Fuzzy product configuration by replacing product features*

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Abstract

Product configuration provides an important opportunity for taking advantage of a number of the benefits of mass customization. Mass customization is aimed at developing a wide external variety of products to satisfy individual customers, with managed internal diversity to prevent cost proliferation. In this context, we propose an iterative product configuration method applying fuzzy logic which is designed to improve product configuration by replacing features which are of less interest to the customer with features the customer prefers. Fuzzy preference relations are used to evaluate the various configurations through the iterative product configuration process. To measure the level of customer satisfaction for each configuration, a satisfaction rate is also proposed. The integration of fuzzy preference relations and an adapted pseudo-order preference model constitute the basis for the proposed configuration method. An illustrative example is provided to show the applicability and practicality of the method.

Key words: product configuration, fuzzy preference, fuzzy ranking, fuzzy sets, mass customization.

1 Introduction

Manufacturers today are faced with fierce competition in the global marketplace, and, as a result, try to develop better and more accessible products for their customers. Their objective is to satisfy customer wants and needs without sacrificing efficiency, effectiveness, and profit [1]. Mass customization provides a way to achieve this, and product configuration is an important key to taking advantage of mass customization in the product development process. Many strategies have been proposed to make mass customization a reality, including modular design, delayed differentiation, platforms, modularity, and commonality, among others. Some of these strategies include fuzzy logic, in order to access more accurate information for their processes.

Fuzzy logic has the capacity to consider vague information related to human decisions. Recently, it has been applied in fields like decision-making and product development. In this vein, we propose an iterative method here for product configuration in which the fuzzy preference relation is applied to evaluating the relationship between different variables. A satisfaction rate is calculated to measure the change in the level of customer satisfaction as a result of the upgrade in product configuration.

This paper is organized as follows: section 2 presents a literature review focusing on product development, product configuration, and fuzzy product configuration; section 3 describes the proposed method for product configuration and a detailed illustrative application; and section 4 concludes the paper and suggests some future research directions.

2 Literature review

2.1 Mass customization

During the last two decades, mass customization has been adopted by many companies to produce more variety of products but at the same time keep low costs by the standardization of components and processes. According to [2] mass customization plays an important role for the operation of many companies, because products are pulled through the plant based on customer needs making necessary more flexible manufacturing processes to respond to market changes.

A great deal of research has been carried out towards the improvement of the product design from a mass customization viewpoint. [3] proposed an analytical framework to guide companies in the development of an explicit mass customization strategy, and even if they considered that every company is unique four areas should be considered in every strategy, these are: customer sensitivity, process amenability, competitive environment, and organizational readiness. Another framework for mass customization by developing product family architecture was presented by [4] to deal with tradeoffs between diversity of customer requirements and reusability of design and process capabilities. Six factors for successful mass customization systems were identified by [5] these include: (1) customer demand for variety and customization must exist, (2) market conditions must be appropriate, (3) value chain should be ready, (4) technology must be available, (5) products should be customizable, and (6) knowledge must be shared. [6] presented an analysis to identify customization requirements to provide a commercial configuration knowledge base by applying constraint based generic modeling elements for customizable industrial product.

Basically, two strategies have been developed to achieve the mass customization; modular design, and delayed differentiation [7], but more recently other strategies such as platforms and product families are being widely developed as well. [8] proposed a method to design choice menus for mass customization to enable customers to co-design products or services based on their own preferences.

2.2 Product development

According to [9], product development can be divided into three consecutive stages: product definition, product design, and process design. *Product definition* is mapping the customer needs in the customer domain to functional requirements in the functional domain, and is characterized by the portfolio of products that represents the target of mass customization. *Product design* is mapping the functional requirements in the functional domain to design parameters in the physical domain, these stages are highly supported by QFD, and is an engineering process which involves iterative and complex decision making activities. This process usually starts with the definition of wants and needs, proceeds through the search for an appropriate or optimal solution, and ends with a detailed description of the product design [10]. An important number of works have been carried out in the effort to improve the product design process. Some of these works, such as [10], [11], [12], and [13] are 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. *Process design* is mapping the design parameters in the physical domain to process variables in the process domain. This process is a very important aspect of product development, because a careful design of the product assembly sequence helps to create generic subassemblies, which reduce subassembly proliferation and the cost of offering product variety [14]. [15] presented a model to evaluate the production cost by considering the production cost associated with manufacturing activities. Also, [16] proposed a simulated annealing algorithm to address the problem of module design, focusing on minimizing mean assembly time.

An interested approach for new product development has been proposed by [17] intended to improve the decision making process by applying fuzzy logic to shape the decision into the process. In the same way, [18] presented an integrated approach to evaluate several conceptual design alternatives during the new product development process by the application of the analytic hierarchy process. Also, [19] proposed a framework for the evaluation of new product developments, in this case by using artificial intelligence and fuzzy logic aiming to make appropriate decisions and accelerate the evaluation process.

2.3 Product configuration

In this work, we consider that product configuration is also an important stage in product development, because, during this process, it is possible to design products which are more strongly based on customer requirements and also to develop a large variety of products taking into account a company's constraints and limitations. A considerable amount of work has been presented addressing the issue, some of it considered later in this section. The first part considers literature related to product configuration in a general way, and the second considers the application of fuzzy logic to this issue.

The configuration of a product is the representation of the logical and spatial arrangement of the various parts/subassemblies of that product with respect to one another considering the various kinds of constraints (e.g. technical, commercial) imposed on it [20]. Product configuration is an important area of opportunity for developing competitive products and is strongly correlated to mass customization because of the scope it provides for developing a large variety of products within the constraints and limitations of the manufacturer.

Various approaches, models, and methods have been developed to achieve this. One of these is an approach designed to find configurations that match industry requirements, and consists of three steps: product configuration, bill of materials configuration, and routing configuration [21]. Another, which applies a design structure matrix to show the interaction flow between configuration elements, has been proposed to analyze the product configuration [22], and was designed to evaluate product configuration from the point of view of sales. Other approaches attempt to optimize the product configuration process, such as one based on a multi-objective genetic algorithm, which optimizes the design of the product configuration and focuses on the problem of combination explosion [23]. The models that have been proposed include a decision model to select concepts in product configuration by considering the interactions of the concepts caused by their constraints and functional couplings [24]. Also, an interesting application of the case-based reasoning algorithm has been presented to reduce the time and cost of the design process by generating the right bill of materials from the beginning of the product design process [25]. Similarly, a methodology and architecture designed to incorporate the requirement configuration and the engineering configuration into the configuration design process has been proposed [26]. This work integrates data mining approaches, such as fuzzy clustering and association rule mining to link customer groups with clusters of product specifications. Another product configuration method based on the multi-layer evolution model has been proposed as well [27], which considers the features of the customer requirements and the product configuration design analysis as performed in three layers: function, qualification, and structure, and also considers fuzzy and incomplete customer requirements. Even though fuzzy logic has been applied in some of the above work, these applications remain partial. In the following section, we analyze some work in which fuzzy logic is applied to product configuration in a more significant way.

2.4 Fuzzy product configuration

The application of fuzzy logic has been increasing in recent decades, and it has been used in interesting ways in issues related to product configuration, such as concept evaluation, design requirements, company capabilities, and customer requirements. Some of these uses are explained below.

A fuzzy ranking methodology has been developed to evaluate a conceptual design in the context of mass customization [28], in which a set of alternatives is evaluated and one is selected that can satisfy customer needs, considering the design requirements and technical capabilities of the company. Tsai and Hsiao [29] developed a method to translate customer needs into applicable alternatives to satisfy customer desires, applying fuzzy inference to establish the relationship between customer needs and product alternatives. Also, an integrated approach to designing configurable products based on multiple fuzzy models has been proposed [30], fuzzy methods such as fuzzy product specification, fuzzy functional network, fuzzy physical solution, and the fuzzy constraint model to translate the customer specifications into physical solutions dealing with various forms of uncertainty, such as imprecision, randomness, fuzziness, ambiguity, and incompleteness. Another approach concerns product-level configuration [31], which considers uncertain and fuzzy requirements provided by customers by applying fuzzy multi-attribute decision-making. More recently, this approach has been presented as a method that can be used in a product data management system and on e-commerce websites, making it possible to obtain the customer's preferred product according to the utility value with respect to the whole set of product attributes [32]. In the same context, an iterative method applying fuzzy logic is proposed in the following section for product configuration with the objective of contributing to an increase in customer satisfaction by offering products that more closely match customer desires.

3 Iterative product configuration with fuzzy logic

3.1 General configuration process

This paper proposes a method for fuzzy product configuration, where the fundamental issue is the analysis of the fuzzy preference relation between some selected product features and customer preferences. Figure 1 depicts the proposed method for product configuration.

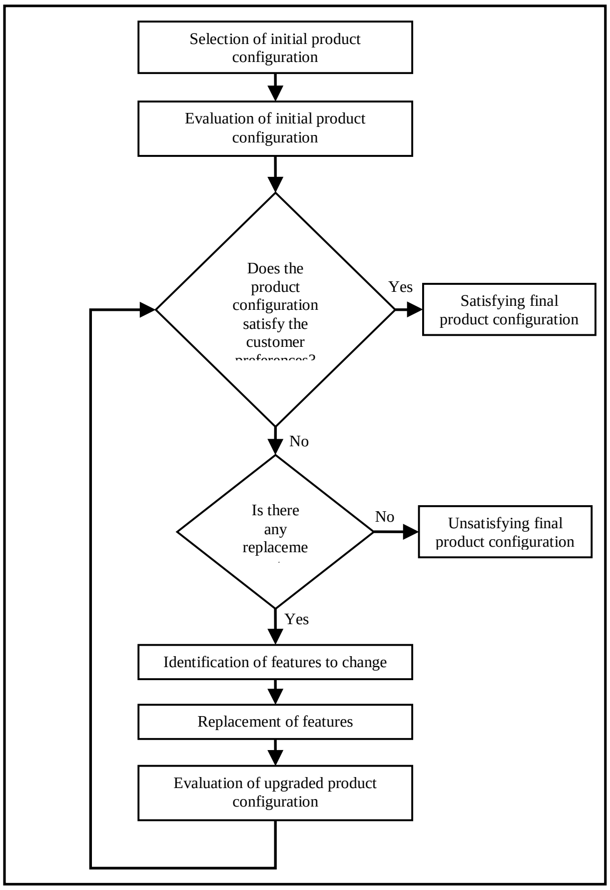

Fig. 1. Flow of the product configuration method

A brief description of each phase depicted in Figure 1 is given below.

Phase 1. Selection of the initial product configuration.

This phase begins with the selection of an initial product configuration which conforms to the cheapest alternative for each feature. All the alternatives should be ranked according to a cost-benefit analysis [33], [34], which makes it possible to order them in such a way as to identify which feature alternatives outperform the others (F_{ij+1} outperforms F_{ij}). For example, F_{11} means that feature F_1 has the lower evaluation, according to the cost-benefit analysis for that feature. In other words, of the two, F_{11} and F_{12}, F_{12} outperforms F_{11}.

Phase 2. Evaluation of the initial product configuration.

Because the initial product configuration is formed by the lowest-valued alternative for each product feature, it is necessary to evaluate whether or not this minimum is enough to satisfy the preferences of a customer. To do that, a four-step method is proposed in this work: (1) market and technical evaluation of product features, (2) general prioritization of features, (3) customer preference consideration for each feature, and (4) evaluation of product configuration. Most of time, the initial product configuration does not satisfy customer expectations, and so this configuration must be upgraded by replacing some features for others that can improve customer satisfaction.

Phase 3. Evaluation of the satisfaction of customer preferences.

After the evaluation of the initial product configuration, it is necessary to measure the level of customer satisfaction (CS), comparing it with a minimum level of customer satisfaction defined between the customer and the suppliers at the beginning of the configuration process. To measure the level of customer satisfaction, a CS rate is proposed in this work. This metric should be applied every iteration to evaluate the level of customer satisfaction with respect to each product configuration (iteration). If the CS is less than a target level of customer satisfaction, then a new iteration should be performed until the CS is equal to or greater than the defined minimum CS level .

Phase 4. Verification of the replacement possibilities.

If the initial configuration does not satisfy customer requirements, potential improvements must be identified through an analysis of the replacement options. To perform this verification, all the alternatives for each feature should be ranked according to a cost-benefit analysis, as indicated for phase 1. All the alternatives have to be listed hierarchically, using the notation A_{ij}, where i identifies the product feature and j identifies its hierarchical position on the list. For example, A_{22} means that this alternative is the second-most valued alternative of feature 2. This verification needs to be performed until each product feature satisfies the CS evaluation.

Phase 5. Identification of the features to change.

If the evaluation of the product feature currently present in the product configuration is less than that of the alternative previously in the configuration (A_{ij}), then there is an opportunity to replace that feature. This evaluation needs to be performed for each feature in need of replacement for upgrading the product configuration.

Phase 6. Replacement of the features.

Once the feature alternatives to be replaced have been identified, they all need to be replaced at the same iteration.

Phase 7. Evaluation of the upgraded product configuration.

To evaluate each upgraded product configuration, step 4 of phase 2 needs to be performed each iteration. Then, the new product configuration is evaluated and compared with its CS level to confirm whether or not it satisfies the customer preferences. A satisfactory product configuration is obtained if the minimum CS level defined in phase 3 is met; otherwise an unsatisfactory product configuration is obtained.

3.2 Detailed product configuration and application

Let us suppose that a laptop manufacturer aims to customize its production according to customer preferences by selecting from a list of configurable key features in an attempt to increase the compatibility between their products and those preferences, considering various criteria such as manufacturability, modularity, commonality, compatibility, functionality, and so on.

Suppose that the following five selected features are the most relevant for the laptop configuration: processor, operating system, display, memory, and hard drive. All these features and their alternatives are illustrated in Figure 2. There are three alternatives for the processor (F_{11}, F_{12}, F_{13}), two for the operating system (F_{21}, F_{22}), six for the display (F_{31},…, F_{36}), four for memory (F_{41},…, F_{44}), and six for the hard drive (F_{51},…,F_{56}). Suppose that a cost-benefit analysis has been performed to prioritize the various alternatives for each feature based on value, and the versions are such that F_{ij+1} outperforms F_{ij}.

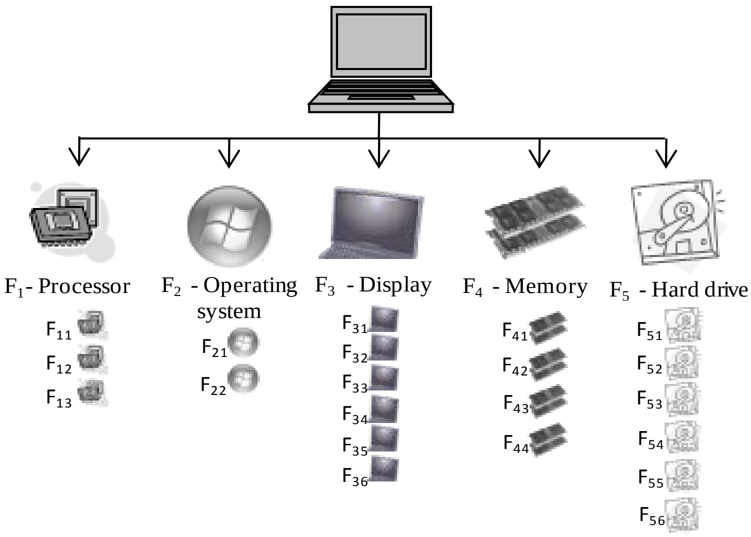

Fig. 2. Configurable features

Phase 1. Selection of the initial product configuration

In our work here, the initial product configuration consists of the lowest-ranking option for each feature; that is, the lowest-ranking option in the hierarchical list of alternatives per feature (F_{11}, F_{21}, F_{31}, F_{41}, and F_{51}) (see Figure 3). This configuration constitutes the base on which to start the iterative process of feature substitution to reach the level of satisfaction demanded by the customer.

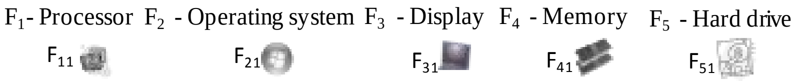

Fig. 3. Features of the initial product configuration

Phase 2. Evaluation of the initial product configuration

The selection of the best product for a customer based on a set of preferences is made possible by applying a method adapted from [35] to determine the best product configuration. It consists of four steps, as follows:

(1) *Market and technical evaluation of product features.* This evaluation can generally be performed by the industry concerned from specialized sources. If these are not available, a survey administered by experts can be used instead. This information must then be represented in fuzzy numbers. This fuzzification process should be performed by those with sufficient knowledge of the industry in question.

(2) *General prioritization of features.* A customer survey can be used to obtain a general feature prioritization for the type of product in question.

(3) *Customer preference consideration per each feature.* By posing a few questions phrased in colloquial or linguistic terms, it is possible to arrive at the customer preference for each feature. All these preferences should be represented by fuzzy numbers based on the general prioritization scale.

(4) *Evaluation of product configuration.* Let R(A,B) be the fuzzy preference relation and μR(A, B) the membership function representation of R(A,B). According to [36], if the membership degree μR(A,B) is equal to 0.5, then A and B are indifferent.

To calculate the fuzzy preference relation R(A,B), we apply a method proposed by [36] and adapted by [37]. Let A and B be two fuzzy numbers which are convex and normal. If there exists an area of overlap between fuzzy numbers A and B (intersection between A and B), then the overlap area is defined as the indifference area. If there exist one or more non-overlap areas between fuzzy numbers A and B, then, for each non-overlap area, either A dominates B or B dominates A (see Figure 4).

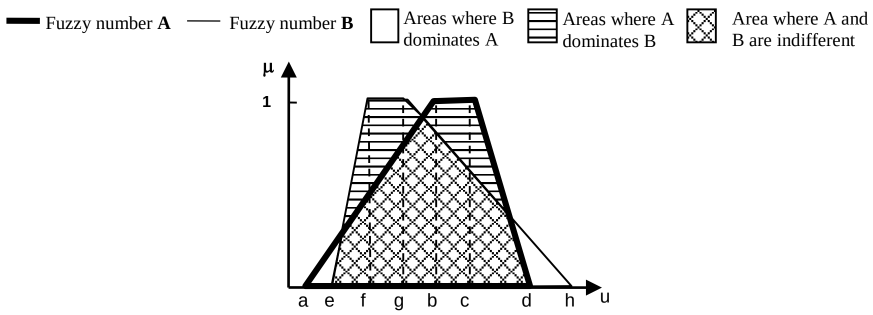

Fig. 4. Dominance and indifference between A and B

If A and B are two normal fuzzy numbers, then the fuzzy preference relations R(A,B) or R(B,A) could be obtained using the following equations:

$$R(A,B) = [D(A,B) + I(A,B)]/[A(A) + A(B)] \tag{1}$$

where D(A,B) is the area in which A dominates B, D(B,A) is the area in which B dominates A, I(A,B) is the area in which A and B are indifferent, and A(A) and A(B) are the areas of A and B respectively.

Since R(A,B) and R(B,A) are reciprocal, that is, R(A, B) + R(B, A) = 1, then

$$R(B,A) = 1 - R(A,B) \tag{2}$$

R(A,B) and R(B,A) are interpreted as the degree to which A is preferred to B and B is preferred to A respectively.

A complete depiction of the entire situation possible between two normal fuzzy numbers has been developed by [38]. This depiction is supported by twenty-nine cases, as depicted in Figure 4, which is enough to consider all the possible situations between two normal and convex fuzzy numbers with different membership functions, such as trapezoidal, triangular, or rectangular.

To evaluate whether or not the initial product configuration satisfies the customer preference, the pseudo-order preference model can be applied, which has already been used in the literature several times [39], [40], [41], [17]. Let the fuzzy preference relation between two ideas A and B for criterion i be obtained by the pairwise comparison of $g_i(A)$ and $g_i(B)$ represented by fuzzy numbers. Three types of preference relation are defined in terms of the fuzzy preference relations between these two alternatives $\forall a, b \in A$ and $i \in C$, as follows:

$$AP_iB \Leftrightarrow P(g_i(A), g_i(B)) - P(g_i(B), g_i(A)) > p_i,$$
$$AQ_iB \Leftrightarrow P(g_i(A), g_i(B)) - P(g_i(B), g_i(A)) \leq p_i,$$
$$AI_iB \Leftrightarrow \left|P(g_i(A), g_i(B)) - P(g_i(B), g_i(A))\right| \leq q_i,$$

where P_i and Q_i depict a strict and a weak preference respectively, and I_i depicts an indifference relation. The preference threshold p_i and the indifference threshold q_i (defined by common sense [39]) are used to discriminate between the indifference, strict preference, and weak preference of two alternatives for criterion i. The three possible types of preference should be read as follows:

- AP_iB, where there is a strict preference between ideas A and B (idea A is strictly preferred to idea B for criterion i)
- AQ_iB, where there is a weak preference between ideas A and B (idea A is weakly preferred to idea B for criterion i)
- AI_iB, where there is no difference between ideas A and B (idea A is not different from idea B for criterion i).

If A represents the product feature and B represents the customer preference, the above types of preference can be applied as follows: AI_iB represents the case where the product feature satisfies the customer preferences fairly well. This situation constitutes the principal target in this work. AP_iB and AQ_iB represent the cases where product feature (A) exceeds customer preferences (B), and BP_iA and BQ_iA the cases where the product features fall short of the customer preferences. These latter situations are outside the scope of this work.

If the fuzzy preference relation for all the pairwise combinations of product features and customer preferences corresponds to the case aI_ib, this means that they can all be part of a possible product configuration, if that case satisfies a fixed percentage of customer satisfaction.

Let us apply all these steps to evaluate the initial product configuration:

(1) *Market and technical evaluation of product features*. Let us suppose that a group of experts in the industry in question evaluated each feature. The values for each are represented by fuzzy numbers as follows:

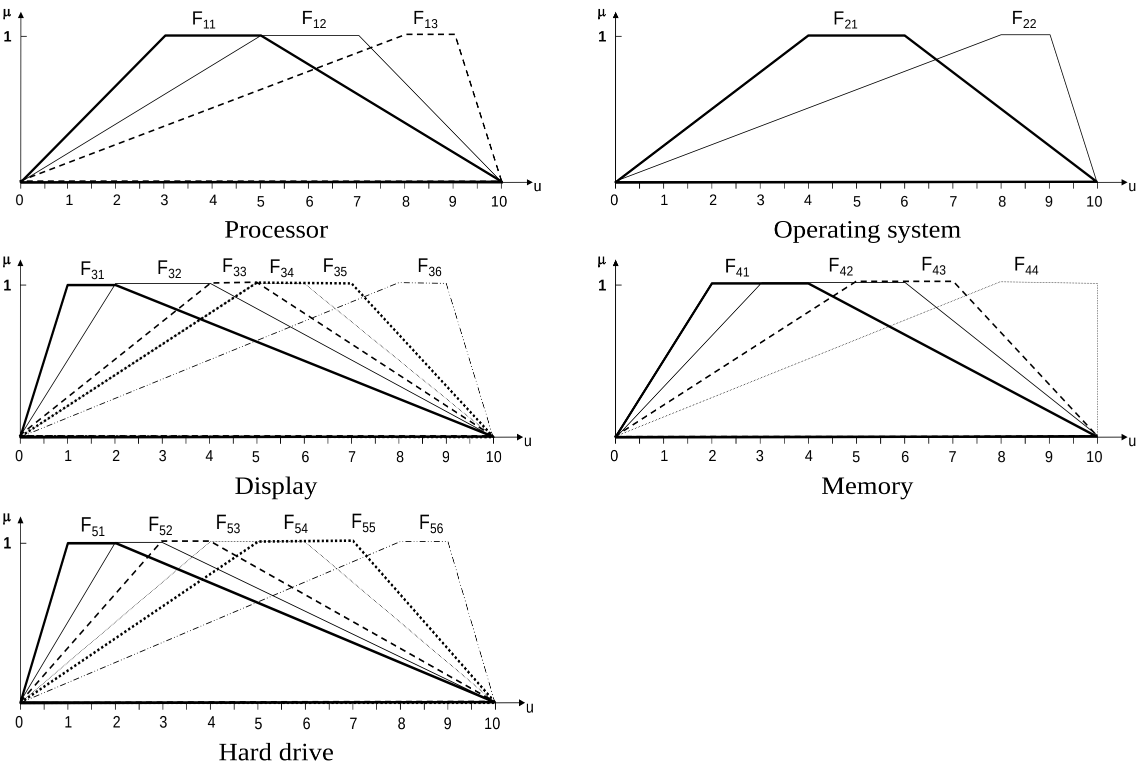

Fig. 5. Customer satisfaction based on a feature's cost-benefit relation

Figure 5 depicts the fuzzy representation of the cost-benefit relation evaluation for each of the selected product's features.

(2) General prioritization of features. In the same way, a general feature prioritization has been created by using a survey to define customer preferences relating to the product in question. These preferences are expressed in colloquial terms, such as *not important*, *less important*, *moderately important*, *important*, and *highly important*, as is depicted in Figure 6.

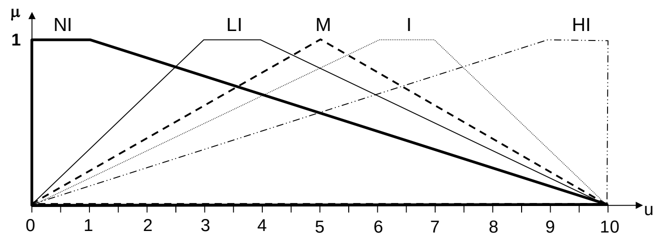

Fig. 6. A feature's general prioritization

The respective fuzzy number for each level of the general prioritization scale shown in Figure 6 is listed in Table 1.

Table 1 Feature's prioritization representation

Level of prioritization	Fuzzy number representation
HI- 'Highly Important'	[0 9 10 10]
I- 'Important'	[0 6 7 10]
M- 'Moderately important	[0 5 5 10]
LI- 'Less Important'	[0 3 4 10]
NI- 'Not Important'	[0 0 1 10]

(3) Customer preference consideration for each feature. The customer preferences for each feature are listed in Table 2, and these preferences are expressed in linguistic or colloquial terms.

Table 2 Feature preferences per customer

Product features	Customer preference per feature		
	Customer 1	Customer 2	Customer 3
F_1. Processor	HI	HI	LI
F_2. Operating system	HI	HI	LI
F_3. Display	HI	NI	NI
F_4. Memory	HI	HI	LI
F_5. Hard drive	HI	NI	HI

(4) *Evaluation of product configuration.* The issue of the fuzzy preference relation is fundamental to the evaluation process, and equation 1 can be applied to calculate such a relation. Let us consider R(A, B) as the fuzzy preference relation between product features (A) and customer preferences (B). If the membership function μR(A, B) is equal to 0.5, then there is no significant difference between them. This situation is displayed in Table 3, where F_{ij} represents the set of features (i) for each configuration (j), and C_{ki} represents the set of customer preferences (k) for each feature (i). If the fuzzy preference relation $R(F_{ij}\backslash C_{ki})$ for all the pairwise combinations between F_{ij} and C_{ki} are equal to 0.5, then an ideal product configuration is obtained corresponding to the case where all the customer preferences are satisfied by the set of product features in such a product configuration.

Table 3 Indifference fuzzy preference

$F_{ij}\backslash C_{ki}$	C_{ki} - $F_{ij}I_iC_{ki}$	C_{ki+1} - $F_{ij+1}I_iC_{ki+1}$	C_{ki+2} - $F_{ij+2}I_iC_{ki+2}$	C_{ki+3} - $F_{ij+3}I_iC_{ki+3}$	C_{ki+4} - $F_{ij+4}I_iC_{ki+4}$
F_{ij}	0.5 - $F_{ij}I_iC_{ki}$				
F_{ij+1}		0.5 - $F_{ij+1}I_iC_{ki+1}$			
F_{ij+2}			0.5 - $F_{ij+2}I_iC_{ki+2}$		
F_{ij+3}				0.5 - $F_{ij+3}I_iC_{ki+3}$	
F_{ij+4}					0.5 - $F_{ij+4}I_iC_{ki+4}$

From Appendix 1a, it is possible to obtain the fuzzy preferences relation and the type of preference of each pairwise combination among all the product features and customer preferences of the initial product configuration for customer 1 (see Table 4). From appendices 1b and 1c, the same information can be obtained for customers 2 and 3 respectively (see Tables 5 and 6).

Table 4 Fuzzy preference relations of the initial product configuration for customer 1

$F_{ij}\backslash C_{ki}$ – Type of relationship	C_{11}	C_{12}	C_{13}	C_{14}	C_{15}
F_{11}	0.3106 – $C_{11}Q_1F_{11}$				
F_{21}		0.3344 – $C_{12}Q_2F_{21}$			
F_{31}			0.2674 – $C_{13}Q_3F_{31}$		
F_{41}				0.2899 – $C_{14}Q_4F_{41}$	
F_{51}					0.2674 – $C_{15}Q_5F_{51}$

In Table 4, the fuzzy preference relation between F_{11} and C_{11}, $R(F_{11}, C_{11})$, is equal to 0.3106, and by reciprocity $R(C_{11},F_{11})$ is equal to 0.6894. So, the type of relationship between C_{11} and F_{11} ($C_{11}Q_1F_{11}$) means that the product feature falls short of the customer preference for feature 1 (F_1). The same situation is presented for the rest of the features in that product configuration for customer 1, that is, a better product configuration is needed, and all the features should be changed to create a better alternative, if this is possible.

Table 5 Fuzzy preference relations of the initial product configuration for customer 2

$F_{ij}\backslash C_{ki}$ – Type of relationship	C_{21}	C_{22}	C_{23}	C_{24}	C_{25}
F_{11}	0.3106 – $C_{21}Q_1F_{11}$				
F_{21}		0.3344 – $C_{22}Q_2F_{21}$			
F_{31}			**0.5455 – $C_{23}I_3F_{31}$**		
F_{41}				0.2899 – $C_{24}Q_4F_{41}$	
F_{51}					**0.5455 – $C_{25}I_5F_{51}$**

In Table 5, we can note that,the fuzzy preferences for F_3 and F_5 are bigger than 0.5, and their types of relationship (**$C_{23}I_3F_{31}$** and **$C_{25}I_5F_{51}$**) correspond to the case where these product features satisfy the customer preferences for such features. For the rest of the features (F_1, F_2, and F_4), neither the fuzzy preference relation nor the type of relationship corresponds to the previous case, so a better product configuration needs to be found, if possible.

Table 6 Fuzzy preference relations of the initial product configuration for customer 3

$F_{ij}\backslash C_{ki}$ – Type of relationship	C_{31}	C_{32}	C_{33}	C_{34}	C_{35}
F_{11}	**0.5217 – $C_{31}I_1F_{11}$**				
F_{21}		**0.5652 – $C_{32}I_2F_{21}$**			
F_{31}			**0.5455 – $C_{33}I_3F_{31}$**		
F_{41}				**0.4783 – $C_{34}I_4F_{41}$**	
F_{51}					0.2674 – $C_{35}Q_5F_{51}$

Similarly, in Table 6, we can note that the fuzzy preferences for F_1, F_2, and F_3 are bigger than 0.5, and their types of relationship (**$C_{31}I_1F_{11}$, $C_{32}I_2F_{21}$, $C_{33}I_3F_{31}$**) correspond to the case where these product features satisfy the customer preferences for these features. The fuzzy preference for feature F_4 is lower than 0.5, but its type of relationship corresponds to the case where that feature alternative satisfies the preferences of the customer for this feature. For feature F_5, neither the fuzzy preference relation nor the type of relationship corresponds to the previous case, making it necessary to find a better product configuration by changing this feature (F_5) for a better one, if possible.

Phase 3. Evaluation of the satisfaction of customer preferences

Customer satisfaction (CS) is evaluated using equation 4:

$$CS_j = \left[\frac{\sum_{j=1}^{m} R(A_{ij}, B_{ki}) / m}{0.5} \right] x100 \tag{4}$$

where:

$R(A_{ij},B_{ki})$ is the fuzzy preference relation between A_{ij} and B_{ki}.

$A_{ij}=\{A_{11}, A_{21}, \ldots, A_{nm}\}$ is the set of features (i) for each configuration (j) $\forall$ i $\in$ [1, n], and $\forall$ j $\in$ [1, m].

$B_{ki}=\{B_{11}, B_{12},\ldots,B_{pn}\}$ is the set of customer preferences (k) for each feature (i) $\forall$ k $\in$ [1, p], and $\forall$ i $\in$ [1, n].

Once a possible product configuration has been found, it is necessary to evaluate the level of customer satisfaction for such a configuration. This evaluation can be obtained by applying Equation 4. If the percentage of customer satisfaction is less than the level fixed for acceptance, then replacement features should be considered, if they are available. For this application, six different evaluations have been performed (see Table 7 and Figure 7).

Phase 4. Verification of the replacement possibilities

If the percentage of customer satisfaction does not match customer expectations, then it is necessary to check whether or not other features are available for replacement. To perform this evaluation, all product features must be listed hierarchically, such that the first option belongs to the lowest ranking option for each feature. For example, if there exist five options for feature 1 (A_1), a hierarchical code can be expressed as (A_{ij}), where (i) identifies the feature and (j) identifies the hierarchical precedence as A_{11}, A_{12}, A_{13}, A_{14}, A_{15}. For this application, there exist five different options for feature 1 (F_1), and their hierarchical codes are expressed as (F_{ij}), where (i) and (j) identify the feature and the hierarchical precedence as F_{11}, F_{12}, F_{13}, F_{14}, F_{15} respectively.

Phase 5. Identification of the features to change

If the hierarchical precedence of feature (A_{ij}) in the current product configuration is less than the maximum A_{ij} ($j<jmax$), then there exists a replacement opportunity for this feature. An evaluation should be performed for each feature.

Phase 6. Replacement of features

Once all the replacement opportunities for each feature have been identified, they must all (A_{ij}) be replaced by the next feature (A_{ij+1}).

Phase 7. Evaluation of the upgraded product configuration

For each replacement iteration, the upgraded configuration must be evaluated by applying the procedure explained in step 4 of phase 2.

To verify whether or not the final product configuration satisfies customer preferences, it is necessary to check if If the percentage of customer satisfaction is greater than or equal to the acceptance percentage fixed by the customer, then the new product configuration satisfies its preferences. If not, an unsatisfactory product configuration is obtained. For this application, let us consider a minimum level of customer satisfaction of 90%.

Table 7 Product satisfaction rate per product configuration

Number of iterations	Configuration improvement by configuration per customer		
	Customer 1	Customer 2	Customer 3
1	58.788	81.036	95.124
2	68.452	89.132	95.792
3	75.960	94.492	96.548
4	82.856	99.132	97.804
5	84.476	------	98.920
6	91.852	------	102.608

Table 7 displays the changes in the customer satisfaction percentage for all six possible iterations to obtain a new product configuration. Figure 7 shows the behavior of this iterative process graphically. Appendices 1a, 1b, and 1c list the fuzzy preference relations for the all the iterations used to obtain the customer satisfaction percentages for each product configuration.

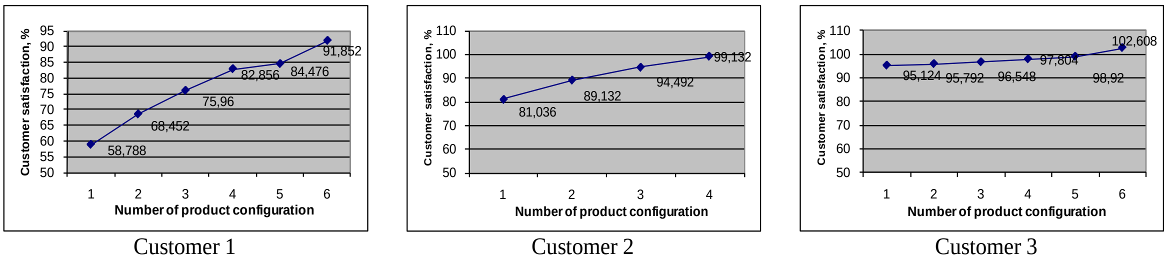

Fig. 7. Configuration improvement per customer

Table 7 and Figure 7 show the best product configuration for customers 1, 2, and 3 that were obtained during iterations 6, 4, and 6 respectively. According to the information presented in Appendices 1a, 1b, and 1c, the product configuration for customers 1, 2, and 3 are made up of the features (F_{13} - F_{22} - F_{36} - F_{44} - F_{56}), (F_{13} - F_{22} - F_{31} - F_{44} - F_{51}), and (F_{11} - F_{21} - F_{31} - F_{41} - F_{56}) respectively.

The best product configuration for customer 1 was obtained during iteration 6, because all the product features were highly important to this customer. For customer 2, the product configuration was obtained during iteration 4, because F_3 (Display) and F_5 (Hard drive) were not important to that customer, and the lowest valued alternatives of these features, considered in the initial product configuration, were more than enough to satisfy the customer's preferences for these features, avoiding the necessity to replace them with other, better alternatives (see Appendix 1b). Similarly, for customer 3, F_1 (Processor) and F_2 (Operating system) were of little importance, and F_3 (Display) was not important at all, and so their first alternatives considered in the initial product configuration were more than enough to satisfy the customer's preferences. For F_4 (Memory), even though $R(F_{41},C_{34})$ was 0.4783, according to the seudo-order preference model, its type of relationship ($C_{34}I_4F_{41}$) corresponds to the case where the product feature satisfies the customer preferences for this feature, avoiding the necessity for replacement as well. But, due to fact that F_5 was highly important to that customer (3), its product configuration was obtained during iteration 6 (see Appendix 1c).

4 Conclusions

Product configuration is a key issue in the development of better products aimed at increasing the level of customer satisfaction. In our work here, fuzzy logic has been applied to enrich this issue from a mass customization viewpoint allowing designing products which are more strongly based on customer preferences, and also permitting to develop more variety of products keeping low costs thanks to standardization of some components and process. We are proposing a method to configure a suitable product for specific customers by replacing some product features looking to include the features which best meet the customer's desires. This paper differs from prior studies, because it applies the fuzzy preference relation analysis which has showed its advantages over other methods of defuzzification used for similar purposes. Fuzzy preference relation and an adapted pseudo-order preference model have been applied as principal tools into the proposed method for the evaluation of the product configurations, also a metric to measure the customer satisfaction for each configuration has been proposed. The application of fuzzy logic into the method makes it possible for decision makers to profit from information expressed in linguistic terms which are frequently vague and imprecise in the real world. The illustrative application presented in section 3 reveals the practical applicability of fuzzy logic in the various areas, like the configuration of modular and scalable products. The output of the proposed method is personalized products in which the preferences of each customer are considered. This method contributes at allowing forming product closer to the customer preferences increasing the customer satisfaction and at the same time taking advantage of mass customization. However, it is important to underline that the proposed method is limited to the replacement of interchangeable product parts making necessary more research to consider the replacement of other product components in lower levels among the product parts. Other future research directions could include the integration of the proposed method and fuzzy logic in a general methodology to design families of products.

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Appendix 1a: Fuzzy preference relations for customer 1

$F_{ij}\backslash C_{ki}$ – Type of relationship	C_{11} [0 9 10 10]	C_{12} [0 9 10 10]	C_{13} [0 9 10 10]	C_{14} [0 9 10 10]	C_{15} [0 9 10 10]	Iteration number
F_{11} [0 3 5 10]	0.3106 – $C_{11}Q_1F_{11}$					1
F_{21} [0 4 6 10]		0.3344 – $C_{12}Q_2F_{21}$				
F_{31} [0 1 2 10]			0.2674 – $C_{13}Q_3F_{31}$			
F_{41} [0 2 4 10]				0.2899 – $C_{14}Q_4F_{41}$		
F_{51} [0 1 2 10]					0.2674 – $C_{15}Q_5F_{51}$	
F_{12} [0 5 7 10]	0.3623 – $C_{11}Q_1F_{12}$					2
F_{22} [0 8 9 10]		**0.4545 – $C_{12}I_2F_{22}$**				
F_{32} [0 2 4 10]			0.2899 – $C_{13}Q_3F_{32}$			
F_{42} [0 3 6 10]				0.3205 – $C_{14}Q_4F_{42}$		
F_{52} [0 2 3 10]					0.2841 – $C_{15}Q_5F_{52}$	
F_{13} [0 8 9 10]	**0.4545 – $C_{11}I_1F_{13}$**					3
----------------		**0.4545 – $C_{12}I_2F_{22}$**				
F_{33} [0 4 5 10]			0.3247 – $C_{13}Q_3F_{33}$			
F_{43} [0 5 7 10]				0.3623 – $C_{14}Q_4F_{43}$		
F_{53} [0 3 4 10]					0.3030 – $C_{15}Q_5F_{53}$	
----------------	**0.4545 – $C_{11}I_1F_{13}$**					4
----------------		**0.4545 – $C_{12}I_2F_{22}$**				
F_{34} [0 5 6 10]			0.3497 – $C_{13}Q_3F_{34}$			
F_{44} [0 8 10 10]				**0.4783 – $C_{14}I_4F_{44}$**		
F_{54} [0 4 6 10]					0.3344 – $C_{15}Q_5F_{54}$	
----------------	**0.4545 – $C_{11}I_1F_{13}$**					5
----------------		**0.4545 – $C_{12}I_2F_{22}$**				
F_{35} [0 5 7 10]			0.3623 – $C_{13}Q_3F_{35}$			
----------------				**0.4783 – $C_{14}I_4F_{44}$**		
F_{55} [0 5 7 10]					0.3623 – $C_{15}Q_5F_{55}$	
----------------	**0.4545 – $C_{11}I_1F_{13}$**					6
----------------		**0.4545 – $C_{12}I_2F_{22}$**				
F_{36} [0 8 9 10]			**0.4545 – $C_{13}I_3F_{36}$**			
----------------				**0.4783 – $C_{14}I_4F_{44}$**		
F_{56} [0 8 9 10]					**0.4545 – $C_{15}I_5F_{56}$**	

Appendix 1b: Fuzzy preference relations for customer 2

$F_{ij}\backslash C_{ki}$ – Type of relationship	C_{21}	C_{22}	C_{23}	C_{24}	C_{25}	Iteration number
	[0 9 10 10]	[0 9 10 10]	[0 0 1 10]	[0 9 10 10]	[0 0 1 10]	
F_{11} [0 3 5 10]	0.3106 – $C_{21}Q_1F_{11}$					
F_{21} [0 4 6 10]		0.3344 – $C_{22}Q_2F_{21}$				
F_{31} [0 1 2 10]			**0.5455 – $C_{23}I_3F_{31}$**			1
F_{41} [0 2 4 10]				0.2899 – $C_{24}Q_4F_{41}$		
F_{51} [0 1 2 10]					**0.5455 – $C_{25}I_5F_{51}$**	
F_{12} [0 5 7 10]	0.3623 – $C_{21}Q_1F_{12}$					
F_{22} [0 8 9 10]		**0.4545 – $C_{22}I_2F_{22}$**				
----------------			**0.5455 – $C_{23}I_3F_{31}$**			2
F_{42} [0 3 6 10]				0.3205 – $C_{24}Q_4F_{42}$		
----------------					**0.5455 – $C_{25}I_5F_{51}$**	
F_{13} [0 8 9 10]	**0.4545 – $C_{21}I_1F_{13}$**					
----------------		**0.4545 – $C_{22}I_2F_{22}$**				
----------------			**0.5455 – $C_{23}I_3F_{31}$**			3
F_{43} [0 5 7 10]				0.3623 – $C_{24}Q_4F_{43}$		
----------------					**0.5455 – $C_{25}I_5F_{51}$**	
----------------	**0.4545 – $C_{21}I_1F_{13}$**					
----------------		**0.4545 – $C_{22}I_2F_{22}$**				
----------------			**0.5455 – $C_{23}I_3F_{31}$**			4
F_{44} [0 8 10 10]				**0.4783 – $C_{24}I_4F_{44}$**		
----------------					**0.5455 – $C_{25}I_5F_{51}$**	

Appendix 1c: Fuzzy preference relations for customer 3

$F_{ij}\backslash C_{ki}$ – Type of relationship	C_{31} [0 3 4 10]	C_{32} [0 3 4 10]	C_{33} [0 0 1 10]	C_{34} [0 3 4 10]	C_{35} [0 9 10 10]	Iteration number
F_{11} [0 3 5 10]	**0.5217 – $C_{31}I_1F_{11}$**					1
F_{21} [0 4 6 10]		**0.5652 – $C_{32}I_2F_{21}$**				
F_{31} [0 1 2 10]			**0.5455 – $C_{33}I_3F_{31}$**			
F_{41} [0 2 4 10]				**0.4783 – $C_{34}I_4F_{41}$**		
F_{51} [0 1 2 10]					0.2674 – $C_{35}Q_5F_{51}$	
----------------	**0.5217 – $C_{31}I_1F_{11}$**					2
----------------		**0.5652 – $C_{32}I_2F_{21}$**				
----------------			**0.5455 – $C_{33}I_3F_{31}$**			
----------------				**0.4783 – $C_{34}I_4F_{41}$**		
F_{52} [0 2 3 10]					0.2841 – $C_{35}Q_5F_{52}$	
----------------	**0.5217 – $C_{31}I_1F_{11}$**					3
----------------		**0.5652 – $C_{32}I_2F_{21}$**				
----------------			**0.5455 – $C_{33}I_3F_{31}$**			
----------------				**0.4783 – $C_{34}I_4F_{41}$**		
F_{53} [0 3 4 10]					0.3030 – $C_{35}Q_5F_{53}$	
----------------	**0.5217 – $C_{31}I_1F_{11}$**					4
----------------		**0.5652 – $C_{32}I_2F_{21}$**				
----------------			**0.5455 – $C_{33}I_3F_{31}$**			
----------------				**0.4783 – $C_{34}I_4F_{41}$**		
F_{54} [0 4 6 10]					0.3344 – $C_{35}Q_5F_{54}$	
----------------	**0.5217 – $C_{31}I_1F_{11}$**					5
----------------		**0.5652 – $C_{32}I_2F_{21}$**				
----------------			**0.5455 – $C_{33}I_3F_{31}$**			
----------------				**0.4783 – $C_{34}I_4F_{41}$**		
F_{55} [0 5 7 10]					0.3623 – $C_{35}Q_5F_{55}$	
----------------	**0.5217 – $C_{31}I_1F_{11}$**					6
----------------		**0.5652 – $C_{32}I_2F_{21}$**				
----------------			**0.5455 – $C_{33}I_3F_{31}$**			
----------------				**0.4783 – $C_{34}I_4F_{41}$**		
F_{56} [0 8 9 10]					**0.4545 – $C_{35}I_5F_{56}$**	