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REVIEW ARTICLE

The use of fuzzy logic in product family development: literature review and opportunities

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Abstract Over the past few years, a number of key issues related to the product family design have been addressed, and a great deal of work has been done to improve it. Many different tools have been employed in this effort, such as mass customization, modularity, delayed differentiation, commonality, platforms, product families, and so on. The purpose of this paper is to analyze how fuzzy logic has been applied and how it can help to improve the entire process of product family development. Given its powerful capability to represent aspects that binary variables cannot, we show how fuzzy logic has been used to take advantage by considering the vague parameters related to the human character in different processes. Our aim is to contribute to the understanding and improvement of product family development process by identifying essential applications of fuzzy logic. An extended overview of the product family development process is provided, and also this work highlights the role of fuzzy logic in it. Fourteen fuzzy logic tools and thirteen topics into the product family development process are identified and summarized as a framework to analyze the role of fuzzy logic and at the same time to identify further application opportunities.

Keywords Literature review · Product family development · Fuzzy logic · Shortcomings · Opportunities

Introduction

Competitive companies are involved in a race to increase customers' satisfaction as well as enlarge their market share. They are pushed to improve their products in terms of quality, price, variety, safety, flexibility, delivery time, etc. To achieve these goals, many companies have developed design strategies to incorporate all the actors (customers and suppliers) and their perspectives into the business game as effectively as possible.

On this way, mass customization permits the identification and fulfilment of individual wants and needs of different types of customers, without sacrificing efficiency, effectiveness and low cost (Pine 1993). To make mass customization a reality, many strategies have been developed in recent decades, such as modular design, delayed differentiation, platforms, and product families, among others. By developing products as a family, reusing a common product platform, firms can reduce the cost of developing individual product variants (Krishnan et al. 1999). The development of product families has been recognized as a mean for optimizing internal complexity and external variety (Meyer et al. 1997). According to Jiao et al. (1998) product portfolio is a parameter that should be optimized by considering different domains: physical, technical and functional, looking for the balance between customer desires and product designs. A product family can result in a large variety of products supported with managed development and manufacturing costs.

Even if many important topics around product family development have been significantly explored, there are still some unexplored such as fuzzy logic. We believe that based on the ability of fuzzy logic to handle vague parameters related to the human character in the decision-making process; this powerful capability represents a critical aspect that could advantageously improve the process of designing product families.

In this work, we consider the integration of fuzzy logic as a fundamental aspect to success in the whole process of product family development. This integration represents a major challenge, but the result could be very useful. So far, most

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of presently published works contain isolated applications of fuzzy logic rather than integral applications. This paper aims to tackle this situation, by presenting a literature review on the main topics related to the development of product families, and at the same time by analyzing current application of fuzzy logic to identify and propose new possible applications.

This paper is organized in the following sections. Section "Product family development" provides an overview of the product family development process as reference framework to understand different phases and topics related to such process. Section "Fuzzy logic in product family development" presents an analysis of the role of fuzzy logic in the product family development process. This section consists of two parts: (1) summary and analysis, and (2) classification of applied fuzzy tools. In Sect."Opportunities for fuzzy logic applications in product family" some potential applications of fuzzy logic into the product family development process are proposed. Section "Conclusions" concludes the paper.

Product family development

A great deal of work has been carried out to try to improve and optimize some aspects in different phases of the development of product families. Some of these works include various philosophies, strategies, approaches, frameworks, methods, models, algorithms and methodologies (see Table 1).

Prior to analyze these works, it is important to define what "product family" covers. According to Erens and Verhulst (1997) a product family can be defined as set of products that share identical internal interfaces. These interfaces must be standardized in each of the functional, technological and physical domains to allow the full exchange of components. More recently, Moon et al. (2006) defined a product family as a group of related products based on a product platform, facilitating mass customization by providing a variety of products cost-effectively for different market segments.

In this paper, we depict the development of product families as a process in four main phases: (1) consideration of customer desires, (2) design of the product family and its architecture, (3) evaluation of the product family, and (4) redesign of the product family (see Fig. 1).

Figure 1 depicts the product family development process as a reference framework giving a big picture about different topics related to the entire process. Also, Fig. 1 shows the three main views (functional, technical and physical) that appear in most works related to product families, and should be considered before creating the product family design. The design of the product family and its architecture is presented in two principal processes; product development and mass customization. Product development is divided in three processes (product definition, product design, and process design), and the use of platforms is considered to achieve the mass customization. Four strategies are considered to support the platform formation (commonality, modularity, scalability, and postponement). A significant amount of literature related to the development of product families is reviewed in this section and classified in Table 1.

Consideration of customer desires

Companies around the world aim to satisfy the customer desires. They try to avoid all the drawbacks, such as loss of a segment of the potential markets and shortening of the life cycle of the product due to a deficient identification of the customer needs. For several years now, a powerful tool used to translate the customer's needs and wishes into product specifications has been Quality Function Deployment (QFD). Hanumaiah et al. (2006) proposed a QFD-AHP methodology made up of three main phases. The first phase involves prioritizing the tooling requirements (driven by customer preferences) applying AHP. In the second phase, priority ratings are used for selecting the most appropriate tooling process using QFD. Finally, QFD is used again for identifying critical process parameters. These tools have amply demonstrated their valuable contributions to the design of better products closer to customer's expectations, and that is why these are in continues improvement by including other tools such as fuzzy logic. These applications are analyzed in Sect."Fuzzy logic in product family development".

Design of product family and its architecture

The design of product family architecture is one of the most critical tasks faced by the design team. According to Erens and Verhulst (1997) the design of product families requires a product's architecture in three domains or views: functional, technical, and physical. In the functional view, the functional merit of a product family architecture is judged by the capability of its product portfolios to target identified market niches. The technical view looks to highlight differentiation (variety) in product design resulting from different solution technologies applied to meet diverse customer needs. Finally, the physical view in a product family architecture displays the variety resulting from manufacturing concerns. There are many types of architectures for individual products or for product portfolios, among them modular, integral and mixed configurations, as well as adjustable configurations (Gonzalez-Zugasti et al. 2000). To deal with product family architecture design, some approaches (Du 2000; Dahmus et al. 2001) and different methodologies (Jiao 1998; Siddique and Adupala 2005) have been proposed as a way to reach the mass customization through the product families. Also, different approaches (Anderson 1997; Hsiao and Liu 2005; Zhang 2006) and a methodology (Agard and Kusiak

Table 1 Review of product family development

Publications	Cons. of customer desires	Product definition	Product design	Process desgin	Product family architecture	Mass customization	Platform	Commonality	Modularity	Scalability
Agard and Kusiak (2004a)						*				
Agard and Kusiak (2004b)			*			*				
Agard and Tollenaere (2003)			*			*			*	
Anderson (1997)		*	*	*	*	*			*	
Biao et al. (2004)						*				
Burgess (1997)				*		*				
Callahan (2006)			*							*
Chen and Weng (2006)		*	*							
Da Cunha and Agard (2005)				*					*	
Da Cunha et al. (2007)				*		*			*	
Dahmus et al. (2001)		*	*		*		*		*	
Deciu et al. (2005)			*			*				
Du (2000)			*		*	*		*	*	
Fellini et al. (2005)							*	*		
Fellini (2003)							*	*	*	
Gonzalez-Zugasti et al. (2001)			*				*			
Gonzalez-Zugasti et al. (2000)					*		*			
Gupta and Krishnan (1998)				*						
Hanumaiah et al. (2006)	*	*		*						
He and Kusiak (1997)				*					*	
Hsiao and Liu (2005)										
Jiao (1998)		*	*	*	*	*	*	*	*	*
Jiao and Tseng (1999)					*	*				
Jiao et al. (1998)		*				*				
Kim (1998)			*					*		
Krishnan et al. (1999)							*			
Kuo et al. (2006)			*							
Lee and Tang (1997)						*				
Meng et al. (2007)									*	
Messac et al. (2002)			*				*	*		*
Meyer et al. (1997)							*			
Mishra (1999)								*		

Table 1 continued

Publications	Cons. of customer desires	Product definition	Product design	Process desgin	Product family architecture	Mass customization	Platform	Commonality	Modularity	Scalability
Moon et al. (2006)						*	*		*	
Nanda et al. (2005)								*		
Park and Simpson (2005)				*						
Rai and Allada (2003)									*	
Sered and Reich (2006)				*		*	*		*	
Siddique and Adupala (2005)				*	*					
Simpson and Mistree (1999)							*			*
Simpson et al. (2001)			*				*	*		
Sivard (2001)							*		*	
Sopadang et al. (2001–2002)			*	*						*
Su et al. (2005)						*				
Thevenot et al. (2007)										
Thevenot et al. (2005)								*		
Thevenot and Simpson (2006)			*					*		
Thevenot (2006)			*					*		
Van Hoek (2001)										
Wang et al. (2005)									*	
Zha et al. (2004)			*			*				
Zhang et al. (2006)									*	

Publications	Postponement	Product family design	Product family evaluation	Product family redesign	Approach	Framework	Method	Methodology	Model	Algorithm
Agard and Kusiak (2004a)		*			*			*		
Agard and Kusiak (2004b)								*		
Agard and Tollenaere (2003)	*	*						*	*	
Anderson (1997)		*			*					
Biao et al. (2004)	*					*				
Burgess (1997)									*	
Callahan (2006)		*							*	
Chen and Weng (2006)									*	

Table 1 continued

Publications	Postponement	Product family design	Product family evaluation	Product family redesign	Approach	Framework	Method	Methodology	Model	Algorithm
Da Cunha and Agard (2005)										*
Da Cunha et al. (2007)										*
Dahmus et al. (2001)					*					
Deciu et al. (2005)					*				*	
Du (2000)					*					
Fellini et al. (2005)		*			*					
Fellini (2003)		*						*		
Gonzalez-Zugasti et al. (2001)		*							*	
Gonzalez-Zugasti et al. (2000)					*		*			
Gupta and Krishnan (1998)		*			*			*		*
Hanumaiah et al. (2006)					*	*		*		
He and Kusiak (1997)					*					
Hsiao and Liu (2005)		*			*					
Jiao (1998)						*		*		
Jiao and Tseng (1999)								*		
Jiao et al. (1998)		*			*					
Kim (1998)					*					
Krishnan et al. (1999)		*							*	
Kuo et al. (2006)							*			
Lee and Tang (1997)	*								*	
Meng et al. (2007)		*						*	*	
Messac et al. (2002)		*			*					
Meyer et al. (1997)		*					*			
Mishra (1999)									*	
Moon et al. (2006)		*					*			
Nanda et al. (2005)		*		*	*	*		*		
Park and Simpson (2005)		*				*	*			
Rai and Allada (2003)		*			*	*	*			
Sered and Reich (2006)		*					*			
Siddique and Adupala (2005)		*				*	*			
Simpson and Mistree (1999)		*					*			
Simpson et al. (2001)		*			*		*			
Sivard (2001)		*							*	

Table 1 continued

Publications	Postponement	Product family design	Product family evaluation	Product family redesign	Approach	Framework	Method	Methodology	Model	Algorithm
Sopadang et al. (2001–2002)		*					*			
Su et al. (2005)	*								*	
Thevenot et al. (2007)				*		*				
Thevenot et al. (2005)				*				*		
Thevenot and Simpson (2006)		*	*				*			
Thevenot (2006)				*			*			
Van Hoek (2001)	*					*				
Wang et al. (2005)		*					*			
Zha et al. (2004)			*		*	*			*	
Zhang et al. (2006)		*			*					

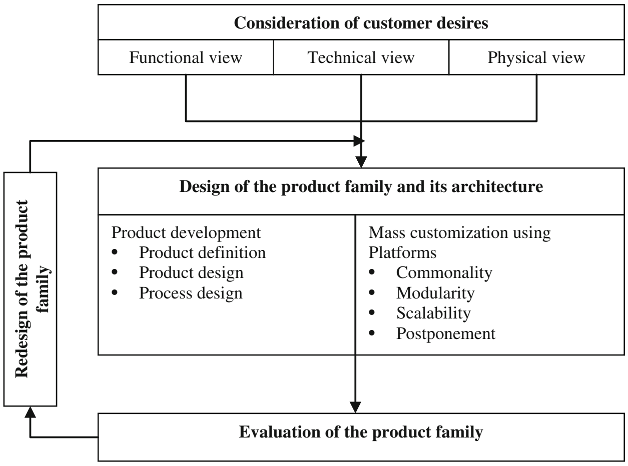

Fig. 1 Overview of the product family development

2004a) haven been presented to design product families by managing the required variety to satisfy different segments of the market.

Product development

Product development represents an essential part of the product family design. According to Jiao and Zhang (2005) it can be divided into three consecutive stages: (1) product definition, (2) product design, and (3) process design.

(1) *Product definition.* Product definition is characterized by the portfolio of products that represents the target of mass customization which then becomes the input to the downstream design activities and is propagated to product and process platforms (Jiao and Zhang 2005).

(2) *Product design.* Product design is an engineering process involving iterative and complex decision-making. It usually starts with the definition of a need, proceeds through a sequence of activities to find an optimal solution, and ends with a detailed description of the product (Deciu et al. 2005). A great deal of research has been carried out in the effort to improve the product design process. Among this research, papers related to the development of product families are mostly devoted to mass customization.

(3) *Process design.* Optimization of product and process designs is a key to make the performance minimally sensitive to the various causes of variation (Nepal 2005). A model to evaluate the investment in process improvement as a means of responding to changing market forces characterized by the mass customization paradigm was published by Burgess (1997). A careful design of product assembly sequence helps to create generic subassemblies which reduce subassembly proliferation and the cost of offering product variety

(Gupta and Krishnan 1998). In the same context (Park and Simpson 2005) presented a production cost model associated with manufacturing activities. Also, Da Cunha and Agard (2005) proposed a simulated annealing algorithm to address the problem of module design, focusing on minimizing mean assembly time.

Next sections will show that fuzzy logic could be advantageously employed in the different steps of product development in order to better represent uncertainty.

Mass customization using platforms

Mass customization using platform is critical in product family development, it enables to introduce various degrees of standardization. Product families are partitioned into subfamilies to better match distinct market segments, and subfamily can be customized according to specific customer segment (Agard and Kusiak 2004b). Two strategies widely applied to achieve the mass customization are the delayed product differentiation and modular design (Agard and Tollenaere 2003).

According to (Messac et al. 2002) the key to a successful product family is the common product platform around which the product family is derived. Four basic platform strategies have been successfully identified (Huang et al. 2005). These are commonality, modularity, scalability and postponement.

(1) *Commonality.* The success of a product family relies heavily on properly balancing the commonality of the product platform with the individual product performance within the product family. To help resolve this trade-off, (Simpson et al. 2001) proposed a product variety trade-off evaluation method for assessing alternative product platform concepts with varying levels of commonality. Also, Dai (2005) proposed a decision method in order to achieve a meaningful trade-off between the technical and monetary aspects of the product family. Jiao and Tseng (2000) identified two sources of commonality: components and process. Thevenot and Simpson (2004) analyzed commonality indices from the literature based on the ease with which data can be collected, and their repeatability and consistency. Kim (1998) focused on the demand and on the cost side-effects of commonality. It suggests a notion of customer valuation change due to commonality and demonstrates the effect of the valuation change on optimal product design. For modelling the commonality of components, two models were presented by Mishra (1999): the multiple product-multiple common components, and the multiple product-single common components. A methodology for performing commonality optimization in choosing product components to be shared without exceeding user-specified bounds on performance and allowing the maximization of commonality at different levels was proposed by Fellini (2003); Fellini et al. (2005). Besides these propositions are limited in the way that they do not consider any uncertainty from the customers' requirements.

(2) *Modularity.* According to Jose and Tollenaere (2005), modularization was first mentioned in the literature in the 1960s. Modularity was then proposed to group components of products in a module for practical production objectives. Today, modularity and standardization are promising tools in product family development, because they make it possible to design a variety of products using the same modules of components, called platforms. Salvador et al. (2002) explored how manufacturing characteristics affect the appropriate type of modularity to be embedded in the product family architecture, and how the types of modularity relate to component sourcing. Different approaches have been proposed (He and Kusiak 1997; Rai and Allada 2003; Zhang et al. 2006) for tackling the modular product family design using various tools, such as multi-objective optimization, and search-based algorithms. Some methods for developing a modular product family have been presented as well. Sered and Reich (2006) proposed a method called SMDP (standardization and modularization driven by process effort), which focuses the engineering effort on product platform components when applying standardization or modularization. Meng et al. (2007) presented a methodology for identifying the constituent modules of product families. Da Cunha et al. (2007) proposed various heuristic algorithms to design modular elements in a mass customization context, focusing on minimizing the manufacturing and transportation cost in a supply chain. Also, in these works, it is always considered that the customers know exactly what they want from a product perspective, the propositions then focus on satisfying these customers with the best possible performance (depending on different criteria).

(3) *Scalability.* To facilitate the product family design process based on a scalable product platform, (Simpson and Mistree 1999) introduced the product platform concept exploration method. Callahan (2006) developed a model called the extended generic product structure by focusing on capturing reusable and non-reusable design definitions. Messac et al. (2002) proposed a product family penalty function to optimize the product family design process. This function determines which parameters should be common throughout the product family, and which should be the scaling variables. Also, a methodology to identify a scaling factor for product family-based product and process design employing the tools

of experimental design and analysis was presented by Sopadang et al. (2001–2002). These works suppose a minimal knowledge of the demand, expressed in non variable characteristics.

(4) *Postponement.* The development of product families allows high volumes to be produced at low cost through standardization. The downside is that this approach represents a move away from real needs in an increasingly heterogeneous and evolving market. To compensate for this negative effect, companies produce standardized goods, but incorporate a degree of differentiation, which makes it possible to personalize each product in the final phase of the production process. This strategy is called delayed differentiation (Lee and Tang 1997), and it is based on the modular design (Kusiak 1999). Delayed differentiation makes it possible to produce almost-finished goods which can be personalized in the last phase. According to Feitzinger and Lee (1997) the key to effective mass customization is postponing product differentiation for a specific customer until the latest possible point in the supply chain or network. Postponement can be defined as an organizational concept whereby some of the activities in the supply chain are not performed until customer orders are received (Van Hoek 2001). Postponement has become mandatory for many companies, due the current levels of market globalization, increasing demand for product variety and customization, rapid technological innovation, shortening product life cycles and intense competition (Biao et al. 2004). Su et al. (2005) have been developed some models to represent two possible mass customization postponement structures, Time Postponement and Form Postponement, and study their performance in terms of total supply chain cost and the expected customer waiting times. If postponement makes it possible to support some degree of fuzziness in the customers demand (not yet precisely defined options could be postpone), present literature review did not reveal such interest.

Product family evaluation

A knowledge decision support approach to product family design is necessary to help managers and engineers to make decisions. Zha et al. (2004) presented an evaluation and selection for the mass customization process. In this approach, product family design is viewed as a selection problem with the following stages: product family generation, product family design evaluation and selection for customization. In the same way, Thevenot and Simpson (2006) introduced a comprehensive metric for commonality to evaluate product family designs on a 0–1 scale; this is based on the components in each product, their size, geometry, material, manufacturing process, assembly and costs, and the allowed diversity in a family. Once again, there is no mention to any fuzziness in the product family design, all alternatives and product descriptions are completely defined, which is not always the case in real world problems.

Product family redesign

Thevenot et al. (2005; 2006) developed a methodology for product family redesign that is based on the use of a genetic algorithm and commonality indices—metrics to assess the level of commonality within a product family. It consists of four phases. Phase 1 is designed to obtain the necessary data for the product family concerned. In phase 2, the commonality within a product family is measured. Phase 3 considers the product family design optimization. Finally, phase 4 gives redesign recommendations. Also, Nanda et al. (2005) proposed two approaches for redesigning a product family: (1) a component-based approach, and (2) a product-based approach. In the component-based approach, the emphasis is placed on a single component which could be shared among different products. In the product-based approach, multiple products from a product family are selected, and commonality is improved among the selected products. In the same way, Thevenot et al. (2007) proposed a five steps framework for product family redesign. These steps are: (1) collect information, (2) store information, (3) retrieve information, (4) reuse information for product family redesign, and (5) represent information. Uncertainty in the product family definition has many impacts on metrics adopted, and may drastically change the decisions.

Fuzzy logic in product family development

Summary and analysis

Product family is a powerful tool that makes it possible to take advantage of product similarities to reduce design and manufacturing costs. Besides uncertainty on the customers' expectations has great impacts on the design of product families which would be improved by applying fuzzy logic into the whole process. Fuzzy logic permits opinions, knowledge and expertise to be provided in linguistic values allowing deal with incomplete and/or imprecise information. This information can be used for making better and more accurate decisions. Fuzzy logic is increasingly used in decision-aided systems, since it offers several advantages over other traditional decision-making techniques.

This section presents the analysis of literature about the application of fuzzy logic in some topics of the product family development process. Table 2 classifies several works indicating in which topics the application of fuzzy logic has been addressed. Furthermore, for each work, the type of tool

Table 2 Review of product family development with fuzzy logic

No.	Reference	Cons. of customer desires	Product definition	Product design	Process design	Product family architecture	Mass customization	Platform	Commonality	Modularity
1	Ahmed et al. (2008)									
2	Buyukozkan and Feyzioglu (2004a)		*	*						
3	Buyukozkan and Feyzioglu (2004b)									
4	Chen et al. (2004a)	*	*	*						
5	Chen and Weng (2006)		*	*						
6	Chen (1999)									
7	Chen et al. (2005)	*	*	*						
8	Chen et al. (2006)	*	*	*						
9	Chen et al. (2004b)	*	*							
10	Deciu et al. (2005)			*			*			
11	Dong et al. (2001)		*							
12	Feyzioglu and Büyüközkan (2006)									
13	Fung et al. (2002)	*	*	*						
14	Fung et al. (1999)	*	*							
15	Gungor and Arikan (2000)									
16	Jiang and Chi-Hsing (2001)				*					
17	Jiao (1998)		*	*	*	*	*	*	*	*
18	Jiao and Tseng (1998)			*						
19	Jiao and Tseng (1999)					*	*			
20	Jiao and Zhang (2005)	*	*	*	*		*			
21	Kalargeros and Gao (1998)	*	*							
22	Kim et al. (2000)	*	*	*						
23	Koga and Ohta (2005)	*	*							
24	Kuo et al. (2006)			*						
25	Lin and Chen (2004)		*	*						
26	Moon et al. (2006)						*	*		*
27	Nepal (2005)			*	*					*
28	Ramasamy and Selladurai (2004)	*	*							
29	Shipley et al. (2004)	*	*	*						
30	Vanegas and Labib (2001a)	*	*							
31	Vanegas and Labib (2001b)			*						
32	Vanegas and Labib (2005)			*						
33	Wang et al. (2005)									*
34	Wang (1999)	*	*							
35	Zha et al. (2004)			*			*			
36	Zhang (2006)									

Table 2 continued

No.	Reference	Scalability	Postpone-ment	Product family design	Product family evaluation	Product family redesign	Approach	Framework	Method	Methodology	Model
1	Ahmed et al. (2008)				*		*				
2	Buyukozkan and Feyzioglu (2004a)						*				
3	Buyukozkan and Feyzioglu (2004b)						*				
4	Chen et al. (2004a)								*		
5	Chen and Weng (2006)										*
6	Chen (1999)										*
7	Chen et al. (2005)						*				*
8	Chen et al. (2006)								*		
9	Chen et al. (2004b)						*				*
10	Deciu et al. (2005)						*				*
11	Dong et al. (2001)			*				*	*		
12	Feyzioglu and Büyüközkan (2006)							*			
13	Fung et al. (2002)										*
14	Fung et al. (1999)						*				
15	Gungor and Arikan (2000)								*		
16	Jiang and Chi-Hsing (2001)										*
17	Jiao (1998)	*						*		*	
18	Jiao and Tseng (1998)									*	
19	Jiao and Tseng (1999)									*	
20	Jiao and Zhang (2005)									*	
21	Kalargeros and Gao (1998)								*		
22	Kim et al. (2000)										*
23	Koga and Ohta (2005)								*		
24	Kuo et al. (2006)								*		
25	Lin and Chen (2004)						*				
26	Moon et al. (2006)			*					*		
27	Nepal (2005)							*		*	
28	Ramasamy and Selladurai (2004)								*		
29	Shipley et al. (2004)										*
30	Vanegas and Labib (2001a)								*		
31	Vanegas and Labib (2001b)								*		
32	Vanegas and Labib (2005)						*				
33	Wang et al. (2005)			*					*		
34	Wang (1999)						*				
35	Zha et al. (2004)				*		*	*			*
36	Zhang (2006)			*			*				

offered is identified. Although fuzzy logic has not yet been applied to the entire, it has, however, been used more and more in recent years to perform several tasks in that process.

It is interesting to note that an important number of publications listed in Table 2 contain at least one application of fuzzy logic. The most of these are partial applications; different fuzzy tools are used in one or more topics of the product family development process. Topics such as: product definition, consideration of customer desires, product design, and mass customization are addressed in most fuzzy logic applications. On the contrary, the topics that are less addressed with fuzzy logic applications are postponement, and product family redesign with not any work found with fuzzy logic. Also, topics such as process design, product family architecting, platforms, commonality, modularity, scalability, and product family evaluation presented a minimal number of works addressed in this way.

A very few part of these works applied fuzzy logic as a tool for developing product families. Two works in this sense have been proposed recently. The first one (Dong et al. 2001) was a product family configuration method based on constraints and fuzzy decisions, in which fuzzy optimum selection is used in the reasoning process to select between similar current components. The second one (Zhang 2006) proposed an approach to develop a new product family which consists of a process evaluation method to determine whether or not some factors contribute to the new product family; it follows an application of the fuzzy analytic hierarchy process to weight the importance of the factors. Even if some works presented any application of fuzzy logic into the product family design process, these applications are partial and still necessitate more development to achieve the integration of fuzzy logic into the entire development of product families.

Classification of applied fuzzy tools

Thirteen fuzzy logic tools may be identified through the papers examined in this review about product family development (see Table 3). This table shows how fuzzy tools have been developed and applied to support different topics related to the development of product families. Also, the most relevant references for each topic are listed in the last column of Table 3, and these reference numbers correspond to the numbers assigned to each reference listed in Table 2.

(1) *Fuzzy analytical hierarchy process.* Fuzzy analytical hierarchy process has been used for different purposes such as distribution of weights for the establishment of fuzzy relationship matrix (Wang et al. 2005), to weight the importance of the factors determine whether or not some factors contribute to the new design (Zhang 2006), to construct the hierarchical structure of environmentally conscious design indices into the green fuzzy design analysis (Kuo et al. 2006), to choose the best project alternative in the decision-making process (Buyukozkan and Feyzioglu 2004a), and to describe more accurately the evaluation and decision-making process (Buyukozkan and Feyzioglu 2004b).

(2) *Fuzzy clustering.* Jiao and Tseng (1999) employed the fuzzy cluster analysis to evaluate the similarities of customers needs by applying c-means clustering analysis. Moon et al. (2006) used fuzzy c-means clustering to determine initial clusters representing modules and to identify the platform and its modules by a platform level membership function and classification. Jiao and Zhang (2005) adopted a fuzzy clustering approach to create a hierarchical decomposition of the given set of objects, and to form groups in different levels of similarity. Zha et al. (2004) developed a knowledge-intensive support scheme and a comprehensive systematic fuzzy clustering and ranking methodology for the evaluation and selection in product family design.

(3) *Fuzzy goal programming.* Fuzzy goal programming has been adopted to determine the fulfillment levels of the engineering design requirements, where the coefficients in these models are also fuzzy in order to expose the fuzziness of the linguistic information (Chen and Weng 2006), and to simultaneously optimize multiple objectives for product modularization (Nepal 2005).

(4) *Fuzzy inference.* Fuzzy inference has been significantly used for numerous purposes such as determination of the priority of customer demands (Chen et al. 2004a), to accommodate the possible imprecision and vagueness during the interpretation of the voice of the customers during the interpretation of the qualitative and sometimes imprecise customer requirements (Fung et al. 1999), to process new product ideas into the evaluation of products by using a neuro-fuzzy inference system Buyukozkan and feyzioglu (2004b; 2006), to adjust the membership function to enhance their systematic fuzzy clustering and ranking model by adopting a neural network technique (Zha et al. 2004), to perform the learning process of the fuzzy inference system by using adaptive neuro-fuzzy inference systems (ANFIS) (Buyukozkan and Feyzioglu 2004a,b; Feyzioglu and Büyüközkan 2006). Also, more recently, Ahmed et al. (2008) proposed an approach for product family evaluation by using a fuzzy inference system based on a five-level maturity scale to establish a relationship among four variables of software product family.

(5) *Fuzzy multiple attribute decision-makings.* The integration of multiple attributes during the decision-making process has been considered an important issue to make accurate decisions. Jiang and Chi-Hsing (2001) used fuzzy logic decision model and fuzzy multiple attribute decision making model to construct a goal

Table 3 Fuzzy logic tools applied in product family development

Fuzzy logic tools	Product family development topics													Related references
	Product definition	Product design	Process design	Product family architecture	Mass customization	Platform	Commonality	Modularity	Scalability	Postponement	Product family design	Product family evaluation	Product family redesign	
Fuzzy analytical hierarchy process		*						*			*			2, 24, 33, 36
Fuzzy clustering	*	*	*	*	*	*		*			*	*		19, 20, 26, 35
Fuzzy goal programming	*	*						*						5, 27
Fuzzy inference	*	*										*		1, 2, 3, 4, 12, 14, 35
Fuzzy multiple attribute decision-makings		*	*		*									16, 24, 29
Fuzzy numbers	*	*												2, 3, 8, 25, 28, 30, 31, 32
Fuzzy optimization	*	*									*			9, 11, 13
Fuzzy outranking	*	*												2, 15, 34
Fuzzy preference			*	*	*	*	*	*	*			*		2, 15, 17, 18
Fuzzy quality function deployment model	*	*												4, 7, 9, 13, 14, 21, 23, 28, 29, 30, 34
Fuzzy ranking	*	*	*	*	*	*	*	*	*			*		17, 19, 35
Fuzzy regression	*	*												6, 9, 22
Fuzzy weighted average	*	*												2, 5, 8, 25, 31, 32

and activity decision spaces for a manufacturability evaluation decision model. Shipley et al. (2004) used a fuzzy-set based multi-criteria decision-making process to determine the distributions of effort directed toward technical changes. Kuo et al. (2006) used fuzzy multi-attribute decision-making techniques into a method for green fuzzy design analysis.

(6) *Fuzzy numbers.* Fuzzy numbers have been widely applied for different purposes. Vanegas and Labib (2001a) used fuzzy numbers to represent the imprecise nature of the judgments, and to define more appropriately the relationships between engineering characteristics and customer attributes in QFD. Vanegas and Labib (2001b) to develop a new fuzzy weighted average trying to reduce the obtained imprecision during the evaluation of engineering, and also to capture the relative importance of the various criteria and performance levels of the alternatives in the evaluation process for engineering design (Vanegas and Labib 2005). Chen et al. (2006) to express and represent the input data in order to calculate the importance of the technical attributes in the fuzzy QFD. Others applications include Lin and Chen (2004) used fuzzy numbers to describe the criteria ratings and their corresponding importance in the proposed method for new product screening, Buyukozkan and Feyzioglu (2004a) to represent the performance of different ideas into the fuzzy preference relation. Buyukozkan and Feyzioglu (2004b) to express the assessments of the decision makers into the fuzzy analytical hierarchy process, and Ramasamy and Selladurai (2004) applied fuzzy triangular membership functions to represent the customer attribute and engineering characteristic into the rule-based fuzzy logic system to examine their relationships.

(7) *Fuzzy optimization.* Some important applications of fuzzy optimization include Dong et al. (2001) employed fuzzy optimum selection in the reasoning process, where the constraint satisfaction and fuzzy optimum selection interact to search the optimum solution, Fung et al. (2002) applied a fuzzy non-linear optimization model for QFD planning to obtain a set of feasible solutions to support more practical and cost-effective QFD planning under resource constraints, and Chen et al. (2004b) applied fuzzy optimization theory with symmetric or non-symmetric triangular fuzzy coefficients to model the relational functions between engineering characteristics and customer requirements in QFD methodology.

(8) *Fuzzy outranking.* Wang (1999) proposed a new fuzzy outranking approach and an outranking decision model to select the critical design requirements for product development in the imprecise and uncertain design environment in the QFD planning process. Focusing on the application of the outranking approach, Gungor and Arikan (2000) used the outranking approach to model an imprecise preference structure in a project selection problem, Buyukozkan and Feyzioglu (2004a) applied the outranking concept into the pseudo-order fuzzy preference model to discriminate the set of alternatives without the information about their information. An interesting comparison of three different outranking methods (Roy's, Brans et al.'s and Siskos et al.'s) to evaluate the design requirements was made by Ertay and Kahraman (2007) concluding that all the methods outrank the same alternative.

(9) *Fuzzy preference.* Jiao (1998) developed a fuzzy ranking methodology by employing the fuzzy preference relation to model the fuzziness in conceptual design evaluation. Some applications of fuzzy preference include Jiao and Tseng (1998) applied fuzzy preference relation for modelling the fuzziness in the proposed fuzzy ranking methodology for concept evaluation in configuration design, Gungor and Arikan (2000) to represent the imprecise preference relation between design alternatives. Buyukozkan and Feyzioglu (2004a) used the pseudo-order fuzzy preference model to discriminate between different ideas without the relative importance of each considered criterion of evaluation into their proposed approach for new product development.

(10) *Fuzzy quality function deployment.* Ramasamy and Selladurai (2004) proposed a fuzzy logic-quality function deployment to determine optimum rating of engineering characteristics by using a rule-based fuzzy logic system. Also, Shipley et al. (2004) presented a model to develop the QFD into a fuzzy-set based multi-criteria decision-making process to determine the distributions of effort directed toward technical changes. This tool has recently evolved through the addition of other improvements, such as fuzzy logic methods. Fuzzy logic uses the customer inputs to reveal the relative importance of their needs and to facilitate their implementation. Several works have been developed in this way, (Kalargeros and Gao 1998; Fung et al. 1999; Wang 1999; Vanegas and Labib 2001a; Fung et al. 2002; Chen et al. 2004a; Ramasamy and Selladurai 2004; Shipley et al. 2004; Chen et al. 2004b, 2005; Koga and Ohta 2005) trying to simplify and rationalize the application of QFD using fuzzy logic tools. They consider fuzzy inference techniques to accommodate the possible imprecision and vagueness, fuzzy outranking to prioritize the design requirements, fuzzy numbers to represent the imprecise nature of judgments and to fuzzy regression to define the relationships between engineering characteristics and customer requirements.

(11) *Fuzzy ranking.* A fuzzy ranking methodology by employing the fuzzy preference relation to model the

fuzziness in conceptual design evaluation in configuration design for mass customization was developed by Jiao (1998). Jiao and Tseng (1999) developed a fuzzy ranking approach and methodology using information-content measure for solving the multi-attribute design evaluation problem. More recently, focusing on the product family development process Zha et al. (2004) developed a ranking methodology for the product family design evaluation and selection.

(12) *Fuzzy regression.* Chen (1999) developed a fuzzy regression applying nonlinear programming to solve the fuzzy ranking problem. Kim et al. (2000) employed fuzzy regression to consider mathematically the inherent fuzziness during the estimation of the functional relationship between customer requirements and engineering characteristics in the QFD application. Chen et al. (2004b) considered the fuzzy linear regression with symmetric triangular fuzzy coefficients to model the relational functions between engineering characteristics and customer requirements considered traditionally in QFD methodologies.

(13) *Fuzzy weighted average.* Vanegas and Labib (2001b) developed a new fuzzy weighted average to produces fuzzy numbers as a better basis for making decisions more credible, and with less imprecision. Fuzzy weighted average has been used for different purposes such as the ranking of projects in the new product development process (Buyukozkan and Feyzioglu 2004a), the aggregation of fuzzy numbers into the product rating process (Lin and Chen 2004), to calculate the overall performance of the alternatives considered in the evaluation of designs (Vanegas and Labib 2005), to determine the fuzzy technical importance rating of design requirements in their fuzzy QFD proposed approach (Chen and Weng 2006), and to rank technical attributes in fuzzy QFD and to calculate their importance (Chen et al. 2006).

Table 3 also aims to show the status of current applications of fuzzy logic along the entire product family development process, presenting an interesting summary that lists and classifies the most and less developed topics throughout such process. Tables 2 and 3 allow noting how fuzzy logic has been applied. Significant applications in mass customization and product family design can be noted, but it must be pointed out that, in this work, mass customization and product family design are addressed as general topics. Mass customization is made up of other subtopics, such as platforms, commonality, modularity scalability and postponement. Product family design involves all the subtopics, from consideration of customer desires and product development to product family architecture and mass customization. Although fuzzy logic has been widely used in the product development process with several works related to QFD, it can be further exploited to embrace all the topics in the product family development process. In the same way, Tables 2 and 3 can be analyzed to identify shortcomings in the application of fuzzy logic and, consequently, to detect significant applications of fuzzy logic in all the sub-processes in product family development. Even though many works in the sample are related to product family design, just a few parts of them correspond to work with a fuzzy logic application.

Opportunities for fuzzy logic applications in product family

In Tables 2 and 3 can be noted that topics such as postponement and product family redesign do not contain any application of fuzzy logic. Also, product family evaluation is a topic which has not been developed much with application of fuzzy logic. This situation could represent an opportunity to take advantage of fuzzy logic in future developments. With the exception of consideration of customer desires, product definition and product design, there is a significant opportunity to use fuzzy logic in the rest of the topics, specifically in the evaluation and redesign phases. Table 4 lists some possible opportunities to apply fuzzy logic for the development of product families. These applications are classified by considering the structure depicted in Fig. 1.

Table 4 presents potential applications of fuzzy logic into the development of product families. This table contains the four principal phases (in bold type) and ten topics depicted in the framework on Fig. 1. Each potential application is described as follows.

(1) *Consideration of customer desires.* Fuzzy logic may be applied in different product family development issues, including generic product structuring, association methods, and optimization trying to avoid a deficient identification of the customer needs. More specifically *QFD* has been a powerful tool widely used to translate the customer's needs and wishes into product specifications. As mentioned in the previous phase, the customer desires consideration can be improved through the fuzzy logic applications.

(2) *Design of the product family and its architecture*. The design of a product family architecture is one of the most critical tasks faced by the product family design team. Some important issues such as generic product structuring, optimization, decision-making tools, and activity-based costing can be enhanced by applying fuzzy logic as a way to reach the mass customization benefits. In *product definition* issues such as generic product structuring, optimization, decision-making tools, activity-based costing may be improved with fuzzy logic

Table 4 Potential applications of fuzzy logic in product family development

Product family development phases and topics	Potential fuzzy logic applications
Consideration of customer desires	Generic product structuring, optimization, association methods
Quality function deployment	Generic product structuring, method for determining optimum targets in QFD
Design of the product family and its architecture	Generic product structuring, optimization, decision-making tools, activity-based costing
Product definition	Generic product structuring, optimization, decision-making tools, activity-based costing
Product design	Multi-criteria analysis, preference aggregation, decision-making tools, activity-based costing, optimization, association methods, product family penalty function, product variety tradeoff evaluation
Process design	Optimization, analytical hierarchal process, activity-based costing, assembly simulation, scaling factor identification
Mass customization	Generic product structuring, optimization, decision-making, activity-based costing, association methods, variation mechanisms
Platform	Generic product structuring, optimization, decision-making, activity-based costing, product family penalty function, association methods, product platform concept exploration
Commonality	Generic product structuring, optimization, decision-making, preference aggregation, cluster analysis, commonality indices, activity-based costing, product family penalty function, commonality indices-metrics
Modularity	Generic product structuring, optimization, decision-making, activity-based costing, association methods, multi-objective analysis
Scalability	Optimization, decision-making, activity-based costing, product family penalty function, scaling factor identification
Postponement	Optimal characterization and optimization
Product family evaluation	Comprehensive commonality metrics, and knowledge decision support systems
Product family redesign	Optimization, commonality indices-metrics to assess the level of commonality, comprehensive metric for commonality

application to obtain generic products by optimizing common components groped in modules to minimize the labour and resources requirement per unit. In *product design* multi-criteria analysis, preference aggregation, decision-making tools, activity-based costing, optimization, association methods, product family penalty function, product variety trade-off evaluation are some of possible issues that could be enhanced by applying fuzzy logic. These issues are important to properly parameterize the product designs according to the customer desires, and at the same considering functional requirements of the product. In the *process design*, for mapping design parameters to process variables in the process domain, some issues such as optimization, analytical hierarchal process, activity-based costing, and assembly simulation, scaling factor identification can be improved by the incorporation of fuzzy logic. Also in *mass customization,* generic product structuring, optimization, decision-making, activity-based costing, association methods, and variation mechanisms are some of the issues where fuzzy logic can be applied to make the mass customization a success reality. One of the most important aspects to obtain a successful product family is the *product platform* around which the product family is derived. Fuzzy logic may be applied into different issues including generic product structuring, optimization, decision-making, activity-based costing, product family penalty function, and association methods to get a common product platform for all the product family. Four basic platform strategies (commonality, modularity, scalability, and postponement) have been applied successfully for the platform development. A proper *commonality* balance of the product platform with the individual product performance within the product family is a very important aspect for its success. Issues such as generic product structuring, optimization, decision-making, preference aggregation, cluster analysis, commonality indices, activity-based costing, product family penalty function, and the development of commonality indices and metrics may be enhanced with the application of fuzzy logic to obtain more accurate common platforms. fuzzy logic can be used in some issues related to *modularity* including generic product structuring, optimization, decision-making, activity-based costing, association methods, and multi-objective analysis to makes possible to design a variety of products using the same modules of components, called platforms. With *scalability,* optimization, decision-making, activity-based costing, product family penalty function, and scaling factor identification are some of the issues that may be improved by applying fuzzy logic to facilitate the product family design process by developing generic product structures and scalable product platforms. Also *postponement* makes it possible to produce almost-finished goods which can be personalized in the last phase. To facilitate the product family design based on a scalable product platform, issues such as optimal characterization and optimization can be improved with the incorporation of the fuzzy logic.

(3) *Product family evaluation.* Comprehensive commonality metrics and knowledge decision support systems could be improved by using fuzzy logic to support the evaluation of product families. Some fuzzy logic tools such as fuzzy preference, fuzzy clustering, and fuzzy ranking have been partially applied in some issues related to the evaluation of product families. Others indices to evaluate the amount of modularity, scalability, manufacturability, among others may be improved by adopting fuzzy logic in their processes.

(4) *Product family redesign.* Fuzzy logic could be applied to support the phase of product family redesign in issues such as the development of multiple metrics needed to evaluate current families of products including metrics to measure the amount of commonality, modularity, scalability, postponement, manufacturability, reliability, customer satisfaction, and so on. Also, fuzzy logic may be applied in the optimization of all these metrics and the optimization of the product family design process as well.

Conclusions

Product family development is a broad subject, which includes a number of topics that have been considered throughout this work. An analysis of these topics permits to understand the importance of developing tools with greater scope. A large number of application opportunities appear to take advantage of fuzzy logic for improving product family development. The topics with the most potential for fuzzy logic applications are presently postponement and product family redesign, as no studies have been found that contain a fuzzy logic application. Topics with potential are still product family architecture, platforms, commonality, modularity, scalability, product family evaluation and process design. Even though there is some application of fuzzy logic in these topics, this application is minimal. By contrast, consideration of customer wishes, product definition and product design have already received large development.

The analysis about the application of fuzzy logic in different topics through all phases in product family development process allowed constructing a summary to prioritize such topics (Table 2); this summary shows opportunities for application of fuzzy logic in such process. That is, it already lists the most developed topics around the product family development process and at the same time rank such topics according the fuzzy logic application permitting to identify application shortcomings.

It is important to say that there are other important issues to consider with respect to product family development; external factors, such as legal, moral and environmental aspects, could be better modelled using fuzzy logic. The most of companies are subject to rules that must be respected when designing products. From the moral perspective, it is necessary to solve the dilemmas to develop safe products for the customer. Recycling, for example, must be considered by producers, which means recovering materials to be used again. The term "design for recycling" defines the capacity to disassemble and reprocess a used product to recover any of its components that can be recycled. Most of these issues have already been considered into different topics of product family development though without applying fuzzy logic.

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