ONTOLOGICAL MODELLING OF THE AEROSPACE COMPOSITE MANUFACTURING DOMAIN

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Abstract

This paper focuses on the development of an ontology for the aerospace composite manufacturing domain. It uses an amalgam of ontology development methodologies to arrive at a semi-formally declared ontology, which is tested for practical validity in a case study focusing on construction of an architecture for a knowledge management solution for an aerospace OEM.

1 Introduction

In recent years, headlines in aerospace engineering news have frequently focused on the large-scale adoption of composite materials in new aircraft programs, as evidenced by the development of the Boeing B787 and the Airbus A350 XWB (Extra Wide Body). The use of composites in aerospace applications has been on a steady rise in the last decades. However, the development of the B787 and the A350 XWB represents a milestone as the major aerospace producers now put their weight behind a whole-hearted switch from predominantly aluminium to predominantly composite structures. From a manufacturing perspective, this is a major step change. One critical aspect of this change is that it imposes the need to create and update existing knowledge bases to adapt industry to this new demand. Converted and newly developed knowledge bases must be supported by the right knowledge structure to ensure that the maximum benefit from the included knowledge is reached; in particular, the capture, sharing, consistent exploitation and re-use of knowledge throughout its life-cycle are important to ensure. To create such a knowledge structure, it is critical to have a solid understanding of the concepts of the attendant domain, as well as the interrelationships and the underlying concept attributes. Ontologies are widely used to model these aspects, resulting in reliable, verifiable and computer-interpretable mappings of a domain.

In this paper, a semi-formal ontology is developed which specifically addresses the aerospace composite manufacturing domain; the reported ontology is work in progress. Targeted ontological modeling of the aerospace composite manufacturing domain has not been performed in earlier research (as discussed in Section 2), but would contribute greatly to initiatives for sharing, management and re-use of knowledge in this particular domain. Furthermore, this paper briefly illustrates a case study in which the ontology is used to construct an architecture for a knowledge management (KM) solution. This KM solution aims to deliver knowledge use and re-use benefits to an aerospace OEM, thus validating the ontology approach in practice.

To enable the construction of the aerospace composite manufacturing domain ontology, existing perspectives on ontologies and supporting development methodologies are discussed in Section 2. Following this, the ontology construction process is illustrated in Section 3, which includes amongst others the elicitation of concepts, hierarchical structuring, relationship modeling via predicates and implementation in Protégé-OWL. The resulting ontology has been converted and implemented in a knowledge management application, which is elaborated in Section 4. Finally, conclusions, limitations and recommendations for further research are presented.

2 Ontologies: A Theoretical Perspective

Ontologies are defined as 'explicit (formal) specifications of a conceptualization' [1]. Four elements in this definition need further clarification:

- **Conceptualization:** as Uschold [2] notes, a conceptualization can be seen as 'a world view, a way of thinking about a domain that is typically conceived and/or expressed as a set of concepts, their definitions and their inter-relationships'.
- **Specification:** an ontology necessarily includes a vocabulary of terms and a specification of their meaning [2]. Without a specification, the set of concepts would be variously interpretable by different sets of users.
- **Explicit:** the conceptualization of a domain may be implicit (e.g. existing only in someone's head) or it is explicit, meaning that it is or can be articulated, coded and stored in certain media, and readily transmitted to others. Ontologies require an explicit conceptualization.
- **Formal:** the formality of the ontology indicates the level of expression in an artificial, formally defined language, which extends to the possible ontology property of being machine-interpretable. Ontologies can be expressed along a range of formality degrees, as explained later.

Alternatively, an ontology is 'a definition of a common vocabulary for researchers who need to share information in a domain. It includes machine-interpretable definitions of basic concepts in the domain and the relations among them' [3]. The definitions clearly overlap in their attention to a shared vocabulary consisting of well-defined concepts and interrelationships that are expressed in a formal, machine-interpretable manner.

Ontologies can be characterised along various dimensions. Uschold [2] identifies three key dimensions along which ontologies vary:

- **Formality:** the degree of formality by which a vocabulary is created and meaning is specified. Uschold [2] posits a formality continuum that moves from highly informal (loose expressions in natural language) via structured informal (restricted and structured form of natural language) and semi-formal (expressed in an artificial formally defined language) to rigorously formal (meticulous definition of terms with formal semantics, theorems and proofs of properties such as soundness and completeness). The ontology developed in this paper can be characterised as semi-formal.
- **Purpose:** Uschold and Gruninger [4] identify three main categories of use for ontologies: communication, interoperability and achieving system engineering benefits. Both the first and the last are relevant for the aerospace composite manufacturing ontology. This ontology can provide a unifying framework and enable a shared understanding and communication between users with different needs and viewpoints arising from their particular contexts; this will be substantiated in Section 4. Furthermore, the composite manufacturing ontology achieves system engineering benefits by facilitating knowledge acquisition and knowledge re-usability; this is one of the central benefits in the knowledge management application that is shown in Section 4.
- **Subject matter:** Uschold [2] recognizes that the subject matter of an ontology can be 'anything at all', but identifies three main categories, namely domain ontologies, task/problem solving ontologies, and meta-ontologies. The latter are also called foundational ontologies [5]. The aerospace composite manufacturing ontology is unequivocally a domain ontology, which is defined as 'focusing specifically on one particular

subject domain (e.g. medicine, geology, engineering) or sub-domain' [2]. Of course, the aerospace composite manufacturing domain is a sub-domain of the engineering domain. Ontologies for the manufacturing domain are available [5,6], as are ontologies for the aerospace domain, from both academia [7] and business [8]. Furthermore, ontology work in the composite material domain is also available [9,10]. However, when looking at the combinations of these domains, research becomes scarcer. There are ontology development efforts that combine the aerospace and manufacturing viewpoints [11]. There are also (proposed) ontologies for the composite manufacturing domain [12]. However, an ontology for the combined aerospace composites manufacturing field has not been developed and presented in literature yet. Given the developments in this field (e.g. the aforementioned B787 and A350 XWB, and other development programs), this constitutes a significant research gap. This paper addresses this specific research gap by proposing an aerospace composite manufacturing ontology and highlighting its first development steps.

To develop an ontology, a number of ontology construction methodologies are available. Examples include the methodologies by Uschold [2], Noy & McGuinness [3], Uschold & Gruninger [4] and the METHONTOLOGY methodology [13]. All these methodologies share common steps, though the exact representations may vary from methodology to methodology. The common steps have been summarized by Pinto & Martins [14]:

1. **Specification:** identification of the purpose and scope of the ontology.
2. **Conceptualization:** identification of the domain concepts and the relationships between concepts.
3. **Formalization:** organizing the concepts into class hierarchies and subsequent construction of axioms to formally model the relationships between concepts.
4. **Implementation:** codification of the class hierarchies and axioms into a formal knowledge representation language.
5. **Maintenance:** updating and correcting the implemented ontology.

These steps are supported throughout the development cycle by knowledge acquisition, evaluation (from both technical and user perspectives) and documentation [14]. A particularly important additional supporting activity as recommended by Noy & McGuinness [3] is to re-use existing ontologies to avoid unnecessary rework.

For the construction of the aerospace composite manufacturing ontology, the first four steps of the five mentioned above have been carried out, while respecting the aforementioned supporting activities. The specification, conceptualization and formalization steps are performed in Section 3: Ontology Development for the Aerospace Composite Manufacturing Domain. Implementation in the context of this paper concerns both codification into a formal knowledge representation language (see Section 3.4) and practical implementation of the ontology as a backbone for a knowledge management application (Section 4).

3 Ontology Development for the Aerospace Composite Manufacturing Domain

The development of the aerospace composite manufacturing ontology development follows the steps identified by Pinto & Martins [14], which is reflected in the structure of this section.

3.1 Specification

The purpose of the aerospace composite manufacturing ontology is two-fold. In a wide sense, the purpose of this ontology development effort is to fill a research gap by introducing a new domain ontology. In a narrow sense, the purpose of the ontology is to support a knowledge management application by providing a knowledge structure, allowing the use and re-use of composite manufacturing knowledge in several business processes. The scope of the ontology is limited to its domain, aerospace composite manufacturing, where *aerospace* relates to objects in the domain of flight (aircraft, spacecraft), *composite* is defined as 'a heterogeneous combination of two or more materials that maximizes specific performance properties traceable to one of the constituent materials or to the aggregate composite material' [9] and *manufacturing* is defined as the transformation of raw materials into finished goods. Within this scope, the emphasis lies on the concepts and relationships that are employed in the business process (as shown in Section 4).

3.2 Conceptualization

To elicitate the applicable concepts and relationships for the aerospace composite manufacturing ontology, various sources have been employed. First of all, a small number (N = 4) of experts from a large aerospace manufacturer and integrator company have been interviewed. The results have been augmented by analysis of company sources (including product and process specifications), as well as analysis of general literature (e.g. [15]). Furthermore, a number of existing ontologies [5, 16, 17] have been studied to enable re-use of previous development efforts and to check for compliance of the aerospace composite manufacturing ontology with meta-ontologies. In particular, the Activity and Resource classes from the Knowledge Management (KM) ontology [17], the Activity, Constraint and Entities classes from the informal model of MOKA (Methodology and tools Oriented to Knowledge-based engineering Applications [16]) and the Product and Process plan classes from ADACOR (ADAptive holonic COntrol aRchitecture for distributed manufacturing systems [5]) have been identified as viable contributing classes from upper-level ontologies. MOKA's informal model (known as ICARE) also includes Illustrations and Rules. The former two are deemed irrelevant for the composite manufacturing ontology at this point, though Rules are a viable candidate for inclusion at a later point.

The source analysis has resulted in a library of concepts and relationships. The ontology top-level concepts and their interrelationships have been expressed in Fig. 1.

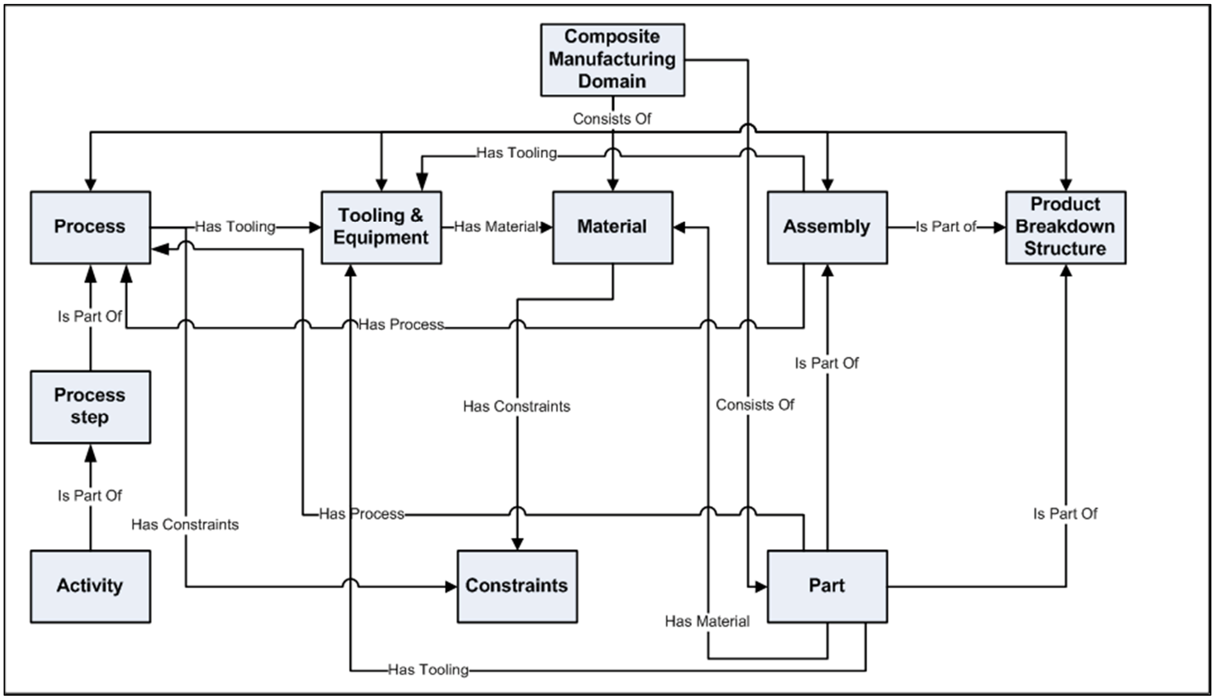

Fig. 1. Top-level Ontology Structure

The top-level classes share some similarity with the previously identified classes from MOKA, the KM ontology and ADACOR [5, 16, 17]. The Activity class is now a contributing class to a Process – Process step – Activity chain, wherein the former always contain at least one of the latter (i.e. a process consists of ≥1 process step, which consists of ≥1 activity). The Process class in some aspects resembles the Process plan class from ADACOR. The Resource class from the KM ontology [17] has been developed into the manufacturing-specific classes of Tooling & Equipment, and Material. The Constraint class from MOKA has been literally adopted, whereas the Entity class has been developed into the aerospace manufacturing-specific Product Breakdown Structure class with contributing Part and Assembly classes, which share similarities with the Product class from ADACOR.

3.3 Formalization

The top-level classes have evolved into class hierarchies. An example of an implemented class hierarchy is given in Fig. 2, in which the Process hierarchy has been developed.

During the development of the classes, the appropriate properties have been assigned. For example, the top-level Process class has Process_Cycle_Time and Process_Lead_Time as properties. Many potential properties have been identified; so far, just 80 datatype properties have been implemented as the focus of the ontology development effort lies more on class and relationship development.

The relationships (including the top-level relationships shown in Fig. 1) have been formalized into the ontology as predicates. Examples include:

- HasPart(x,y): assembly x has part y.
- HasConstraint(x,y): part or process x has constraint y.

The inverse predicates have also been modeled. Predicates such as the last one (HasConstraint) are developed into hierarchies themselves to avoid semantic confusion. For example, HasConstraint has sub-predicates HasConstraint_Part and HasConstraint_Process to distinguish between the related classes. These hierarchies are taken even further by including predicate types; e.g. the HasConstraint predicate hierarchy includes predicates for different types of constraints, such as geometric and resource constraints.

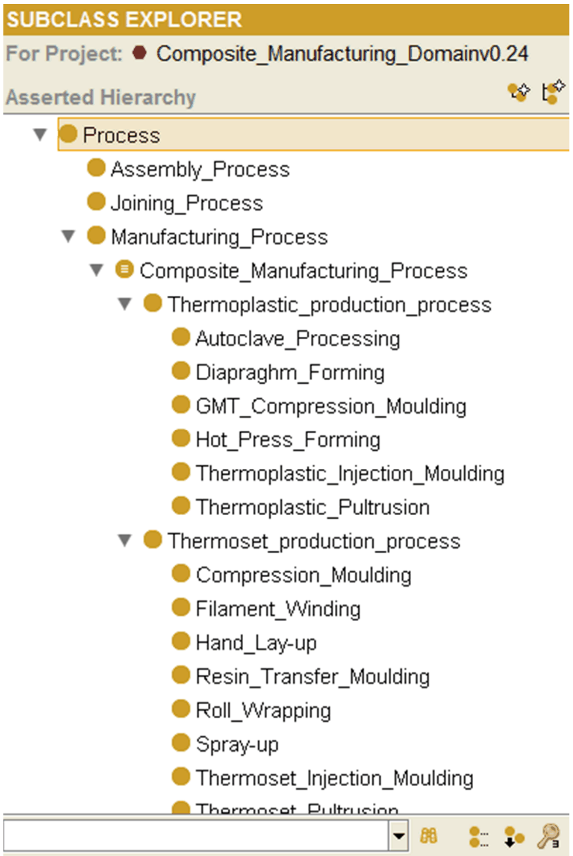

Fig. 2. Process hierarchy (Protégé implementation)

With classes and predicates in place, the elements for declaring axioms are available. The top-level concepts and their relationships have been modeled in axioms using the predicates. However, the aerospace composite manufacturing ontology is currently still in the first steps of expression into axioms; most sub-classes in the various hierarchies have not been expressed in axioms yet. Consequently, the ontology is still semi-formal. There are some examples of axioms available, but as these are based on literature and the input of a few experts and have not been validated in a large expert group, no examples will be given at this point in time.

3.4 Implementation

The class hierarchies, attendant properties and predicates have been implemented in Protégé-OWL. An example hereof has been given already in Fig. 2. A more involved example that shows some of the class properties and axioms is shown in Fig. 3.

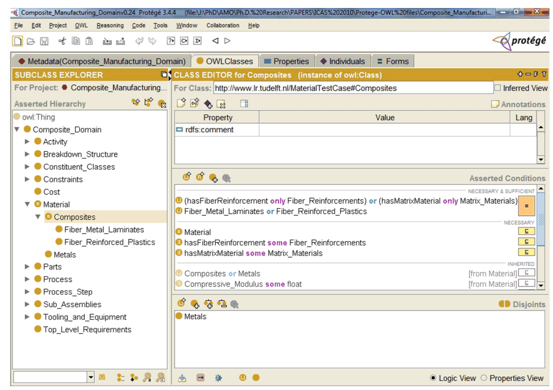

Fig. 3. Ontology implementation in Protégé-OWL

The current iteration of the Protégé implementation has 188 classes with 152 restrictions. 46 predicates along with the inverse versions account for 92 predicates (object properties in the Protégé-OWL nomenclature). Finally, 80 datatype properties have been included.

4 Ontology Application as Knowledge Management (KM) Architecture

To validate the completeness and usability of the ontology, it has been used to generate the main knowledge architecture in a knowledge management (KM) application. This KM application has subsequently been used to support two business tasks of an aerospace OEM: the generation of composite manufacturing brochures and the support of composite manufacturing cost modeling in the conceptual design phase. In this paper, the development of the knowledge architecture will be highlighted – the applications themselves are presented in more detail in related literature [18].

The KM application of choice for performing these tasks is Ardans Knowledge

Maker (AKM) [19]. This application offers a range of options designed to enable user-friendly management of knowledge, for instance through easy categorization and creation of knowledge articles (see Fig. 4 for an example).

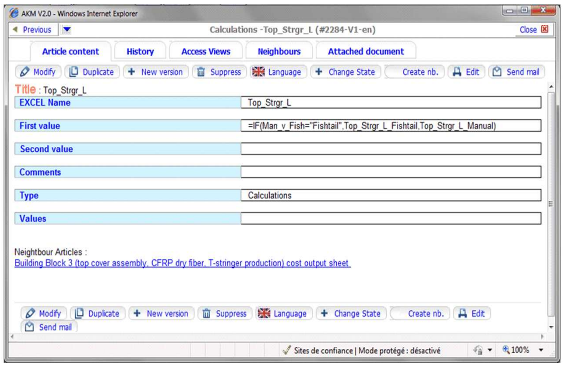

Fig. 4. AKM Knowledge Article

AKM complies with vital knowledge requirements by focusing on traceability, security and knowledge life-cycle management provision. Traceability and knowledge life-cycle management are achieved through various knowledge article features, including author tracking, tracking of version history, status accounting through user group authorization and article status management. Each knowledge element (e.g. individual parameters or geometric models) can be stored into its own AKM knowledge article, which retains the traceability, security and life-cycle management provisions described above.

AKM has been chosen after a benchmark which included other KM solutions. The advantages of AKM, also with respect to its competitors, outweighed its disadvantages, which include the non-trivial disadvantage of not being directly compatible with ontologies and ontology formats. AKM is a web-based application that rests on an underlying relational database. It does not support the use of inference mechanisms, which is one of the strengths in common ontology applications. Furthermore, existing ontologies cannot be imported directly into AKM. Therefore, a conversion is necessary to achieve the transition between the semi-formalized aerospace composite manufacturing ontology and its actual representation as a knowledge architecture in AKM.

AKM offers the possibility to implement class hierarchies directly. Furthermore, it has a facility to create knowledge models. These can be tied directly to the class hierarchy. Furthermore, these knowledge models can be used to define class properties and their slots (e.g. value ranges, value types). The knowledge models can also be used to prescribe the allowed relations between knowledge elements. Finally, the knowledge models can be associated automatically within the implemented class hierarchies. These provisions make it possible to 're-create' the ontology in AKM in a roundabout manner.

When instantiating a knowledge model, the resulting knowledge article is a class instantiation with the required class properties. It is possible to directly create so-called neighboring knowledge articles, which are instantiations of a different class and automatically share a pre-defined relationship with the original knowledge article. In this manner, the ontology relationship predicates are implemented in practice.

The class hierarchies, class properties and relationships have been implemented in AKM. Together, these provide a knowledge structure which is subsequently used to support business tasks. For both the aforementioned generation of manufacturing brochures and support of composite cost modeling, the knowledge structure enables efficient capture, storage and retrieval of knowledge. A snapshot of the search process is provided in Fig. 5.

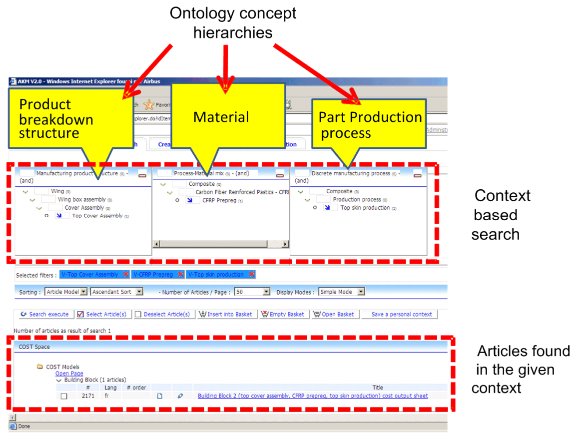

Fig. 5. Searching knowledge in AKM using the knowledge structure

In the search environment, the class hierarchies are accessible through specific context search boxes. Selection of applicable concepts leads to a down-selected context search result. The resulting knowledge article(s) can be selected, inspected (which gives the opportunity to inspect the related knowledge articles) and exported to support the business tasks. More information about the practical implementation and the support for knowledge-based cost modeling can be found in forthcoming literature [18].

6 Conclusions

A semi-formal ontology for the aerospace composite manufacturing domain has been presented. This ontology can be used to support business tasks in this domain, either directly or through other applications. In this paper, it has been shown that the ontology can be used in a knowledge management environment to support engineering tasks.

The aerospace composite manufacturing domain ontology is subject to a number of limitations. First, the ontology is currently in a semi-formal format and possesses a low level of axiomatic expression. Furthermore, the concepts, their definitions and the concept relationships have been verified by a small user group only. Consequently, recommendations for future research are to establish an independent expert group that can serve to confirm or refuse ontology elements. By user group interaction, the informal expressions of the concepts and relationships of the current ontology can be tested, improved and validated. Subsequent expression of the ontology into an axiomatic form will enable the use of automatic inference capabilities, such as consistency and completeness checking and handling. Finally, further research will focus on expansion of ontology implementation to support business tasks.

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