Ontology-based knowledge provision for decision support in product development

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Abstract

The product development process confronts engineers with numerous decision problems. In this context, it is a challenge to consider all underlying heterogeneous data sources and decision methods to avoid incorrect decisions. Regarding these issues, ontologies offer the possibility to represent knowledge in a structured and adaptable way. Thus, this contribution proposes a methodical conception of a product development ontology and a novel approach to support developers in solving interrelated decision problems by providing relevant knowledge in a target-oriented way. In addition, the application is demonstrated by an exemplary development scenario for the axle design of a micromobility solution.

Keywords

Ontology, product development process, decision-making, requirements management, knowledge management

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1. Motivation

Developers are faced with countless decision-making methods and data sources for preparing and solving problems within the product development process. The key challenge is to identify and acquire all necessary data and information, and to consider, prioritise and provide it in a structured way. Supporting product developers to solve these challenges reduces the risk of insufficiently prepared decision-making situations and the probability of poor decisions based on them. Especially in the case of interrelated decisions, for example, when the result of a decision is reused in subsequent process steps of the development, wrong decisions lead to product fails or expensive iterations.

To avoid wrong decisions, ontologies are a promising approach to providing reasonable knowledge for decision-making situations due to their flexible knowledge mapping and networking as well as the "open world assumption" [1]. Additionally, ontologies enable the structuring of the embedded knowledge and its terminology in a consistent way with logical linking. In this way, ontologies serve as a knowledge management solution and capture semantic data using formal language [2].

This contribution analyses the methodology and challenges of designing an ontology for decision-making processes in product development using an example from the field of developing a micromobility solution. In ontology development, reusing existing ontologies is a core modelling strategy. For this reason, the aim is to include existing ontologies from the area of product development to link them in a way that has not been done before.

2. State of the art

Since the proposed approach unifies decision-making and knowledge provision, particularly by ontologies, the following two subsections present the fundamentals.

2.1. Decision-making in product development

In general, a decision problem occurs when different choices are available, and the result of specific actions may have consequences that need to be considered. Accordingly, a decision is the rational or intuitive choice of possible alternatives [3], whereby manifold methods supporting the decision-making process in product development exist. In this way BREIING AND KNOSALA [4] introduce different manual evaluation methods, such as the technical-economic evaluation [5] or the utility analysis, according to ZANGEMEISTER [6]. These are partially adaptable in simplified systems that access only a small data basis. Due to multi-criteria decisions in modern product development, which require a well-founded knowledge base, computer-assisted systems are appearing nowadays. These systems focus on the target-oriented provision of necessary data. While BERGER ET AL. [7] present a method for interactive decision support with rule-based optimization, based on the available product data, BUCHERT ET AL. [8] introduce a tool for comparing pareto-optimal decision paths for predefined alternatives, thus supporting decision-making in early product development phases.

2.2. Knowledge provision in product development

Knowledge is generated in many different ways and in numerous forms of representation in the product development process. CHANDRASEGARAN ET AL. [9] classify an extract of these representations, such as CAD models, computer algorithms, production rules but also customer requirements or verbal communication. Besides pure structuring of heterogeneous data, supporting the decision-making process requires interconnecting the different knowledge sources.

Thus, BERNERS-LEE ET AL. [10] proposed the Semantic Web in 2001, which focuses on the meaning of data and information as well as their relations and listed ontologies as an essential tool for combining heterogeneous data sources and rules for identifying conclusions. GRUBER [11] defines an ontology as an explicit specification of a conceptualisation. Therefore, an ontology describes a specific view of a certain context within a predefined structure. The underlying knowledge is provided through defined classes embedded in a class hierarchy. Compared to classical databases, both the linking of the classes with their slots and the specification by their instances enable a comprehensive semantic knowledge preparation. The individual components of ontologies can be combined into a so-called semantic triple for structuring the semantic relationships, which consists of subject, object and predicate and is demonstrated in the following example: engineer (subject) selects (predicate) most suitable concept (object).

Within the area of multi-criteria decision-making, ontologies have been established, especially due to the immediate usage of stored information, the improved possibility to automate processes and the reuse of complex decision concepts [12]. Due to the multiplicity of heterogeneous data sources as well as the many decision-making situations during the development process, for which KRISHNAN AND ULRICH [13] provide a comprehensive overview, the use of ontologies within product development is target-oriented. Existing concepts in this context refer, for example, on the basis of SysML to the reuse of the decision history [14] or combine, e.g., product development with decision-making [15] however without a link to the underlying product requirements.

3. Need for action and methodical approach

Existing ontologies primarily offer isolated solutions and focus on specific use cases. In order to be able to use an ontology-based approach for decision support in a targeted manner, all disciplines and areas of a company must be interconnected. Thus, this contribution proposes a proper linkage between product development, decision-making as well as requirements management and identifies relevant data, such as CAD data, requirement relations as well as simulations, and information for decisions. This combination is not yet available with the current approaches in the state of research and requires a methodical approach for implementation to achieve a target-oriented and structured setup of the ontology. Consequently, the research questions of the paper are:

1. How can the relevant domains be linked in order to provide support for decision-making problems in product development?
2. How can the developed ontology be used in practical product development, and what potentials can be exploited?

The methodological approach of this contribution begins with the structured development of the ontology using the methodology of Ontology Development 101 [16]. This includes seven steps, whereby iterations are possible between these:

- Step 1: Determine the domain and scope of the ontology
- Step 2: Consider reusing existing ontologies
- Step 3: Enumerate important terms in the ontology
- Step 4: Define the classes and the class hierarchy
- Step 5: Define the properties of the classes - slots
- Step 6: Define the properties of the slots
- Step 7: Create instances

The main results of these seven steps are presented below in sections 4.1 to 4.6. The properties and the instances of the ontology are defined on the basis of the associated example application, an electrified micromobility solution. The key advantage of ontologies is their reuse, so existing approaches are analysed and linked to complement the self-developed ontology. This reveals interrelations which were not obvious before. Based on the application example, the usability in a development scenario (section 5) is also examined. Finally, the results are critically discussed (section 6) and, based on the answers to the research questions, the contribution closes with a conclusion and outlook in section 7. Thereby, the first research question can be answered with the help of the methodological procedure of Ontology Development 101 [16]. Additionally, the second one can be sufficiently clarified by means of further methodological procedures.

4. Development of an ontology for decision support in product development

Based on the methodology presented in the previous chapter, an ontology is stepwise designed in the following and modelled using the ontology editor Protégé [17].

4.1. Step 1: Determine the domain and scope of the ontology

The domain of the ontology involves decision-making in the development of technical products. The specific use is the provision of knowledge to support the user in decision-making in the product development process. In this context, the user is the person with decision-making authority. The designed ontology should provide answers to which information and knowledge is needed to make a certain decision in the most efficient way. The following competency questions, which serve as a validation for the later querying of the ontology, have been formulated in the development context of the micromobility example:

1. Which formulas are relevant for dimensioning the bearing of the axle?
2. Which information on parameters is still missing in order to be able to apply the formula?
3. Which parameters change due to the modification of the shaft diameter?

4.2. Step 2: Consider reusing existing ontologies

A significant advantage of ontologies is the reuse of existing concepts. The review of relevant ontologies focused on potential connections to the four main concepts. A summary of these can be found in Table 1, which also identifies the ontologies used in the following decision-making process. Since there are rarely mature or easily adaptable solutions for *requirements management*, they are not further considered for reuse. The AI4PD ontology identifies data-driven methods for the use in *product development* [18], which is applied for the specification of processes. Despite computer-aided methods, people are an important factor in the product development process and therefore act as customers or model developers. In order to be able to describe the people involved in a comprehensive way, the Friend Of A Friend Ontology (FOAF) [19] is applied. For a sufficient specification of the requirements, these and the associated evaluation criteria and value functions must be sufficiently quantified and dimensioned, which is supported by the Quantities, Units, Dimensions and Types Ontology (QUDT) [20]. The *decision* process itself is represented in more detail using the Sample Decision Ontology, which describes the fundamental principles of decisions [21]. In order to be able to characterise the decision-maker sufficiently, the FOAF ontology [19] is applied here as well. Possible *data* to be included can, for example, be taken from the tribAIn ontology [22], which is a knowledge representation in the field of tribology, or the ontology for mechanical joining processes [23]. The AI4PD ontology [18] is used to characterise the data types itself.

Table 1: Extract of relevant ontologies for reuse, in addition the use of the presented ontologies in this contribution is shown

concepts	ontologies	used
Requirements management	*no relevant ontologies identified*	no
Product development	AI4PD (Artificial Intelligence for Product Development) [18]	yes
	FOAF (Friend of A Friend Ontology) [19]	yes
	ONTO-PDM (Ontology for Product Data Management) [24]	no
	ONTO-STEP [25]	no
	QUDT (Quantities, Units, Dimensions and Types Ontology) [20]	yes
Decision-making	DO (Sample Decision Ontology) [21]	yes
	FOAF (Friend of A Friend Ontology) [19]	yes
Data	tribAIn [22]	yes
	Mechanical Joining Ontology [23]	yes
	AI4PD (Artificial Intelligence for Product Development) [18]	yes

4.3. Step 3: Enumerate important terms in the ontology

The definition of the relevant terms is assigned to the four basic concepts of requirements management, decision-making, product development and data (see Table 2). The terms of requirements management represent the approaches of HORBER ET AL. [26] and describe the primary input of product development. This classifies the development of a model with its product, function and development concept into the product development process and takes into account the variety of variants as well as the possibility of intervention by the developer. In decision-making, the decision-making process is considered with its problem description, decision request and the intended purpose, which requires sufficient documentation for the optimal decision by the decision-maker. The concept of decision-making serves the purpose of identifying the information that is made available to the product developers to support their decisions. A profound database is a fundamental element of a digital concept, for which reason data is integrated as the fourth concept, which is clustered in its database and data types. For a subsequent description of the relations between the concepts described here, the terms of the so-called slots must also be defined. These can be found in the right column of Table 2.

Table 2: Categorisation of the terms as well as the slots to be connected

<table>
<tr><th>concepts</th><th colspan="2">terms</th><th colspan="2">slots</th></tr>
<tr><td>Requirements management</td><td>characteristics
customer
evaluation criteria
pairwise prioritisation
properties</td><td>relations
requirements
requirements specification
value functions</td><td rowspan="4">considers
creates
defines
describes
evaluates
fulfils
implies
includes
influences</td><td rowspan="4">initializes
is a
is a process
is based on
link
obtains
provides
specifies</td></tr>
<tr><td>Product development</td><td>development concept
function
model
model developer</td><td>product
product development process
variants</td></tr>
<tr><td>Decision-making</td><td>decision
decision-maker
decision-making process
decision-making request</td><td>documentation
problem description
purpose</td></tr>
<tr><td>Data</td><td>data base
data types</td><td></td></tr>
</table>

4.4. Step 4: Define the classes and the class hierarchy

Based on the documented concepts, the classes, their hierarchy and their relations to each other are defined. The development of the class hierarchy follows USCHOLD AND GRUNINGER [27] and is oriented on the top-down approach, whereby the generalised basic concepts are first defined and then systematically specified. Figure 1 shows an extract of the resultant structure using the example of *productDevelopment* and *data*. Figure 2 provides a comprehensive overview of the classes and their hierarchy.

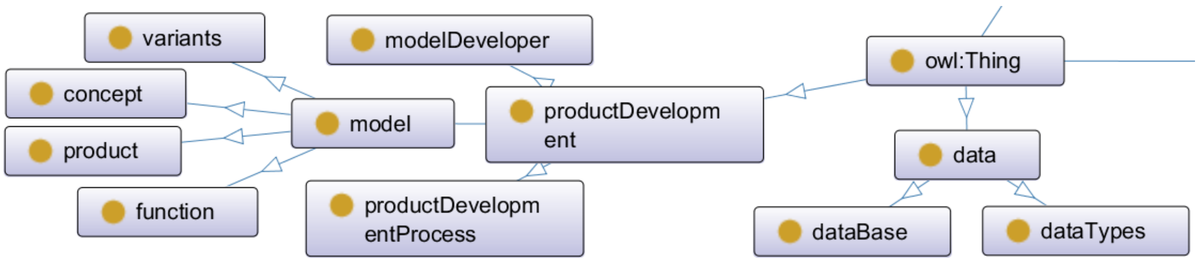

Figure 1: Extract of the class hierarchy of the ontology focusing on the product development process

4.5. Step 5 and 6: Define the properties of classes—slots and the facets of the slots

The previously defined slots (see Table 2 and legend in Figure 2) are assigned to their classes in the following. This results in the ontology shown in Figure 2. In order to be able to describe the slots logically, the facets of the slots must be defined. The classes *product*, *function* and *concept* are recursive, which means a concept can be specified again in its subordinate concepts. For reasons of convenience, a detailed description of the defined cardinalities, value types, domains and ranges has been omitted.

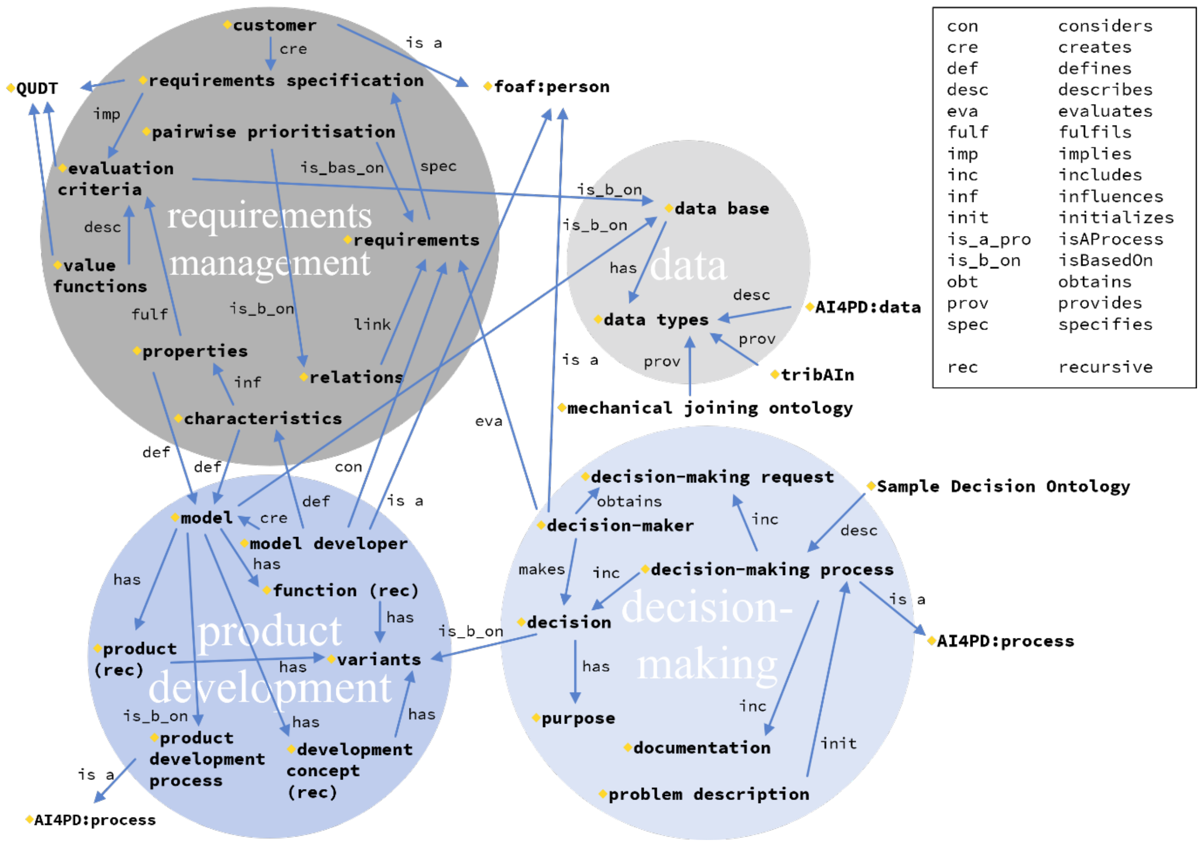

Figure 2: Conceptualised ontology with classes (yellow diamonds) and slots (blue arrows) and associated legend

4.6. Step 7: Create instances

The requirements that are treated as given in the context of conventional lists of requirements can be integrated into the ontology with the support of natural language processing (NLP) [28]. The integration of requirements and other data stored in Excel spreadsheets can also be realised using the Protégé plugin Cellfie. Their contents can be integrated as instances by applying transformation rules [29]. Further approaches for special integration of CAD data are offered by the ONTO-Step plugin [25] and the SEED approach [30].

5. Application example

The exemplary development scenario of the rear wheel axle of a micromobility solution [31] is used to evaluate the ontology and to answer the research questions. With its electric drive, the cross-skate supports the person in motion and is intended to offer an alternative to conventional means of transport. Figure 3 shows the input of the ontology in the form of natural language queries, the requirements from the specifications and the exemplary CAD data of the cross-skate. Thereby, the queries represent the first two identified competency questions (1. Which formulas are relevant for dimensioning the bearing of the axle? 2. Which information on parameters is still missing in order to be able to apply the formula?), which are translated into SPARQL queries to test the application of the ontology. As a result, the designed product development ontology provides the knowledge shown in Figure 3 on the right. First, the requested formulas for dimensioning the bearings are provided and can be immediately applied by the user. In particular, the missing parameters that have not yet been defined in the ontology and are needed to be able to solve the represented formulas, are also output. Therefore, the ontology offers the advantage of identifying coupled decision problems, as they occur, for example, due to the dependency between bearing selection, shaft design and the required running smoothness.

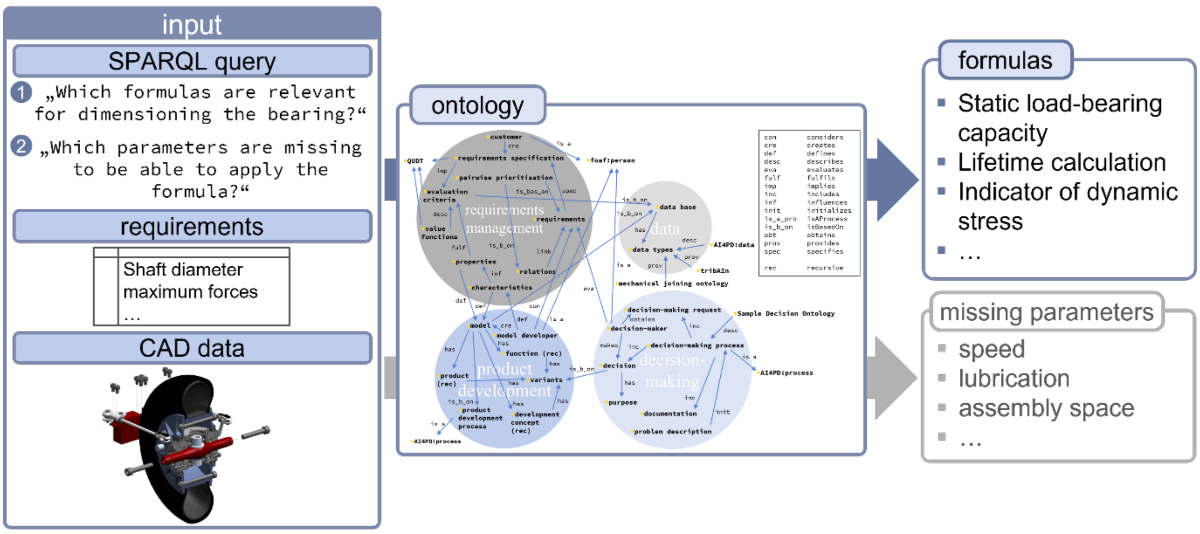

Figure 3: Application of the developed ontology using the example of bearing selection

The third competency question (Which parameters change due to the modification of the shaft diameter?) is also translated into a SPARQL query (see Figure 4) by querying the influences of the shaft diameter, which are assigned to the parameters as instances. The answer contains the parameters that are to be considered when modifying the *shaftDiameter*, such as *forces*, *speed*, *bearingDiameter* or *loadCapacity_Bearings*.

```
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX owl: <http://www.w3.org/2002/07/owl#>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>
PREFIX: <http://www.semanticweb.org/pickel/ontologies/2023/6/untitled-ontology-45#>
SELECT ?y
WHERE { ?shaftDiameter: influences ?y
}
```

Figure 4: SPARQL query of competency question 3

6. Results and discussion

The application of the developed ontology illustrates the support for decision-making within product development, providing the necessary knowledge to the decision-maker in a target-oriented way. Based on the application example, the previously posed competency questions could be answered sufficiently. However, the ontology was designed for more complex applications, which are particularly affected by cross-linked decisions, such as the simultaneous consideration of cost- and sustainability-focused aspects. Due to the ontological approach, it can be extended as desired, with the limitation of observing consistency preservation.

The introduced ontology requires manual interaction, especially for the completion of missing relevant variables. The possibility to further automate the decision-making process is of special interest. In this context, the AI4PD ontology can be used to identify and integrate data-driven methods in product development [18]. With regard to the reuse of decision situations, the application of classification methods with the help of training data is a suitable option. Existing approaches, such as the linking of customer needs and product variants for a complete semantic description by means of a decision tree classifier, can be used [32]. Since decisions in the product development process are not exclusively taken within the development department and are sometimes closely related to other company departments, a clustering of decision-making situations is recommended [13].

7. Conclusion and outlook

The research questions contributing to a proper support of the decision-making process are first answered by identifying and linking the relevant concepts, namely product development, requirements management, decision-making and data. This is realised through the semantic description of the concepts and their relations to each other by following an ontology-based approach and reusing existing ontologies. The methodological structure consistently follows the procedure of Ontology Development 101 [16].

Moreover, the application of the proposed product development ontology proved its potential by avoiding manual human intervention in the product development process due to the partially automated multi-criteria decision-making by means of the targeted provision of decision-relevant knowledge. Errors that result from not taking all relevant data into account are consequently reduced. Through the flexible application of the ontology across all product development phases, cost and time savings can be achieved.

In summary, the use of the ontology in the context of the development scenario is approved. Nevertheless, other areas of knowledge, e.g. on the basis of test and simulation data [33], must be integrated for general applicability beyond the interconnection of product knowledge. For example, the examination of the ability to automate decision-making processes through data-driven methods is a promising future research direction enabled by the already existing AI4PD ontology [18].

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