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A semantic knowledge management system for laminated composites

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ABSTRACT

The engineering of laminated composite structures is a complex task for design engineers and manufacturers, requiring significant management of manufacturing process and materials information. Ontologies are becoming increasingly commonplace for semantically representing knowledge in a formal manner that facilitates sharing of rich information between people and applications. Moreover, ontologies can support first-order logic and reasoning by rule engines that enhance automation. To support the engineering of laminated composite structures, this work developed a novel Semantic LAminated Composites Knowledge management System (**SLACKS**) that is based on a suite of ontologies for laminated composites materials and design for manufacturing (DFM) and their integration into a previously developed engineering design framework. By leveraging information from CAD/FEA tools and materials data from online public databases, **SLACKS** uniquely enables software tools and people to interoperate, to improve communication and automate reasoning during the design process. With **SLACKS**, this paper shows the power of integrating relevant domains of the product life cycle, such as design, analysis, manufacturing and materials selection through the engineering case study of a wind turbine blade. The integration reveals a usable product-life-cycle knowledge tool that can facilitate efficient knowledge creation, retrieval and reuse from design inception to manufacturing of the product.

1. Introduction and motivation

The use of laminated composites in engineered products has seen a rapid rise in recent years. Companies dealing with projects involving laminated composites have a difficult time trying to efficiently manage the large amount of knowledge throughout the product life cycle. There is usually some loss of clarity about the information in the design-to-manufacturing process flow as the cycle advances [1]. This is especially true in the case of automobile and aerospace industries where laminated composites are heavily used. For example, consider the construction of Boeing's Dreamliner. It includes thousands of parts and involves designing laminated composite structures for which the design engineers spend days trying to evaluate the right choice of material combinations. This is because there is an abundance of materials to choose from in the design of a laminated composite part. Ideally, design engineers will constantly interact with the analysis and manufacturing engineers to brainstorm and discuss major issues of laminated composites such as materials selection, zonal stresses, failure criteria, fiber orientations, draping and warpage, to name a few [2]. However, in reality, design, analysis and manufacturing engineers do not work together constantly. Instead, they often tend to recede from the big picture and focus on their own domains, often leading to conflicts of interest [2]. Thus, the large amount of knowledge coupled with a serial product development process usually causes multiple design iterations, excessive design reviews, large lead times and high costs.

Since the design and manufacturing of laminated composites are highly knowledge intensive activities, efficient mechanisms for capturing, reusing, and sharing the wealth of knowledge involved are sorely needed. The first challenge is the creation of web-enabled knowledge bases that will replace existing knowledge structures to facilitate consistent exploitation of knowledge throughout its life cycle. Creation of such knowledge models requires a solid understanding of the concepts of the attendant domain along with the interrelationships and concept attributes [3]. Also, the problem of the increasingly heterogeneous and distributed nature of current engineering environments and the lack of synergy needs to be addressed [4]. Hence, the second challenge is to bridge the gap between legacy systems and to integrate the various product life cycle domains. This can be done, for example, by leveraging output information from Computer Aided Design (CAD) or Finite Element Analysis (FEA) software typically used in organizations that design with laminated composites.

Another critical aspect is that the scientific data and knowledge such as laminated composite materials testing data generated in

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organizations and institutes are available on the Internet as Wikis, e-Journals, and online databases [5]. These resources are often decoupled or at best loosely linked with each other, and their "representation, terminology, and formats are not standardized" [5]. Hence, the third challenge is to develop an efficient knowledge structure which unifies such existing web resources for laminated composite materials and integrates these information resources with the design, analysis and manufacturing domains for laminated composite products.

Ontologies are extensively used to formalize domain knowledge with concepts, attributes, relationships and instances resulting in "reliable, verifiable and computer-interpretable knowledge mappings of a domain" [3]. Formal engineering ontologies can also address semantic interoperability issues between legacy systems because of their compatibility with the Semantic Web. Thus, ontologies offer the promise of efficient integration and transfer of knowledge between the various domains in the product life cycle. Further, automated reasoning capabilities of ontologies can provide us with a semantic knowledge base that can act as an expert system for engineers to aid in certain design situations such as materials selection. Hence, we find that ontologies are potentially a powerful tool to help address all of the three challenges mentioned before.

In summary, the engineering of laminated composite products (1) involves a large volume of information and knowledge spread across the domains of design, manufacturing, and analysis, (2) there is a general lack of formal semantic information models for capturing and sharing this engineering information and knowledge, and (3) the result is a disjoint nature of work between the domain experts that hinders efficient collaboration, and a lack of reuse of information and knowledge. To resolve this situation, we developed **SLACKS** – the **S**emantic **LA**minated **C**omposites **K**nowledge Management **S**ystem. The foundation of **SLACKS** is a laminated composite materials ontology that can assist the design engineers in finding adequate and relevant information. Furthermore, the laminated composite materials ontology standardizes the domain knowledge structure to enable consolidation of scientific and engineering data from existing resources. The design of laminated composites is closely related to its manufacturing processes and techniques, as the lay-up on the mold and the curing stage describe the setting of the final design. This is one specific reason for multiple design reviews and increased production times in laminated composites manufacturing environments. Hence, better integration of design, analysis and manufacturing domains in laminated composites engineering is required. Accordingly, **SLACKS** includes complementary ontologies related to the design for manufacturing (DFM) of laminated composite products. To facilitate a holistic approach to the laminated composites design process, **SLACKS** is integrated with a previously developed suite of ontologies for facilitating engineering design, called the e-Design framework (see [6–15]). The application and effectiveness of **SLACKS** is demonstrated through the design, analysis, and manufacturing of a laminated composite wind turbine blade.

2. Engineering knowledge management

The field of knowledge management and representation has been evolving continuously over the past three decades. Alavi and Leidner [16] summarize the conceptual foundations, taxonomies and research issues in the field of knowledge management systems. Of particular importance are the definitions for data, information and knowledge. In short, data are facts, information is processed data and knowledge is personalized information [16]. Therefore, one can possibly have too much information or too little knowledge. However, there exist knowledge taxonomies based on different perspectives. Examples include tacit, explicit, declarative and pragmatic types of knowledge [16]. In the case of engineering design, we tend to deal mostly with explicit knowledge.

In the engineering realm, collaboration between knowledge experts in different domains is one of the first steps towards effective knowledge management strategies [17–19]. In 1994, the International Organization for Standardization (ISO) came up with ISO 10303 – STandard for the Exchange of Product model data (STEP) for efficiently exchanging electronic product data between computer-based product life cycle tools. Pratt [20] has given a brief review of STEP. Since then, there has been a strong push to effectively use structured knowledge to improve the work in the engineering domain. For instance, one of the key research efforts was the Methodology and tools Oriented to Knowledge-based engineering Applications (MOKA) project [21]. The MOKA project aimed at developing a standard methodology for the development and maintenance of knowledge-based engineering applications for product design [21]. Szykman et al. [22] introduced the concept of design repositories through the National Institute of Standards and Technology (NIST) Design Repository Project that helps store a large amount of corporate engineering design knowledge and thus reduce product development times. Also, an infrastructure for efficient exchange of information to address the issue of poor interoperability between Computer-Aided Engineering (CAE) software tools was put forth by Szykman et al. [23]. The drive towards the importance of knowledge in representing product models along with representing design rationale began with Szykman et al. [24]. Substantial efforts on the NIST Design Repository Project later evolved into the NIST Core Product Model (CPM) which divides artifact information into categories of form, function and behavior [25]. Unified Modeling Language (UML) diagrams detail the structure of CPM [25].

The use of ontologies in engineering and scientific knowledge management can be dated as far back as 1994 when the Plinius ontology for ceramic materials was created [26]. In 1996, an ontology for managing requirements in engineering design was proposed by Lin et al. [27]. Horváth et al. [28] then proposed formalizing design concepts using ontologies. It was becoming evident that ontologies not only provided formal structures for concepts and vocabularies, but they also had the potential for supporting inferences based on collective knowledge [29]. Shortly thereafter, the vision of a machine-interpretable "Semantic Web" was born [30]. The application of the Semantic Web in the field of knowledge management is discussed by Fensel et al. [31]. Earlier efforts in semantic mark-up languages include the Extensible Markup Language (XML), Resource Description Framework (RDF), Ontology Inference Layer (OIL) and Defense Advanced Research Projects Agency (DARPA) Agent Markup Language (DAML). Currently, the Web Ontology Language (OWL) is the de facto standard for developing and representing ontologies. OWL is recommended by the World Wide Web Consortium (W3C) as the ontology language of the Semantic Web. OWL uses RDF/XML as the standard serialization which means that OWL-based ontologies can be parsed through open-source web-based technologies. OWL-DL is a sub-language of OWL that employs Description Logic (DL), which is an implementation of first-order logic. Mocko et al. [32] have discussed DL in detail and the necessities for its use in engineering information management.

Recent research efforts focused on ontologies and ontology development methods for engineering design include the Product Family Ontology Development Methodology (PFODM) by Nanda et al. [33]. Ahmed et al. [34] describe a six-stage methodology for developing ontologies for engineering design. Also, an ontology-based approach is used to develop product configuration systems [35]. Li et al. [36] propose an Engineering Ontology (EO) based