Advanced Engineering Informatics 29 (2015) 985–1000

Contents lists available at ScienceDirect

Advanced Engineering Informatics

journal homepage: www.elsevier.com/locate/aei

An ontology-based knowledge framework for engineering material selection

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ARTICLE INFO

Article history:
Received 10 February 2015
Received in revised form 29 August 2015
Accepted 2 September 2015
Available online 16 September 2015

Keywords:
Engineering materials
Material selection
Knowledge representation
Ontology

ABSTRACT

Engineering material selection intensively depends on domain knowledge. In the face of the large number and wide variety of engineering materials, it is very necessary to research and develop an open, shared, and scalable knowledge framework for implementing domain-oriented and knowledge-based material selection. In this paper, the fundamental concepts and relationships involved in all aspects of material selection are analyzed in detail. A novel ontology-based knowledge framework is presented. The ontology-based Semantic Web technology is introduced into the semantic representation of material selection knowledge. The implicit material selection knowledge is represented as a set of labeled instances and RDF instance graphs in terms of the concept model, which provides a formal approach to organizing the captured material selection knowledge. A knowledge retrieval and reasoning approach integrating ontology concepts, instances, knowledge rules, and semantic queries encoded with Query-enhanced Web Rule Language (SQWRL) is proposed. The presented knowledge framework can provide powerful knowledge services for material selection. Finally, based on this knowledge framework, a case study on constructing a mold material selection knowledge system is provided. This work is a new attempt to build an open and shared knowledge framework for engineering material selection.

1. Introduction

With the development of technologies, the available set of engineering materials is rapidly growing in both type and number. It is estimated that there are more than 80,000 engineering materials available in the world, and new materials are emerging constantly [1]. Engineering materials are usually coupled with series of manufacturing processes. It is estimated that there are at least 1000 different manufacturing processes that can convert engineering materials into desired products [1]. In the material selection process, design engineers have to take into account a large number of factors, such as physical properties, mechanical properties, thermal properties, material cost, and impact on the environment. Hence, the vast number of materials and processes and the complex relationships between the different selection parameters often make the selection of materials for a given component a difficult task [2].

Information on engineering materials presents in two categories: data and knowledge. Data is defined as the result of measurements that can be presented as numerical values, whereas knowledge represents the connections between the items of data [3]. As the materials involve a large amount of data, it is necessary to employ database information systems to effectively manage, retrieve, and update the material data. A large number of material databases have been built, most of which can be accessed online [4]. Due to their data-oriented representation mode, the material databases still lack a knowledge inference mechanism and are not able to associate the data with facts.

Material selection is a highly knowledge-intensive activity, involving knowledge mapping among different concepts, knowledge inference, and multiple objective decision-making. Hence, efficient mechanisms for capturing, representing, reusing, and sharing the material selection knowledge involved are sorely needed. As a result, much research on knowledge-based engineering material selection tools and methods has been carried out. However, many challenges in knowledge-based material selection still exist, as in any other knowledge-based engineering [5]. One challenge is that the material selection knowledge is implicit and unstructured; therefore, it is very difficult to capture the material selection knowledge and give it formal representation. Another challenge is that material selection depends on applications in

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http://dx.doi.org/10.1016/j.aei.2015.09.002
1474-0346/

different domains; therefore, an open, scalable, and shared knowledge framework is required. Based on this knowledge framework, the material selection knowledge base for different domains can be effectively constructed and updated.

Recently, knowledge representation technology based on ontologies and Semantic Web technologies have received more attention and been gradually used in the knowledge representation of various domains. An ontology can effectively combine the domain knowledge with the information representation and has many advantages over other concept modeling technologies in classification, sharing, and formalization [6–9]. The ontology technology provides a feasible solution to addressing the issues and challenges.

With this in mind, this paper analyzes the knowledge requirements for material selection and discusses the common characteristics and relationships among the engineering materials, manufacturing processes and applications. A novel ontology-based knowledge framework for engineering material selection is proposed that includes three layers, namely, the knowledge base layer, the reasoning layer, and the user interface layer. The main contributions of this paper include (i) an ontology-based concept model for representing material selection knowledge, (ii) an approach to representing implicit material selection knowledge by knowledge instances and rules, and (iii) an approach to semantically retrieving material selection knowledge and screening desired materials from the knowledge base. The presented work will lay the foundation for constructing an open, shared, and scalable material selection knowledge framework.

2. Literature review

As mentioned above, due to the importance of material selection in engineering design, material selection tools and methods have been extensively researched. Details can be found in [3]. Here, we limit our review of previous works to those discussing knowledge-based material selection.

2.1. Knowledge-based material selection

A knowledge-based system (KBS) is a computer program that reasons and uses a knowledge base to solve complex problems. In recent decades, knowledge-based material selection methods attracted much research. Goel and Chen [10] early employed an expert network for material selection in engineering design. Sapuan and Abdalla [11] presented a prototype knowledge-based system for the selection of polymer-based composite materials for a pedal box system of an automotive. Sanyang and Sapuan [12] developed an expert system using Exsys Corvid software to select suitable biobased polymer materials for packaging products. In their developed expert system, an ''If–Then'' rule is utilized in the material selection process, whereas a scoring system was formulated to facilitate the ranking of the selected materials. Zarandi et al. [13] proposed a material selection methodology and an expert system for sustainable product design. Ipek et al. [14] proposed an expert system based material selection approach to manufacturing. Urrea et al. [15] developed an expert system for the selection of materials to be used in the construction of the main structure of a transfer crane. In their approaches, the expert system determines the appropriate material properties for the product design and then searches for appropriate materials having these properties in the materials knowledge base. Zha [16] described the selection of suitable manufacturing processes and materials in concurrent design according to a fuzzy knowledge. Based on the proposed method, a prototype web-based knowledge-intensive manufacturing consulting service system was developed. Kumar and Singh [17] presented an intelligent system for the selection of materials for progressive die components. Amen and Vomacka [18] used case-based reasoning (CBR) as a tool for material selection. CBR is a procedure of solving new problems based on the solutions of similar past problems. Ullah and Harib [19] presented an intelligent method for selecting optimal materials. The presented method uses material properties instead of production rules and inference calculations, but its application scope is limited.

From the published literature, the following issues exist in the current expert systems and knowledge systems for material selection:

(1) The material selection knowledge is mainly represented as a set of general ''IF–THEN'' production rules. Few systems can comprehensively use concepts, instances, and rules to represent the complex material selection knowledge, which is implicit and unstructured. The knowledge instance created from material selection and applications is an important knowledge representation form.
(2) The research on semantic representation for material selection knowledge at the conceptual level is generally lacking. For example, the variables in the production rules are not defined from shared concepts and closely coupled with the application program; therefore, it is difficult to modify variables or add new variables to the rule base. As a result, such an expert system for material selection is often limited to a specific application domain. It is necessary to define a set of shared knowledge concepts and use these concepts in the representation of knowledge rules and instances.
(3) Current material selection systems commonly do not use open knowledge processing platforms. An open knowledge modeling platform (including a modeling language, inference engine, and developing tools) can promote the development and application of the material selection knowledge system.

2.2. Ontology-based knowledge systems for material selection

According to Gruber [20], an ontology is an explicit specification of a conceptualization. Borst [21] further specified the definition of an ontology as a formal specification of a shared conceptualization. The two definitions indicate that the ontology is a concept representation of an abstract domain and is understood and shared among human and machines (software agents). The ontology and Semantic Web technologies provide powerful reasoning capabilities; therefore, ontology-based modeling has many advantages over other concept modeling technologies in classification, sharing, and formalization. Ontologies have been extensively used to formalize domain knowledge with concepts, attributes, relationships, and instances in many scientific and industrial fields. There is a tendency to both convert existing models into ontologies and to create new ontology-based models. For example, Zhan et al. [22] presented a semantic approach that uses ontologies to share knowledge related to product data in CAD/CAE applications. Zhang et al. [23] presented an ontology-based knowledge representation for unit manufacturing processes. Matsokis and Kiritsis [24] developed an ontology-based approach for product lifecycle management. Sanya and Shehab [25] developed an ontology framework for developing platform-independent knowledge-based engineering systems in the aerospace industry.

Some efforts have been made in engineering material information representation and processing. The Materials Markup Language (MatML) [26] made efforts to create a materials information exchange standard based on XML schemas. However, due to the lack of semantics in XML representation, it is difficult to realize the goal