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FUZZY INFORMATION AXIOM APPROACH FOR DESIGN CONCEPT EVALUATION

Shafin Tauhid [1] and Gül Okudan [1]
[1]The Pennsylvania State University, University Park, USA

ABSTRACT
The evaluation of design concepts is one of the critical phases of the product development process due to its influence on all subsequent phases with regards to cost, quality and performance of the end-product. This paper presents a new Concept Selection Method (CSM), which utilizes Fuzzy Information Axiom (FIA), and demonstrates its application on a case study. The un-weighted Axiomatic Design approach developed in this work includes both crisp and fuzzy criteria. FIA has the capability to solve multi-criteria decision-making problems, and is particularly useful for overcoming vague and multi-criteria structure of the concept evaluation problem. The selection process has been aided by developing a code in MATLAB, which carries out both crisp and fuzzy calculations, to select the best possible concepts.

Keywords: Concept Evaluation, Fuzzy Information Axiom, Multi-attribute Selection, Uncertainty

1. INTRODUCTION
The first stage of the design process identifies the requirement of the customers. From these requirements, a list of product specifications is developed. The specifications are a list of functions that the product must provide and is given in a solution neutral form. The following stage is concept design, and involves establishing a conforming set of sub-systems. Each of these sub-systems can perform a subset of the functions given in the specifications and, when taken as a whole, the entire set can perform all the required functions [7].
The evaluation of design concepts is the most vital phase of the product development process due to its influence on all subsequent phases with regards to cost, quality and performance of the end-product. This evaluation can be defined as a multi-criteria decision making problem under uncertainty owing to multiple, mostly conflicting criteria and imprecise information in the early design stage. During conceptual design, a number of different sub-systems are generated to perform each subset of the specified functions. After these various concepts have been outlined, the best combination of harmoniously conforming sub-systems is selected in terms of highest performance and lowest cost. This process is concept selection, and is often the Rubicon in the design process. It is vital that the best initial concepts are selected, as they determine the direction of the design embodiment stage; and hence nearly 60-80% of the cost is committed at this stage [2].
As development progresses on a selected component, it becomes more difficult to make design changes due to cost and schedule implications, and thus, selecting the best available concept is very important. Despite the fact that many approaches have been proposed and implemented for concept selection, most do have limitations relating to three issues: 1) functional decomposition and potential couplings among various functional areas (and hence generated concepts) are not taken into account, 2) despite rigor and increased computational complexity some solution methods do not warrant improved solutions, and 3) most methods do not incorporate uncertainty to the concept selection process.
Today's world, characterized by major changes in market and economic conditions, and with increased domestic and global competition, necessitates a very fast innovation process. This results in design practices becoming more complex than ever before, and concept selection is therefore a vital part in the design process. Given the need for companies to produce more and more innovative products in an

increasingly competitive market place, it follows that designers have to consider an increased number of design options [2]. However, a major problem faced in concept selection is that of uncertainty, as design alternatives always contain ambiguity and multiplicity of meaning. The Axiomatic Design process, proposed by Suh [19], is centered on the satisfaction of functional requirements which are defined as the minimum set of independent requirements characterizing the component design goals [23]. The multi-attribute fuzzy axiomatic design approach, developed by Kulak *et al.* [10], solves multi-criteria decision problems while taking into consideration uncertainty or fuzziness of available data.

This paper proposes Fuzzy Information Axiom (FIA) for overcoming vague and multi-criteria structure of the concept selection problem, while taking into account coupled decisions. The information axiom has the capability to solve multi-criteria decision making problems. Fuzzy theory provides quantification of uncertainty. A detailed case study illustrating the application of FIA is presented in the paper.

In Section 2, we present a review of popular Concept Selection Methods (CSMs). The literature review includes a number of techniques used to assist a designer in selecting a concept with respect to four different requirements, namely, to be systemized, to incorporate multi-attribute selection, to consider coupled decisions, and to be clear for the user to understand. The paper continues in Section 3 with a review of axiomatic design principles and the areas where they have been applied. Section 4 describes a Fuzzy Axiomatic Design approach, using the information axiom, applied to multi-criteria decision making problems.

Section 5 details the FIA approach that has been established for concept selection while taking into consideration coupled decisions, and this methodology has been applied to the concept selection of an ink pen, demonstrated by King and Sivaloganathan [7]. Section 6 discusses how this methodology can be applied to other problems.

2. A SUMMARY OF CONCEPT SELECTION METHODS

King and Sivaloganathan [7] indicate four criteria for use when comparing different CSMs:

1. The systematic nature of the CSM – are all steps clearly understood?
2. Multiple attributes – can a number of criteria be 'weighed' with varying levels of importance, as found in most real-life scenarios?
3. Coupled decisions – can the effects of one 'sub-decision' on others be incorporated to decision-making?
4. Simplicity and 'user-friendliness' – can the method be reasonably used in real-life environments without the need for lengthy training and preparation?

Despite the amount of research on the subject, different Multi-attribute Decision Making (MADM) methods tend to produce different outcomes for selecting or ranking a set of decision alternatives involving multiple attributes [5]. Hence, selecting a MADM method that produces optimal or near optimal results while incorporating the above mentioned criteria is of critical importance. Utility theory was first developed for economic decision making and has since been incorporated into a number of systematic design models [7]. While Thurston [22] developed an optimization method for utility functions, Reddy and Mistree [16] introduced a method that carried out uncertainty modeling. Pahl and Beitz [14] were among the first to incorporate Utility Theory into a systematic design method, where the concepts are ranked according to their overall utility score, satisfying all design criteria, and then a selection is made. This method though simple to implement does not accommodate coupled decisions. Saaty first developed the Analytic Hierarchy Process (AHP) method for multi-criteria decision making and Marsh et al. developed a more specific method directly for design decision-making [2]. In AHP, a pairwise comparison of all criteria is carried out to determine the relative importance of each criterion. Pairwise comparisons of all alternatives are then conducted for each criterion, and an overall selection is made. While AHP allows useful comparisons of all criteria and alternatives, the number of questions put forward to the decision maker is extremely high, and coupled decisions are not taken into account. Ayag [2] used a two stage approach to apply Fuzzy AHP for concept selection. Wang [25] postulated a fuzzy outranking for concept design evaluation in a valve selection problem. Pugh [15] suggested a simple graphical evaluation of different concepts which was very simple and fast, but did not allow for coupled decisions. King and Sivaloganathan [7] developed a new CSM which utilizes a compatibility matrix where all concepts are scored for their design functions as well as their compatibility with other concepts. This method allowed for coupled decisions where an aggregate score was created for concept designs that provided highest functionality of requirements and greatest compatibility with other concepts. Okudan and Shirwaiker [13] proposed an extension of King and Sivaloganathan's CSM, which utilized a dynamic programming approach and formulated the final score as a maximization of the shortest path problem. However, the King et. al. [7] and Okudan [13] method, though allowing for coupled decisions, do not incorporate uncertainty in their methods. Readers are referred to Okudan and Shirwaiker [13] for a comprehensive review of concept selection methods.

Overall, while developments in the field are in the right direction, (i.e., approaches more frequently cover the requirement for consideration for coupled decisions, etc.), there is room for improvements such as incorporation of uncertainty in decision-making. Accordingly, below we review axiomatic design principles and Fuzzy Information Axiom for their potential in supporting concept selection problems.

3. AXIOMATIC DESIGN

3.1 Axiomatic Design Principles

Axiomatic Design (AD) has its beginnings in 1978, when Suh *et al.* [19] and Suh [20-21], proposed a bold hypothesis: "there exists a small set of global principles, or axioms, which can be applied to decisions made throughout the synthesis of a global manufacturing system. These axioms constitute guidelines or decision rules that lead to correct decisions, i.e., those which maximize the productivity of the manufacturing system, in all cases" [18].

Axiomatic Design helps to create a synthesized solution that satisfy perceived needs through mapping between functional requirements (FRs) and design parameters (DPs). An FR is the goal to achieve and is defined in the functional domain, while a DP is determined in the physical domain as the means to achieve the goal. Mapping is a process to choose a relevant DP in the physical domain, which satisfies a given FR in the functional domain. According to AD, the essence of the design process lies in the hierarchies as illustrated in Figure 1. Designers begin the design from comprehensive FRs, and a design can decompose FRs into many hierarchies. But the decomposition of FRs must be carried out at the same time with the decomposition of DPs. The zigzagging between FRs and DPs is necessary because the two sets of each level are connected and mutually dependant [25].

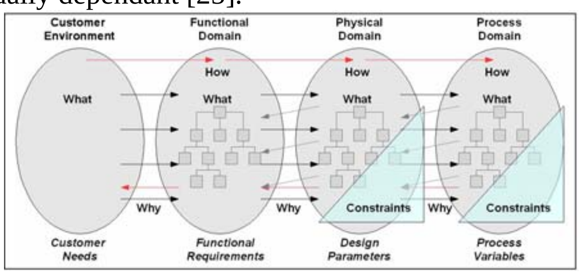


Figure 1. Concept of domain, mapping and spaces.

Rinderle and Suh [17] proposed seven "hypothetical axioms", which after trial and evaluation in manufacturing case studies were reduced to the following two fundamental axioms [17]:

1. *The independence axiom*: maintain the independence of functional requirement (FR).
2. *The information axiom*: minimize information content.

The Independence Axiom states that the independence of FRs must be maintained. In the real world, engineers tend to tackle a complex problem by decomposing it into sub-problems and attempt to maintain independent solutions for these smaller problems [8, 10].

The Information Axiom (for crisp values) states that among those designs that satisfy the Independence Axiom, the design that has the smallest information content is the best design. Information is defined in terms of the information content, I_i, that is related in the simplest form to the probability of satisfying the given FRs. I_i determines that the design with the highest probability of success in the best design. Information content I_i for a given FR_i is defined as follows:

$$I_i = \log_2\left(\frac{1}{p_i}\right) \qquad (1)$$

where p_i is the probability of achieving the functional requirement FR_i and log is the logarithm in base 2 .
In any design situation, the probability of success is given by what the designer wishes to achieve in terms of tolerance (i.e., design range) and what the system is capable of delivering (i.e., system range). As shown in Figure 2(a), the overlap between the designer specified "design range" and the system capability range "system range" is the region where the acceptable solution exists. Hence, in the case of uniform probability distribution function, p_i may be written as

$$p_i = \left(\frac{\text{Common Range}}{\text{System Range}}\right) \qquad (2)$$

Therefore, the information content is equal to

$$I_i = \log_2\left(\frac{\text{System Range}}{\text{Common Range}}\right) \qquad (3)$$

However, using Eq. (3), alternatives that are over-designed (i.e. the system range lies beyond the design range) are penalized only. In the case of under-design (i.e. system range lies with the design range), the information content obtained will be minimum, which is zero. In other words, alternatives that lie within the design range but do no meet the requirements exactly are not penalized. This necessitates the calculation of information content over the design range also. Thus, the total information content is calculated as:

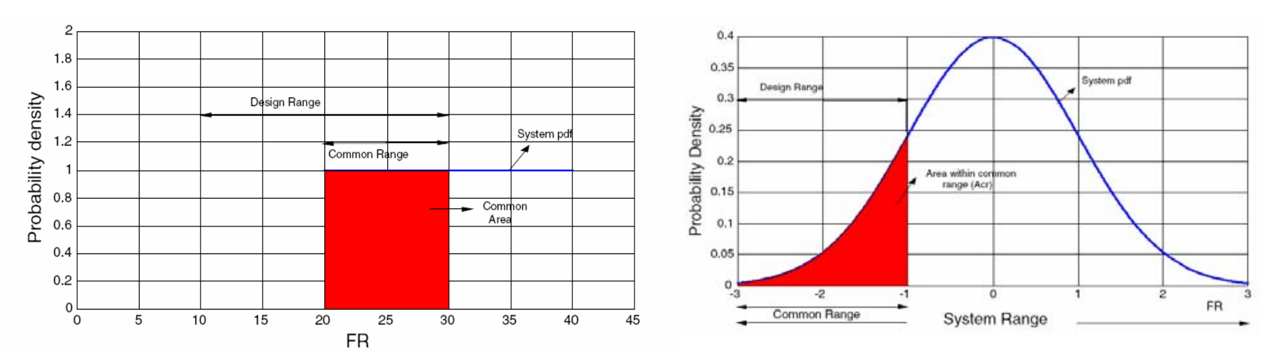
$$I_i = \log_2\left(\frac{\text{System Range}}{\text{Common Range}}\right) + \log_2\left(\frac{\text{Design Range}}{\text{Common Range}}\right) \qquad (4)$$

The probability of achieving FR_i in the design range may be expressed, if FR_i is a continuous random variable, as

$$p_i = \int_{dr^l}^{dr^u} p_s(FR_i)\,dFR_i \qquad (5)$$

where $p_s(FR_i)$ is the system pdf (probability density function) for FR_i. Eq. (5) gives the probability of success by integrating the system pdf over the entire design range (i.e. the lower bound of design range, dr^l, to the upper bound of the design range, dr^u). In Figure 2(b), the area of the common range (A_{cr}) is equal to the probability of success P [8, 10].
Therefore, the information content is equal to:

$$I = \log_2\left(\frac{1}{A_{cr}}\right) \qquad (6)$$



(a) (b)

Figure 2. (a) Probability density function of a FR; (b) Probability density function of a FR expressed as a continuous random variable (Adopted from Kulak [10]).

3.2 Research on Axiomatic Design

Ever since Suh developed a general and flexible conceptual design methodology, several researchers have applied this logic to solve far reaching problems in engineering design. The first axiom requires that the FR be satisfied individually by their corresponding DPs. The second axiom intends to maximize the probability of an item to be designed / manufactured successfully. The design axioms provide a framework to indicate the adequacy of proposed designs. They are used for considering, evaluating and comparing different alternatives to satisfy the needs or requirements of a specific product or system. A key benefit of the axiomatic design approach is the structured development of the design formulation. This effort leads to a better understanding of the design requirements and their relative importance [18].

Albano and Suh [1] used design axioms as a framework for concurrent engineering to implement the concept of multidisciplinary designs which suffer from a lack of a formal design process, causing problems in areas of group decision, decision making and information management. Suh also implemented axiomatic principles to design theory of systems for different systems, such as manufacturing systems, software, product, and organizations [20]. Togay *et al.* [23] successfully developed a software compare methodology based on Axiomatic Design theory and Design Structure Matrix which helped overcome anomalies and functional problems such as deadlock. Guenov and Barker [6] integrated Axiomatic Design Matrices with Design Structure Matrices to solve potential conflicts in the design solution, and allow groups of design parameters to be explored in greater detail. Babic [3] applied axiomatic design theory to work as an effective decision support system for FMS designers in determining the appropriate FMS configuration at the design stage. Kulak *et al.* [12] provided a framework for transformation of traditional manufacturing systems from process orientation to cellular orientation. Coelho *et al.* [5] modified the QFD method by employing axiomatic design. It was concluded by him that AD provides a systematic procedure to decompose the design object, a set of unchanging criteria that is essential to promptly assess engineering design decisions at any point, and an intrinsically concurrent working background that promotes the fast generation of new design solutions.

4. FUZZY INFORMATION AXIOM

The approach listed in the earlier section, and the research carried out on axiomatic design, utilizes crisp numbers, i.e., the information provided is a certain quantified value. However, in many design scenarios, it is generally very difficult to provide exact information to the design team. To illustrate, in the area of concept selection, when there are a large number of concepts to select from, it proves extremely difficult for the decision to quantify the entire FRs for a particular concept. It would be much easier for the decision maker to classify a FR of the concept as 'good' or 'average'. Although the crisp information axiom approach can be used for the solution of decision-making problems under certainty, it cannot be applied with incomplete information, since the expression of decision variables by crisp numbers would be ill-defined [9]. The use of fuzzy set theory allows the decision makers to incorporate unquantifiable information, incomplete information, non-obtainable information and partially ignorant facts into the decision model [10]. Kulak and Kahraman [11] developed a fuzzy multi-attribute information axiom which was applied to the selection among punching machines while investing in a manufacturing system.

The data relevant to the criteria incomplete data can be expressed as fuzzy data. The fuzzy data can be linguistics terms, fuzzy sets, or fuzzy numbers. If the fuzzy data are in linguistic terms, they are transformed into fuzzy numbers. Then, these numbers (or fuzzy sets) are assigned crisp scores. Kulak *et al*. [10] proposed a numerical approximation system to systematically convert linguistics terms to their corresponding fuzzy numbers. The system contains five conversion scales as shown in Figure 3.

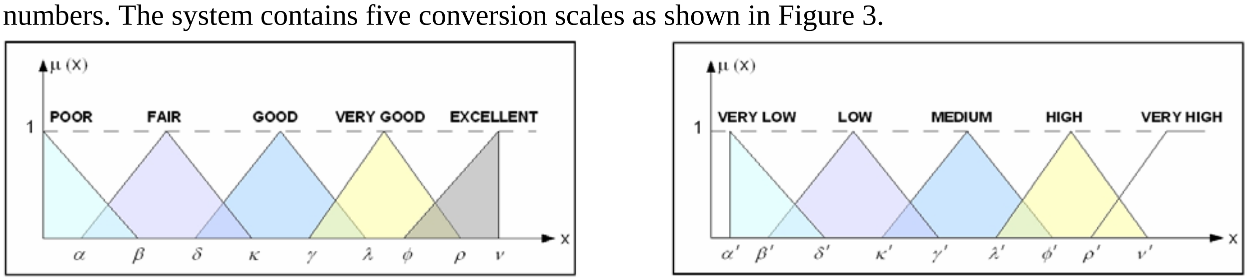


Figure 3. The numerical approximation for intangible factors (left) and tangible factors (right).

In a fuzzy case, incomplete information about the system and design ranges is provided. The system and design range for a certain criterion will be expressed by using ‘over a number’, ‘around a number’ or ‘between two numbers’. Triangular or trapezoidal fuzzy numbers (TFN) will be used to represent these kinds of expressions. A membership function of the TFN now exists, which is similar to the probability density function in the crisp case. So, the common area is the intersection of triangular or trapezoidal fuzzy numbers, as shown in Figure 4 [9].

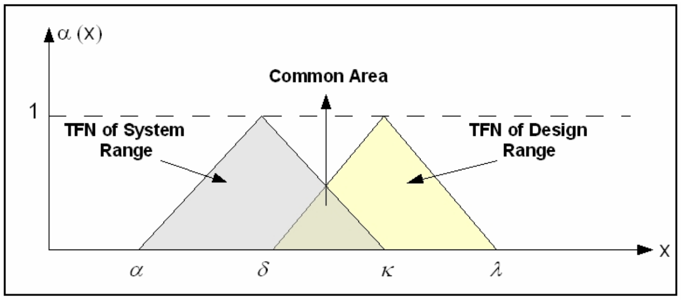


Figure 4. The common area of system and design ranges.

Therefore, the information content for fuzzy evaluation is equal to:

$$I = \log_2\left(\frac{\text{TFN of System Range}}{\text{Common Area}}\right) + \log_2\left(\frac{\text{TFN of Design Range}}{\text{Common Area}}\right) \quad (7)$$

5. A CASE STUDY

5.1 Problem Definition

The design of an ink-pen, as demonstrated by King & Sivaloganathan [6], has been selected in this study. The authors developed a new CSM, a compatibility matrix, to select various concepts required to satisfy different functions. A total of twelve concepts are available for selection, and four primary functional requirements are to be fulfilled. The definition of the criteria (functions) and alternatives (criteria) along with their notations are listed in Table 1, and these notations would be used for both the applied methods.

Table 1. Notation of functions and concepts.

Notation	Definition	Notation	Definition
F1	Store Ink	C5	Gravity nib
F2	Transmit ink to paper	C6	Absorbant fiber
F3	Allow easy holding	C7	1-piece plastic shank
F4	Protect from damage	C8	2-piece plastic shank
C1	Plastic cartridge	C9	2-piece metal shank
C2	Rubber reservoir	C10	Removable lid
C3	Pre-sealed chamber	C11	Twist-body retraction
C4	Roller ball	C12	Linear-slide in & out

The compatibility matrix is shown in Table 2. In the table, F1-F4 represents functions on the ink-pen; and C1-C12 represents the potential concepts that can be applied to the design. This method also allowed for concept coupling where each concept was evaluated for its compatibility with another concept. The compatibility is represented by the intersection cell of the concept rows and columns and one compatibility rating for each concept pair is provided. As shown in Table 3, three concepts fulfill one function, and hence a total of four concepts are to be selected. The theoretical number of possible configurations is $12^4 = 20736$, which assumes that any concept can fulfill any function. However, as only three concepts satisfy any one requirement, the total number of configurations to be evaluated is $3^4 = 81$. The methodology suggests finding which configuration has the highest overall score, which has been automated using a Macro program. The calculation is carried out in two stages; the summation of the concept score, and then the multiplication of the compatibility score. The configuration with the highest concept-function score is then selected as the best possible combination of concepts to fulfill the functional requirements. The selected configurations of concepts along with their overall scores are displayed on the top of the compatibility matrix.

Table 2. Compatibility Matrix.

Meaning			**Value**	**Score**	**Configuration**									**C12**
Highly Compatible			2	14.4	3	6	7	10					0	**C11**
Mod. Compatible			1.5	13.5	3	4	7	10				0	0	**C10**
Independent			1	12.6	1	5	9	10			1.5	1	1	**C9**
Mod. Conflicting			0.5	9	3	4	7	11		0	1.5	1	1	**C8**
Highly Conflicting			0	8.7	1	5	8	10	0	0	1.5	1	0.5	**C7**
								1.5	1	1	1	0.5	0.5	**C6**
							0	0.5	1	1	2	0.5	0.5	**C5**
Compatibility Matrix						0	0	1.5	1	1	1.5	1	1	**C4**
					2	0.5	2	2	0.5	0.5	1	1	1	**C3**
				0	1	2	1	0	1	1	1	1	1	**C2**
			0	0	1.5	2	1	0	1	1.5	1	1	1	**C1**
	Weight	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**	**C10**	**C11**	**C12**	
F1	**0.25**	**0.45**	**0.2**	**0.35**	0	0	0	0	0	0	0	0	0	
F2	**0.35**	0	0	0	**0.3**	**0.3**	**0.4**	0	0	0	0	0	0	
F3	**0.25**	0	0	0	0	0	0	**0.45**	**0.3**	**0.25**	0	0	0	
F4	**0.15**	0	0	0	0	0	0	0	0	0	**0.4**	**0.4**	**0.2**	

5.2 Proposed Approach

The compatibility matrix provides a quick and efficient solution to solve multi-criteria problems with concept couplings. The main drawback of that method is that it does allow for uncertainty or fuzziness in the design data. As mentioned earlier in the paper, design requirements for evaluating concept design alternatives always contain ambiguity and multiplicity of meaning. The proposed methodology aims to solve the vagueness and uncertainty of the concept selection problem by utilizing the fuzzy information axiom.

An *Information Matrix (IM)* similar to the compatibility matrix is used in this method, as illustrated in Table 3. The IM consists of the design requirements, which forms the '*design range*', where F1-F1 represent the range of the functional requirement for each of the twelve concepts in C1-12 in crisp numbers, with the first column representing the lower bound and the second column representing the upper bound for each concept, which is set by the decision-maker. The intersection cell of the of the concept rows with the concept columns represents the desired compatibility of that concept with another concept. The compatibility of concepts is expressed in linguistic terms, as shown in Figure 5. The decision-maker lays down the desired concept compatibility with the linguistic term "*ICPT*" meaning incompatible to which a score of (0,0,0) is assigned over 19; "*POOR*" is assigned a score of (1,1,7) over 19; "*FAIR*" is assigned a value of (5,8,11) over 19; "*GOOD*" is assigned a value of (9,12,15) over 19; and "*BEST*" is assigned a score of (13,19,19) over 19. Similarly, the decision-maker or the vendor (one who designs the concept) subjectively evaluates the presented concepts for their capabilities of the functional requirements as well as their compatibility with each other. This constitutes the '*system range*' and is shown in Table 3.

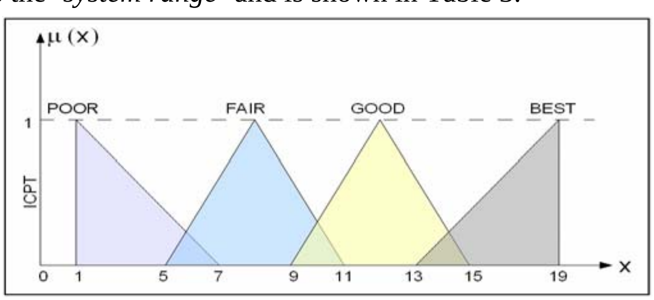


Figure 5. TFNs for concept compatibility.

Table 3. The information matrix (IM) showing (a) the Design Requirements and (b) the System Capabilities.

(a) Design Requirements

																									C12
																							Icpt		**C11**
																					Icpt		Icpt		**C10**
																			Good		Fair		Fair		**C9**
																	Icpt		Best		Fair		Fair		**C8**
															Icpt		Icpt		Good		Fair		Poor		**C7**
													Good		Fair		Fair		Fair		Poor		Poor		**C6**
											Icpt		Fair		Fair		Fair		Best		Poor		Poor		**C5**
									Icpt		Icpt		Good		Fair		Fair		Good		Fair		Fair		**C4**
							Best		Poor		Best		Best		Poor		Poor		Fair		Fair		Fair		**C3**
					Icpt		Fair		Best		Fair		Icpt		Fair		Fair		Fair		Fair		Fair		**C2**
			Icpt		Icpt		Fair		Best		Fair		Icpt		Poor		Good		Fair		Fair		Fair		**C1**
	C1		**C2**		**C3**		**C4**		**C5**		**C6**		**C7**		**C8**		**C9**		**C10**		**C11**		**C12**		
F1	**0.4**	**0.55**	**0.2**	**0.35**	**0.35**	**0.5**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
F2	0	0	0	0	0	0	**0.2**	**0.3**	**0.2**	**0.3**	**0.4**	**0.55**	0	0	0	0	0	0	0	0	0	0	0	0	
F3	0	0	0	0	0	0	0	0	0	0	0	0	**0.45**	**0.6**	**0.15**	**0.35**	**0.2**	**0.35**	0	0	0	0	0	0	
F4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.4**	**0.55**	**0.4**	**0.55**	**0.15**	**0.3**	

(b) System Capabilities

																									C12
																							Icpt		**C11**
																					Icpt		Icpt		**C10**
																			Fair		Fair		Poor		**C9**
																	Icpt		Good		Poor		Good		**C8**
															Icpt		Icpt		Best		Good		Icpt		**C7**
													Fair		Poor		Good		Poor		Icpt		Fair		**C6**
											Icpt		Poor		Good		Poor		Good		Fair		Poor		**C5**
									Icpt		Icpt		Best		Poor		Poor		Fair		Fair		Good		**C4**
							Good		Fair		Best		Best		Icpt		Fair		Fair		Poor		Good		**C3**
					Icpt		Poor		Good		Poor		Icpt		Good		Poor		Poor		Good		Fair		**C2**
			Icpt		Icpt		Good		Good		Poor		Icpt		Fair		Good		Poor		Good		Fair		**C1**
	C1		**C2**		**C3**		**C4**		**C5**		**C6**		**C7**		**C8**		**C9**		**C10**		**C11**		**C12**		
F1	**0.4**	**0.6**	**0.1**	**0.25**	**0.35**	**0.5**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
F2	0	0	0	0	0	0	**0.25**	**0.35**	**0.15**	**0.25**	**0.4**	**0.55**	0	0	0	0	0	0	0	0	0	0	0	0	
F3	0	0	0	0	0	0	0	0	0	0	0	0	**0.4**	**0.6**	**0.1**	**0.3**	**0.25**	**0.35**	0	0	0	0	0	0	
F4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.35**	**0.5**	**0.45**	**0.6**	**0.15**	**0.35**	

The decision-making process has been aided by using a code developed in MATLAB, where the available data in the IM is fed into the program. The decision process is carried out in two stages. In the first stage, the program evaluates the feasibility of all the concepts for their respective FRs using the crisp AD approach using Eq. 4. The compatibility of concepts with one another is calculated using the fuzzy AD approach as in Eq. 7. To illustrate, for C1 the Design Range (DR) is 0.4-0.55 = 0.15 and the System Range (SR) is 0.4-0.6 = 0.20. Hence the Common Range (CR) would be 0.15. Using Eq. 4, the Functionality Content is:

$$I_{C1} = \log_2\left(\frac{0.20}{0.15}\right) + \log_2\left(\frac{0.15}{0.15}\right) = 0.415 + 0 = 0.415$$

Similarly, while looking at compatibility between C1 and C4, the Design Requirement is *"FAIR"* while the System Capability is *"GOOD"*. This when converted to TFNs would be as illustrated in Figure 6. For this, the common area is 0.3333, and using Eq. 7 the Compatibility Content is:

$$I_{C1C4} = \log_2\left(\frac{3.0}{0.3333}\right) + \log_2\left(\frac{3.0}{0.3333}\right) = 3.1699 + 3.1699 = 6.3399$$

It is important to note that when the DR is "*ICPT*" (meaning that the two concepts are incompatible) and the SR is also "*ICPT*", and "*ICPT*" has a TFN of (0,0,0) as shown in Figure 5, the compatibility content would be $\log_2(0)$, which would return a value of *'- Infinity'*. Since, only absolute values are considered in this case, the compatibility content would be *'Infinity'*.

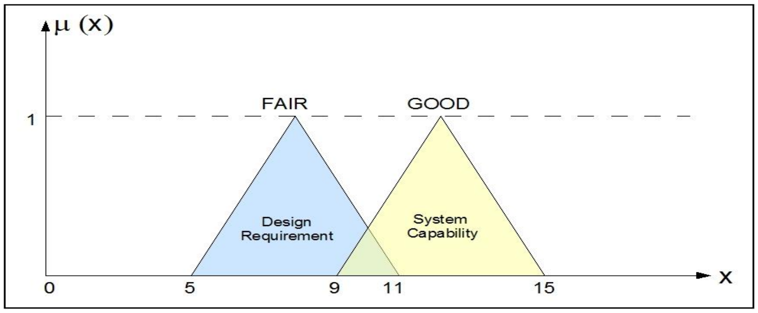


Figure 6. TFNs for concept compatibility between C1 and C4.

In both crisp and fuzzy AD approaches, there are three possible outcomes is terms of intersection between the design range and the system range, namely, when there is no intersection; there is partial intersection; and; there is complete overlap. Ideally, one would prefer a complete overlap of system and design ranges, but this is rarely the case, where the information content returned would be '*zero*'. In most cases a partial intersection is obtained, or there is zero overlap where the information content returned is '*Infinity*'. The *Information Content Matrix (ICM)* obtained using Eq. 4 and Eq. 7, as shown in Table 4, is obtained for all the concepts with their respective functionality content for the FRs as well as their compatibility content for each other.

In the second stage, data from the *Information Content Matrix (ICM)* is used to arrive at a decision. Similar to the compatibility matrix by King [7], in the ICM, F1-F4 represents the FRs of the ink-pen and C1-C12 represents the potential concepts, and the intersection of concept rows and columns denotes the compatibility information content for each concept pair.

For each of the 81 possible concept combinations the *Functionality Content* and their *Compatibility Content* with each other is calculated from the data in the ICM. The functionality content is sum of the information contents of each of the concepts for their respective functions. The compatibility content is the sum of the information contents of their compatibility with each other. The functionality content and compatibility content values have been normalized to ensure that equal importance is given to functional requirements as well as concept compatibility. The *Total Information Content* is the sum of the normalized functionality content and normalized compatibility concept. This calculation is illustrated in Table 5 for the concept combination 3-6-7-10. Some of the best and worst combinations with their information contents and ranks are listed in Table 6.

Table 4. The Information Content Matrix (ICM)

Information Content Matrix													
													C12
												Inf	**C11**
											Inf	Inf	**C10**
										7.512	0	7.512	**C9**
									Inf	7.512	7.512	6.339	**C8**
								Inf	Inf	7.512	6.339	Inf	**C7**
							6.339	7.512	6.339	7.512	Inf	7.512	**C6**
						Inf	7.512	6.339	7.512	7.512	7.512	0	**C5**
					Inf	Inf	7.512	7.512	7.512	6.339	0	6.339	**C4**
				7.512	7.512	0	0	Inf	7.512	0	7.512	6.339	**C3**
			Inf	7.512	7.512	7.512	Inf	6.339	7.512	7.512	6.339	0	**C2**
		Inf	Inf	6.339	7.512	7.512	Inf	7.512	0	7.512	6.339	0	**C1**
	C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**	**C10**	**C11**	**C12**	
F1	0.415	3.169	0	Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf	
F2	Inf	Inf	Inf	2	2	0	Inf	Inf	Inf	Inf	Inf	Inf	
F3	Inf	Inf	Inf	Inf	Inf	Inf	0.415	0.830	0.585	Inf	Inf	Inf	
F4	Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf	1.169	1.169	0.415	

Table 5. Calculation for concept combination 3-6-7-10.

Concept Combination	Functionality Content	Compatibility	Compatibility Content
3	0	3 & 6	0
6	0	3 & 7	0
7	0.415	3 & 10	0
10	1.169	6 & 7	6.339
		6 & 10	7.512
		7 & 10	7.512
Sum	1.584		21.363
Normalized Functionality Content = 0.221 / 1.000			
Normalized Compatibility Content = 0.474 / 1.000			
Total Information Content = 0.695 / 2.000			

Table 6. Ranking of best and worst concept combinations.

Ranking Order	Concept Combination				Functionality Content	Compatibility Content	Total Information Content
1	3	6	7	10	0.2211	0.4740	0.6950
2	1	6	9	12	0.1984	0.6406	0.8380
3	3	6	9	10	0.2448	0.6146	0.8594
4	3	6	9	12	0.1395	0.7813	0.9208
:	:	:	:	:	:	:	:
80	3	6	8	12	0.1737	Inf	Inf
81	3	6	9	11	0.2448	Inf	Inf

From Table 6, it is observed that for concept combination 3-6-9-12 ranked 4, the concept content is lower than for combinations ranked from 1-3. However, as the compatibility content more than combinations ranked 1-3, it is easy to see that combinations 3-6-7-10, 1-6-9-12 and 3-6-9-10 are preferred. According to the information axiom, the concept combination with the lowest total information content is selected. Hence, all combinations returning an infinite value are eliminated as they do not fulfill the functional requirements or that they are incompatible with each other.

6. CONCLUSION

Concept selection is one of the most critical phases of product development. In today's world, with highly competitive markets, it is imperative that the best possible concepts be selected, as improper selections have disastrous effects on all subsequent phases with regards to cost, quality and performance of the end product. In this paper, a new concept selection approach is proposed and applied, which is based on Axiomatic Design and Fuzzy Information Axiom. Axiomatic design is the framework of a good design especially when the functional requirements are known and the problem is well decomposed. The proposed approach has improvements on King and Sivaloganathan [6] and many other methods presented earlier. As mentioned earlier in the paper, uncertainty is the biggest problem encountered during the concept evaluation phase. It is very difficult for a designer to provide accurate data so early in the product development phase, especially in regard to concept compatibility. The use of fuzzy set theory allows us to incorporate unquantifiable information, incomplete information, non obtainable information, and partially ignorant facts into the decision model [8]. The proposed method overcomes the problem of uncertainty by utilizing Fuzzy Information Axiom. Furthermore, while incorporating uncertainty, the new CSM also takes into account concept coupling, undoubtedly an integral part of product development. It is interesting to note, from Table 10, that concept combination 3-6-9-12 ranked at # 4 satisfies the functional requirements best, but due to poor compatibility is ranked lower as compared to the first three. This clearly indicates the importance of compatibility in concept selection considerations. The proposed method ensures that all concept combinations that are incompatible with each other are eliminated. In addition, this method can be applied to large scale problems, and as it is user-friendly and as is relatively easy to code it in MATLAB there is no requirement for any complex software packages. It is not necessary for the decision maker to score the concepts to unity for the functional requirements, which would be very difficult in large scale problems. The decision maker is only required to set the design requirement and then evaluate the capability of the proposed concepts. In the considered case study, all functional requirements are given equal importance, as is the functionality and compatibility of concepts. Weights can easily be given to the FRs, where the most important FR would be given a smaller weight and the least important FR will be given the highest weight. The case study demonstrates that this approach can be applied to effectively to the multi-criteria decision making problem of concept selection under uncertainty.

The methodology of axiomatic design is to find a common overlap between the design requirements and the system capabilities. This also serves as an advantage because alternatives that are over-designed or under-designed are severely penalized. Thus, the alternative that is closest to the design requirements is selected. Future work on the proposed method is to evaluate the feasibility of using FIA compared to other methods incorporating uncertainty in design concept evaluation such Fuzzy AHP and Fuzzy Outranking methods.

A limitation of the mentioned approach is that it is not possible to evaluate how good or bad a concept combination is among the eliminated combinations, as all eliminated combinations have an information content of 'infinity'. For concepts that do not satisfy the design requirements, the decision maker may assign a 'large value' that indicates by how much that particular concept failed to meet the design requirements. This would allow a quantitative comparison of all the concept combinations, both which have accepted as well the ones that are eliminated.

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