Centre interuniversitaire de recherche
sur les réseaux d'entreprise, la logistique et le transport

Interuniversity Research Centre
on Enterprise Networks, Logistics and Transportation

The Use of Fuzzy Logic in Product Family Development: Literature Review and Opportunities

Marco Barajas
Bruno Agard

July 2009

CIRRELT-2009-31

Bureaux de Montréal :
Université de Montréal
C.P. 6128, succ. Centre-ville
Montréal (Québec)
Canada H3C 3J7
Téléphone : 514 343-7575
Télécopie : 514 343-7121

Bureaux de Québec :
Université Laval
Pavillon Palasis-Prince, local 2642
Québec (Québec)
Canada G1K 7P4
Téléphone : 418 656-2073
Télécopie : 418 656-2624

www.cirrelt.ca

The Use of Fuzzy Logic in Product Family Development : Literature Review and Opportunities

Marco Barajas[1], Bruno Agard [1,*]

[1] Interuniversity Research Centre on Enterprise Networks, Logistics and Transportation (CIRRELT) and Department of Mathematics and Industrial Engineering, École Polytechnique de Montréal, P.O. Box 6079, Station Centre-ville, Montréal, Canada H3C 3A7

Abstract. Over the past few years, a number of key issues related to the product family design process have been addressed, and a great deal of work has been done to improve it. Many different philosophies, approaches, frameworks, methods and methodologies 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 in such process. 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 in the product family process and at the same time to identify further application opportunities in such process.

Keywords. Literature review, product family development, fuzzy logic, shortcomings, opportunities.

Acknowledgement. The authors wish to acknowledge the support of the Natural Sciences and Engineering Research Council of Canada (NSERC). This research was also supported by the Fonds québécois de la recherche sur la nature et les technologies (FQRNT).

---

* Corresponding author: Bruno.Agard@cirrelt.ca

Dépôt légal – Bibliothèque et Archives nationales du Québec,
Bibliothèque et Archives Canada, 2009

1 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 applied design strategies that 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 various customers, without sacrificing efficiency, effectiveness and low cost (Pine II, 1993). Product portfolio is a parameter that should be optimized looking for a balance between customer desires and the product family design in different domains, such as the physical, technical and functional domains, and yet at the same time keeping costs low (Jiao *et al.*, 1998). 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). 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 topics such as Fuzzy logic (FL), it has the capacity to manage 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 a product family.

Processes used in companies present a systemic behaviour; they are interconnected to some degree. Product family development (PFD) presents a similar behaviour; all its processes are interconnected, this makes an integral application of FL necessary, instead of isolated applications. This represents a major challenge, but the improvements will be very useful. Unfortunately, most of presently published works contain isolated applications of FL rather than an integral application.

This paper presents a review of the literature on the main topics related to the PFD process, analyzing the application of FL. This work is organized as follows: Section 2 provides an overview of the PFD process and the role of FL in it, including consideration of the customers' desires, design of the product family and creation of its architecture, evaluation of the product family, and redesign of the product family. Each phase is explained below, and several tools, such as product development, mass customization, platforms, commonality, modularity, scalability and postponement, are explained as well. Section 3 presents an analysis of the role of FL in the PFD process. This analysis is presented in three parts. These are: classification of the work carried out on PFD, current applications of FL in the PFD process, and identification of the shortcomings and opportunities inherent in applying FL to improving the process. Section 4 concludes the paper.

2 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 PFD process. These include various philosophies, strategies, approaches, frameworks, methods, models, algorithms and methodologies. Prior to analyze this work, 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 work, the process of PFD is presented in four main phases. These are: consideration of customer desires, design of the product family and its architecture, evaluation of the product family, and redesign of the product family. An overview of the PFD process is depicted in Figure 1.

Figure 1 Overview of the product family development

Figure 1 shows the three main views that appear in most works related to product families. These are the functional, technical and physical views that should be considered before creating the product family design. The following section explains the main phases of the product family overview.

2.1 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 market and shortening of the life cycle of the product due to a deficient identification of the customer needs.

The design of a product family requires a product's architecture in three domains (Erens and Verhulst, 1997). In the functional view, the functional merit of a Product Family Architecture (PFA) 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 PFA displays the variety resulting from manufacturing concerns. This view represents product information by means of a description of the physical realization of a product design, and bears a strong relationship to product construction.

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). This tool has recently evolved through the addition of other improvements, such as FL methods. FL 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, 2001; Fung *et al.*, 2002; Chen *et al.*, 2004a; Ramasamy and Selladurai, 2004; Shipley *et al.*, 2004; Chen *et al.*, 2004b; Koga and Ohta, 2005) trying to simplify and rationalize the application of QFD using FL 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 define the relationships between engineering characteristics and customer attributes, fuzzy regression to identify the relational functions between, and among, engineering characteristics and customer requirements. At the same time, environmental issues are being increasingly addressed. For example, Chen *et al.* (2005) proposed a novel fuzzy expected value operator approach to model the QFD process in a fuzzy environment.

2.2 Design of the product family and its architecture

The design of PFA is one of the most critical tasks faced by the design team. There are many types of architectures for individual products or for product portfolios, among them modular, integral and mixed configurations, as well as an adjustable configuration (Gonzalez-Zugasti *et al.*, 2000). To deal with PFA design, some approaches (Du, 2000; Dahmus *et al.*, 2001) and different methodologies (Jiao, 1998; Jiao and Tseng, 1999; Siddique and Adupala, 2005) have been proposed as a way to reach the mass customization through the product families.

Different approaches (Anderson, 1997; Hsiao and Liu, 2005; Zhang, 2006) and diverse methodologies (Dong *et al.*, 2001; Agard and Kusiak, 2004a) haven been presented to design product families. They manage the required variety to satisfy the different segments of the market. A very few part of these works applied the FL 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.

2.2.1 Product development

The product development process represents an essential part of the product family design and it can be divided into three consecutives stages (Jiao and Zhan, 2005): (1) product definition—mapping customer needs in the customer domain to functional requirements in the functional domain; (2) product design—mapping functional requirements in the functional domain to design parameters in the physical domain, these stages are highly supported by QFD; and (3) process design—mapping design parameters in the physical domain to process variables in the process domain.

2.2.1.1 Product definition

According to Anderson (1997) one important phase in the product development is 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).

2.2.1.2 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 to the problem, 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. It seeks to apply many concepts, such as standardization or mass customization, modular products, product platform, component sourcing, evolutionary product, real-time design, information exploitation, etc. Among this research works are devoted to mass customization, and some of it related to the development of product families as a tool to achieve mass customization.

Different approaches, methods, and models have been proposed for the product design process (Deciu *et al.*, 2005; Shaowei, 2006; Chen and Weng, 2006; Kuo *et al.*, 2006) based on different fuzzy models, such as fuzzy goal programming models to determine the level of fulfilment of the design requirements, green fuzzy design analysis for evaluating product design alternatives based on environmental considerations using FL, and the fuzzy multi-attribute decision-making to select the most desirable design alternative.

Other technologies, like the Internet, are being used in this field, some examples of which include: (Siddique and Ninan, 2005), who presented an Internet-based framework which uses a grammatical approach to represent and develop models of customized products. Another example of an Internet application is a web-based virtual design environment method which allows customers to participate in product design and help designers conveniently adjust the structure of their products (Shen *et al.*, 2005).

2.2.1.3 Process design

The optimization of product and process designs is very important 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). A manufacturability evaluation decision model based on FL and multiple-attribute decision-making in a concurrent engineering environment was proposed by Jiang and Chi-Hsing (2001). In the same context (Park and Simpson, 2005) presented a production cost model based on a production cost framework 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.

2.2.2 Mass customization using platforms

Many manufacturers define product families in order to introduce some degree of standardization. These product families could be further partitioned into subfamilies to better match distinct market segments. Then, each subfamily can be customized according to the needs and preferences of a 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). Also, (Agard and Kusiak, 2004b) suggested that data mining can be applied to standardize the components, products and processes thanks to knowledge extracted from databases.

Two dimensions for classifying product families were proposed by Wijnstra (2005). The first deals with coverage of the product family platform. The second deals with the variation mechanisms used to derive a specific product from the generic platform. The key to a successful product family is the common product platform around which the product family is derived (Messac *et al.,* 2002).

There are two recognized approaches to product family design (Simpson, 2004). The first is a top-down (proactive platform) approach, wherein the company's strategy is to develop a family of products based on a product platform and its derivatives. The second is a bottom-up (reactive redesign) approach, wherein a company redesigns and/or consolidates a group of distinct products to standardize components and thus reduce costs.

In a general way, an important number of works has been published for developing platforms. These works include methods for identifying a platform using data mining techniques and fuzzy clustering (Moon *et al.*, 2006), methods for the platform development applying preference aggregation, optimization, and cluster analysis (Gonzalez-Zugasti *et al.*, 2001; Dai, 2005; Dai and Scott, 2006).

More specifically, four basic platform strategies have been applied successfully for the platform development. These are commonality, modularity, scalability and postponement (Huang *et al.*, 2005). A brief summary of the work carried out related to these strategies follows.

2.2.2.1 Commonality

The success of the 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) presented a product variety trade-off evaluation method for assessing alternative product platform concepts with varying levels of commonality.

Jiao and Tseng (2000) identified two sources of commonality: in the component part, and in the process part. In this way, Thevenot and Simpson (2004) compared and contrasted six of the commonality indices from the literature based on the ease with which data can be collected, and their repeatability and consistency.

An analytical approach focuses on the demand side-effects of commonality and on the integration of the cost side-effects of commonality was presented by Kim (1998). It suggests a notion of customer valuation change due to commonality and demonstrates the effect of the valuation change on optimal product design. In the same way, Dai (2005) proposed a method to make an appropriate commonality decision in order to achieve a meaningful trade-off between the technical and monetary aspects of the product family.

For modelling the commonality of components, two models were presented by Mishra (1999). These methods are: 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 of acceptable performance was proposed by Fellini (2003) and Fellini *et al.* (2005).

2.2.2.2 Modularity

According to Jose and Tollenaere (2005), modularization was first mentioned in the literature in the 1960s. Modularity was proposed to group components of products in a module for practical production objectives. Today, modularity and standardization are promising tools in PFD, 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. Wang *et al.* (2005) proposed a method based on simulated annealing algorithm to develop a modular product family. Also, 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. Xianghui *et al.* (2007) presented a methodology for identifying the constituent modules of product families including four principles such as identification and isolation of individualized components into modules, identification and isolation of components with high possibility of replacement into one module, improvement of the functional independency of the modules, and improvement of the structural independency of the modules. 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.

2.2.2.3 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. In the same way, Callahan (2006) developed a model called the extended generic product structure. This model focuses on capturing reusable and non-reusable design definitions, as well as the hierarchical product design structures composed from them. 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. If a parameter cannot be made constant across the products without adversely affecting the design objectives, then it should be considered a good candidate for becoming a scaling parameter. 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).

2.2.2.4 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). Companies can then finalize the output in accordance with customer preferences, and even customize their products. 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.

2.3 Product family evaluation

A knowledge decision support approach to product family design evaluation and selection for the mass customization process was presented by Zha *et al.* (2004). 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. This approach supports the imprecision inherent in decision-making with fuzzy customer preference relations, and uses fuzzy analysis techniques for evaluation and selection. Also, this work focuses on the development of a knowledge-intensive support scheme and a comprehensive systematic fuzzy clustering and ranking methodology for product family design evaluation and selection.

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. This method improves the accuracy, repeatability and robustness of the results by minimizing user input, and helps designers resolve the trade-off between variety and commonality in a product family.

2.4 Product family redesign

Thevenot *et al.* (2005) 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, as follows. Phase 1: Data input. This phase is designed to obtain the necessary data for the product family concerned. Phase 2: Commonality assessment. In this phase, the commonality within a product family is measured. Phase 3: Product family design optimization. Phase 4: Data output and redesign recommendations. More recently, a systematic method to generate recommendations during the process of product family redesign using a new commonality index, the comprehensive metric for commonality was introduced by Thevenot (2006), it is made up of the same four phases.

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 a PF to increase commonality. In the product-based approach, multiple products from a PF 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.

3 Fuzzy logic in product family

3.1 Summary and analysis

The product family is a powerful tool that makes it possible to take advantage of product similarities to reduce design and manufacturing costs. Moreover, the design of product families can be improved in many processes in a wide range of areas by the application of FL. FL allows opinions, knowledge and expertise to be provided in linguistic way. This information can be used for making better and more accurate decisions. FL is increasingly used in decision-aided systems, since it offers several advantages over other traditional decision-making techniques. The fuzzy decision support system can easily deal with incomplete and/or imprecise information.

During the process of product family design, it is necessary to consider many important aspects, such as operational capabilities (normally called “design for operations” in a company context), product life cycle, and external factors. Not to do so can result in a reduction in productivity and quality, and also may generate an incremental rise in costs. The life cycle of a product is important because it distinguishes the differences between products in their various phases.

A summarized list of the works considered in this paper is displayed in Table 1. This table indicates in which publications the topics are addressed. The topics considered are product definition, product design, process design, product family architecture, mass customization, platform, commonality, modularity, scalability, postponement, product family design, product family evaluation and product redesign. Furthermore, for each work, the type of tool offered is identified. The classification is divided into the following categories: approach, framework, method, methodology, algorithm, and model. Finally, the last column in the table indicates whether or not the work has a FL application. Although FL may not yet have been applied to the entire process of development of product families, it has, however, been used more and more in recent years to perform several tasks in that process.

Table 1 Classification of developed works related to product family development

Table 1 Classification of developed works related to product family development (continued)

It is interesting to note that an important number of publications into the analyzed sample in Table 1 contain at least one FL application. The most of these are partial applications; that is to say, different FL tools are used in one or more phases in the PFD process. Product definition, consideration of customer desires, product design, and mass customization are the topics addressed in most FL applications. On the contrary, the topics that are less addressed with FL applications are postponement, and product family redesign with not any work found with FL. 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. Even if some considered works presented any application of FL into the product family design process, these applications are very partial and still necessitate developing new powerful tools for the entire PFD process.

Several fuzzy logic tools may be identified through the papers examined in this review. In this work, thirteen fuzzy logic tools around PFD have been identified and these are explained as follows.

(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 into the modular product family development process (Wang *et al*., 2005), to weight the importance of the factors determine whether or not some factors contribute to the new design of a product family (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. In the same way, 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 product family design evaluation and selection.

(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*., 2004), 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 product evaluation process by using a neuro-fuzzy inference system (Buyukozkan and Feyzioglu, 2004b; Feyzioglu and Buyukozkan, 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; Buyukozkan and Feyzioglu, 2004b; Feyzioglu and Buyukozkan, 2006).

(5) Fuzzy multiple attribute decision-makings. The consideration 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 the goal decision and activity decision spaces respectively into the proposed 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 to develop a method for green fuzzy design analysis, which involves simple and efficient procedures to evaluate product design alternatives based on environmental consideration to select the most desirable design alternative.

(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 during the engineering design evaluation process trying to reduce the obtained imprecision during such process, Vanegas and Labib (2005) to capture the relative importance of the considered criteria and performance levels of the different alternatives in the evaluation process for engineering design, and 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*. (2004) 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.

(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 PFD 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*. (2004) 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).

The following Table 2 shows how the different FL tools have been developed and applied to support different important topics related with the PFD process.

Table 2 Fuzzy logic applications into Product Family Development

Table 2 also aims to show the status of current applications of FL along the entire PFD process, presenting an interesting summary that lists and classifies the most and less developed topics throughout PFD. In Table 2, it is easy to note that topics as product definition, product design, and modularity are the topics with the most addressed topics in current applications of FL, topics as product family evaluation and scalability are topics with minimal applications of FL, and topics as product family redesign and postponement are not addressed topics in current FL application.

Tables 1 and 2 allow noting how FL 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 FL 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 PFD process. In the same way, Tables 1 and 2 can be analyzed to identify shortcomings in the application of FL and, consequently, to detect significant applications of FL in all the subprocesses in PFD. Even though many works in the sample are related to product family design, just a few parts of them correspond to work with a FL application.

3.2 Opportunities for fuzzy logic applications

As it can be noted in Tables 1 and 2, some topics such as postponement and product family redesign do not contain any application of FL, but sometimes this situation can be understandable due to the nature of the topic. Product family evaluation and redesign are topics which have not been developed much with application of FL. Hence, there is an opportunity to take advantage of FL in future developments related to these topics. With the exception of consideration of customer desires, product definition and product design, there is a significant opportunity to use FL in the rest of the topics, specifically in the evaluation and redesign phases. Table 3 aims to identify some opportunities for fuzzy logic application through the different PFD phases and topics depicted in Figure 1.

Table 3 Classification of potential fuzzy logic applications in product family development

Table 3 presents four phases (in bold type) and ten topics related to the PFD process listed in the first column. The second column presents the identified potential applications to these phases and topics. Each is described as follows.

Consideration of customer desires: FL may be applied in different PFD issues, including generic product structuring, association methods, and optimization trying to avoid a deficient identification of the customer needs. More specifically *Quality Function Deployment* 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 FL applications in different issues such as generic product structuring, and QFD optimum targets determination.

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 FL 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 FL 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 tradeoff evaluation are some of possible issues that could be enhanced by applying FL. 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, assembly simulation, scaling factor identification can be improved by the incorporation of FL. Also in *mass customization*, generic product structuring, optimization, decision-making, activity-based costing, association methods, and variation mechanisms are some of the issues where FL 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. FL 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. Each is discussed as follows. 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 FL to obtain more accurate common platforms. FL 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 FL 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 FL.

Product family evaluation. Comprehensive commonality metrics and knowledge decision support systems could be improved by using FL to support the evaluation of product families. Some FL 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 FL in their processes.

Product family redesign. FL 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, FL may be applied in the optimization of all these metrics and the optimization of the product family design process as well.

4 Conclusions

Product Family Development (PFD) 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 (FL) for improving PFD. The topics with the most potential for FL applications are presently postponement and product family redesign, as no studies have been found that contain a FL 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 FL 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 FL in different topics through all phases in PFD process allowed constructing a summary to prioritize such topics (Table 2), this summary shows opportunities for application of FL in such process. That is, it already lists the most developed topics around the PFD process and at the same time rank those topics according the FL application permitting to identify application shortcomings (Table 3). By considering the shortcomings as opportunity to apply FL into the topics related to PFD process, it may allows to companies to offer better products according to the customer desires.

It is important to say that there are other important issues to consider with respect to PFD; external factors, such as legal, moral and environmental aspects, could be better modelled using FL. 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 PFD though without applying FL.

5 References

Agard, B. and Kusiak, A. (2004a). Data-mining-based methodology for the design of product families. *International Journal of Production Research,* **42,** 2955-2969.

Agard, B. and Kusiak, A. (2004b). Standardization of components, products and processes with data mining. *International Conference on Production Research Americas 2004.* Santiago, Chile.

Agard, B. and Tollenaere, M. (2003). Design of product families: methodology and application. *Stockholm: 14th International Conference on engineering design-ICED'03.* Stockholm, Sweden.

Anderson, D.M. (1997). *Agile product development for mass customization*, Chicago, IL, USA: Irwin Professional Publishing.

Biao, Y., Burns, N.D., and Backhouse, C.J. (2004). Postponement: a review and an integrated framework. *International Journal of Operations and Production Management* **24,** 468-487.

Burgess, R.H. (1997). Mass customization and process improvement: competitive dynamic model. *Proceedings of the 1997 Annual Meeting of Decision Sciences Institute.* San Diego, CA, USA.

Buyukozkan, G., and Feyzioglu, O. (2004a). A fuzzy-logic-based decision-making approach for new product development. *International Journal of Production Economics* **90**, 27-45.

Buyukozkan, G., and Feyzioglu, O. (2004b). A new approach based on soft computing to accelerate the selection of new product ideas. *Computers and Industry* **54**, 151-167.

Callahan, S. (2006). Extended generic product structure: An information model for representing product families. *Journal of Computing and Information Science in Engineering* **6**, 263-275.

Chen, C.Y., Chen, L.C., and Lin, L. (2004). Methods for processing and prioritizing customer demands in variant product design. *IIE Transactions (Institute of Industrial Engineers)* **36,** 203-219.

Chen, L.H. and Weng, M.C. (2006). An evaluation approach to engineering design in QFD processes using fuzzy goal programming models. *European Journal of Operational Research* **172,** 230-248.

Chen Y-S. (1999). Fuzzy Ranking and Quadratic Fuzzy Regression. *Computers and Mathematics with Applications* **38**, 265-279.

Chen, Y., Fung, R.Y.K., and Tang, J. (2005). Fuzzy expected value modelling approach for determining target values of engineering characteristics in QFD. *International Journal of Production Research* **43,** 3583-3604.

Chen, Y., Fung, R.Y.K., and Tang, J. (2006). Rating technical attributes in fuzzy QFD by integrating fuzzy weighted average method and fuzzy expected value operator. *European Journal of Operational Research* **174**, 1553-1566.

Chen, Y., Tang, J., Fung, R.Y.K., and Ren, Z. (2004). Fuzzy regression-based mathematical programming model for quality function deployment. *International Journal of Production Research* **42,** 1009-1027.

Da Cunha, C., and Agard, B. (2005). Composition of modules' stock using simulated annealing. *IEEE International Symposium on Assembly and Task Planning (ISATP),* July 19-21, 2005. Montreal, QC, Canada.

Da Cunha, C., Agard, B., and Kusiak, A. (2007). Design for cost: Module-Based Mass Customization. *IEEE Transactions on Automation Science and Engineering* **4**, 350-359.

Dahmus, J.B., Gonzalez-Zugasti, J.P., and Otto, K.N. (2001). Modular product architecture. *Design Studies* **22,** 409-424.

Dai, Z. (2005). Robust product family design. *Thesis (PhD).* University of Illinois.

Dai, Z. and Scott, M.J. (2006). Effective product family design using preference aggregation. *Transactions of the ASME. Journal of Mechanical Design* **128,** 659-667.

Deciu, E.R., Ostrosi, E., Ferney, M. and Gheorghe, M. (2005). Configurable product design using multiple fuzzy models. *Journal of Engineering Design* **16,** 209-235.

Dong, J., Xiao T., and Qiao G. (2001). Study on a configuration framework for product family. *High Technology Letters (English Language Edition)* **7,** 58-62.

Du, X. (2000). Architecture of product family for mass customization. *Thesis (PhD).* Hong Kong University.

Erens, F. and Verhulst, K. (1997). Architectures for product families. *Computers in Industry* **33,** 165-178.

Ertay, T. and Kahraman, C. (2007). Evaluation of design requirements using fuzzy outranking methods. *International Journal of Intelligent Systems* **22**, 1229-1250.

Feitzinger, E. and Lee, H.L. (1997). Mass Customization at Hewlett-Packard: the Power of Postponement. *Harvard Business Review* **75**, 116-120.

Fellini, R., Kokkolaras, M., Papalambros, P. and Perez-Duarte, A. (2005). Platform selection under performance bounds in optimal design of product families. *Journal of Mechanical Design, Transactions of the ASME* **127,** 524-535.

Fellini, R.A. (2003). A model-based methodology for product family design. *Thesis (PhD).* University of Michigan.

Feyzioglu, O. and Büyüközkan, G. (2006). Evaluation of New Product Development Projects using Artificial Intelligence and Fuzzy Logic. *World Academy Of Science, Engineering And Technology* **11**, 183-189.

Fung, R.Y.K., Tang, J., Tu, Y. and Wang, D. (2002). Product design resources optimization using a non-linear fuzzy quality function deployment model. *International Journal of Production Research* **40,** 585-599.

Fung, R.Y.K., Law, D.S.T. and Ip, W.H. (1999). Design targets determination for inter-dependent product attributes in QFD using fuzzy inference. *Integrated Manufacturing Systems* **10,** 376-383.

Gonzalez-Zugasti, J.P., Otto, K.N. and Baker, J.D. (2001). Assessing value in platformed product family design. *Research in Engineering Design - Theory, Applications, and Concurrent Engineering* **13,** 30-41.

Gonzalez-Zugasti, J.P., Otto, K.N. and Baker, J.D. (2000). Method for architecting product platforms. *Research in Engineering Design - Theory, Applications, and Concurrent Engineering* **12,** 61-72.

Gungor, Z. and Arikan, F. (2000). A fuzzy outranking method in energy policy planning. *Fuzzy Sets and Systems* **114**, 115-122.

Gupta, S. and Krishnan, V. (1998). Product family-based assembly sequence design methodology. *IIE Transactions (Institute of Industrial Engineers)* **30,** 933-945.

Hanumaiah, N., Ravi, B. and Mukherjee, N.P. (2006). Rapid hard tooling process selection using QFD-AHP methodology. *Journal of Manufacturing Technology Management* **17**, 332-350.

He, D.W. and Kusiak, A. (1997). Design of assembly systems for modular products. *IEEE Transactions on Robotics and Automation* **13,** 646-655.

Hsiao, S.W. and Liu, E. (2005). A structural component-based approach for designing product family. *Computers in Industry* **56,** 13-28.

Huang, G.Q., Simpson, T.W. and Pine II, B.J.. (2005). The power of product platforms in mass customisation. *International Journal of Mass Customisation* **1,** 1-13.

Jiang, B.C., and Chi-Hsing H. (2001). Fuzzy decision modeling for manufacturability evaluation under the concurrent engineering environment. *Proceedings Joint 9th IFSA World Congress and 20th NAFIPS International Conference, Vancouver, BC, Canada. IEEE* **3**, 1511-16.

Jiang, Z. H., and Yan, J.Q. (2003). Research and development on constraint-based product family design and assembly simulation. *9th International Manufacturing Conference, August 18-17, 2000: Journal of Material Processing Technology Hong Kong, China. Elsevier* **139**, 257-62.

Jiao, J. and Tseng, M.M. (2000). Understanding product family for mass customization by developing commonality indices. *Journal of Engineering Design* **11,** 225-243.

Jiao, J., Tseng, M.M., Duffy, V.G., and Fuhua L. (1998). Product family modeling for mass customization. *22nd International Conference on Computers and Industrial Engineering.* Cairo, Egypt.

Jiao, J. (1998). Design for mass customization by developing product family architecture. *Thesis (PhD).* Hong Kong University.

Jiao J. and Tseng M.M. (1998). Fuzzy Ranking for Concept Evaluation in Configuration Design for Mass Customization. *Concurrent Engineering: Research and Application* **6**, 189-206.

Jiao, J. and Tseng, M.M. (1999). A methodology of developing product family architecture for mass customization. *Journal of Intelligent Manufacturing* **10,** 3-20.

Jiao, J. and Zhang, Y. (2005). Product portfolio identification based on association rule mining. *CAD Computer Aided Design* **37,** 149-172.

Jose, A. and Tollenaere, M. (2005). Modular and platform methods for product family design: Literature analysis. *Journal of Intelligent Manufacturing* **16,** 371-390.

Kalargeros, N. and Gao, J.X. (1998). QFD: Focusing on its simplification and easy computerization using fuzzy logic principles. *International Journal of Vehicle Design* **19,** 315-325.

Kim, K. (1998). Commonality and product design. *Thesis (PhD).* University of Illinois.

Kim, K.J., Moskowitz, H., Dhingra, A., and Evans, G. (2000). Fuzzy multicriteria models for quality function deployment. *European Journal of Operational Research* **121**, 504–518.

Koga, T. and Ohta, H. (2005). A new method of operating on fuzzy sets in quality function deployment. *Journal of Japan Industrial Management Association* **56,** 191-199.

Krishnan, V., Singh, R. and Tirupati, D. (1999). A model-based approach for planning and developing a family of technology-based products. *Manufacturing & Service Operations Management* **1,** 132-156.

Kuo, T.C., Chang, S.-H. and Huang, S.H. (2006). Environmentally conscious design by using fuzzy multi-attribute decision-making. *International Journal of Advanced Manufacturing Technology* **29,** 209-215.

Kusiak, A. (1999). *Engineering Design: Products, Processes and Systems*. San Diego: Academic Press.

Lee, H.L. and Tang, C.S. (1997). Modelling the costs and benefits of delayed product differentiation. *Management Science* **43,** 40-53.

Lin, Ch-T., and Chen, Ch-T. (2004). A Fuzzy-Logic-Based Approach for New Product Go/NoGo Decision at the Front End. *IEEE Transactions on Systems, Man, and Cybernetics Part A:Systems and Humans,* **34**, 132-142.

Messac, A., Martinez, M.P. and Simpson, T.W. (2002). Introduction of a product family penalty function using physical programming. *Journal of Mechanical Design, Transactions of the ASME* **124,** 164-172.

Meyer, M.H., Tertzakian, P. and Utterback, J.M. (1997). Metrics for managing research and development in the context of the product family. *Management Science* **43,** 88-111.

Mishra, A.K. (1999). Optimization models for component commonality in assemble-to-order systems. *Thesis (PhD).* University of Pittsburgh.

Moon, S.K., Kumara, S.R.T. and Simpson, T.W. (2006). Data mining and fuzzy clustering to support product family design. *2006 ASME International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, DETC2006.* Philadelphia, PA, United States: American Society of Mechanical Engineers, New York, NY.

Nanda, J., Thevenot, H.J., and Simpson, T.W. (2005). Product family representation and redesign: Increasing commonality using formal concept analysis. *DETC2005: ASME International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*. Long Beach, CA, United States: American Society of Mechanical Engineers, New York, NY.

Nepal, B.P. (2005). An integrated framework for modular product architecture. *Thesis (PhD)*. Wayne State University.

Park, J., and Simpson T.W. (2005). AN activity-based costing method for product family design in the early of development. *DETC2005: ASME International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*. Long Beach, CA, United States: American Society of Mechanical Engineers, New York, NY.

Pine II, J. (1993). Mass customization: The new frontier in business competition, *Boston, Massachisetts: Harvard Business School Press.* Boston, MA.

Rai, R. and Allada, V. (2003). Modular Product Family Design: Agent-Based Pareto-Optimization and Quality Loss Function-Based Post-Optimal Analysis. *International Journal of Production Research* **41**, 4075-4098.

Ramasamy, N.R. and Selladurai, V. (2004). Fuzzy logic approach to prioritise engineering characteristics in quality function deployment (FL-QFD). *International Journal of Quality Reliability Management*, **21,** 1012-1023.

Salvador, F., Forza, C. and Rungtusanatham, M. (2002). Modularity, product variety, production volume, and component sourcing: Theorizing beyond generic prescriptions. *Journal of Operations Management*, **20,** 549-575.

Sered, Y. and Reich, Y. (2006). Standardization and modularization driven by minimizing overall process effort. *CAD Computer Aided Design*, **38,** 405-416.

Shaowei, G. (2006). Discussion of the design philosophy and modified non-expert fuzzy set model for better product design. *Journal of Engineering Design*, **17,** 533-548.

Shen, L., Zhou, Z., Li, M., Zhao, W., Li, Y., Wu, M., and Zheng, J.J. (2005). Costumer oriented virtual cooperative product design. *9th International Conference on Computer Supported Cooperative Work in Design*, May 24-26 2005. Coventry, United Kingdom: Institute of Electrical and Electronics Engineers Computer Society, Piscataway, NJ.

Shipley, M.F., de Korvin, A. and Yoon, J.M. (2004). Fuzzy quality function deployment: determining the distributions of effort dedicated to technical change. *International Transactions in Operational Research* **11,** 293-307.

Siddique, Z. and Adupala, R. (2005). Product family architecture reasoning. *DETC2005: ASME International Design Engineering Technical Conferences and Computers and Information in Engineering Conference,* Sept. 24-28, 2005. Long Beach, CA, United States: American Society of Mechanical Engineers, New York, NY.

Siddique, Z. and Ninan, J.A. (2005). A grammatical approach to support real-time design of customized products. *DETC2005: ASME International Design Engineering Technical Conferences and Computers and Information in Engineering Conference,* Sept. 24-28, 2005. Long Beach, CA, United States: American Society of Mechanical Engineers, New York, NY.

Simpson, T.W. (2004). Product platform design and customization: Status and promise. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing: AIEDAM* **18**, 3-20.

Simpson, T.W., and Mistree, F. (1999). A Concept Exploration Method for Product Platform and Product Family Design. *Optimization in Industry II Conference - 1999,* June 6-11, 1999. Banff, AB, Canada: American Society of Mechanical Engineers. **2**, 371-386.

Simpson, T.W., Seepersad, C.C. and Mistree, F. (2001). Balancing commonality and performance within the concurrent design of multiple products in a product family. *Concurrent Engineering Research and Applications* **9,** 177-190.

Sivard, G. (2001). A generic information platform for product families. *Thesis (PhD).* Kungliga Tekniska Hogskolan (Sweden).

Sopadang, A., Cho, B.R., and Leonard, M.S. (2001-2002). Development of a scaling factor identification method using design of experiments for product-family-based product and process design. *Quality Engineering* **14,** 319-29.

Su, J.C.P., Chang, Y.L. and Ferguson, M. (2005). Evaluation of postponement structures to accommodate mass customization. *Coordinating Product Design, Process Design and Supply Chain Design Decisions: Journal of Operations Management* **23,** 305-318.

Thevenot, H.J., Nanda, J. and Simpson, T.W. (2007). Redesigning product families using heuristics and shared ontological component information. *Proceedings of the 2006 IEEE International Conference on Information Reuse and Integration,* Waikoloa Village, HI.

Thevenot, H.J., Nanda, J. and Simpson, T.W. (2005). A methodology to support product family redesign using a genetic algorithm and commonality indices. *DETC2005: ASME International Design Engineering Technical Conferences and Computers and Information in Engineering Conference,* Sep 24-28 2005. Long Beach, CA, United States: American Society of Mechanical Engineers, New York, NY.

Thevenot, H.J., and Simpson, T.W. (2004). A comparison of commonality indices for product family design. 2004 ASME Design Engineering Technical Conferences *and Computers and Information in Engineering Conference,* Sept. 28-Oct. 2, 2004. Salt Lake City, UT, United States: American Society of Mechanical Engineers, New York, NY.

Thevenot, H.J. and Simpson, T.W. (2006). A comprehensive metric for evaluating component commonality in a product family. *2006 ASME International Design Engineering Technical Conferences and Computers and Information In Engineering Conference, DETC2006,* Sept. 10-13, 2006. Philadelphia, PA, United States: American Society of Mechanical Engineers, New York, NY.

Thevenot, H.J. (2006). A method for product family redesign based on component commonality analysis*.* *Thesis (PhD)* Pennsylvania State University.

Van Hoek, R.I. (2001). The rediscovery of postponement a literature review and directions for research. *Journal of Operations Management* **19,** 161-184.

Vanegas, L.V. and Labib, A.W. (2001a). A fuzzy quality function deployment (FQFD) model for deriving optimum targets. *International Journal of Production Research* **39,** 99-120.

Vanegas, L.V. and Labib, A.W. (2001b). Application of new fuzzy-weighted average (NFWA) method to engineering design evaluation. *International Journal of Production Research* **39,** 1147-1172.

Vanegas, L.V. and Labib, A.W. (2005). Fuzzy approaches to evaluation in engineering design. Journal of Mechanical Design, Transactions of the ASME 127, 24-33.

Wang, H.J., Zhang, Q. and Zhao, T.T. (2005). A SA-based method for developing modular product family. *International Conference on Machine Learning and Cybernetics, ICMLC 2005,* Aug. 18-21, 2005. Guangzhou, China: Institute of Electrical and Electronics Engineers Computer Society, Piscataway, NJ.

Wang, J. (1999). Fuzzy outranking approach to prioritize design requirements in quality function deployment. *International Journal of Production Research* **37,** 899-916.

Wijnstra, J.G. (2005). Classifying product families using platform coverage and variation mechanisms. *Software - Practice and Experience* **35,** 413-444.

Xianghui, M., Zuhua, J., and Gq, H. (2007). On the module identification for product family development. *International Journal of Advanced Manufacturing Technology* **35**, 1-2, 26-40.

Zha, X.F., Sriram, R.D. and Lu, W.F. (2004). Evaluation and selection in product design for mass customization: A knowledge decision support approach. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing: AIEDAM* **18,** 87-109.

Zhang, K. (2006). System analysis of new product family development selection. *Wuhan Ligong Daxue Xuebao/Journal of Wuhan University of Technology* **28,** 177-180.

Zhang, W.Y., Tor, S.Y. and Britton, G.A. (2006). Managing modularity in product family design with functional modeling. *International Journal of Advanced Manufacturing Technology* **30,** 579-588.

List of tables

Table 1 Classification of developed works related to product family development

Publications	Consideration of customer desires	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	Approach	Framework	Method	Methodology	Model	Algorithm	Fuzzy application
Agard & Kusiak 2004a						*						*			*			*			
Agard & Kusiak 2004b			*			*												*			
Agard &Tollenaere 2003			*			*			*		*	*						*	*		
Anderson 1997		*	*	*	*	*			*			*			*						
Biao Yang *et al*. 2004						*					*					*					
Burgess 1997				*		*													*		
Buyukozkan & Feyzioglu 2004a		*	*												*						*
Buyukozkan & Feyzioglu 2004b															*						*
Callahan 2006			*							*		*							*		
Chen *et al*. 2004a	*	*	*														*				*
Chen & Weng 2006		*	*																*		*
Chen 1999																			*		*
Chen *et al*. 2005	*	*	*												*				*		*
Chen *et al*. 2006	*	*	*														*				*
Chen *et al*. 2004b	*	*													*				*		*
Da Cunha & Agard 2005				*					*											*	
Da Cunha *et al*. 2007				*		*			*											*	
Dahmus *et al*. 2001		*	*		*		*		*						*						
Dai 2005							*	*				*			*		*				*
Dai & Scott, 2006			*				*					*			*		*				
Deciu *et al*. 2005			*			*									*				*		*
Dong *et al*. 2001		*										*				*	*				*
Du, X. 2000			*		*	*		*	*						*						
Erens & Verhulst 1997	*	*	*		*	*			*												
Ertay & Kahraman 2007	*	*	*																		*
Feitzinger & Lee 1997						*					*										
Fellini *et al*. 2005							*	*				*			*						
Fellini 2003							*	*	*			*						*			
Feyzioglu & Büyüközkan 2006																*					*
Fung *et al*. 2002	*	*	*																*		*
Fung *et al*. 1999	*	*													*						*
Gonzalez-Zugasti *et al*. 2001			*				*					*							*		
Gonzalez-Zugasti *et al*. 2000					*		*								*		*				
Gungor & Arikan 2000																	*				*
Gupta & Krishnan 1998				*								*			*			*		*	
Hanumaiah *et al*. 2006	*	*		*											*	*		*			
He & Kusiak 1997				*					*						*						
Hsiao & Liu 2005												*			*						
Huang *et al*. 2005						*	*	*	*	*	*										
Jiang & Chi-Hsing 2001				*															*		*
Jiang & Yan 2003				*			*					*									
Jiao & Tseng 2000				*		*		*				*									
Jiao *et al*. 1998		*				*						*			*						
Jiao 1998		*	*	*	*	*	*	*	*	*						*		*			*
Jiao & Tseng 1998			*															*			*
Jiao & Tseng 1999					*	*												*			*
Jiao & Zhang 2005	*	*	*	*		*												*			*
Jose & Tollenaere 2005			*				*		*			*									
Kalargeros & Gao 1998	*	*															*				*
Kim 1998			*					*							*						
Kim *et al*. 2000	*	*	*																*		*
Koga & Ohta 2005	*	*															*				*
Krishnan *et al*. 1999							*					*							*		

Table 1 Classification of developed works related to product family development (continued)

Publications	Consideration of customer desires	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	Approach	Framework	Method	Methodology	Model	Algorithm	Fuzzy application
Kuo *et al*. 2006			*														*				*
Kusiak 1999			*	*					*												
Lee & Tang 1997						*					*								*		
Lin & Chen 2004		*	*												*						*
Messac *et al*. 2002			*				*	*		*		*			*						
Meyer *et al*. 1997							*					*					*				
Mishra 1999								*											*		
Moon *et al*. 2006						*	*		*			*					*				*
Nanda *et al*. 2005								*				*		*	*	*		*			
Nepal 2005			*	*					*							*		*			*
Park & Simpson 2005				*								*				*	*				
Pine II 1992		*	*			*			*												
Rai & Allada 2003									*			*			*	*	*				
Ramasamy & Selladurai 2004	*	*															*				*
Salvador *et al*. 2002		*	*		*	*			*			*									
Sered & Reich 2006				*		*	*		*			*					*				
Shaowei 2006			*														*		*		*
Shen *et al*. 2005		*	*																		
Shipley *et al*. 2004	*	*	*																*		*
Siddique & Adupala 2005				*	*							*				*	*				
Siddique & Ninan 2005			*			*									*	*					
Simpson 2004						*	*					*									
Simpson & 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 & Simpson 2004							*	*				*									
Thevenot & Simpson 2006			*					*				*	*				*				
Thevenot 2006			*					*						*			*				
Van Hoek 2001											*					*					
Vanegas & Labib 2001	*	*															*				*
Vanegas & Labib 2001b			*														*				*
Vanegas & Labib 2005			*												*						*
Wang *et al*. 2005									*			*					*				*
Wang 1999	*	*													*						*
Wijnstra 2005						*	*					*									
Xianghui *et al*. 2007									*			*						*	*		
Zha *et al*. 2004			*			*							*		*	*			*		*
Zhang 2006												*			*						*
Zhang *et al*. 2006									*			*			*						

Table 2 Fuzzy logic applications into Product Family Development

Fuzzy logic tools	Product family development topics												
	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		*						*			*		
Fuzzy clustering	*	*	*	*	*	*		*			*	*	
Fuzzy goal programming	*	*						*					
Fuzzy inference	*	*											
Fuzzy multiple attribute decision-makings		*	*		*								
Fuzzy numbers	*	*											
Fuzzy optimization	*	*									*		
Fuzzy outranking	*	*											
Fuzzy preference			*	*	*	*	*	*	*			*	
Fuzzy product knowledge		*	*					*					
Fuzzy quality function deployment model	*	*											
Fuzzy ranking	*	*	*	*	*	*	*	*	*			*	
Fuzzy regression	*	*											
Fuzzy weighted average	*	*											

Table 3 Classification of potential fuzzy logic applications in product family development

PFD 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.

List of figures

Figure 1 Overview of the product family development

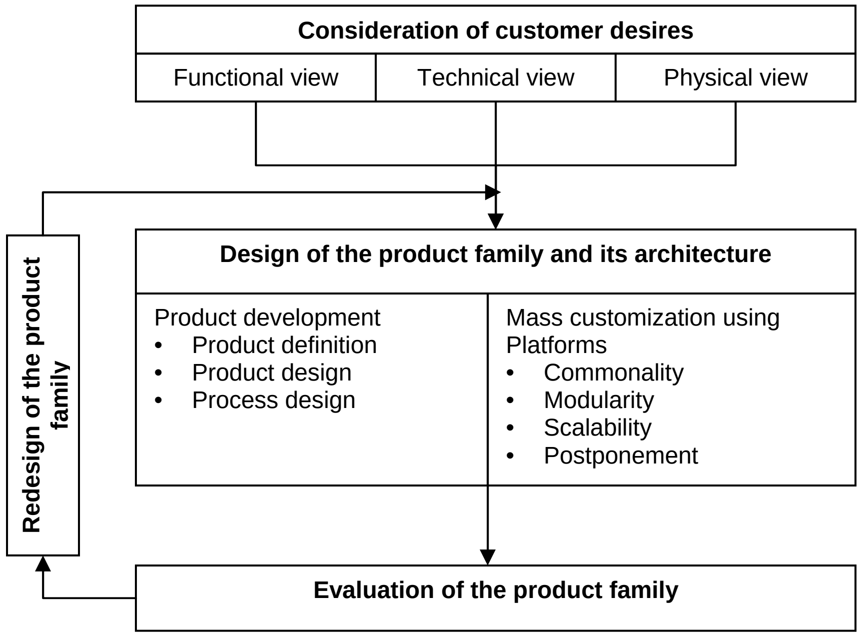

Figure 1 Overview of the product family development