in the KB. The modeled information in the KB is accessed with the self-developed graphical user interface called OntoBREP Viewer.

3.1. Knowledge Representation

The ontologies are built using Protégé[3]. It is used to create the taxonomical structure for the APQP data using class hierarchies and interlinking entities using attributes and property relations. The constructed ontologies are then stored in the graph database GraphDB from Ontotext[4] for centralized data storage and exchange. GraphDB allows multi-level semantic reasoning, accessing the data via SPARQL, interactive visual graphs, and effective integration for frontend API. Geometric data from CAD models, stored in neutral CAD files like STEP or IGES, are automatically transformed into the semantic geometric representations and stored within the KB as well. The geometric representation, according to the OntoBREP format [5], stores all geometric entities like compounds, solids, faces, wires, edges, and others as well as their attributes. This allows to link the geometric entities directly with the APQP knowledge. This consolidation results in a unified knowledge base encompassing both APQP and CAD model data.

3.2. Graphical User Interface

The modeled knowledge is visualized by a self-designed Angular frontend application. The so called OntoBREP Viewer uses dynamically designed SPARQL queries to retrieve APQP knowledge and geometric representations. This integration not only enhances user understanding but also yields aesthetic product visualization, thereby mitigating the need for extensive subject matter expertise at every process step.

Thus, with a KB backend containing APQP and CAD data, and coupled with an Angular frontend, we have engineered an assistance system capable of delivering crucial product information related to APQP process throughout the PLM continuum. Also, due to integration with OntoBREP viewer, it can support workers and engineers during development and production with interactive visualizations.

3.3. Use Case

Our work investigates the product engineering process of a radial bearing. In our case, the most important individual components of the radial bearing are the outer ring and the inner ring with sprocket. Other parts include the sealing and the ball race. These components are made up of aluminum alloy and must meet stringent quality standards for safe operation. Each component or specific surfaces may also need additional processes like surface coating or heat treatment, which affects the physical specifications, e.g., the strength. The bearing finds applications in various domains with a primary focus on automotive and aviation sectors. As a result, the product must go through careful design and extensive testing to ensure stringent compliance standards.

In the following, the ontology design and potential scenarios for stakeholders are outlined, accompanied by corresponding solutions utilizing our APQP ontology and architecture.

[3] https://protege.stanford.edu/

[4] https://graphdb.ontotext.com/

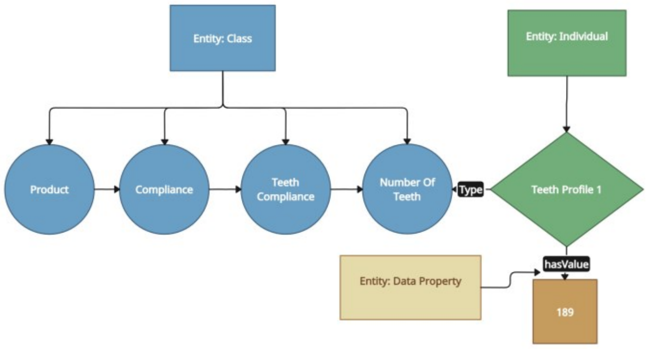

Fig. 3. Taxonomical structure to create individuals storing both textual and numerical data, using the example of the number of teeth.

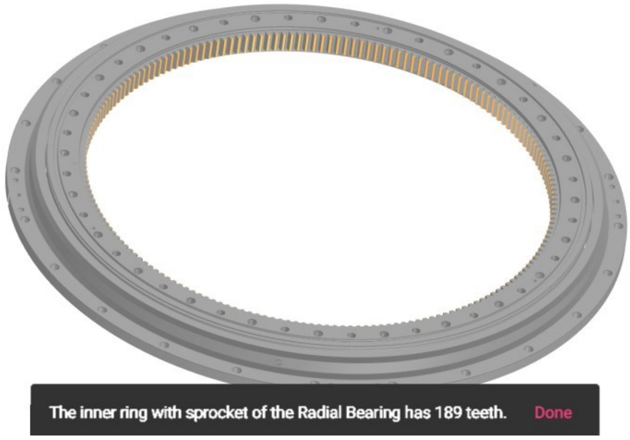

Fig. 4. Highlighting of the teeth geometry when compliance related to teeth is selected.

4. APQP Ontology Design & Implementation

Ontologies are useful in knowledge management, domain-specific application, data integration, decision support systems, and Semantic Web applications. They help integrate multi-source and heterogenous data providing a common vocabulary and a shared understanding of domain concepts. An ontology for the APQP process can state the concepts and objects in the problem statement and process their relations and interrelations. It can also uncover explicit and inferred relations which might exist in different sources that might otherwise elude conventional control. Efficient knowledge sharing, knowledge reuse across different stakeholders, reduced misconceptions between concepts and logical relations, and better clarity become possible through the structured approach of an ontology in the manufacturing domain.

The semantic knowledge base (KB) is modeled utilizing the product, processes, and resources (PPR) paradigm [15] and based on our previous works [16, 17]. In this case, the KB is extended with knowledge about APQP. There are various documents and information in the APQP process. We want to further investigate the customer compliances for the product and the control plan information in APQP. In particular, this section describes the PPR paradigm, the core of the APQP ontology, the knowledge modeling of APQP data, and the implementation and usage of the ontology.

4.1. PPR Paradigm

For individual products, in this case bearings, the product specifications, the manufacturing processes, and the utilized resources are relevant information during design and development stages. Hence, PPR paradigm provides an effective methodology to formalize the knowledge and concepts embedded in the APQP process.

The **product model** encompasses essential data concerning a product's attributes and its interconnections with other entities serving diverse functions. Important information from control plans like component material, geometric dimensions, and tolerances are also stored in the product model. Essentially, the product model serves as a knowledge reservoir to enable effective management and coordination of diverse product-related information.

The **process model** outlines steps or a sequence of activities necessitating the utilization of various resources, including machinery, robotics, and tools, to fabricate a product or a segment thereof from a designated set of input components. Furthermore, control dimensions achieved at each process step are stated, with their specified tolerances, measurement methodology, and frequency of inspection. Thus, it serves as a structured framework for sequence of activities and resources essential for product fabrication while facilitating seamless integration with the product model. This ensures coherence between product attributes and manufacturing processes.

The **resource model** specifies relevant information about the machinery, equipment, human resources, etc. required for the process or during production. The relations allow connectivity of these terminologies to product and processes. Thus, the resource model facilitates informed decision making, fosters operational efficiency, and ensures seamless coordination of resources throughout the APQP continuum.

4.2. Customer Compliances Knowledge Modeling

The customer compliances are recorded in an APQP document usually named as a compliance matrix due to its tabular structure. It contains detailed checklists listing the customer and stakeholder standards that the product must meet. The compliance data are predominantly comprised of lengthy sentences that include textual and numerical information. Thus, the ontology model must formalize both types of data. To achieve this, we utilize natural language processing method and parse sentences into subject, predicate, and object constructs. Furthermore, a detailed taxonomical structure for conceptual depth is build. If necessary, additional classes are modeled to conceptualize domain knowledge and to group concepts.

For example, a document might include a generic sentence like "*The bearing shall not need corrective maintenance achieving the failure rate specified*". To model this as ontology, a class hierarchy starting from the highest context level of "*Product*" is defined. Following this we define the concept of "*Compliance*" and "*Maintenance*" as subclasses which define the type. The compliance task is further defined as "Corrective Maintenance" which is a subclass of "*Maintenance*". Further subclasses for the "*Maintenance*" class can also exist like for

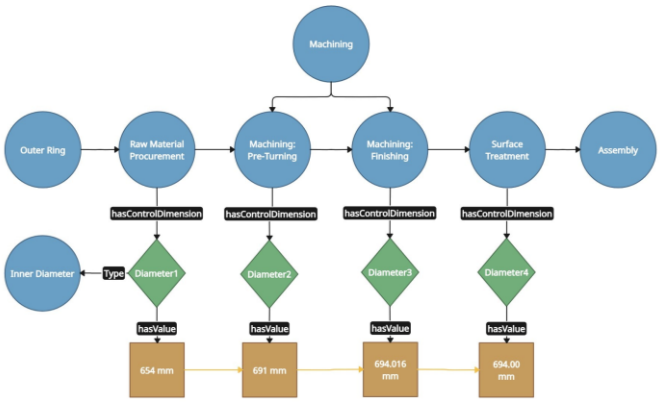

Fig. 5. Taxonomical structure to show the critical dimensions of the different processes for the outer ring stated in the control plan.

example “*Preventive*” or "*Process Installation*” maintenance. An individual instance can then be instantiated with the “Corrective Maintenance” type and have all the information stored using data properties. This is the basic methodology to split textual information into context types for better understanding. Thus, we build a hierarchical taxonomy for every compliance task providing easier contextual understanding.

Similarly, the compliance matrix can also have sentences which contain numeric data as well like “*The bearing shall have 189 teeth.*”. The ontology design of the knowledge in the sentences is shown in Fig. 3, exemplary for the teeth profile. Here, the teeth profile is stated as an individual that stores all the numerical data using data property values. Rather than reading the entire sentence to understand the context, the user can just see as to which class the compliance belongs to, in this case the “*Teeth Compliance*”. The compliances are split into different types depending on the context, e.g., dimensional, operational, load, maintenance, material, legal, or packaging. This detailed taxonomical structure allows for better inference and efficient allocation of resources.

The goal is to move away from simple checklist documents and develop an intuitive user interface. Hence, the compliance matrix is combined with the geometric information given in the KB. In Fig. 4, the automatic highlighting of the teeth is shown. Regarding the example above, counting the number of teeth, a SPARQL query can retrieve the number of teeth due to their specific shape. By clicking the appropriate line in the compliance matrix, the compliance check to be fulfilled is carried out. In this case, the application is showing a number of 189 teeth, i.e., the compliance is fulfilled.

4.3. Control Plan Knowledge Modeling

A control plan document serves as a detailed blueprint outlining the methodology for consistent quality throughout the product lifecycle. It meticulously details the control measures, control dimensions, inspection points, and testing procedures essential for each stage of manufacturing with adherence to customer specifications and regulatory standards. Usually, it is in a tabular or spreadsheet format.

The knowledge modeling is carried out in a similar way as for the compliance matrix. The main difference is that the control plan specifies the sequence of processes that each component goes through. Furthermore, the processes are based on same control dimensions, although the values change as the component progresses through different processes.

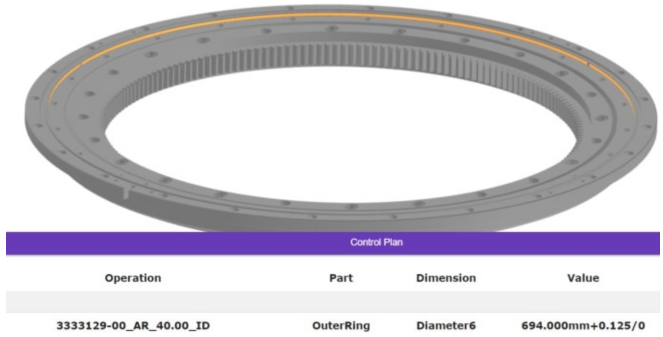

Fig. 6. Highlighting of the inner diameter of the outer ring with the dimension stated in the control plan for the assembly with the inner ring.

The semantic model also includes required or related standards, measurement methods and units. Data properties are used to specify detailed information like the different types of dimension values, tolerances, or measurement method. Compared to the compliance matrix, the semantic modeling of the control plan includes more complex taxonomical structure to capture process sequence. Also, higher number of object and data properties are used to provide the relationships of control dimensions to other entities. In short, the modeled knowledge provides the steps for the production process.

An example process sequence with the critical dimension of an inner diameter of the bearing is shown in Fig. 5. The critical dimensions belong to the outer ring of the bearing. First, the surface starts with raw material procurement, undergoes machining, and finally receives a surface treatment to meet the specified requirements. The final value is critical due to the assemblage with the inner ring.

The critical dimensions and the respective processes in which they are achieved, e.g., inner diameter in finishing, can be directly linked with the semantic geometric representations. In Fig. 6 the combination with the geometric representation can be seen. On the lower part, an excerpt of the modeled control plan is shown. There, the id for the finishing operation, the part, and the critical value of control dimension can be seen. When an appropriate row is selected, the corresponding part geometry is highlighted, in this case the critical dimension of the outer ring. The geometric representation of the inner and outer ring shows the final assembly in the OntoBREP Viewer. Thus, this integration results in a synergetic effect allowing the user to understand and perform the process control tasks better. Even if they are not domain experts. Furthermore, this knowledge could be used to describe the control measurement steps needed during production.

4.4. Product Generic Information

One of the primary goals for the modeled APQP knowledge is to reduce the lead time of product development for the engineer. Typically, when a product engineer receives a customer inquiry for a product, they must sift through a plethora of documents for generic information of the product.

Even general information such as the material used for individual components requires the engineer to go through the individual drawings to determine the material code and then look up the material composition and specification in the handbook. All this generic information required before proceeding to design and development, is available in the semantic APQP models. The information can easily be acquired with intelligent SPARQL queries instead of sifting through the documents. For example, the engineer can obtain the information that the outer ring is made up of an alloy with material code EN-AW-7022. Further, the user can also obtain the material composition of the alloy. Due to the material symbol of EN AW-AlZn5Mg3Cu, the material is clearly specified. I.e., the user also has access to information like the percentage composition and other relevant physical properties, like the strength, density, or others. This enables to easily reuse this knowledge for new products by simply creating relations.

The centralized knowledge storage, the intelligent and efficient query retrieval via SPARQL, and the knowledge reuse results in expedited and informed decision making for product engineers.

5. Conclusion and Outlook

Continuous improvement for product development and engineering is imperative in the current landscape of manufacturing. It has become crucial especially for SMEs to seek methods to boost efficiency, reduce product lead time, and enhance customer satisfaction. This work introduces an ontology-based assistance system for stakeholders to develop products following the APQP process. It integrates a semantic knowledge base with manufacturing and product knowledge relevant to CAD and APQP, which is connected to a self-developed graphical user interface to assist during product development. The linkage of APQP knowledge and geometric representations for visualization reduces the dependency on subject matter experts. A unified representation of data and knowledge avoids the user having to go through several documents even for basic information reducing product lead time. Thus, semantic technologies usage can be seen as providing better insights, productivity gains, and enhancing customer satisfaction through information standardization, centralization, interlinks, and implicit inferences leading to higher level of data autonomy in the manufacturing domain.

In future work, the implemented semantic models and the developed GUI is reused and embedded into a socio-technical assistance system. This will assist during multiple stages of product engineering, like assembly and after-sales support. Therefore, the developed implementation is combined with a computer vision system, a process execution system, and with further knowledge, e.g., about the assemblage of the product.

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