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Axiomatic Design Of A Car Bonnet: A New Decoupling Method Based On Fuzzy Logic Application

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Abstract

In Axiomatic Design Approach, the first axiom, states that independence of functional requirements should be maintained throughout the design process. Para-complete logics, such as Fuzzy logic, represents a powerful instrument to express “mathematical/functional” interaction between Functional Requirements (FRs) and Design Parameters (DPs). Para-complete logics violate the principle of the excluded third party, so that the effects of DPs’ changes on the same FR can be considered partially independent each other. Our paper investigates the changes in Decoupled Design’s concept when para-complete logics are applied in FRs-DPs matrix definition. Paper evaluates the impact of decoupling capability of designer using composition rules on FRs, in order to make the design matrix diagonal or lower triangular by decoupling effects of several DPs on different FRs using Fuzzy formulation.

Keywords: Axiomatic Design, Para-complete Logics, Design Optimization, Fuzzy Set.

Introduction

In industry, unsatisfactory design results in a great number of process iterations, so improving the effectiveness of design is crucial in order to shorten product development time and lower costs. The goal of effective engineering design is to minimize unnecessary process iterations. To reduce the probability of design failures, systematic approaches have become the trend to efficiently realize designs in recent decades.

The Axiomatic Design (AD) method proposed by Suh [1,2,3] representsa powerful approach that provides a systematic guideline for evaluating the acceptability of designs, so we have imagined to use that approach in Concept Design phase, and support it, in Independence and Information evaluation[4,5], using Fuzzy logic [6,7,8].

In designing large and complex systems, some couplings between FRs are weak and have little influence on the design outcome so that they can be ignored, in particular conditions, in order to proceed with fewer interactions, thus expediting the design process. The problem is how to evaluate the weakness of this influence. This paper gives an answer about the way for measuring functional dependency and, if possible, to develop decoupling methods based on the use of para-complete logics, such as Fuzzy logic, in engineering design in order to improve the design process.

The objectives of this research are the following:

(1) To investigate changes in Decoupled Design's concept when para-complete logics are applied in FRs-DPs link definition.

(2) To evaluate the impact of decoupling capability of designer using membership function formulation, in order to make the design matrix diagonal or lower triangular using Fuzzy formulation, and also using α-cut methodology.).

Logics and axioms in design

Fuzzy-analysis fundamentals

Linguistic inexactness (imprecision) is the most common feature of many real life situations. Dutta [9] classifies imprecision according to its source: measurement, stochastic, ambiguous definitions, incomplete knowledge, etc. In customer oriented design, customers have wants and needs that are, often, hard to interpret because they are expressed, linguistically, using terms that have no precise definition. A statement is not always right or wrong; in such cases, a solution can be found using the logics that violate the principle of the excluded third party, like Fuzzy logic. The dichotomous property is the basis of classical set theory but we cannot use it because, for complex systems, a property may be viewed as a continuous measure of some possibility distribution [5,10]. The Fuzzy logic, based on L. Zadeh theory [11,12], allows to express in mathematical terms several not precisely defined concepts; unlike of binary logic, that logic does not require that a proposition assumes a defined truthful value, true or false, but allows to assign a membership value (between 0 and 1) to truthfulness of it. Generally we can declare that an element satisfy a requirement [6] even if this requirements has a not clearly sense, giving to it a membership value in the range {0 – 1}. A fuzzy set accepts objects with certain degree, the so called membership function [13,14]. The fuzzy set A is represented as: $A = \{(FR, \mu_a(FR)) / FR \in FRs\}$ with mf(FR), understood to represent a mapping of membership of

$$FR,\ mf/\ FRs \longrightarrow [0,1],\ FR \longrightarrow mf(FR) \qquad (1)$$

In the crisp case, $\forall FR \in A$, $\mu_a(FR) = 1$ and zero otherwise. For example, FRs can be the universe of fuzzy functional requirements, such as “stylish”, “cheap”, “convenient”, etc. In Design process, it is very important to underline the key role of mapping process between what we want to achieve and how we want to achieve it: using that definition we can declare that Design problem formulation start from Functional requirements (FRs) and Design parameters (DPs) identification. The Fuzzy logic approach helps designers to identify the relationship between FRs and DPs, to formulate a judgment on several design hypotheses and compare different concept-design solutions each other, putting into account exact, not precise and not quantifiable requirements, thanks to the formulation explained in (1).

The concept of membership function plays a key role in that approach: FRs can be correlated, by membership function, to DPs that characterize the project; FRs for a project’s “element” can be decomposed into simple ones (sub-requirements) directly depending from design parameters; this operation allows to decompose complex property, associated to a requirements, in simple ones, and to combine each other by fuzzy membership-function composition laws [15]. In this paper, we have defined the Design Goal through all requirements opportunely weighted or composed by simple rules. Those rules can be combined each other in order to create an Objective Function (OF) that provides all design aspects. The design process finishes with the formulation of several design hypotheses. Each hypothesis has been evaluated and gave a score defined by the final composition rule. The score expresses the membership value to the chosen objective; the best design solution has to be naturally chosen among ones which have the best score [8,13]. There are a lot of papers in literature dealing with membership function definition [6, 7, 8, 17], their construction and methods of composition; for our application we used several simple mf such as triangular, trapeziform and simple mathematical function, for evaluating quantifiable parameters, while, for evaluating several not quantifiable requirements, we used the “One expert direct method”.

“One expert direct method” allows to directly assigning a membership value for each of examined alternatives, in comparison with other methods that indirectly (by membership function) make this operation [8]. For example an interview with an expert is transformed in a membership value by using a table of predefined correspondence judgment<->value.

Once the membership functions are defined, they have to be combined by composition rules; some of these are: minimum rule, maximum rule, arithmetical average rule, geometrical average rule. The first of those is applied in evaluating requirements that have to be necessarily satisfied, and assigns, to requirements, minimum of obtained scores among all; the second one is applied especially when at least one of the requirements has to be satisfied, and assigns to element the maximum among scores; arithmetical average is applied when requirements interact each other compensating themselves, and assigns to the element a score calculated as weighted average of single requirements scores; geometrical average is applied when every judgment on design’s requirement makes worse the final one. Finally the Design Problem requires a Defuzzyfication, in order to extract the physical values of DPs from Fuzzy formulation.

Axiomatic design

In 1990, Suh [1] proposed the use of axioms as the scientific foundations of design. Out of the twelve axioms first suggested, Suh introduced the following two basic axioms along with six corollaries that a design needs to satisfy:

Axiom 1 –

The Independence Axiom:Maintain the independence of the functional requirements

Axiom 2 –

The Information Axiom: Minimize the information content in a design

In axiomatic design approach [2], the engineering design process is described as in Figure 1, in which the array of functional requirements (FRs) is the minimum set of independent requirements that completely characterizes the design objective based on customer attributes (CAs). Design is defined as the creation of synthesized solution to satisfy perceived needs through the mapping between the FRs in the functional domain and the design parameters (DPs) in the physical domain and through the mapping between the DPs and the process variables (PVs) in the process domain.

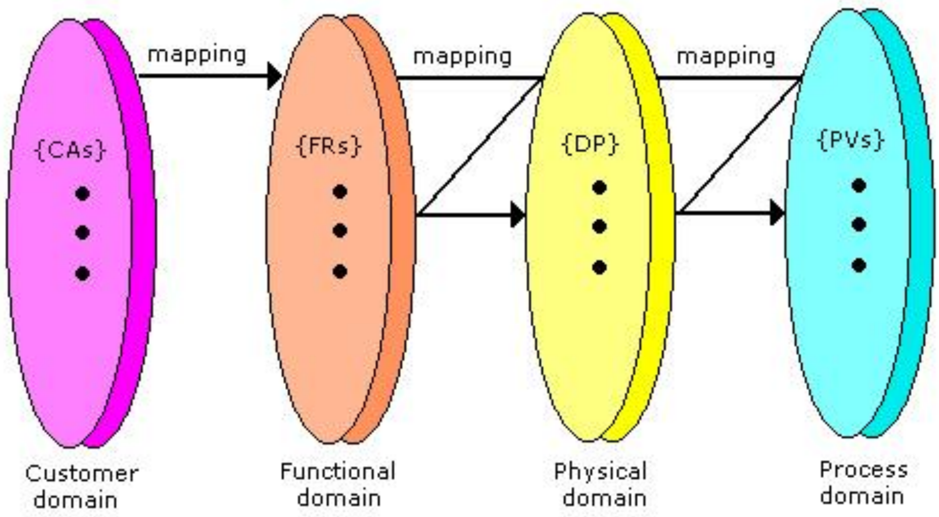

Fig.1: The Axiomatic Design Framework

The physical and process mappings can be expressed mathematically as

$$\{FR\}_{mx1} = [A]_{mxr} \{DP\}_{rx1}$$

$$\{DP\}_{rx1} = [B]_{rxn} \{PV\}_{nx1}$$

where $\{FR\}_{mx1}$ is the vector of independent functional requirements with m components, $\{DP\}_{rx1}$ is the vector of design parameters with r components, $\{PV\}_{nx1}$ is the vector of process variables with n components, A is the physical design matrix, and B is the process design matrix.

Axiom 1 implies that [A] should be either a diagonal matrix or triangular matrix.

After satisfying the Axiom 1, design simplicity is pursued by minimizing the information contents per Axiom 2, where the information content is defined as a measure of complexity. One popular measure of information content is entropy [18]. FRs' entropy is related to the probability of satisfying its specification in the physical mapping (the DP in the process mapping) [5,10].

Entropy and Information content can be mathematically expressed in different ways; the more useful measures are those that evaluate the probability of meeting design specifications, which is the area of intersection between the design range 'dr' , (design specifications) and the system range 'sr' , (process capability). The overlap between design range and system range is called the common range 'cr'. The probability of success is defined as the area (probability) ratio of the common range to system range, i.e. the common measures are based on the logarithmic function: in probability, the information related to an event of probability p is $I = \log_2 (1/p)$; on that concept, we based our Information content evaluation [5,10].

When we formulate the Information Content for the Fuzzy Design approach we can declare that its measure is based not only on the "process capability", but also on the "agreement index" that express how much a DPs value has the capability to achieve a desired FRs value.

Methods of measuring the coupling strength

In order to overcome the shortcoming of the binary design matrix in Axiomatic Design, wherein the dependencies between FRs and DPs are shown as binary measures, an effective method for extracting the quantifiable measure of couplings is needed.

Three methods that are capable of transforming qualitative information into quantitative measures have been analysed: fuzzy techniques, utility theory, and analytic hierarchy process.

The fuzzy theory has been applied to many areas such as control or decision making, and explores the degrees of membership in extension to the binary properties of membership or non-membership in traditional set theory models(Liang and Wang [7] for site selection and personnel selection, Ghotb and Warren [19] for Hospital information system, Naddeo and Cappetti [8] for mechanical topology optimization, Antonsson [13] for automotive structural optimization).

Utility theory has its strength in multi-criteria decision problems. It is a method for assessing the worth of a particular alternative that a decision maker makes during the decision process(Von Neumann and Morgenstern [4], Savage [20] and Keeney and Raiffa [21] explained some different examples of the use of this theory.

The Analytic Hierarchy Process (AHP) method developed by Saaty [22,23] is capable of prioritizing qualitative information using a pair wise comparison technique. It has been demonstrated to be a suitable method for the selection of the functionally most appropriate components of technical systems. AHP has been applied to various areas of multi-criteria decision and conflict solving problems showing the power of the method. It enables the evaluation for comparison consistency and it does not require the explicit unit for the attributes or criteria. AHP method for evaluating coupling strength and for implementing decoupling method was utilized by Su, Chen, Lin [16] with good results.

In our paper Fuzzy Logic shows to be the best method to be applied.

Decoupling idea based on membership function analysis

Our research starts from a basic hypothesis: relationships between FRs and DPs have to be considered as flexible. In fact, concepts about coupled, decoupled and uncoupled design are often formulated without considering the real influence of the design parameters on requirements.

When we have to choose among several different design solutions, it is very useful and interesting to measure the accordance of a design solution to the FRs using a fuzzy membership value. The problem we've used for testing our method is the following: "We have to design a new car bonnet".

Problem analysis takes us to define the following FRs:

FR_1 = Style; FR_2 = Accessibility to the engine compartment; FR_3 = Pedestrian safety.

A stylistically pleasant shape for our bonnet is a must for the front of the car because it affects the aesthetic pleasure, the driver visibility and the aerodynamic property; Our bonnet has to be designed in order to allow the access to the under-bonnet compartment, for maintenance for a front wheel drive vehicle and for loading and unloading operation for a rear wheel drive (rear engine) vehicle;

Pedestrian safety is also to be taken into account by vehicle designer because since 2005 all vehicles have to pass the Pedestrian tests for evaluating the aggressiveness of the front of the vehicle towards pedestrians for being homologated (in Europe).

These are the Design Parameters we have defined for the bonnet:

DP_1 = Stiffness; DP_2 = Shape;

DP_3 = Opening system (opening compound levers and safety opening hook mechanism).

As we can see in the following Fig.2, a car-bonnet is constituted by an external skin (a), a reinforcement frame (b) and an opening system (compound levers and safety opening hook mechanism) (c). External skin sketches the bonnet shape; the reinforcement skin gives to the bonnet the required stiffness; compound levers and hook mechanism allow to open the bonnet, when needed, and to lock it during the drive.

The definition of the relationships between FRs and DPs is made through these statements:

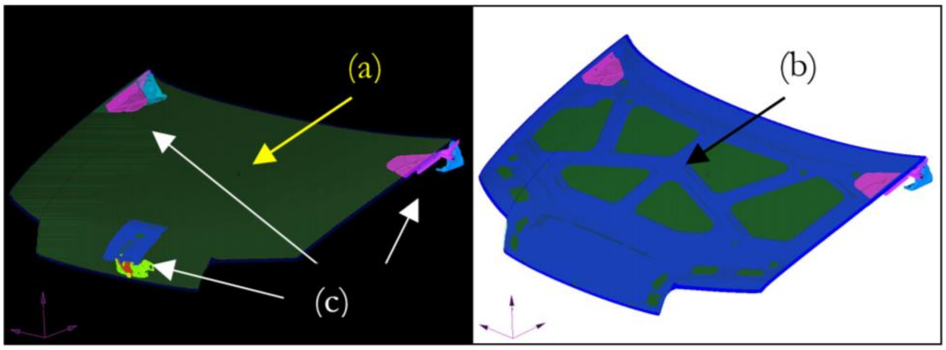

Fig.2: Car-bonnet

The style is obviously influenced by the bonnet shape; the opening system is always positioned under the bonnet but we have to pay attention in hiding the compound levers and the hook for industrial-design reasons; levers and hook have to be also well constrained with the car-frame in order to avoid interferences with other sheet metal parts. Bonnet stiffness is due to reinforcement-frame shape and does not affect bonnet aesthetic. Accessibility to the engine compartment is affected by position of compound levers and also by shape and dimension of the bonnet; the bonnet has to be so stiff that it can support itself, independently from the way to assemble it with the other car parts; the stiffness does not affect the accessibility. Pedestrian safety is obviously affected by all DPs considered because the impact of the head of pedestrian may happen in several different parts of the bonnet, and injuries to pedestrian are seriously dependent by the local bonnet stiffness (the compound lever zone and the hook zone are the hardest for pedestrian impact).

Taking into account the statements, the Design matrix can be expressed as follows:

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{Bmatrix} = \begin{bmatrix} 0 & X & X \\ 0 & X & X \\ X & X & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{Bmatrix} \tag{2}$$

The Design is coupled!

It is evident that the concept of "coupled design" has to be investigated by finding a procedure that allows to compare how much DP_i affects FR_j; it is also important to check if there is a particular sub-domain (in DP functional domain) in which we can choice a DP value without affecting the FR value so that a coupled design problem can became a good-constrained, decoupled design. The fuzzy approach allows to establish a coupling measure that allows to evaluate not numerically quantifiable parameters [8,14]. The first step, starting with Fuzzy approach, is the detailed analysis of the relationship between FRs and DPs for evaluating the "satisfaction" value of the proposition "the bonnet is FR_i" for each FR, on the DPs domain. The satisfaction value has been expressed by the value of membership, whose mean was before explained, to the Fuzzy set individuated for the evaluated proposition.

Our coupled design matrix, expressed by membership function, becomes the following:

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{Bmatrix} = \begin{bmatrix} 0 & 1-mf_{12} & 1-mf_{13} \\ 0 & 1-mf_{22} & 1-mf_{23} \\ 1-mf_{31} & 1-mf_{32} & 1-mf_{33} \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{Bmatrix} = \underline{MF} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{Bmatrix} \qquad (3)$$

If a weak-dependence between a FR and a DP exists, it is expressed by a mf_{ij} like a trapezoid one, for which the "satisfaction range" is wider when the dependence between FR and DP is lower. We have underlined that if, for example, the safety opening hook mechanism is mounted under the bonnet, the aesthetic satisfaction does not change when the joint position and the hook type varies, while the accessibility to the hook varies: that membership function is expressed by the following fig.3. It is evident that since mf_{ij} are defined, we have quantified the dependence between DPs and FRs, but we can encounter three kinds of possibilities:

1. when a mf_{ij} has a value identically equal to zero (0) then the FR_i cannot be never satisfied, so we have to redefine the DPs values
2. If a DPs range for which the membership function is equal to one (1) exists, then the correspondent member of the design matrix became zero: that value means that we can choose, in that range, what value we want for DP_i without affecting the $FR_{k \neq I}$ eventually DP_i dependent.
3. If mf_{ij} has a value too different from 0 or 1 we come back to the original coupled design matrix.

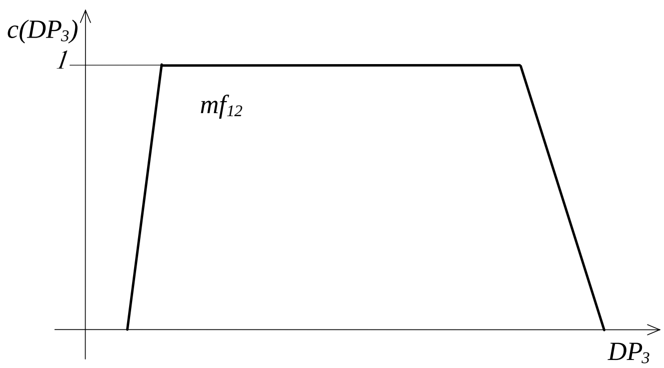

Fig.3: mf_{12}: almost all solutions with under-bonnet hook have high aesthetic satisfaction

Basing our reasoning on what we have considered, we can generally follow those steps:

1) Individuation of FRs
2) Individuation and choice of DPs
3) Design matrix building

4) mf_{ij} definition for each couple FR_i - DP_j
5) Elaboration of MF matrix
6) Individuation of decoupling DPs range (i.e. DPs range in which for one DP_i all the mf_{ij} , with $i \neq j$ has value equal to 1)
7) Definition of Fuzzy constraints on DPs domain
8) Fuzzy decoupling of the problem and re-organization of Design Matrix
9) Defuzzyfication of the problem and transformation of DPs domain constraints in physical constraints
10) Compatibility verification of Physical constraints with Design goal and development.

Another powerful method we can use, accepting a weak approximation (that is a natural way to operate in Fuzzy set definition), is the widening of "fuzzy independence ranges" by α-cut operation: the α-cut allows to consider as satisfactory the solutions for which all the mf_{ij} , with $i \neq j$ have values greater than a value α, lower than 1, chosen by designer. For example, if you see the Fig. 4, for mf_{ij} , with $i \neq 1$ independence range increase itself form [DP_{min}-DP_{max}] to [$DP_{\alpha min}$-$DP_{\alpha max}$], simply using the α-cut operation. This approach can allow to define a right sequence of optimization of FRs: if we consider a different value of α_i for each DP we can diminish each α_i since each DP affects only one FR. Repeating that procedure for each FR we can obtain the ideal optimization sequence and so a decoupled design.

In the "bonnet design" problem, the design steps 1), 2) and 3) of procedure were been yet explained; the relationship between DPs and FRs were been defined through the one-expert method, asking to experts something about our problem; methods for constructing Fuzzy mf_{ij} are explained in scientific literature [6,15]. An example function has been created in order to depend only from one physical parameter for better explaining the method (even if, in real cases, the relationships are often more complex). In this work, the bonnet shape depends only on width, the opening system is defined only by the distance between compound levers and hook mechanism, the stiffness is calculated only using reinforcement frame material characteristics.

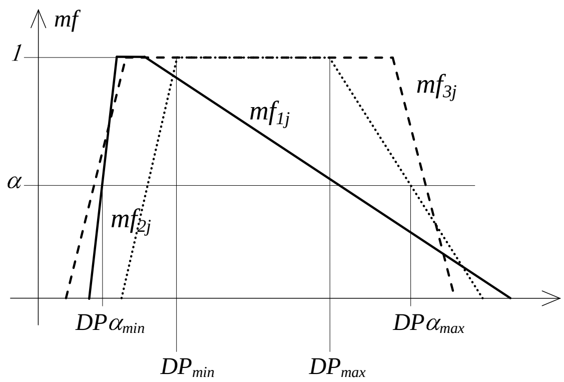

Fig.4: Membership functions and α-level cut

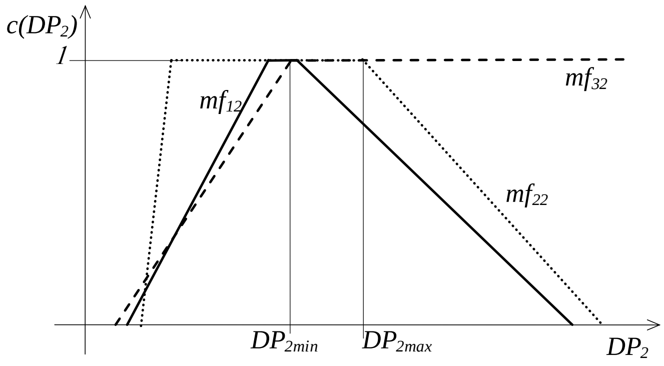

Fig.5: M.f. FRs-DPs

In the Fig. 5 are mf_{i2}:
- a bonnet is aesthetically satisfactory if it is not too small or too big (mf_{12})
- if its width is at least such as the engine one, it easily allows the access to engine compartment, but if the width is too big, the engine will be positioned too far from the bonnet frontal edge, so becoming difficult to reach (mf_{22});
- Pedestrian safety increases when the width is greater (mf_{32}).

Step 6, by analysis of the mf_{ij}, allows the definition of sub-ranges in which DPs can vary without changing the value of more than one FR.

In the Fig.4, dependencies' rules of several FRs in function of DP_2 have been described.

If we choose a DP_2 value in the range [DP_{2min}, DP_{2max}], chosen by individuating the max overlap between mf_{ij}, we can optimize the FR_1 without taking into account what happens to FR_2 and FR_3.

The same process can be made for DP_3, for which the range [DP_{3min}, DP_{3max}], in which it can vary without affecting the other FRs, can be defined.

After the seventh step (Fuzzy constraints definition), the problem becomes uncoupled with the following design matrix:

$$\begin{Bmatrix} FR_3 \\ FR_1 \\ FR_2 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ 0 & X & 0 \\ 0 & 0 & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{Bmatrix} \quad (4)$$

In which DP_1 is defined without constraints, $DP_2 \in [DP_{2min}, DP_{2max}]$, $DP_3 \in [DP_{3min}, DP_{3max}]$

Conclusions

Membership function values for FRs have the same meaning of the quantifying of the common range calculated as overlap of design and system ranges: when a DP value changes we can imagine that a variation of the probability distribution of design range change, with unaltered system range probability distribution, happens [3].

The FR value associated to a DP domain value, by membership function, wants to represent the agreement value (also called agreement index) and so the quantification, in Fuzzy domain, of the overlap between design range and system range.

The application of dependence concept, evaluated by Fuzzy logic, allows to operate with a rigorous method, if possible, in order to optimize coupled design for which is impossible to define an uncoupled or a decoupled version. The explained method allows improving the design objective simply evaluating good constraints for Design parameters.

The powerful of α-level cut has to be investigated because it can play a fundamental role in design development and optimization; it will be explained in the future works.

Finally, the Fuzzy formulation allows us to quantify the Information content of a design solution using the membership values as the measure of common range between probability distributions, so evaluating the project also by second axiom [24].

References

[1] N.P.Suh, The principles of design, Oxford University press Inc. (1990).

[2] N.P.Suh, Axiomatic Design, Advances and applications, Oxford University press Inc. (2001).

[3] B. El-Haik, An Integer Programming Formulation For The Concept Selection Problem With An Axiomatic Perspective (Part II): Fuzzy Formulation, ICAD 2000, Cambridge, MA, June 21-23.

[4] von Neumann, J., & Morgenstern, O. (1947). Theory of games and economic behavior (2nd ed.). New Jersey: Princeton University Press.

[5] Pappalardo M., Information in metric space, Journal of Materials Processing Technology, Volume 157-158, Issue SPEC. ISS., 20 December 2004, Pages 228-231.

[6] G.J. Klir, B. Yuan, Fuzzy sets and Fuzzy Logic, Prentice Hall (1995).

[7] Liang, G., & Wang, M. (1991). A fuzzy multi-criteria decision making method for facility site selection. International Journal of Production Research, 29(2), 2313–2330.

[8] Naddeo, N. Cappetti, M. Pappalardo, A. Donnarumma, Fuzzy-logic application in the structural optimisation of a support plate for electrical accumulator in a motor vehicle, Journal of Materials Processing Technology, Volume 120, Issue 1-3, 15 January 2002, Pages 303-309.

[9] Dutta, Reasoning with imprecise knowledge in expert system, Information Sciences, No. 37, pp. 2-24, 1985.

[10] Naddeo A., Pappalardo M., Failure mode analysis using axiomatic design and non-probabilistic information, Journal of Materials Processing Technology, Volume 164-165, 15 May 2005, Pages 1423-1429.

[11] L.A.Zadeh et alii, Fuzzy sets and their applications to cognitive and decision processes, Academic press inc., 1974.

[12] H.J. Zimmermann, Fuzzy sets theory and its application, Boston (1985).

[13] K.L. Wood, K.N. Otto, E.K. Antonsson, Engineering design calculations with fuzzy parameters. Fuzzy Sets and Systems, Vol. 52, S. 1-20, (1992).

[14] A.Naddeo, Application of Fuzzy logic in design phase of car-platform for an electrical rear-wheel drive vehicle, Proceedings of the XII ADM, 5-7 September 2001.

[15] M.J. Scott, E.K. Antonsson, Aggregation functions for engineering design trade-off, Fuzzy Set and Systems, Vol. 99 (1998), S. 253-264.

[16] J.C. Su, S.G. Chen, L. Lin, A structured approach to measuring functional dependency and sequencing of coupled tasks in engineering design, Journal of Computers and Industrial engineering, vol. 45, 2003, pp. 195-214.

[17] U. Kaymak, H.R. Lemke, A sensitivity analysis approach to introducing weight factor into decision function in fuzzy multicriteria decision making, Fuzzy Set and Systems, Nr. 97, S. 169-182 (1998).

[18] Shannon, C.E. & Weaver, W. (1949) The Mathematical Theory of Communication. University of Illinois Press, Urbana.

[19] Ghotb F., Warren I., A Case Study Comparison of the Analytic Hierarchy Process and a Fuzzy Decision Methodology, The Engineering Economist, Volume 40, Issue 3, 1995.

[20] Savage, L. J. (1954). The foundations of statistics. New York: Wiley.

[21] Keeney, R. L., & Raiffa, H. (1976). Decision with multiple objectives: Preferences and value tradeoffs. New York.

[22] Saaty, T. L. (1980). Multi-criteria decision-making: The analytic hierarchy process. New York: McGraw-Hill.

[23] Saaty, T. L. (1990). How to make a decision: The analytic hierarchy process. European Journal of Operational Research, 48(1), 9–26.

[24] Naddeo A., Axiomatic design of a concept of car-platform for an electrical rear-wheel drive vehicle: a comparison with a fuzzy approach, Proceedings of ICAD2004, The Third International Conference on Axiomatic Design, Seoul – June 21-24, 2004.