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A methodology for building a semantically annotated multi-faceted ontology for product family modelling

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ABSTRACT

Product family design is one of the prevailing approaches in realizing mass customization. With the increasing number of product offerings targeted at different market segments, the issue of information management in product family design, that is related to an efficient and effective storage, sharing and timely retrieval of design information, has become more complicated and challenging. Product family modelling schema reported in the literature generally stress the component aspects of a product family and its analysis, with a limited capability to model complex inter-relations between physical components and other required information in different semantic orientations, such as manufacturing, material and marketing wise. To tackle this problem, ontology-based representation has been identified as a promising solution to redesign product platforms especially in a semantically rich environment. However, ontology development in design engineering demands a great deal of time commitment and human effort to process complex information. When a large variety of products are available, particularly in the consumer market, a more efficient method for building a product family ontology with the incorporation of multi-faceted semantic information is therefore highly desirable. In this study, we propose a methodology for building a semantically annotated multi-faceted ontology for product family modelling that is able to automatically suggest semantically-related annotations based on the design and manufacturing repository. The six steps of building such ontology: formation of product family taxonomy; extraction of entities; faceted unit generation and concept identification; facet modelling and semantic annotation; formation of a semantically annotated multi-faceted product family ontology (MFPFO); and ontology validation and evaluation are discussed in detail. Using a family of laptop computers as an illustrative example, we demonstrate how our methodology can be deployed step by step to create a semantically annotated MFPFO. Finally, we briefly discuss future research issues as well as interesting applications that can be further pursued based on the MFPFO developed.

1. Introduction

One of the challenges of today's manufacturing companies is to offer a range of products that are able to meet different customer needs. With the ever-changing customer preferences on product offerings, manufacturing companies are constantly facing challenges and difficulties in realizing product varieties while optimizing the production cost for the sake of economies of scale. In such a situation, traditional manufacturing concepts, such as mass production, are limited in helping manufacturing firms choose between product variety and production cost. In order to remain competitive in the marketplace, mass customization has been proposed and accepted as an economically viable model. Mass customization can be viewed as a manufacturing strategy that enables manufacturing companies to better differentiate their products while satisfying production process and cost expectation. There have been a number of different approaches introduced under mass customization, such as delayed product differentiation [17] and modular design [13]. Among them, one of the prevailing ones is the design and development of a family of products.

A product family refers to a set of similar products that is derived from a common platform and yet possesses some specific features or functionalities which are intended for niche customer segments [30]. The basic idea of product family design (PFD) is the reuse of common product modules or components in order to generate as many product variants as possible. While PFD comprises all the challenges of single product design, it is added with the complexity of managing the configuration of multiple products in an attempt to increase commonality across a family of products without compromising their distinctiveness or performance [41]. The difficulty of selecting optimal product configurations that meet the aforementioned complexity is the main issue in PFD. Nevertheless, extensive knowledge of customer wants, preferences and

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configurations of products are therefore crucial for decision-making in PFD and highly dependent on how such knowledge is shared among customers and manufacturers [12].

However, with the increasing number of product choices with shorter product lifecycles targeted at different market segments, the issues of information management that are related to efficient storage, effective sharing and timely retrieval of design information have become more complicated. In an actual organizational setting, the situation is often more complex. A past literature review revealed that a typical manufacturing organization can have seven to 12 information systems that are tailored to different needs [19]. It is also evident from another previous literature review that almost 30 percent of an engineer's time is actually spent retrieving, distributing and maintaining information [37]. Therefore, a better management of the ever-increasing design information is imperative not only for better information indexing, navigation and searching, but also to achieve an improved design cycle through streamlining the design processes.

In the context of PFD, efficient product information management relies on a sound design representation that is able to promote the comprehensiveness in modelling product design information with added features for easier change management. In the literature, there is already a number of representation schemes proposed in order to overcome the various challenges and complexities of modelling product families, such as generic bill of materials [18], graph representation [8] and object-oriented representation [46]. Although these representations offer some advantages in the process of product variant derivation, they are generally limited in modelling the complex inter-relations between physical components and other non-component-based information, e.g. product functions and marketing. Among the different design representation schemes proposed, ontology-based representation is identified as one of the promising solutions to the issue of PFD-related information management.

In general, the embedded semantic features of an ontology representation offer the ability to perform semantic-based multi-faceted searches, navigation, knowledge extraction and analysis. For instance, the semantic features of an ontology are deemed helpful in understanding the cause-effect nature of a design-induced error [40]. Besides, an ontology can function as a unified information structure, i.e. as a semantic mediator across different engineering information systems. This feature improves the efficiency of design information management via unified information indexing as well as intelligent semantic information research and retrieval. In the context of product family modelling, with multi-faceted product family information searching, navigation and retrieval, the process of developing a product platform and its associated product variants can be accelerated. This brings many practical benefits such as shorter design cycles and cost reductions.

However, the key challenge of ontology development in design engineering is the amount of resources involved. Typical tasks in ontology engineering, such as concept formation and semantic annotation of product-related information are still time-consuming and human resources intensive. From our literature review, we found that the majority of previous work on deriving ontology in the design engineering domain is performed via domain intensive literature studies, where human annotators are employed to annotate domain specific concepts and relations based on their comprehension of domain literature. Most of the methodologies in ontology development are still manually driven. While such an approach is essential and generic in deriving non-trivial semantic relations and rules, the process will eventually become a burden for human annotators as the ontology evolves with incremental information. In PFD, previously proposed methodology for creating a product family ontology is still largely dependent on human effort. Research on the semantic annotation of multi-faceted relationships between the component facet of product family with other facets of design and manufacturing, such as functions and manufacturing, to the best of our knowledge, is not being undertaken.

In view of the large amount of product offerings available in the market, a methodology for building a product family ontology with the incorporation of multi-faceted semantic information that requires less human effort is therefore necessary. In this study, we propose a methodology for building a semantically annotated multi-faceted ontology for product family modelling that is able to automatically suggest semantically-related annotations based on the design and manufacturing repository. Section 2 surveys the related studies with a focus on ontology development methodology, ontology applications in design engineering, product family modelling and ontology for product family modelling. We present our methodology in building a semantically annotated multi-faceted product family ontology (MFPFO) in Section 3. Section 4 illustrates how the aforementioned ontology can be developed by using a family of laptop computers as an example. Section 5 discusses the related issues involved in the methodology and immediate future work, and finally Section 6 concludes this article.

2. Related work

2.1. Ontology development methodology

There are several works on the methodology for ontology development that are proposed in the area of library science or computer science. The work by Gruber [15] is perhaps one of the earliest attempts to propose a compiled practical guidance from the experiences of building an ontology. Later, there have been a few notable methodologies for building an ontology proposed: Gruninger and Fox [16] proposed a methodology for designing and evaluating an ontology, that is used in developing the TOVE (Toronto Virtual Enterprise) project ontology; Uschold and King [43] suggested a methodology for building an enterprise ontology for enterprise modelling processes; Fernández et al. [11] presented a more systematic approach for building an ontology from scratch, called METHONTOLOGY that is applied in building a chemical ontology; Ontology Development 101 was later introduced by Noy and McGuinness [35]. All these studies have presented useful practical guidelines in ontology building that are referred to by researchers in the design engineering domain.

In relation to the above, there are also other methodologies for ontology building that are specifically tailored to the design engineering domain. Ahmed et al. [1] attempted to develop a methodology of ontology development for indexing design knowledge. With this purpose, their methodology is focused upon the user's domain, where the understanding of user needs in information searching is given attention. They identified four root concepts in their ontology: design process, function, issue and product, in their creation of engineering design integrated taxonomy. Their methodology, however, does not explicitly study the complex inter-relations between the four root concepts. Another methodology of building an ontology proposed by Sarder et al. [39] is called the domain knowledge acquisition process, aimed to create an ontology of product and process design. They adopted a knowledge engineering approach to obtain domain specific knowledge by using an ontology description form based on the IDEF5 standard. Nanda et al. [32] applied formal concept analysis in their methodology to develop a domain specific ontology for a product family. Formal concept analysis is used to identify the similarities among a finite set of design artifacts based on their properties and to ensure consistency in creating a domain concept hierarchy structure. There are also some other research initiatives that have modelled and evaluated ontologies using empiri-