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A data-mining approach for product conceptualization in a web-based architecture

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ABSTRACT

Rapid advancing information technology (IT) has improved the efficiency and effectiveness of product conceptualization and increased the importance of its role in new product development (NPD). However, there are two major omissions in existing work: firstly, a unified framework in the process of product conceptualization has not been well addressed; and secondly, it is imperative to attain an effective data-mining approach to support the product conceptualization process. Based on this understanding, the proposed approach aims at postulating an axiomatic product conceptualization system (APCS) to meet the demand of product concept development. The proposed APCS comprises three cohesively interacting modules, namely, knowledge elicitation module using laddering technique; knowledge representation module using design knowledge hierarchy (DKH); and knowledge synthesis module using restricted Coulomb energy (RCE) neural network. Accordingly, this system offers a method of making design decisions via a web-based data-mining product conceptualization approach. A case study on wood golf club design has been used for system illustration.

1. Introduction

Few companies, especially small- and medium-sized enterprises, now possess sufficient expertise or proficiency to develop a complete product [1]. Nevertheless, companies can gain more control in their competitive arena by cooperating with other companies. Furthermore, enterprises are recognizing that they must devote more effort to product conceptualization rather than later stages of the new product development (NPD) life cycle, because of its disproportionate impact on the final product. Accordingly, it is crucial to improve design consistency yet manage design conflict amongst design participants. To this end, Pahng et al. [2] integrated designer-specified mathematical models for multi-disciplinary and multi-objective design problems. Alternatively, Lu et al. [3] analyzed the relationship between design process and design conflict, and thereafter developed a framework in terms of technical and social factors.

Rapid advancing information technology (IT) has increased the possibilities for product conceptualization and the importance of its role in NPD. This is further enhanced if the companies can use ITs to form an alliance for the purposes of in-depth technical and business process integration [4]. Technologies for product design have been frequently explored and include: a standard for the exchange of product model data (STEP) translation [5]; database management systems (DBMS) (e.g. [6]); real-time 3D CAD systems (e.g. [7]); and virtual reality modelling language (VRML) displays [8]. On the other hand, to enhance the ability of product conceptualization, rather than individual capability alone, research work has focused on communication and coordination amongst distributed resources, e.g., knowledge-based system (KBS) [9], design management system (DMS) [10], and conceptual design tool [11].

Thus, all these methodologies have emphasized embodiment design, rather than product conceptualization, so that exploitation of early design creativity and efficiency has not been fully explored. Accordingly, there still exist a number of critical issues in product conceptualization. As such, product concept development must perform a number of complex functions with respect to design methodology, concurrency, teamwork, knowledge management and design representation [12]. In so doing, the IT realization of conceptualization systems is likely to be a major problem. In this regard, the data-mining technology presents a logical alternative.

In recent years, data mining has been increasingly advocated in academia and industries. Its applications are widespread in such disciplines as marketing [13], engineering [14], biology [15], and web analysis (i.e., web mining) [16]. Specifically for product

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development, a number of research efforts were attempted in product data management (PDM), the scope of which has evolved from the internal efficiency of a company into the incorporation of both internal and external issues [17]. In the past few years, the fundamental paradigm shift in data mining for product development has emphasized on improving outward-facing activities in an organization, such as electronics data interchange (EDI) [18], customer relationship management (CRM) [19], enterprise resource planning (ERP) [20], virtual enterprise (VE) [21], supply chain planning (SCP) [22], and Internet-based commerce (IBC) [23].

However, some issues have not been well addressed in the previous work, such as lacking of quantitative analysis methods, low knowledge transparency, extensibility and predictability, and scarcity of effective customer management. To deal with these problems, some researchers recognized the importance of knowledge-based data-mining approaches, such as feature space theory [24], knowledge refinement [25] and rule-based classification [26]. Furthermore, in NPD, the product development team should incorporate customer concerns into product concepts. This may bring a significant benefit to the company because of higher customer satisfaction to the product, for example, CRM-based methodology [13] and web-mining model [27].

Nevertheless, there are two major omissions in existing work: first, a unified framework in the process of product conceptualization, which integrates customer requirements with design knowledge management in the early stages of product development, has not been well addressed; and second, it is imperative to attain an effective data-mining approach to support the product conceptualizing process. Based on this understanding, an axiomatic product conceptualization system (APCS) has been developed to meet the demand of product concept development. The proposed APCS comprises three cohesively interacting modules: namely, knowledge elicitation module using laddering technique; knowledge representation module using design knowledge hierarchy (DKH); and knowledge synthesis module using restricted Coulomb energy (RCE) neural network. Accordingly, this system offers a method of making design decisions via a web-based data-mining product conceptualization approach. A case study on wood golf club design has been used to illustrate and validate the system. The details of the validation are discussed.

2. Axiomatic design for product conceptualization

2.1. Background

Axiomatic design has gained wide attention in recent years. To date, many researchers have attempted applying axiomatic design theory to such disciplines as product design [28], software system design [29], mechanical system design [30], manufacturing system design [31], design for environment [32], and design for ergonomics [33]. Moreover, owing to axiomatic design is a general theoretical framework, rather than a specific modelling methodology, it has frequently been integrated with other technologies in product design. Amongst them, Chen [34] proposed a robust concept exploration method (RCEM) for enhancing productivity in product design, in which robust design technique as well as concurrent engineering technology were combined with Suh's design axioms [35]. For the purpose of improving system quality and problem solving, Engelhart [36] suggested a design analysis approach that integrates axiomatic design theory with several quality control tools and designed experiments. In addition, Seliger [37] treated axiomatic design as one of the methods for product innovation with regard to inductive and deductive innovation. In advent of rapidly developing Internet technologies, Huang [38] postulated a web-based design infrastructure, so-called systematic theory of axiomatic design review (STAR), which defines the design review as a mapping process between the design objects and the review criteria.

In essence, the key concepts of axiomatic design [35] involve: (1) the existence of four domains, viz., the customer, functional, physical and process domain; and (2) the characteristic vectors within the domains can be decomposed into hierarchies through zigzagging. Based on these notions, research efforts have been made on synthesizing or mapping between consecutive domains. In this respect, most work has been contributed to the mapping between functional requirements (FRs) and design parameters (DPs) [39], or that between design parameters (DPs) and process variables (PVs) [40]. As stated by Suh [35], a product or system can effectively be classified according to the number of FRs. Accordingly, the FRs play a crucial role in axiomatic design process. A complete axiomatic design process provides a traceable path beginning with the original customer attributes (CAs) through each domain of a sequential procedure. Hence, the CAs elicitation becomes the starting point of employing axiomatic design theory for product conceptualization, viz. the mapping between CAs and FRs. In this regard, Tesng and Jiao [41] developed a tool-kit to support the organization of FRs based on CAs. The approach focuses on recognizing functional requirement patterns from past design efforts via axiomatic design and taking into account product migration, technological trends and customer voices. Similarly, Suh and Do [42] attempted to synthesize the elicited CAs with FRs in designing a software system. However, it still remains problematic in product conceptualization, especially customer voices involvement and incorporation, such as

- how to genuinely solicit CAs form the voice of customers (VoCs);
- how to subsequently represent the CAs in a well-organized manner, such as a hierarchical structure;
- how to effectively synthesize the relationship between CAs and FRs; and
- how to consequently flag competitive opportunities and technical targets through the synthesis between customer and functional domain.

The mapping between CAs and FRs is one of the essential premises for developing successful product concepts. In this stage, a design team explores a combination of customer needs, corporate objectives, product ideas and related technological capabilities, and concludes the process with a set of product definition, i.e., FRs. Usually, FRs can be represented as a list of product specifications or target values, which are often a mixture of quantitative values and qualitative descriptions of a product. The imperatives in dealing with CAs and FRs via axiomatic design include:

1. Acquisition of CAs and FRs using a single and effective technique that has a broad coverage of design knowledge from such knowledge carriers as customers and designers.
2. Representation of CAs and FRs under a unified yet simple framework, e.g., a hierarchical structure.
3. Synthesis between CAs and FRs for product conceptualization.

2.2. System architecture

In general, the APCS starts from the customer domain, which is stemmed from the voice of customers (VoCs), followed by the functional domain. In order to solicit broad knowledge (or