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A Research Review on the Key Technologies of Intelligent Design for Customized Products

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ABSTRACT

The development of technologies such as big data and cyber-physical systems (CPSs) has increased the demand for product design. Product digital design involves completing the product design process using advanced digital technologies such as geometry modeling, kinematic and dynamic simulation, multidisciplinary coupling, virtual assembly, virtual reality (VR), multi-objective optimization (MOO), and human-computer interaction. The key technologies of intelligent design for customized products include: a description and analysis of customer requirements (CRs), product family design (PFD) for the customer base, configuration and modular design for customized products, variant design for customized products, and a knowledge push for product intelligent design. The development trends in intelligent design for customized products include big-data-driven intelligent design technology for customized products and customized design tools and applications. The proposed method is verified by the design of precision computer numerical control (CNC) machine tools.

1. Introduction

Product digital design involves completing a product design process using advanced digital technologies such as geometry modeling, kinematic and dynamic simulation, multi-disciplinary coupling, virtual assembly, virtual reality (VR), multi-objective optimization (MOO), and human-computer interaction. Although there is no universal definition for customized design, its basic meaning is that a customized product is designed to satisfy the customer's individual and diversified requirements as quickly and at as low a cost as possible. Many scholars have carried out research into the methodology and key technology of product design [1–3]. Customized design usually involves a strategy in which customer-oriented design is separated from order-oriented design [4]. Customer-oriented design is based on an analysis of customer requirements (CRs), and involves a modular pre-formed product family that is developed through serialization. Order-oriented design, which is based on an existing product family, rapidly designs a product's structure in order to satisfy the customized requirements of customers by configuration methods when customer orders arrive. Customer-oriented design influences the cost and time required to market new products. Designing for customer orders affects the delivery of individual customized products. Customized products are designed and manufactured on a per-order basis.

Complex equipment—such as computer numerical control (CNC) machine tools, cryogenic air-separation units (ASUs), plate-fin heat exchangers (PFHEs), and injection-molding equipment—has many characteristics such as demand diversity, fuzzy dynamics, a cumbersome design response, and a complex design process. The question of how to satisfy customers' individual requirements and achieve rapid design and innovation of complex customized equipment has become an important factor that determines the survival and competitiveness of equipment-manufacturing enterprises.

Therefore, it is urgently necessary to develop an intelligent design platform in order to support the development of manufacturing products. In this way, the digital design or products will develop in the direction of intelligence and customization.

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2. Key technologies

Experts have predicted that more than half (> 50%) of future manufacturing will involve personal customization. Although the studies conducted by the Chinese Mechanical Engineering Society [5] indicate that manufacturing enterprises will generate stronger demands for product development and changes, the harsh reality is that modern enterprises lack advanced design ability. It is worth mentioning that many institutions [6,7] have carried out research into big data and the design technology of customized products. Stanford University's [8] structured design model combines requirements, technology, and product performance mapping. Yale University [9] has also carried out analysis methods based on big data to support design research.

The key technologies of intelligent design for customized products include: the description and analysis of CRs; product family design (PFD) for a customer base; configuration and modular design for customized products; variant design for customized products; and a knowledge push for product intelligent design.

2.1. Description and analysis of customer requirements

CRs usually include obvious features such as fuzziness, uncertainty, or dynamism. It is important to describe fuzzy CRs in an accurate way for the realization of customized design.

Designing for customization involves forming customized requirements to meet the CRs by means of analysis, data mining, and prediction. Common design methods include the analytical methods based on the Kano model and quality function deployment (QFD). In the Kano analytical method [10], CRs are divided into basic requirements, expected requirements, and exciting requirements. Customized design should first satisfy the basic requirements, and then satisfy the expected and exciting requirements as much as possible. The QFD method [11] is a multi-level deductive analysis method that translates CRs into design requirements, part characteristics, process requirements, and product requirements. It then builds a product planning matrix called a "house of quality." At this point, the difficulty of requirements-based design lies in how to analyze, predict, and follow the potential requirements of customers.

Regarding the description and analysis of CRs, Jin et al. [12] investigated information representativeness, information comparativeness, and information diversity and proposed three greedy algorithms to obtain optimal solutions for the optimization problem. Wang and Chin [13] proposed a linear goal programming (LGP) approach to evaluate the relative weight of CRs in QFD. Juang et al. [14] proposed and developed a customer requirement information system (CRIS) in the machine tool industry, by using fuzzy reasoning and expert systems. Haug [15] developed a conceptual framework based on 10 industrial designers' interviews and studies on reference projects; this framework defined the overall CR emergence models and associated communicative issues, enabled designers to elicit CRs more efficiently, and allowed designers to reduce delay in the emergence of client requirements and avoid wasting effort on design paths. Wang and Tseng [16] proposed a Naïve Bayes-based approach to describe clients' technical functional requirements and subjective preferences, and to map them according to detailed attributes and design parameters. Raharjo et al. [17] proposed a novel systematic approach to deal with the dynamics of customer demands in QFD. Elfvengren et al. [18] studied the usefulness and usability of group decision support system (GDSS) in the assessment of customers' needs in industrial companies. Çevik Onar et al. [19] proposed a hesitant fuzzy QFD that could reflect a human's hesitation more objectively than the classical extensions of other fuzzy sets; they then applied it to computer workstation selection problems. Osorio et al. [20] proposed the extension of a universal product data model (PDM) to mass customization (MC) and sustainability paradigms in order to meet the requirements of supporting a sustainable mass-customized (S-MC) product design process.

Regarding the description of product requirements, research has focused on the following: the description of requirements based on set theory, the broader description of requirements based on ontology, and the description of requirements based on fuzzy clustering.

Requirements-based design faces the following challenges:

(1) **Modeling generalized requirements for customization**. To rapidly improve the standardization of customized requirements and guarantee the accuracy and consistency of the design process for an understanding of CRs, it is necessary to build a multi-level model of the generalized requirements from the time dimension, space dimension, process dimension, and so on.

(2) **Predicting and mining customized requirements**. With the development and maturation of big data, it is possible to collect data through the Internet and the Internet of Things. It is important to mine users' behavior patterns and consumption habits from massive data in order to forecast customized requirements and determine hidden customized requirements.

(3) **Mapping and transforming customized requirements**. To ensure consistency, accuracy, and timeliness in the transformation from CRs to technical requirements, it is necessary to build a model that automatically maps and transforms CRs, including dynamic, fuzzy, and hidden CRs, into technical requirements.

(4) **Creating value design for the customized requirements of customers**. It is difficult to predict and create new CRs based on analyses of existing CRs, and it is also difficult to build customization while considering factors such as cost, feasibility, and urgency.

The description and analysis of CRs form the basis of intelligent design for customized products. The layout scheme design for a lathe-mill cutting center is shown in Fig. 1.

2.2. Product family design for a customer base

PFD refers to the extraction of product variant parameters in accordance with CRs for a specific customer base, and the formation of a variable model of dynamic products that includes the main structure, main model, main document, and so forth. According to different variant-driven modes, the PFD method can be module driven or parameter driven [21]. A module-driven product family includes a series of basic, required, and optional modules, and can satisfy different requirements from customers through a combination of different modules. A parameter-driven product family includes a series of products that have the same public variables but different adjustable variables; the structure and performance of products can then be changed by scaling the adjustable variables up or down while maintaining the same public variables, in order to satisfy the individual CRs.

PFD focuses on ensuring product family optimization, data consistency, and traceability in the product life cycle. The challenges of PFD include:

(1) **A design program for the product family**. Given the preference to and importance of the requirements from customers and the performance characteristics of the products, it is difficult to program the rational variant parameters of the product family and value range so as to achieve integrated optimization of cost and competitiveness for the product family.

(2) **Modularization of the product family**. The design of the modularized product family focuses on forming a series of functional and structural modules along with a main structure based on the design constraint. It is difficult to form individual products that satisfy different customized requirements using a combination of different modules.

(3) **A dynamic model of the product family**. Due to market