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KNOWLEDGE SUPPORT FOR CONCEPT EVALUATION AND SELECTION IN DESIGN FOR MASS CUSTOMIZATION

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Abstract

This paper presents a research effort on knowledge support for concept evaluation and selection in customer-driven design for mass customization (CDFMC). In this paper, the fundamental issues underlying knowledge support for CDFMC are first discussed. Then, a knowledge support framework is described for module-based product family design for mass customization. Under this framework, a systematic fuzzy clustering and ranking method is proposed for the concept evaluation and selection in CDFMC. It models imprecision inherent in decision-making with fuzzy customers' preference relations and carries out fuzzy analysis and evaluation that is capable of handling linguistic as well as ordinary quantitative information, thus solving the multi-criteria decision-making problem during the early design stage. The focus of this paper is on the development of a knowledge-intensive support scheme and a comprehensive systematic fuzzy clustering and ranking methodology for the concept evaluation and selection in the context of CDFMC. A case study with a scenario of knowledge support for power supply product evaluation, selection, and customization is provided for illustration.

Keywords: Design for mass customization, product family design, concept evaluation and selection, fuzzy clustering, fuzzy ranking, and knowledge decision support

1. Introduction

Today's highly competitive, global marketplace is redefining the way that companies do business. Mass customization embarks a new paradigm for manufacturing industries, whereby variety and customization supplant standardized products, heterogeneous and fragmented markets spring from once homogeneous markets, and product life cycles and development cycles spiral downward [1,2]. To adopt the mass customization paradigm, many companies are being faced with the challenge of providing as much variety as possible for the market with as little variety as possible between products in order to maintain economies of scale while satisfying a wide range of the customer requirements.

Family-based product design has been recognized as an efficient and effective means to realize sufficient product variety to satisfy a range of customer demands in support for mass customization [1]. Customized product development is resembled as the configuration design, in which a family of products can widely variegate the selection and assembly of modules or pre-defined building blocks at different levels of abstraction so as to satisfy diverse customization requirements. The essence of configuration design is to synthesize product structures by determining what modules or building blocks are in the product and how they are configured to satisfy a set of requirements and constraints. Thus, the conceptual evaluation plays an important role in this process as a poor selection of either a building block or module or a configuration structure is difficult to be compensated at later design stages and can give rise to a great expense of redesign costs [3]. Resulting from its paramount importance in the configuration design, the alternative (concept) evaluation and selection problem has received much attention both in academia and in industry. Although a number of methods have been investigated, there is still much to be desired due to the hindrance inherent in the concept evaluation and selection process. Difficulties associated with such a task lie in problem solving complexity, various decision criteria, and product performance assessment [2].

Contemporary design process becomes increasingly knowledge-intensive and collaborative. Knowledge-intensive support becomes more critical in the design process and has been recognized as a key solution towards future competitive advantages in product development. To improve the design for mass customization process, it is imperative to provide knowledge support and share design knowledge among distributed designers. The aim of this paper is to develop methodologies and technologies of knowledge support for the concept evaluation and selection in customer-based product family design for mass customization.

The organization of this paper is as follows. Section 2 reviews existing approaches to a design evaluation. Section 3 discusses the customer-based modular product family design for mass customization and its knowledge support framework. Section 4 discusses a knowledge support scheme for the concept evaluation in design for mass customization. A fuzzy clustering and ranking methodology is proposed and discussed. Section 5 provides a case study and a scenario of knowledge support for product customization in power supply family design. Section 6 summarizes the paper and points out the future work.

2. Literature Review

The literature on design alternative evaluation and selection can be generally classified into five categories [2]: multi-criteria utility analysis, fuzzy set analysis, design analytic methodology, the hybrid approach, and the information content approach, but the first three approaches are prevalent. Multi-criteria utility analysis is an analytical method for evaluating a set of alternatives, given a set of multiple criteria. It has been widely applied in the areas of engineering and business for decision-making. For example, Thurston [6] has applied this technique to the material selection problem that evaluates alternatives based on utility functions that reflect the designer's preferences for multiple criteria. Mistree *et al.* [8,9] modeled design evaluation and optimization as a compromise decision support problem (cDSP) and employed goal-programming techniques to make optimal selection decisions. While mathematical programming and utility analysis enhance algorithm-rigorous optimization modeling, such methods require the expected performance with respect to each criterion to be represented with a quantitative form. They are not appropriate for use in the early design stage, where some qualitative design criteria, *i.e.*, intangible criteria, are involved and difficult to quantify [7]. The main drawback of these evaluation methods is that they ignore the inconsistency issue on the part of the decision maker, which occurs when the solution does not match the decision maker's preference and results from the randomness of the decision maker's judgments [11]. Fuzzy analysis, based on fuzzy set theory [10], is capable of dealing with qualitative or imprecise inputs from designers by describing the performance of each criterion with some linguistic terms, such as “good,” “poor,” and “medium.” It has been proven to be quite useful in decision-making problems with multiple goals or criteria, especially rank alternatives at very early stages of the preliminary design process [12]. The fuzzy set analysis approach is most appropriate when there are imprecise design descriptions, whereas the probability analysis approach is most appropriate for dealing with stochastic uncertainty. It excels in capturing semantic uncertainty with linguistic terms. However, it requires discreet deliberation in dealing with crisp information, and a domain-specific method is needed to fuzzify each tangible criterion whose evaluation is naturally estimated as an ordinary real variable. Another challenge for the fuzzy set analysis approach is the incomparability between various criteria, which necessitates some mechanisms to be capable of converting various types of performance evaluation with respect to different criteria to a common metric so as to specify suitable membership functions for them. The design evaluation usually involves both tangible and intangible criteria, along with quantitative and qualitative performance measures. This motivates the hybrid approach of combining the quantitative, normative problem structuring capabilities of operations research techniques with the qualitative, descriptive problem-solving approach used in artificial intelligence techniques. For example, Maimon and Fisher [13] presented a robot selection model using integer programming and a rule-based expert system. A good number of efforts have been devoted to fuzzy goal programming to model mathematically the imprecise relationships using fuzzy goals and soft constraints. However, they mostly model a particular aspect of uncertainties in design evaluation, such as imprecise relationships, imprecise information, and uncertain information [14]. It is difficult for a fuzzy goal-programming model to consider all sources of uncertainty coherently at the preliminary design stage [15]. In addition, the computational complexity is a key issue, especially in case of a large number of design alternatives and criteria being involved [16,17]. There are also many other product feasibility and quality assessment tools that are useful for planning the design of products, such as quality function deployment (QFD) [18], concurrent function deployment [19], concept selection matrix [20], Taguchi robust design method [21], etc. While these methodologies provide high-level guidelines for design evaluation, detailed supporting techniques are essential, 4Ms (models, methods, metrics and measures) are the core in integrated product development.

3. Knowledge Support Framework for Customer-Based Design for Mass Customization

To support the customized product differentiation, a product family platform is required to characterize customer’s needs and subsequently to fulfill these needs by configuring and modifying well-established building blocks. The process of customer-based design for mass customization ranges from capturing voices of customer, analyzing market trends, generating design objectives and product design specifications to customizing products for customer satisfaction [23]. To assist the designer in this process, a knowledge support framework is further proposed based on the rationales of customer-based design for mass customization, as illustrated in Figure 1. Design knowledge is classified into two categories: product information and knowledge, and process knowledge. These two categories of knowledge are utilized to support the customer-based design for mass customization that has two application scenarios: the product planning and the product family design. The knowledge support scheme for a modular product family design and its key research issues are described in [24]. With understanding of the fundamental issues in the modular product family design, the knowledge support scheme aims to provide support for customer requirements' modeling, product architecture modeling, product platform establishment, product family generation, and product assessment for customization.

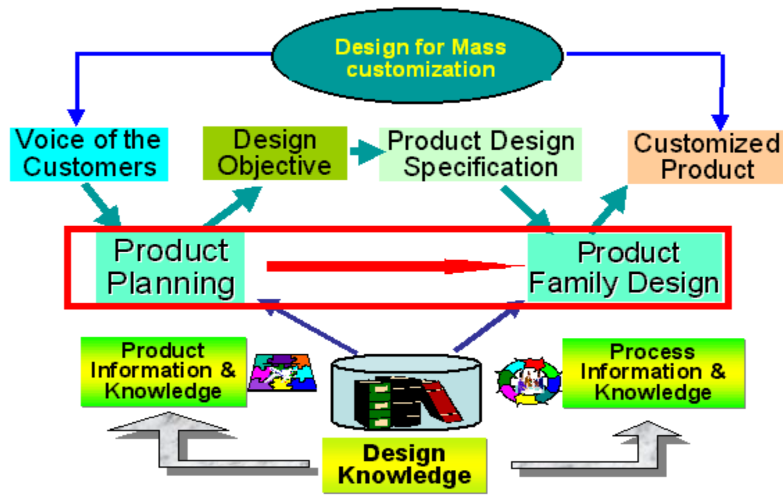


Figure 1 Knowledge intensive support framework for CDFMC

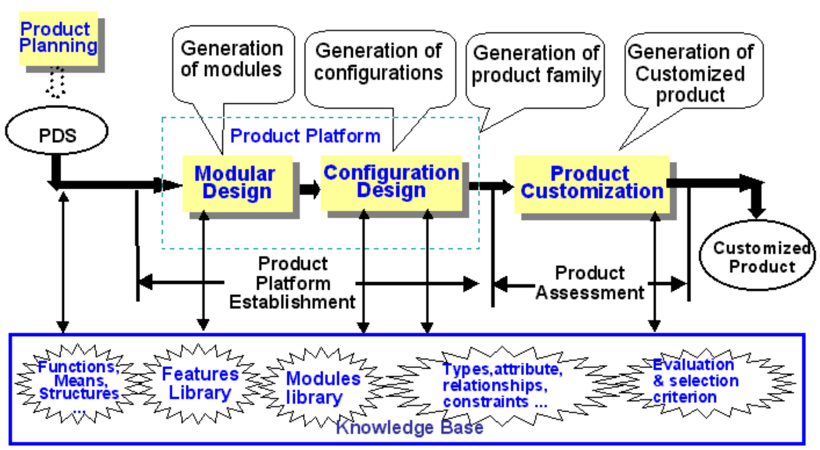


Figure 2 Modular product family design process for mass customization

As shown in Figure 2, the whole process of the customer-based modular product family design for mass customization can actually be divided into two main stages: the product platform generation and the product customization, which is implemented through the product planning for design specifications generation, modular design, and configuration design and product evaluation for customization. The product evaluation for customization stage aims at obtaining a feasible architecture for a product family member through reasoning and decision support in the product family module space according to the customer requirements. The customization stage includes two steps. First, the customer requirements, including function, assembly, reuse, etc, need to be converted to constraints. Then, the reasoning or decision support is performed at two levels, namely the module level and the attribute level, to determine the feasible product family member architecture at the conceptual level. Typically, this stage characterizes from the feasible set of products generated from a product platform as an input to the final customized product as an output, experiencing the elimination of unacceptable alternatives, the evaluation of candidates for customization, and the final decision under the customers' requirements and the design constraints. The research focus of this paper is on how knowledge supports the designer to perform the concept evaluation and selection at this stage. Details will be discussed below.

4. The Concept Evaluation and Selection in Design for Mass Customization

In this research, a knowledge decision support scheme developed for the concept design evaluation and selection in the context of design for mass customization is based on fuzzy clustering and ranking algorithms for a multi-criteria decision-making problem. Details are discussed below.

4.1 The Concept Evaluation and Selection Problem

During the process of modular product family design, the selection and assembly of the modules or pre-defined building blocks at different levels of abstraction can generate a family of products. Therefore, the main task of CDFMC is to synthesize product structures by determining what modules or building blocks are in the product and how they are configured to satisfy a set of requirements and constraints. In this connection, the concept evaluation and selection are crucial for CDFMC.

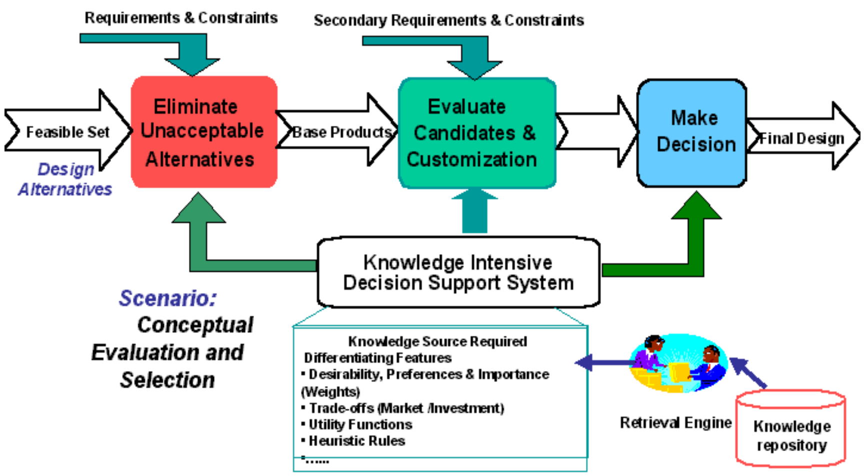


Figure 3 Knowledge decision support for product evaluation in mass customization

With respect to the traditional approaches [2,3], we propose an approach to the concept evaluation and selection for product customization from a knowledge support perspective. The knowledge resource utilized in the process extensively include differentiating features, customers' requirements, desirablities, preferences and importance (weights), trade-offs (e.g. market vs investment), and utilities functions, and heuristic knowledge, rules, etc. Figure 3 shows a knowledge decision support scheme for the product evaluation and customization process. The kernel of the scheme is fuzzy clustering and ranking algorithms for the design evaluation and selection that will be discussed below.

4.2 Evaluation /Customization Metrics

In order to model and/or design a family of products for mass customization, suitable metrics are needed to assess the appropriateness of a product platform and a corresponding family of products. The metrics should also be useful for measuring various attributes of a product family and assessing the modularity of a platform. There are many econo-technical metrics that can be used in the customer-based design for mass customization [2]. The following two typical metrics were used for the customization process in this research [22]:

(1) Market efficiency-a tradeoff between marketing and design, by offering the least amount of variety so as to satisfy the greatest amount of customers, i.e., targeting the largest number of market niches with the fewest products.

(2) Investment efficiency-a tradeoff between manufacturing and design, by investing a minimal amount of capital into machining and tooling equipment while still being able to produce as large a variety of products as possible.

The market efficiency and the investment efficiency can be represented by the following two equations respectively:

$$\eta_M = N_{tm}/N_M \tag{1}$$

$$\eta_I = C_m/N_v, \tag{2}$$

where, N_{tm} and N_M are the numbers of the targetable market niches and the total market numbers, respectively; C_m and N_v are the manufacturing equipment costs and the number of the product varieties, respectively. Of course, there is also a trade-off between the market efficiency and the investment efficiency as an increase in the investment efficiency through a decrease of the product variety can cause a decrease of the market efficiency.

4.3 Fuzzy Clustering and Ranking Method

As discussed above, due to the fuzziness of the voice of customers or customer requirements, it is difficult to evaluate and select product concepts and assess the performance of product platform and product variants in the context of CDFMC. The method used in this research is based on the fuzzy clustering and ranking algorithms. Using the design solution clustering techniques, a reasonable number of possible design alternatives can be obtained. The fuzzy clustering algorithm follows four steps as [4]:

(1) Find the smallest element in distance matrix d_i to merge the corresponding two objects.
(2) Select a point as a reference in the merged group using some rules, e.g., the nearest neighbor or the centroid cluster.
(3) Recalculate the distance matrix between the new group and the remainders, named d_{i+1}.
(4) Repeat step 1 until all the objects are merged into one group.

The remaining procedure is to examine the design alternatives against the marketing and the econo-technical and even the ergonomic and aesthetic criteria. This is actually a multi-criteria decision-making problem. One of the well-known methods for the multi-criteria decision-making is the procedure for calculating a weighted average rating $\overline{r}_i$ by use of the value analysis or cost-benefit analysis [3]:

$$\bar{r}_i = \sum_{j=1}^{n} (w_j r_{ij}) / \sum_{j=1}^{n} w_j \tag{3}$$

where, i=1,2,…,m, j=1,2,3,…, n , r_{ij} denotes the merit of alternative a_i according to the criterion C_j; w_j denotes the importance of criterion C_j in the evaluation of alternatives. The higher $\bar{r}_i$ is, the better is its aggregated performance.

However, this procedure is not applicable for the situations where uncertainty exists and the information available is incomplete. For example, the terms "very important," "good," or "not good" themselves are a fuzzy set. In what follows, the problem of fuzzy ranking a set of alternatives against a set of criteria is described. Let a set of m alternatives A={a_1, a_2,...,a_m} be a fuzzy set on a set of n criteria C={C_1,C_2,...,C_n } to be evaluated. Suppose that the fuzzy rating r_{ij} to certain C_j of alternative a_i is characterized by a membership function $\mu_{R_{ij}}(r_{ij})$, where, $r_{ij} \in R$, and a set of weights W={w_1,w_2,...,w_n} are fuzzy linguistic variables characterized by $\mu_{W_j}(w_j)$, $w_j \in R^+$. Consider the mapping function $g_i(z_i): R^{2n} \to R$ defined by:

$$g_i(z_i) = \sum_{j=1}^{n} (w_j r_{ij}) / \sum_{j=1}^{n} w_j \tag{4}$$

where, $z_i = (w_1 w_2 ... w_n, r_{i1} r_{i2} ... r_{in})$. Define the membership function $\mu(z_i)$ by

$$\mu_{Z_i}(z_i) = \overset{\circ}{\bigwedge}_{j=1,...,n} \mu_{W_j}(w_j) \overset{\circ}{\bigwedge}_{k=1,...,n} \mu_{R_{ik}}(r_{ik}) \tag{5}$$

Thus, through the mapping $g_i(z_i): R^{2n} \to R$, the fuzzy set Z_i induces a fuzzy rating set R_i with membership function

$$\mu_{R_i}(r_i) = \sup_{Z_i g(z_i) = r_i} \mu_{Z_i}(z_i), r_i \in R \tag{6}$$

The final fuzzy rating of design alternative a_i can be characterized by this membership function. But it does not mean the alternative with the maximal $\mu_R(r_i)$ is the best one. The following procedure further evaluates the two fuzzy sets as [4]:

(1) a conditional fuzzy set is defined with the membership function:

$$\mu_{I/R}(i \mid r_1,...r_m) = \begin{cases} 1 & if \quad r_i > r_k, \forall k \in (1,2,...,m) \\ 0 & \text{otherwise} \end{cases} \tag{7}$$

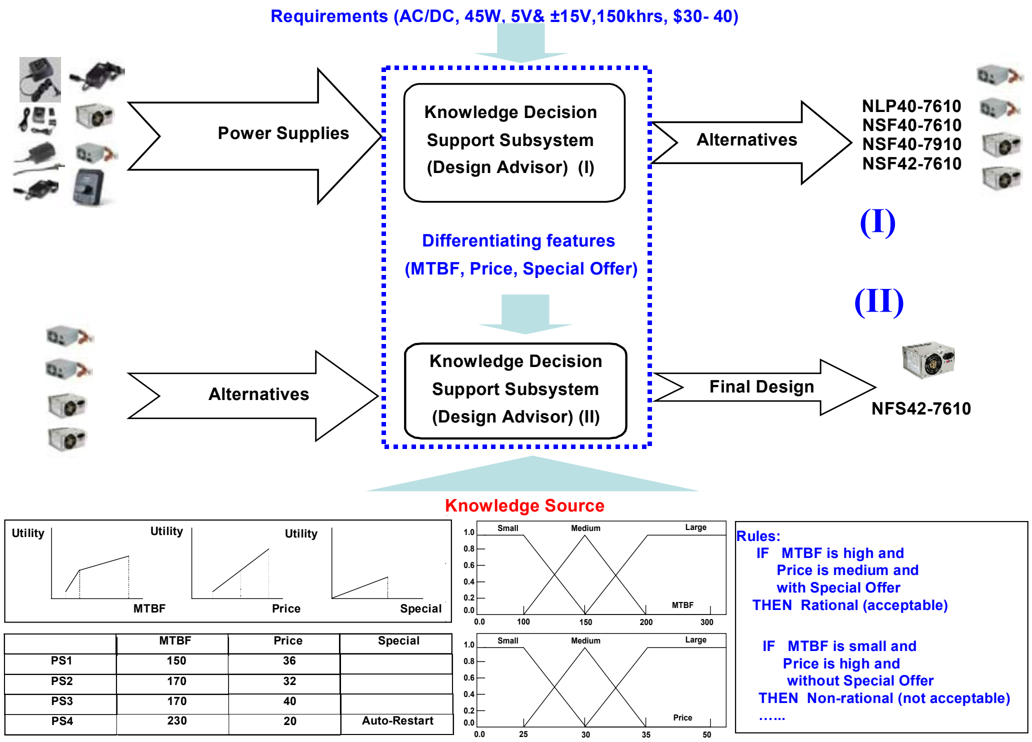
(2) a fuzzy set is constructed with membership function:

$$\mu_R(r_1,...r_m) = \overset{\circ}{\bigwedge}_{i=1,...,m} \mu_{R_i}(r_i) \tag{8}$$

A combination of these two fuzzy sets induces a fuzzy set I which can determine a best design alternative with the highest final rating, i.e.,

$$\mu_I(i) = \sup_{r_1,...r_m} \mu_{I/R}(i \mid r_1,...r_m) \overset{\circ}{\wedge} \mu_R(r_1,...r_m) \tag{9}$$

Comparing with Eq.(3), the fuzzy ranking for design is more flexible and presents uncertainty better. Based on this method, the designer can use linguistic rating and weights such as "good", "fair," "important," "rather important," for design alternatives evaluation. Therefore it looks natural and attractive in practical use.



	MTBF	Price	Special
PS1	150	36	
PS2	170	32	
PS3	170	40	
PS4	230	20	Auto-Restart

Figure 4. A scenario of knowledge support for product evaluation and selection in mass customization

5. Case Study: Power Supply Family Evaluation and Customization

To illustrate and validate the approach discussed above, a scenario of knowledge support for product customization in power supply family design is provided in this section. From a customer's point of view, a power supply product is defined on these required features: power, output voltage, output current, size, regulation, mean time between failure (MTBF), etc. From an engineer's point of view, the power supply product is designed by determining these parameters: core of transformer, coil of transformer, switch frequency, rectifier, heat sink type, heat sink size, control loop, etc. There are three product families Family-I, II and III generated based on three different topologies, which have 4,5 and 3 base products respectively. Each topology has its own range with regard to the particular product features and/or the design parameters.

With reference to the knowledge decision support scheme for product evaluation (Figure 3), a scenario of knowledge support for power supply product customization in Family-I is shown in Figure 6. The customers' requirements for Family-I power supplies include AC/DC, 45W, 5V & ±15V, 150khrs, $20-50, etc. The knowledge decision support system first eliminates unacceptable alternatives and determines four acceptable alternatives, i.e., NLP40-7610, NFS40-7610, NFS40-7910, and NFS 42-7610. It then reaches the final design decision based on the knowledge resources given in the bottom of Figure 4, including differentiating features (MTBF, price, and special offer) and their utility / membership functions, fuzzy rules, and etc. The final design decision made by the system is NFS 42-7610 as it has maximum MTBF, medium price and special offer of auto-start function and it is acceptable based on the rules. The system can explain the reasoning process, and this makes a great difference between the knowledge support system and the traditional program (e.g. [2]).

6. Conclusions and Future Work

This paper presented an approach on the knowledge decision support for the concept evaluation and selection in design for mass customization. A comprehensive knowledge support scheme and the relevant technologies were developed for customer-based design for mass customization. The proposed systematic fuzzy clustering and ranking methodology can be used for concept evaluation and selection in CDFMC. This CDFMC models the imprecision inherent in the decision-making with the fuzzy preference relations and compensates for the typical barriers to the decision-making process including the incomplete and the evolving information, the uncertain evaluations, and the inconsistency of team members' inputs. The results obtained from the case study illustrate and validate the knowledge support scheme. The developed methodology is flexible enough to be used in a variety of decision problems. The future work is desired to develop a knowledge-based fuzzy decision support system for product family design for mass customization.

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