**BUDAPESTI MŰSZAKI ÉS GAZDASÁGTUDOMÁNYI EGYETEM**
**Gépészmérnöki kar**
**Gép- és Terméktervezés Tanszék**

**Ph.D. Thesis Booklet**

# Application of the fuzzy based evaluation method in the mechanical design

**Attila Piros**

supervisor:
**Dr. Bercsey Tibor**

Budapest, 2012.

## 1. Introduction

Nowadays in the mechanical design process there are more and more complicated design variations exists. There are decreasing time is given to the engineers to adjust this high complexity variations to the concerning multi-level requirements. The application of the Digital Mock-Up (DMU) and the virtual simulations on it is the fruitful way to meet this new challenge. The computer aided design technology helps the engineers in the generation of the new design variations but the manual multi-aspect evaluation of these variations are getting more and more problematic.

The the fuzzy logic appears frequently in the field of the modern design evaluation processes as it showed in the following chapters. The fundamentals of the fuzzy logic is introduced by Zadeh in 1965. This logic can handle that cases when the conventional binary logic fails. The other advantage of the fuzzy logic, that the set-up and the work flow in this logic is very similar to the human thinking.

## 2. The short review of the literature

The development of the design methodology is pointed into the that methods which are applicable in the computer algorithms. There are many methods try to decrease the human factor in the design process [1][2][3][4]. One of the possible development ways is the methods which try to eliminate the human intuition by application of automated generation of the solutions [5][6][7][8]. These methods include the stochastic and the autogenetic ones [9][10]. All of these methods can only produce limited solution space because the initial parameter range is also limited. Therefore, criticism can be formulated as that the modern methods has not exploited the potential of today's computers capacity.

Any way we try to improve the procedures for finding the best solutions there is no garantee to find a good solution for all. The local searches can stuck in a local extremum [11]. The modern global optimum search methods (like Genetic Algorithms, Particle Swarm, Ant Colony, etc.) could not provide the total confidence of finding the global optimum [12][13]. A good resolution of this problem the evaluation of the whole solution space with evaluation of each separate solution [14][15]. The correspondence of the design to many different requirements could not be provide in each case. The multicriterial methods are also loaded with this mathematical problem [16].

The review of the concerning literature clearly shows that the fuzzy logic plays more important role in the modern evaluation methods. The fuzzy logic gives a good opportunity to apply the human thinking scheme in the process of evaluation [17][18][19]. As a criticism we can say that nowadays the fuzzy logic mainly used to evaluate the linguistic expressions but this logic could make more easier the mathematical evaluation of the other technical parameters. The fuzzy method enables the handling of both quantitative and qualitative measures and parameters. The performance of the fuzzy method is also important in case of processing the whole solution space. The fuzzy logic is applied in many areas the technical projects from the signal processing [20] thorough analysing the geological data [21] up to the mathematical handling of aesthetic requirements [22]. There are some application of the fuzzy logic exist in the field of the mechanical design. Usually this logic helps the evaluation of the different design variations [23]. Remarkable that the concerning literature uses mainly triangular or trapezoid-shaped fuzzy membership functions [24][25], but the application of the modern IT methods enables the handling of other type of the mathematical functions.

Although the fuzzy logic has found its place in the decision making and supporting systems, but the method needs to further development. In one side currently the fuzzy method needs too much human interaction and it causes unacceptable subjectivity. Eliminating this effect is an important goal in the future development [26][27]. On the other hand the current fuzzy methods are good to algorithms but the performance of these algorithms need improvements. An important aim is the better utilization of the available computer capacity in case of effective processing the large number of data [28][29][30].

## *3. The goals of the research*

The review of the concerning literature highlighted some shortcomings. One of these the rare application of the fuzzy logic in the elimination of the uncertainty from the mechanical design process. It is caused by the inadequate constrains of the application of this logic in the specific fields of the mechanical design. I have assumed at the beginning of my research that not only the triangle and trapezoid-shaped fuzzy membership functions, which prevalent in the literature, are applicable in evaluation of the design variants. In some specific cases different types of the mathematical functions are applicable in the description of the design requirements. The incorrect and incomplete information results further uncertainty in the design process. In case of the design of the drive chains makes uncertainty the lack of the proper information about the specific component. Many times the engineer has only partial information about the exact working of the component or he/she don't has any information about the relations among the parameters. This uncertainty makes the selection procedure harder and obstructs the finding of the best parameter combinations.

The other goal was in my research the justification for the assumption that the production and fuzzy evaluation of large number of design combinations in some cases can eliminate the need for direct human involvement in the creation of a suitable design.

To approve these assumptions the following goals were selected in the research process:

- Extension of the fuzzy logic into the field of the evaluation phase of the mechanical design. This extension includes the handling of the numeric base requirements.
- Problem and case oriented analysis and development of the shape of fuzzy membership functions connecting to the previous goal.
- Development of the method to simplify the working of the conventional, multi-stage fuzzy inference systems.
- Development of the fuzzy based evaluation method to help the automation of the mechanical design for configurations.
- Extension of this method to the field of parametric design.
- Verification of the research results by application of specific mechanical design projects.

## *4. Research methods in the dissertation*

The first stage of the research I analysed some industrial projects and categorized the design requirements and the derived criteria. After that I specified the shape of the fuzzy membership functions in the categories.

I studied more methods to aggregate the values of the fuzzy membership functions in the mechanical design process. I have compared the results of the geometric mean, conventional fuzzy inference system and the corrected fuzzy mean.

The last stage of the research I have justified the applicability of the corrected fuzzy mean based design method in finding the best solutions in the industrial projects. I compared the results of my method to the constructions designed by the participant engineers.

# 5. Results of the research

## 5.1. Analysis of the design criteria in complex mechanical design projects

Design processes today are more complex than ever. In many cases the designs coming out of these processes exceed the attainable quality of a simple engineering documentation. As a tendency, the designs need to meet such complex criteria system that in most cases they cannot be satisfied without creating a virtual product, i.e. a digital mock-up (DMU). Furthermore, it is usually not enough to have a DMU that meets all the requirements, but a whole range of virtual tests has to be made to check the adequacy of the designs.

Defining the product requirements and the appropriate product conception has a crucial role in the early design phase. Without these the product costs and the innovation process (time) increase, and quality (function) lowers. In the Frontloading phase lots of information is processed within a short period of time. Principal design decisions are also made in this phase. Moreover, 70-80% of the product and project costs can be defined at the beginning of the design procedure, when the costs of modifications are low and the chance to reduce expenses is high. All these requirements can be grouped from a completely different point of view, if the accuracy of criteria definition is our main focus. This kind of grouping points out the real difficulty of converting criteria into a mathematical formula. On this principle requirements can be put into three main and several subcategories:

- Purely quantitative:
  - Accurate numerical requirement: criteria that can be given with one number or a number range.
  - Precise feature: such a grammatical expression that gives a precise description of the required criterion.
- Mixed quantitative/subjective:
  - Reference-based: such a reference that makes the interpretation of the criterion obvious.
  - Relative: it can be compared with other criterion, thus becomes interpretative.
- Purely subjective:
  - Subjective: criterion can only be interpreted if the person or group setting the requirement is known.
  - Non-specifiable: with the current knowledge and means the transformation of the requirement into the design process is impossible.

In the dissertation I have defined in these categories the type of the applicable fuzzy membership functions and I have also proposed the acceptable limitations and conditions of the application.

## 5.2. Evaluation method based on the corrected fuzzy mean

I have developed an evaluation method to simplify the conventional multi-stage fuzzy inference process. My procedure is based on a novel aggregation of the fuzzy values which Corrected Fuzzy Mean (CFM) named. I have compared the results of my method to the results of the geometric mean and the conventional. Fuzzy Inference System (FIS). I have realized that my method is equal with the other two methods, but faster than the FIS and projects the result into a wider range than the geometric mean. Therefore the CFM method is well suited for the automatic evaluation algorithms.

The developed method only applicable in case of that kind of evaluation when all of the parameters have high importance and all of the evaluated results of these parameters have to reach a minimum requirement level. These basic criteria connected with logical AND in the evaluational process. This fact decreases the area of the application of my method but it have already has advantages in the evaluation of the basic design requirements. The fuzzy methods are based on three stages of the parameter evaluation, fuzzyfication of the input data, operations with the fuzzyficated values and finally defuzzyfication of the results of the internal operations. The fuzzyfication itself is a quite simple and fast operation, but the remaining phase of the fuzzy evaluation requires much more mathematical procedures and computer capacity. This fact was the motivation the introduction of a simplified operation in the 2nd 3rd and 4th phases of the fuzzy evaluation. By introducing the Corrected Fuzzy Mean (CFM) the fuzzy evaluation significantly shorten compared with the traditional fuzzy evaluation (FIS) (Fig.1).

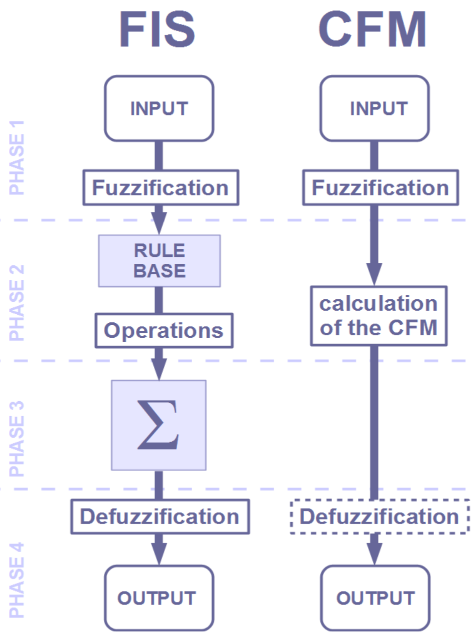


*Fig.1: Comparsion of the the FIS and the CFM method*

### *5.2.1. Calculation of the Corrected Fuzzy Mean (CFM)*

Introducing the corrected fuzzy mean (RFZ) there is a good opportunity to summarize as many results of the fuzzy membership function as it is required to evaluate the specific design. This *($R_{FZ}$)* value is much simpler to calculate than the traditional results of the fuzzy inference systems. The formula of this mean is the following without weighting:

$$R_{FZ}=\frac{u_{VAR\,1}\cdot u_{VAR\,2}\cdot\ldots\cdot u_{VAR\,n}}{\frac{\sum_{i=1}^{n} u_{VAR\,i}}{n}} \tag{1}$$

The formula of this mean is the following with weighting:

$$R_{FZ}=\frac{u_{VAR\,1}^{W'_{VAR\,1}}\cdot u_{VAR\,2}^{W'_{VAR\,2}}\cdot\ldots\cdot u_{VAR\,n}^{W'_{VAR\,n}}}{\frac{\sum_{i=1}^{n} u_{VAR\,i}}{n}} \tag{2}$$

### 5.3. Evaluation of the design for configurations

If the goal of the design process build from components with totally known parameters then this design process is a configurable design. The process work-flow displayed in the following image (Fig.2).

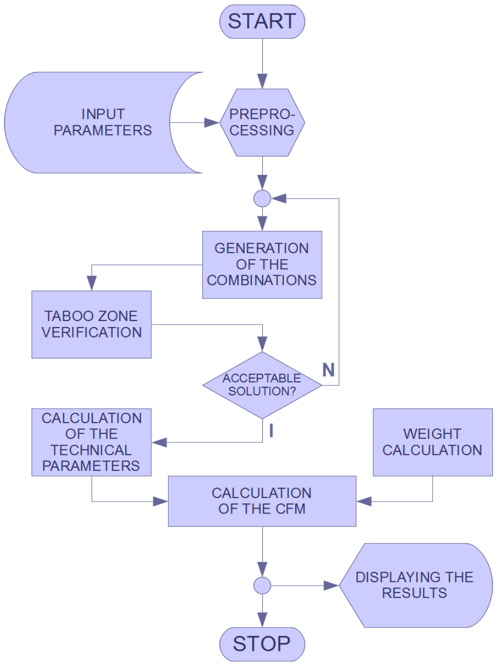


*Fig.2: Project workflow in the design for configurations*

The process itself is very similar to the other design processes therefore I only highlight the main differences. These differences are the followings: generation of the configurations, set up of the taboo zones, weighting the evaluating criteria, calculation of the quality values with fuzzy method.

#### *5.3.1. Generation of the configurations*

In the concerning researches the generation of the total solution space was the method to create each component configuration. The number of the combinations were between some ten thousands to more millions of results. The generation was calculated with the MATLAB software. Although this software is not specialized to the fast calculations but the performance of the MATLAB was good enough to perform these operations. Usually the creation of the millions by millions matrices last only some seconds using the built in codes of the central processor. The continuous development of the computer hardware enables the evaluation of the larger and larger structures in the future. The case studies in the dissertation were limited, but the larger projects with more components might causes combinatoric explosion and that case needs special handling (application of initial estimations, different kind of cuts in the generation process, etc.).

In this stage all of the possible configurations are automatically generated to cover the whole design space. Generating means that the components are only paired without any tests. However, this generation procedure is quite fast, further evaluation requires many more related calculations. Using special prohibited areas (so called taboo zones) the number of possible valid sets are significantly decreased.

### 5.3.2. Declaration of the taboo zones in the solution space

These taboo zones could be defined in many ways. In case of configurable product design testing the compatibility leads to an obvious method to define these zones. Introduction of compatibility functions makes this kind of testing procedure really simple. A specific $CP_i(a_i,b_i)$ compatibility function is a logical function with the required parameters $(a_i,b_i)$ on its input. The function itself uses simple relations to decide on the compatibility of the given inputs:

$$CP_i(a_i\ b_i)=f(a_i\ b_i) \quad CP_i\in[0\,1] \tag{3}$$

### 5.3.3. Weighting and normalizing the properties

Weighting the properties is a good method to consider the boundary conditions of the design. These conditions could be the human preferences or construction related specialities. Both variant and invariant properties are initially weighted on a ten degree scale. After this initial set-up of the weights there are two different ways to normalize the weights.

In case of the parameter variant properties the weights are transformed to an $RW_{min}$ – $RW_{max}$ range. Further studies confirm that (0.5-1) range results the smoothest corrected fuzzy mean function. Two different ranges (0.8-1 and 0.2-1) were also tested but their results were more rough than the chosen one. A specific $W_{VAR\ i} \rightarrow W'_{VAR\ i}$ weight transformation is calculated with the following formula:

$$W'_{VAR\ i} = RW_{max} - \frac{RW_{max}-RW_{min}}{10}\cdot W_{VAR\ i}$$
$$RW_{max}=1 \quad RW_{min}=0.5 \tag{4}$$
$$1\leqslant W_{VAR\ i}\leqslant 10 \quad 0<W'_{VAR\ i}\leqslant 1$$

The invariant weights are normalized and distributed on the parameters' $P_{IV\ min}$ – $P_{IV\ max}$ range. Weighting and normalizing the parameter invariant properties are based on the following formula:

$$W_{IV\ j} = \frac{\left(\frac{P_{IV\ max}-P_{IV\ j}+1}{P_{IV\ max}-P_{IV\ min}}\cdot 9\right)}{10} \tag{5}$$
$$0.1\leqslant W_{IV\ j}\leqslant 1 \quad \left[P_{IV\ max},P_{IV\ min}\right]\in\mathbb{Z} \quad \mathbb{Z}: \textit{egész számok halmaza}$$

### 5.3.4. The fuzzy based calculation of the quality values

At the first step the $Q_{VARi}$ variant quality values must be calculated in each design configuration:

$$Q_{VAR\ i} = R_{FZ}(u_{VAR\ i}) \tag{6}$$

After these values are weighted with the $W_{IV}$ invariant weights to calculate the $Q_{UTi}$ united quality value:

$$Q_{UT\ i} = W_{IV\ i}\cdot Q_{VAR\ i} \tag{7}$$

The highest $Q_{UTi}$ value marks the best design configuration among the sets.

## 5.4. Evaluation of the parametric design process

The goal of the configurable design process to select that components from a given range which results a good configuration of the specific product. In case of parametric design the goal is to specify the parameter values of these components. In my researches I handled the parametric design similar to the configurable case and in this way I don't have to change the software code of the evaluation.

### *5.4.1. Introduction of the generalized mechanical functions*

During the conceptual design many different physical principles and mechanical functions are handled. The following section introduces a statistically based method to create mathematical models for these functions.

The statistically based model is established on analyses of the existing solutions. The aim of this method is to create a usable model without knowing the exact principles and the inside relations of the function. The method statistically analyses many instances and fits generalized functions to the results. The mathematical model is based on these functions. The different variations of a function are resulted by modifying this model.

In case if there is only one dimensional parameter that describes a property the creation of the generalized function is quite obvious (Fig.3).

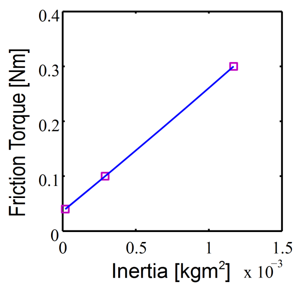


*Fig.3: Generalized 1-dimensional parameter*

The interpolation was performed by using of polynomial fitting:

$$y = p_1 x^n + p_2 x^{n-1} + \ldots + p_n x + p_{n+1} \quad (8)$$

Some of the parameters of the existing components are not one dimensional. The typical two dimensional properties are displayed in characteristic diagrams. The three dimensional extension of these diagrams results the generalized function for this case (Fig.4).

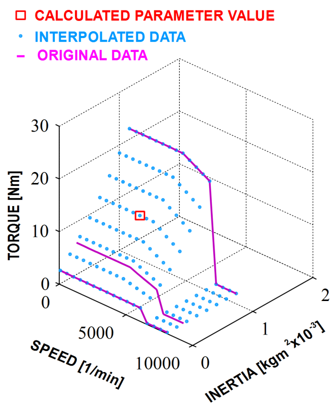


*Fig.4: Generalized 2-dimensional parameter*

The introduction of the generalized function/component models brings some new opportunities in handling the unknown parameter values. This mathematical method is founded on real data of realized functions. Therefore the calculated intermediate values are realistic. In this way the parameters of the optimized function are close to the realizable ones.

### 5.5. Evaluated case studies

Finally I have developed a MATLAB software to automatic search some partial solutions of the design process. The software will not replace the human creativity but it can help the engineers in the resolution of the subtasks. The set up of the software is very close to the way of the human thinking. I have applied this software in three different design projects and it was verified that the method is suitable for solving specific design sub-tasks automatically. In the first case study I have evaluated the result of the motion axis design in a large capacity tool magazine both in configurable and parametric ways. The second case study on a drive-train of the agricultural tractor was evaluated in terms of operating parameters in order to find a positive control. The last case study, the subassembly of a fusion power plant is investigated focusing on the layout of the maintenance aspects.

The first study was a typical case study of configurable product design. In this case the task is to select the linear drive system components for a robot. A schematic arrangement of a linear motion system is shown in Figure 4. The robot itself is integrated into a tool magazine. There are hundreds of milling tools stored in this magazine and the robot manages the tool transfer inside the magazine. In the selection procedure the following components are varied in case of three robot motion axes: linear guide with drive mechanism (5 types), gearbox (25 types), coupling (9 types), servo motor (11 types). Most of the parameters are obvious but some parameters required additional study to clarify the concerning fuzzy membership function. The final stage of this case the task was to find the appropriate parameters for the components of a linear drive system.

The first study was the fuzzy based evaluation of an engine – transmission combination. The evaluation is based on the investigation of engine a four-valve, turbocharged, intercoolered, low-emission diesel engine and a Steyr S-Matic infinitely variable transmission (IVT) unit. These components were integrated in a Case IH 195 Puma tractor. A modern tractor is one of the most important machine in the agricultural mechanization and its transmission system is a key component representing about 30% of the total tractor first cost.

In the third design project was the study of the component arrangement in the ITER fusion reactor. The ITER project aims to build a fusion device, twice the size of the largest current device JET, with the goal of demonstrating the scientific and technical feasibility of fusion power. It is a joint project between the European Union, China, India, Japan, South Korea, the Russian Federation and the USA. ITER will be constructed in Europe, at Cadarache in the southern part of France. ITER is expected to start operating in early 2020. The evaluation focused on the maintenance requirements of a specific module of the reactor.

## *6. Theses*

### Thesis 1.

[P-2008][BKNPR-2008][P-2009][P-2010-B][PB-2012]
The total generation of the solution space combined with fuzzy logic based evaluation is suitable to handling and eliminating of the uncertainties in the requirements and the criteria in the mechanical design process. The application of this method requires fuzzy membership functions with proper shape. In the dissertation there are three categories of the criteria studied (purely quantitative, mixed quantitative/subjective and purely subjective) and the concerning applicable fuzzy membership functions are defined.

### Thesis 2.

[P-2010-A][PB-2010-B][PB-2011-B]
I have developed a method to aggregate the values the fuzzy membership functions with low computational capacity. The introduced Corrected Fuzzy Mean (CFM) only applicable in case of that kind of evaluation when all of the parameters have high importance and all of the evaluated results of these parameters have to reach a minimum requirement level. These basic criteria connected with logical AND in the evaluational process. I have compared the results of my method to the results of the geometric mean and the conventional. Fuzzy Inference System (FIS). The comparison justify the applicability of my method in finding the best design parameters in the evaluating process.

### Thesis 3.

[PB-2010-A][PB-2010-C][PB-2011-A][FPBJ-2012][PF-2012]
I have developed a design method to support the configurable and parametric design. I have compared the evaluated results in the two cases and I determined that the compared results are well aligned and the method is capable of locating new good parameter values.

**3.a)** The whole solution space is generated and each solution is evaluated in this method. It is justified that the method can select the best solutions from the solution space in the evaluation the results of the configurable design process.

**3.b)** I have introduced the generalized mechanical functions based on the analysis of the components with same functions. The parameters of this model are interpolated on the known parameters of the analysed components. By using this model an extended study can be executed with discrete increments.

**3.c)** I have extended configurable resolution of the drive chain design into the parametric case. There is an opportunity to use of the non-realized intermediate parameters based on interpolation in the evaluation process. In specific cases the parameter range of the mechanical components can be extended with a small increment by using extrapolation.

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