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Knowledge graph for manufacturing cost estimation of gear shafts – a case study on the availability of product and manufacturing information in practice

Fynn Hellweg[a,b]*, Harry Brückmann[a], Thomas Beul[a], Constantin Mandel[b], Albert Albers[b]

[a]*Robert Bosch GmbH, Renningen, 70465 Stuttgart, Germany*

[b]*IPEK – Institute of Product Engineering, Karlsruhe Institute of Technology, Kaiserstr. 10, 76131 Karlsruhe, Germany*

* Corresponding author. Tel.: +4971181148157; *E-mail address:* fynn.hellweg@de.bosch.com

Abstract

Growing cost pressure forces companies to actively manage their product costs to secure profitability. Here, manufacturing cost estimation within product development estimates manufacturing and material costs. As most products are developed in generations, needed product and manufacturing information can origin from reference system elements (RSE), for example similar components of prior product generations. Problematically, this product and manufacturing information as well as the knowledge of its interrelation is often stored in an unstructured way, document based or at least not machine-readable. This makes manufacturing cost estimation an effortful, time consuming and mainly manual activity with low traceability, where a wide manufacturing knowledge is required. Trends in production, like new manufacturing processes and production systems further increase the need for manufacturing information and knowledge. Knowledge graphs as semantic technologies can improve the findability and reusability of reference system elements and enable automatic information processing.

Within this research, cost estimation of research and development of a large automotive supplier was used as research environment. Guided by the model of PGE an ontology for the manufacturing cost estimation domain was developed. Then, a knowledge graph was instantiated based on product and manufacturing information from gear shafts of electric axles. A case study was carried out to evaluate process-specific cycle time calculation as exemplary use case of the knowledge graph. Process-specific cycle times are generally effortful estimated based on detailed manufacturing information and then used together with machine hourly rates to estimate manufacturing costs. Here, the structured and machine-readable manufacturing information of identified reference system elements is extracted from the knowledge graph to reduce the effort, increase the traceability and enable future automation. The case study shows exemplary, how a knowledge graph can support manufacturing cost estimation of gear shafts where product and manufacturing information is automatically identified using reference system elements.

Keywords: Manufacturing Cost Estimation; Product Development; Gear Hobbing; Ontology; Knowledge Graph; Semantic Technologies; Reference System Elements

1. Introduction

One major challenge for companies is rising cost pressure [1]. It forces companies to actively manage their product costs to secure profitability. An example is the electromobility market with its high-volume production, where manufacturing cost estimation is used to identify cost drivers and support cost efficient product development early on. Here, the creation of process chains and the calculation of cycle times is needed. Therefore, profound manufacturing information and knowledge is required, which often is of bad quality or not easily available. Manufacturing and cost information from prior products are often stored in local documents, not machine-readable and without connection to the product. The

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knowledge behind the information is often exclusive to the person gathering it in the past. It is effortful to get information and knowledge needed for manufacturing cost estimation and when leaving the company or on holiday, the information and knowledge is not available. Within this research, an ontology and a knowledge graph were developed in the domain of manufacturing cost estimation to make the relevant reference system elements better available for example in terms of machine-readability.

This article is structured in seven sections. The next section 2 describes the state of research. Section 3 includes the description of the research environment, shows the research gap and states research questions. Following section 4, which describes the development of the domain ontology and the knowledge graph, the result is presented in section 5. Section 6 describes a case study of a gear hobbing cycle time calculator as use case for the developed knowledge graph. Then the research questions are discussed in section 7 which is followed by a conclusion and outlook in section 8.

2. State of research

2.1. PGE – Product Generation Engineering

According to Albers et al. [2] most products are developed in generations. New products and product generations can be classified according to the share of newly developed and carried over subsystems to handle risks and costs [3]. Within the model of PGE – Product Generation Engineering the reference system is a collection of all reference system elements, that function as sources of information for current development [4]. Reference system elements can originate for example from competitive products, predecessors, R&D projects or university research [5]. Richter et al. identify a lack of methodology for identification of reference system elements and collect different approaches within a predevelopment project [6] and derive a process model to support the search for relevant reference system elements [5].

2.2. Manufacturing cost estimation

To measure and reduce product costs, large manufacturing companies set up methods, teams and tools. Cost estimation as part of Design to Cost [7,8] is a method for predicting costs based on preliminary data and assumptions [9]. Niazi et al. [10] give an overview of cost estimation techniques with differentiating advantages and limitations. Due to its importance in corporate cost estimation, this research focusses on bottom-up manufacturing cost estimations as operation-based quantitative technique. Manufacturing cost estimations calculate the sum of material costs and manufacturing costs [11]. Therefore, they use detailed product, manufacturing and cost information [11]. As most of the costs are set within development and design, manufacturing cost estimation should happen within product development [12]. Xu et al. [13] identify improved sharing of product and manufacturing information as important for future research. Based on an interview study, benefits in the use of reference system elements for better support regarding manufacturing information transfer to cost estimation was seen. The information transfer was stated as dependent on personal networks and experience [14].

2.3. Ontology and knowledge graph

Since ontologies have the purpose of formally representing knowledge domains, they are used to capture relations as well as dependencies to support knowledge management. They mostly target specific domains. Product development and manufacturing are domains where ontologies are increasingly being developed and applied. The aim of many ontologies in the product development area is either the consistent use of terms to communicate requirements more clearly [15] or the representation of development process models [16]. Furthermore, ontologies were developed for the reuse of components and linguistic or parametric design information [17], similar requirements [18] or general knowledge from existing modeling methods [19].

A wide variety of ontologies have already been developed for the use in manufacturing as well. They also mostly focus on specific areas such as aerospace [20], steel production [21] and electronics [22] or on specific manufacturing processes like packaging [23], maintenance [24] or production scheduling [25].

The ontology introduced by Chhim et al. [26] connects the key concepts of product design and manufacturing process knowledge. It focuses on the knowledge resulting from Process Failure Mode and Effects Analyses (PFMEA) and Design Failure Mode and Effects Analysis (DFMEA). The ontological approach for cost estimation in early stages of product development by Voltolini et al. [27] considers costs but does not correlate individual design features with manufacturing in terms of product cost impact.

A knowledge graph is a network of entities, relationships between entities and often based on specific semantic types and properties. [28] Those can be defined in ontologies. Additionally, the knowledge graph is used as machine readable graph-theoretic representation for human knowledge. [29] Knowledge graphs have been used in different domains to increase findability and reusability of data and enable the automatic processing by algorithms. [30]

3. Methodology and approach

3.1. Research Environment

Within cost estimation of a large German automotive supplier a 12-month on-site observation was done. Six cost engineering experts were consulted for the development of the ontology, knowledge graph and for evaluation. Moreover, product information of different electric axle gear shafts was used for instantiation and validation of the ontology, resulting in a knowledge graph (Fig. 1). Gear shafts were chosen due to their variety and cost impact on system level.

Within the research environment, a case study was carried out to evaluate an exemplary use case for the developed knowledge graph. Therefore, a cycle time calculator for the gear hobbing manufacturing process, which is used for manufacturing cost estimation was chosen. The cycle time calculator uses detailed manufacturing information together with design information of gearings to calculate cycle times, that can be used for detailed and transparent estimations of manufacturing costs if combined with hourly machine costs. Feedback on the knowledge graph-based cycle time calculator was conducted from the six cost estimation experts and potential users in unguided feedback workshops of 30 to 60 minutes.

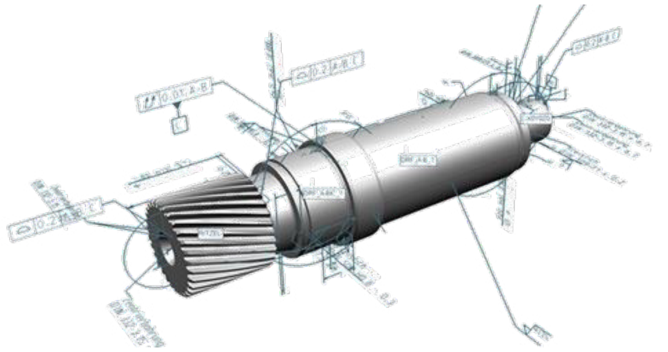

Fig. 1. 3D-Master of exemplary gear shaft

3.2. Research gap and research questions

Within the state of research, problems in information reuse and information transfer for manufacturing cost estimation were identified. A need for increased availability of product and manufacturing information is seen. Knowledge graphs have been applied within other domains on similar problems. Therefore, the aim of this research is to evaluate the potential of knowledge graphs to increase the availability of product and manufacturing information through identification of reference system elements for manufacturing cost estimation.

Within the research environment it was observed that the information detail regarding product design and manufacturing must be high and the causal connection is relevant as well. For example, not only the shape of a product, but also its surface quality can set additional, cost driving process steps, like grinding. When detailed information is available, it is usually stored in an unstructured and not machine-readable manner. In practice, the use of PowerPoint, OneNote, screenshots and not standardized Excel sheets was observed. This information is usually not further described or linked to specific elements of the component. So even if there exists a documentation of an associated manufacturing process, it is only possible to link it to the corresponding surface of the component by experience.

Different ontologies in product design, manufacturing and even at the intersection of both are presented in the state of research. But as ontologies are developed specific to the target domain and use cases, no fitting ontology in terms of detail level could be identified in the state of research. Therefore, an ontology for the domain of manufacturing cost estimation was developed and based on it a knowledge graph instantiated. This was guided by research question 1:

RQ1: **How to model product and manufacturing information and knowledge in needed detail for manufacturing cost estimation?**

Then a case study was done within the research environment to identify further challenges and potentials on application of the knowledge graph to practice. The case study was guided by research question 2:

RQ2: **How can the knowledge graph exemplary be used to lower the effort spent and increase the traceability within manufacturing cost estimation?**

4. Development of the ontology and knowledge graph

Different methods for domain specific ontology development exist. Those are often similar and differ mainly in the level of detail. Albers et al. [31] postulate the elements found in most process models. These are specification, knowledge acquisition, conceptualization, formalization, integration as well as evaluation and documentation. Chhim et al. [26] provide a similar but more compact approach. Alternatively, Gaag [32] follows Sure et al. [33] and integrates elements from Ahmed et al. [34] to present a detailed ontology development method.

The method for ontology development used in this research is a combination of the mentioned methods adapted to the application domain of manufacturing cost estimation for gear shafts to capture interdisciplinary knowledge about cost relevant relations of product and manufacturing information in a machine-readable form.

The development was supported by two tools. The ontology editor TopBraid Enterprise Data Governance (TopBraid EDG) provided a user interface for easy creating, editing, consistency checking and visualization of the ontology. The source code was created in the standard W3C ontology language OWL. Stardog, a scalable knowledge graph platform, was used for data population. Based on the concepts of the ontology, instances were created according to the gear shaft examples. This led to the knowledge graph, the graph database that contains knowledge and information in machine-readable form. As the data amount was low due to the prototype scope, a pure RDF approach, with all concepts and relations stored in subject-predicate-object triples in Turtle format, was chosen. The final evaluation was done by querying exemplary instances and relations.

Geometric product information as well as product manufacturing information (PMI) were sourced from technical drawings and 3D-Models (3D Master, [35]). Relevant manufacturing information was collected in non-machine-readable format on department drives and in different software applications. The semantics and the context of the relations between product and manufacturing information were mostly developed based on implicit expert knowledge that was conducted from experts within the research environment.

The use for manufacturing cost estimation purposes defines the level of necessary entities and relations. An approach with function-based grouped elements was pursued, as function-oriented design helps specifying tolerances for functionally relevant elements and supports the interaction with MBSE – Model Based Systems Engineering activities.

5. Ontology and knowledge graph

5.1. Ontology

For the function-oriented component analysis the concepts *functional element*, *auxiliary element*, *group of elements* and *part attribute* are used and form the product information core of the ontology. *Functional elements* are the smallest set of *geometry elements* of one component, needed to perform one or more functions. Following the understanding of the C&C^2 approach, those *functional elements* are *active areas* and need interaction with a counterpart to fulfill a function [36]. They are described as objects that can have properties such as position, direction, size or tolerances. For example, the gearing of a gear shaft represents a *functional element* as a selection of several *geometry elements* (e.g., surfaces).

Auxiliary elements are the smallest set of *geometry elements* exclusively relevant for manufacturing processes. Nevertheless, *auxiliary elements* must be designed and manufactured which makes them relevant regarding costs. Centering bores in turned components, for example, have no direct relevance to the product function, but are required for clamping during the manufacturing process.

The grouping of related *functional* and *auxiliary elements* leads to the *group of elements*. The bearing seat for a ball bearing serves as a *group of elements* consisting of the *functional elements* "bearing radial" and "bearing axial" as well as the *auxiliary element* "undercut" (Fig. 2).

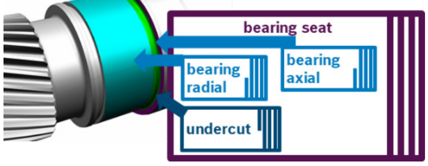

Fig. 2. Concepts for the representation of cost-relevant product design aspects by the example of a bearing seat

Part attributes are necessary for a complete definition, may affect manufacturing and therefore must also be considered. Examples are component volume, weight, material and maximum dimensions having a significant influence on the furnace loading for heat treatment.

Similar to product information, cost relevant manufacturing information must be modeled as well. Therefore, different concepts have been defined (Fig. 3).

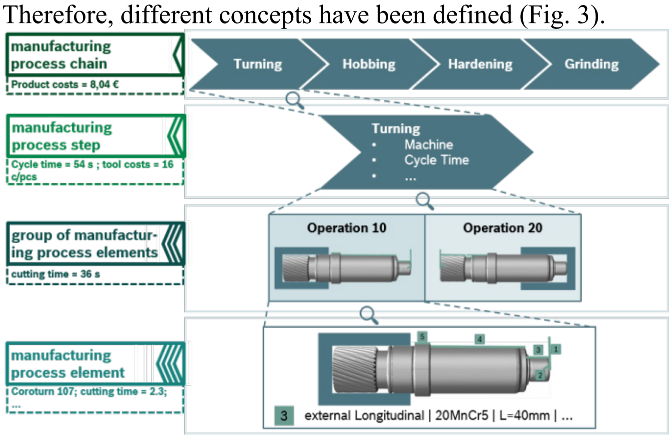

Fig. 3. Concepts for the representation of cost-relevant manufacturing aspects by the example of turning a bearing seat

Manufacturing process chains represent sequential series of manufacturing technologies. Within the process chains the individual steps are described by the concept *manufacturing process steps*. *Manufacturing process elements* represent single operations and are grouped in *group of manufacturing process elements*, for example by the clamping.

Summarizing, Fig. 4 shows the main concepts and relations of the developed ontology.

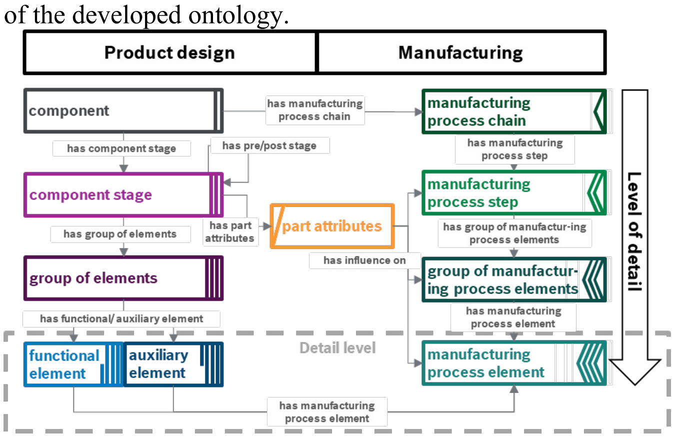

Fig. 4. Main concepts and relations of the ontology connecting manufacturing with product design in the domain of manufacturing cost estimation

5.2. Knowledge graph

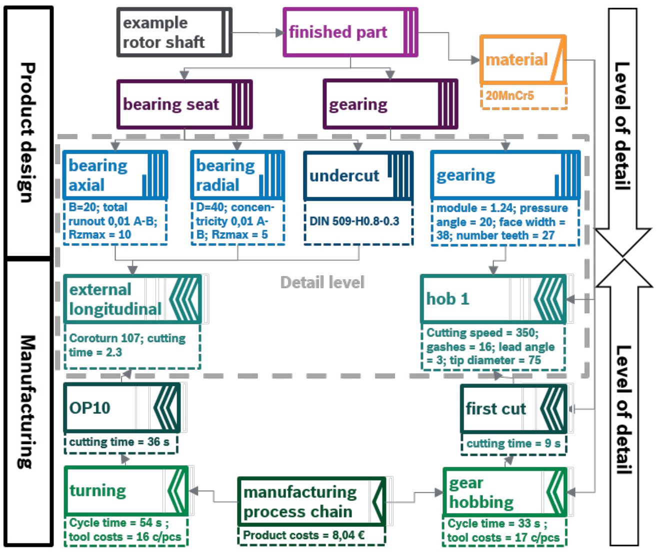

Fig. 5. Exemplary extract of the knowledge graph by the examples of turning a bearing seat and gear hobbing

Figure 5 shows an extract of the knowledge graph by the examples of turning a bearing seat and gear hobbing in a graphic overview while Figure 6 shows exemplary subject-predicate-object triples in Turtle format. Therefore, the concepts and relations of the ontology (Fig. 4) were used.

```
x_idea_costengineering_ontology_v03:Hobbing
    rdf:type          owl:Class ;
    rdfs:subClassOf   x_idea_costengineering_ontology_v03:ManufacturingProcessStep ;
    rdfs:comment      "Hobbing is a machining process for gear cutting, ..."@en ;
    sh:property       x_idea_costengineering_ontology_v03:Hobbing-hasCuttingSpeed.

:Hobbing-ExampleRotorShaft
    a                            x_idea_costengineering_ontology_v03:Hobbing ;
    x_idea_costengineering_ontology_v03:hasCuttingSpeed      350.00 .
```

Fig. 6. Exemplary subject-predicate-object triples of the knowledge graph by the example of gear hobbing in Turtle format

6. Case study: gear hobbing cycle time calculator

Today, cycle times are often roughly estimated or calculated through implicit personal knowledge, contacting colleagues or searching in unstructured old project documentations. Another option are cycle time calculators including manufacturing knowledge as formulas. Cycle time calculators are then used to calculate process-specific cycle times with input of product and manufacturing information. This manufacturing information, same as the implicit personal knowledge, is often difficult to acquire. The cycle time is used together with time dependent values like machine hourly rates or personnel costs per hour to estimate detailed process-specific manufacturing costs.

Within the provision of manufacturing information into cycle time calculators, a use case for the presented knowledge graph is seen. This is realized for a cycle time calculator of the gear hobbing process within the research environment. Based on product information, the knowledge graph is queried via SPARQL for similar *functional elements* of the type “gearing” to find fitting gear hobbing manufacturing information. This is done with an application programming interface (API) of Stardog with the pystardog library in python. Then, the queried parameters are used to calculate the cycle time based on formulas from literature, for example [37]. The calculated cycle time is then stored with relevant information in the knowledge graph for further expansion thereof. Fig. 7. Shows this interaction.

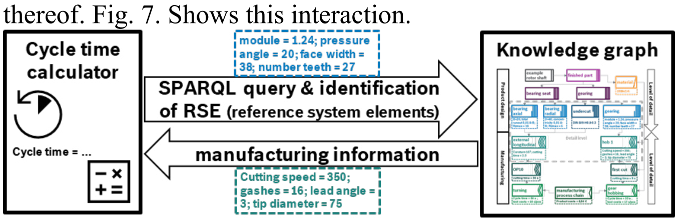

Fig. 7. Interaction of knowledge graph and cycle time calculator

The gear hobbing cycle time calculator was used within the research environment by cost estimation experts. All of them see potential within its use. The tool automatically identifies similar reference system elements and supplies manufacturing information from similar parts within seconds. Due to its prototype status the tool shows some difficulties. For example, it must be used in a python development environment and the amount of reference system elements is limited.

7. Discussion

This research answers the two research questions introduced earlier:

RQ1: **How to model product and manufacturing information and knowledge in needed detail for manufacturing cost estimation?**

Heavyweight ontologies can be used to model information and knowledge machine-readable. Such ontology was developed in the domain of manufacturing cost estimation with the help of a 12-month observation and different domain experts. The ontology connects product design with manufacturing in sufficient detail. For better identification of reference system elements in the understanding of PGE the ontology is based on a functional approach with *functional elements* and *auxiliary elements*. It is difficult to define the required level of detail, therefore it was discussed with domain experts from cost estimation, product design, tolerance management, semantic technologies and manufacturing. If the level of detail is too low, relevant influences of product design on the manufacturing process are not considered. For example, gearing shape tolerances, that could be omitted in an undetailed approach, are required for the cycle time estimation of the gear hobbing process. If the level of detail is too high, the effort of connecting, saving and retrieving the included information is too high to justify, for example by separately considering every *geometry element* (surface, edge, point).

RQ2: **How can the knowledge graph exemplary be used to lower the effort spent and increase the traceability within manufacturing cost estimation?**

The case study shows the time-saving potential of the knowledge graph as part of the developed approach. Instead of rough estimations or time-consuming manual research by cost engineers, a tool queries the knowledge graph automatically and finds fitting manufacturing information. As the current work mode is depending on chance, it is difficult to quantify the effort saved. As the creation and extension of the knowledge graph is dependent on the product, manufacturing processes and expert cooperation, the overall efficiency is to be evaluated in further research.

The knowledge graph increases the data quality in terms of format and structure, e.g., with unified resource identifiers (URI). Through an explicit description of the knowledge regarding design and manufacturing and the possibility of documenting used resources, for example cost estimations that lead to business decisions, the approach improves the traceability. Additionally, it lowers the effort of cost estimation, as an automated cycle time calculator can replace effortful manual calculations and reduces needs for manual inquiries regarding current design and manufacturing information. In the current state, knowledge is often only available to one expert or a small group and difficult to upgrade into company knowledge. The presented approach gives cost engineers the possibility to focus on important innovation-driving thoughts like creative manufacturing alternatives or possible advancing design changes.

8. Conclusion and outlook

It is essential to include manufacturing knowledge into product development to secure companies’ profitability. Further transfer of product and manufacturing information into manufacturing cost estimation is needed, as currently this information of earlier product generations is often not structurally nor machine-readable stored and not adequately re-used. This makes cycle-time-based cost estimation currently an effortful manual task.

This research was guided by two research questions and an ontology and a knowledge graph for manufacturing cost estimation of gear shafts were developed. In a case study a cycle time calculator was introduced based on the manufacturing process gear hobbing in the production of gear shafts for electric axles. Within the case study, the approach shows a better availability of product and manufacturing information and therefore higher traceability and lower effort for manufacturing cost estimation. Other use cases are possible as well.

In future studies the knowledge graph benefit is to be evaluated against the spent effort in general. A need for further cycle time calculators in industrial practice is seen for example in the fields of gear grinding, honing and hardening. The realization of those processes, also for other components, is planned by the authors. Another use case for the knowledge graph is the determination of a process chain. Further benefit is seen by realizing an interface to a function-oriented 3D-Master, accessing *functional elements* already defined in product design. Another open question is how to aggregate large amounts of product and manufacturing information to easily integrate them into the knowledge graph.

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