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USE OF EXISTING ONTOLOGIES AS INPUT FOR STRUCTURAL COMPLEXITY MANAGEMENT

Reducing the Effort for Analysing and Improving Engineering Systems

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Abstract: This paper presents an approach for combining two actual trends in the engineering domain: ontology-based knowledge management and structural complexity management. A focussed engineering system can be analysed and possibilities for improvements can be deduced with low effort by applying structure based algorithms on already existing ontologies. An overview of the current use of ontologies in the engineering domain is given for showing the various options for this application of structural complexity management. Necessary interfaces between ontology-based knowledge management and matrix-based structural complexity management are deduced by comparing both approaches considering data representation and analysis capabilities. The proposed approach is applied and discussed by the example of analysing an ontology originally developed for handling technical solution knowledge in the field of automation industry.

1 INTRODUCTION

Knowledge management has an increasing influence on the success of companies. Corresponding to the overall current trend in knowledge management, ontologies play an increasing role in knowledge management in the engineering domain (Kim et al., 2008). Here, knowledge management systems using ontologies can be found in the various different knowledge-intensive applications for modelling, storing and providing the required knowledge. The goals of using ontologies in this field correspond to the overall goals of using ontologies in knowledge management described by (Tudorache, 2006). Ontologies in the engineering domain are used for sharing a common understanding of the respective domain and enable knowledge sharing between humans and software applications. As a consequence, they enable sharing the terminology defined in the ontology. Furthermore, they make domain knowledge explicit and make reasoning about it possible. By having a formal representation, the knowledge can be used in formal reasoning and querying algorithms. Finally, ontologies permit the reuse of existing knowledge and improve the consistency of the regarded information.

Another actual trend in the engineering domain is the need for handling the complexity in nowadays engineering tasks. In almost all relevant sections of engineering, a steady increase of complexity can be observed (Lindemann et al., 2009). This complexity results from the high, possibly time-variant number of elements and relations that have to be considered. The Structural Complexity Management (StCM) methodology offers generic methods for modelling and analysing the underlying structure of these complex systems (Lindemann et al., 2009). The analyses are computed in a so-called Multiple Domain Matrix (MDM) and are used to identify potential improvements for the focused system.

The research presented in this paper aims at combining these two actual trends in the engineering domain. We claim that StCM methodology can increase the system understanding for the companies by applying the structural analysing algorithms on the knowledge already stored in existing ontologies. This goes beyond the current use of ontologies in knowledge management (e.g. for knowledge storing and querying). Shortcomings and problems of the respective systems can be revealed by applying analysis algorithms of StCM, and subsequently lead to an improvement of the system. As the information needed for the analysis is already stored in existing ontologies, the additional effort is quite low in comparison to the possible profit for the companies. By using existing ontologies, the actual high amount of time for information acquisition in StCM is shortened, the required efforts for system modelling are reduced and the efficient application of the approach is guaranteed.

According to this main hypothesis, the paper is structured as follows: first, we will introduce the steps of StCM methodology and show how systems can be analysed and improved by applying structural computation algorithms. Then, we will give an overview about the use of ontologies in the engineering domain. This shows the various possibilities for applying the structural analysis algorithms on existing ontology-based knowledge repositories. In the following chapter, we will compare ontology data representation with the data representation needed for StCM methodology. This builds the basis for our solution approach for transferring information stored in ontologies to the MDM. The proposed approach will be described and explained by the example of an ontology used for storing information about existing technical solutions in the automation industry. We will conclude this paper with a discussion of the presented approach and an outlook on the next steps.

2 STATE OF THE ART

2.1 Structural Complexity Management

This section provides a short introduction to StCM theory in order to allow the reader to follow the main topic of this contribution. Details of the method can be taken from Lindemann et al. (2009).

Figure 1 shows a system description by elements and relations between them. The elements belong to three domains (indicated by circles, squares and triangles). In terms of engineering, these domains could stand for components, people and functions. On the left side, the system is visualised by a graph representation. On the right side, the systems is modelled in a MDM. This comprehensive matrix model consists of Design Structure Matrices (DSMs), which contain relations between elements belonging to only one single domain and Domain Mapping Matrices (DMMs), which contain relations between elements belonging to two different domains. For example, a DSM describes the links between system functions, whereas a DMM indicates which people are responsible for which components in design.

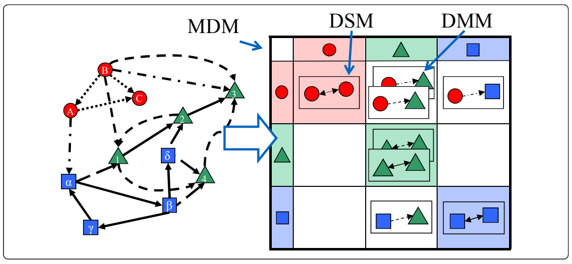

Figure 1: Structure of a MDM.

The MDM represents the core of the StCM methodology that provides a five-step procedure to support users in system definition, information acquisition, deduction of indirect dependencies, structure analysis, and the application on the product design. The initial situation for the application of the approach is a handling or design problem due to the system's complexity. In the first step of system definition it is clarified which system aspects (domains and relations) have to be considered in order to solve the complex problem. Next, information about specific system elements and their direct dependencies have to be acquired. This step represents the highest effort of time within the approach. At this point, the proposed approach in this paper can enable benefit in time and quality as already structure information stored in ontologies can be easily reused. Whereas only direct dependencies are acquired in the previous step, now indirect dependencies are deduced – in case they are required for solving the initial complex problem. For example, relations between components of a product can be deduced on the basis of the performed functions. Based on acquired and deduced structural information, now relevant system structures are analysed. The objective is to identify characteristic constellations, which allow interpretations and system optimization in the following. Finally, findings have to be applied in order to solve the initial problem. Thus the result of the final step of the StCM approach is the improved system management or design due to the application of gained structural understanding.

2.2 Use of Ontologies in the Engineering Domain

As possible input for StCM, this section will review the use of ontologies in the engineering domain and classify the scope of the ontologies according to their general objectives (product, process, organization) and their area of application.

In a quite exhaustive comparative study, thirteen approaches for dealing with different types of engineering problems by applying ontology-based knowledge management are presented (Kim et al., 2008). Seven of them focus on product knowledge, four on process knowledge, and two model both knowledge about product and process (for details about the different ontologies and projects, please see Kim et al. 2008 or the original literature).

Beyond that, several more ontologies in the engineering domain were identified in the present research. Most of them focus on the early phases in the lifecycle of a product, that of product development. (Gaag et al., 2009) developed a product-focused ontology for modelling knowledge about existing technical solutions which supports the automatic annotating of existing solution documents and the retrieval of the stored information in the field of automation industry. Furthermore, an ontology is developed and used for integrating CAx-Systems in the step of virtual and physical validation of parts and prototypes in the automotive sector (Syldatke et al., 2008). Tudorache proposed a generic product ontology that is validated in two scenarios of requirements management and concurrent engineering (Tudorache, 2006). An ontology for improving design communication which contains process-related knowledge was developed and applied for improving design collaboration (Uflacker et al., 2009). Furthermore, Darlington and Culley practically evaluated the use of ontologies in “requirements development and capture” as an important phase of engineering design (Darlington and Culley, 2008). In addition, a process-oriented ontology was developed to support the quality-assurance process in the field of electronics design (Yang, 2005). Although, Anderl et al. do not present a precise ontology, they also emphasise the increasing importance of ontologies for product development (Anderl et al., 2009). They propose an ontology-based-product development system that implements the management of access rights for different user groups and functionalities for integrating, releasing and storing information.

Ontologies in the engineering domain are also applied for enhancing manufacturing systems' intelligence. For example, a cognitive machine shop is proposed where machines “know” about their manufacturing capabilities by representing the relevant knowledge about material, work pieces, etc. in an machine-interpretable ontology (Shea et al., 2010).

3 USING ONTOLGIES AS INPUT FOR StCM

This section provides the basis for the proposed approach by showing similarities and differences between knowledge management using ontologies and StCM. We will discuss the data representation capabilities of ontologies and MDMs to identify possible losses during the transformation of information from an ontology to a MDM. Finally we will show the analysis and computation capabilities of StCM and deduce the constraints concerning the needed information input from ontologies.

3.1 Data Representation

The main elements of domain knowledge in ontologies are concepts, relations, functions, procedures, instances, axioms and production rules (Corcho and Gómez-Pérez, 2000). For each of these main elements, ontology languages provide various different features. For example, for describing concepts in an ontology, features like meta-classes, definition of attributes and definition of properties of attributes can be used in most of the languages.

In contrary to this feature-variety in ontology languages, the data representation used in StCM is – on the first glance – quite simple-constructed. In a standard MDM the focus lies on domains, elements of a domain, relations between the elements and attributes of elements or relations. This can be explained by the fact that MDM theory is based on a matrix and graph representation of the system. Therefore, features like meta-classes (e.g. for building a taxonomy of classes) or functional relations between elements are mostly not focused. Approaches for modelling this enhanced knowledge representation that burst the bounds of traditional matrix-based constraints exist, but are still not common. For example, logical dependencies (which can be interpreted as production rules in ontology modelling) were implemented and evaluated in the so-called “why-matrix” (Maurer and Braun, 2008). A hierarchical view of the system and the introduction of a hierarchy for the domains was proposed for the reduction of efforts for data acquisition (Biedermann et al., 2010). Also, the “1.5 Matrix” allows a hierarchical view on the elements of a system by interpreting attributes of elements as meta-classes (Eppinger, 2009). A further approach aims at overcoming the strictly domain-oriented representation of a system in form of a MDM by proposing flexible domain modelling (Kohn and Lindemann, 2010).

Summing up this comparison of data representation, it can be said that not all information stored in an ontology can be transferred into a MDM. Nevertheless, all information needed for analysing complex systems in StCM methodology (domains, elements and relations) can be found structured in ontologies. Therefore, ontologies can generally be used as information input for StCM.

3.2 Analysis Capabilities

In a further step, we will now describe the computation and analysis capabilities of StCM and discuss the resulting constraints for the needed information input from ontologies.

In StCM methodology, there are two main types of computations. First of all, indirect dependencies are deduced in the third step of StCM. Here, the direct dependencies modelled in the DSMs or DMMs are used for the computation of further DSMs or DMMs (which then contain indirect dependencies between their elements). This is done by applying computation algorithms from the field of matrix algebra. Several types of indirect dependencies exist. For example, a DSM can be computed using only one DMM, or using another DSM and two DMMs. The degree of indirect dependency provides information about the strength and therefore the relevance of the indirect dependency. Both the direct dependencies and the indirect dependencies are then used for the second type of computations in StCM: the structural analysis algorithms. Using the analysis algorithms, structural significant subparts of the structure can be identified. These algorithms are often matrix-based (e.g. clustering algorithm for static matrices, tearing algorithm for time-based matrices, etc.) or graph-based (e.g. leaves of a structure, significant hubs, etc.). In the next step, the significant subparts of the structure serve for indicating possible improvement potential for the system according to the initial goal of the analysis. Established matrix- and graph-based visualisation techniques are used for showing and presenting the results and serve for enhancing the system understanding.

For the import of information from an ontology, one critical point has to be mentioned concerning the analysis capabilities: all computations done in StCM analysis are based on the elements in a MDM and their relations. Without the elements, the algorithms and therefore the analysis would be obsolete. In contrast, ontologies do not need the instances for reasoning or querying an ontology. They can perform computation only on the taxonomic level of the ontology (also referred to as T-Box – among others (Struckenschmidt, 2009)). Thus, structural analysis algorithms can only be applied on ontologies that contain instances and have a well-populated T-Box. But, as current trends in ontology design goes from pure taxonomic ontologies towards descriptive and instantiated ontologies (Kim et al., 2008), this restriction becomes less significant.

4 APPLYING StCM ON EXISTING ONTOLOGIES IN THE ENGINNERING DOMAIN

The initial question when using StCM on the basis of existing ontologies is whether the information modelled in the ontology can serve for solving a handling or design problem. Therefore, it has to be clarified if the concepts and relations of the ontology and the contained elements suffice for the intended analysis of the system. In some cases, only part of the information stored in the ontology can be used and, consequently, further information sources have to be taken into account. The relevant and useful concepts and relations for the initial problem are then taken for building the meta-model. Subsequently, the elements and their relations in the T-Box of the ontology can be transferred into the matrices of the MDM in the step of information acquisition. The next three steps of deducing indirect dependencies, analysing the structure and application on the system are equal to the original StCM methodology.

By the example of the application in a use case in the field of the automation industry, we will illustrate the presented approach and discuss the benefit of the further analysis capabilities described above. The developed ontology is an OWL-DL ontology and contains information about existing technical solutions (Gaag et al., 2009). This ontology is used for supporting the annotation of existing solution documents and enables their subsequent retrieval by providing different abstraction principles for the similarity of technical solutions (Kohn and Lindemann, 2011).

The following Figure 2 shows an excerpt of the main concepts and properties of the ontology with an exemplary instantiation. A company provides a technical solution that is used in an industrial sector. The technical solution uses function owners that perform certain functions. For example, a robot performs the function “transfer bottle” and the cylinder performs the function “fill bottle”.

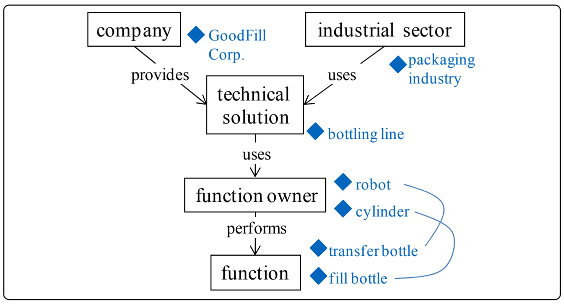

Figure 2: Ontology for describing solution documents with exemplary instantiation.

In our example, we use parts of this ontology to identify possibilities to modularise the technical system by reorganising the function owners into modules. In the engineering domain, this can be done by reorganising and grouping functions owners according to the performed functions. Therefore, we will transform the needed information for this design problem into the meta-model in form of a MDM. The concepts of the ontology are interpreted as domains in the MDM and the properties are the relations between the domains (see Figure 3).

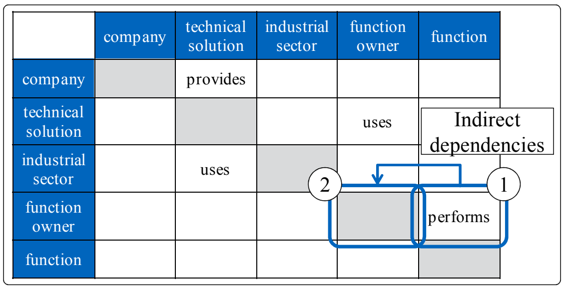

Figure 3: Meta-model of the system in form of a MDM.

In our case, we only need information about function owners and functions (in Figure 3 labelled as number 1). In a next step, the instances and the relations between instances are transferred from the ontology to this matrix. Properties of instances become relations of elements in the system. For transferring the information in the ontology, the property "perform" of the function owner "robot" to the function "transfer bottle" becomes a cross in the appropriate field in the DMM "function owner performs function" (Figure 4 a). In a further step, indirect dependencies can be deduced for showing the dependencies between function owners. In this example, indirect dependencies between function owners were computed from the initial DMM and stored in a new DSM with to the relation "two function owners are related when they perform the same function" (in Figure 3 labelled as number 2). In a next step, this newly calculated DSM with indirect dependencies can be used for analysis algorithms. Here, the result of a clustering algorithm is shown in a matrix-based visualisation (Figure 4 c). In this case, two clusters are clearly visible. In terms of engineering the clusters indicate possibilities for a functional modularisation of these function owners, as they perform the same functions. Beyond the matrix-based analysis, graph-based analysis can be used (Figure 4 d). The elements of the system are visualised as the nodes of the graph and the relations as edges. As structural significant system elements, a bridge element connects the two clusters identified above. If this element fails, both clusters would be affected. For our modularisation approach, this element can build the hub between the two modules.

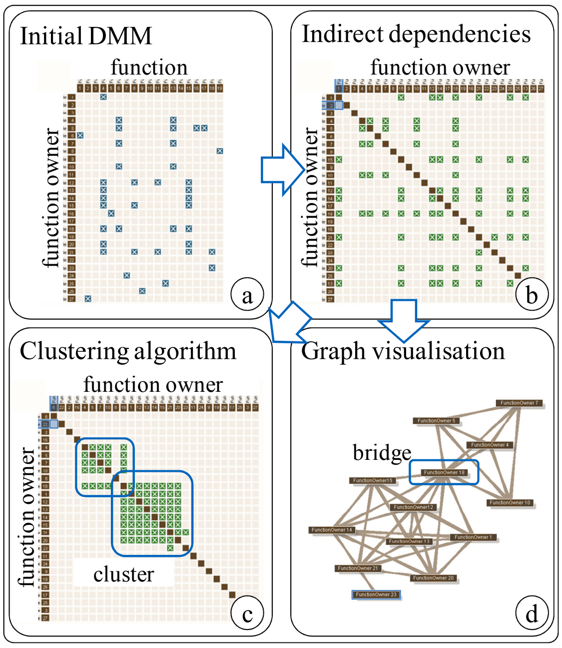

Figure 4: Applying computation, analysis and visualisation algorithms on the MDM.

The example provides a short glance on the possible application of the presented approach. It showed that information stored in an ontology that was originally developed for a different purpose can be successfully used for analysing the underlying system. Possibilities for system improvements concerning a certain design problem can be identified. As the needed information is already stored in the ontology, the effort for the otherwise time-consuming information acquisition is very low.

5 RELATED WORK AND DISCUSSION

A study of related work revealed that combining matrix methodologies and ontologies was presented by different authors before. However, they combined matrix methodologies and ontologies each in a very specific use-case. They did not consider and evaluate the general possibilities for interaction of the two approaches as presented in this research. For example, Yang transforms information stored in an ontology to a Domain Structure Matrix in a process framework for consumer electronic design. He uses the computation capabilities in the DSM for analysing activity dependencies in an ARIS (Architecture for Information Systems) process for removing cyclic dependencies in form of interaction loops (Yang, 2005). Syldatke et al. propose the combination of ontologies and DSM-modelling techniques. They show the possibilities of enhancing DSM-modelling techniques by using semantic technologies (e.g. ontology languages and reasoning capabilities), but did not go into detail considering the conditions for the proposed combination (Syldatke et al., 2008). Finally, existing research reveals a study of using ontologies for the integration of DSM analysis techniques into the planning of construction projects. Here, once again the analysis capabilities of matrix-based algorithms are emphasised and evaluated in the specific use case (Masera, 2007).

Summing up, two different ways of combining the two approaches can be found. First, – as shown in this paper – structural analysis algorithms on the basis of DSM, DMM or MDM applications can be used for enhancing current ontology-based knowledge modelling approaches. The other possibility aims at the opposite direction. Here, achievements of established semantic technologies are proposed to be used for enhancing representation and modelling capabilities of matrix-based approaches. Both approaches can be useful depending on the intended purpose and reveal interesting options for the combination and integration of both approaches.

Regarding the comparison between ontology-based knowledge management and StCM done in this research, the general different scope of these two fields has to be discussed. As shown above, the StCM methodology is directly focused on the structural analysis of complex systems. In contrast, ontologies and ontology development in general have no real focus on a certain application per se. It depends strongly on the individual specification and the desired objectives. Therefore, the capabilities of ontologies are more generic and have to be individually specified corresponding to the application in the respective use-case. This generality can be both benefit and disadvantage. For experts in knowledge engineering this is certainly an advantage. However, for people in the engineering domain, who are often not experienced in building and using ontologies (Kim et al., 2008), predefined analysis criteria as proposed by the StCM methodology could be helpful. Also, the visualisation part and the comprehensibility have to be taken into account. Matrix-based and graph-based visualisations have proved to increase system understanding and help people handling complex systems.

As shown in the previous chapter, an existing ontology can only be used for design or handling problems that require information which is – either direct or indirect – available in the ontology. The quality of the ontology influences the results of the analysis. If the concepts or relations do not provide the needed information or not in satisfying quality, the ontology cannot be used for the specific problem. Then, the definition of the meta-model and the information acquisition has to be done according to the standard StCM methodology.

6 CONCLUSIONS AND OUTLOOK

The research presented in this paper gives an insight into possibilities for the combination of knowledge management with ontologies and StCM in the engineering domain. By applying analysis algorithms on already existing ontologies, the system understanding can be enlarged and possibilities for system improvement according to the analysis results can be deduced. The literature review on existing approaches using ontologies for handling engineering problems reveals the increasing use of ontologies in the engineering domain. This provides the basis needed for the presented approach and confirms its further application possibilities.

The transformation of information stored in ontologies to MDM needed for the structural analysis is shown by comparing ontologies and StCM according to their data structure and analysing capabilities. An example from the automation industry illustrated the presented approach. Here, an ontology originally designed for capturing knowledge about already existing technical solution was exemplarily analysed by selected structural analysis algorithms for the identification of modularisation potential in the system. This application showed that structural analysis algorithms can enhance the analysis of systems already modelled in an ontology with very low information acquisition effort.

Further work will focus on the above mentioned bidirectional combination and the integration of ontology-based knowledge management and StCM in combination with further empirical studies. Using structural analysis algorithms and therewith enabling the corresponding system improvement possibilities directly with an ontology-based system seems to be very promising. Therefore, the already existing analysis algorithms StCM have to be translated into ontology-interpretable defined classes for enabling reasoning or the appropriate ontology queries.

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