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SUPPORTING MULTI-CRITERIAL DESIGN DECISIONS WITH FUZZY METHODS

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ABSTRACT: It is a tendency in today's design projects that the design has to be made within the shortest design time possible and with a criteria system more complex than ever. Although digital mock-ups and the virtual tests carried out on them help engineers, the evaluation of the results also needs remarkable energy and time. Therefore, it is essential to apply an evaluation method which can make numerous automatic design decisions based on requirements of different accuracy with minimal human interference. The application of fuzzy logic, already gaining ground in other fields of engineering, can be the solution for making difficult design decisions.
KEYWORDS: design, fuzzy logic

INTRODUCTION

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.

Since proper design decisions can only be made with the perfect interpretation of requirements, it is absolutely worth focusing on the analysis of the requirements. If one manages to classify the criteria and convert them to a mathematical formula, it will be easier to find a method on which an algorithm can be written, which can definitely support the design engineers' everyday work.

PRODUCT REQUIREMENT MANAGEMENT

Product engineering requires better methods, processes and computer solutions in the production process phase in which product costs can be influenced the most. This early phase is called Frontloading (Figure 1).

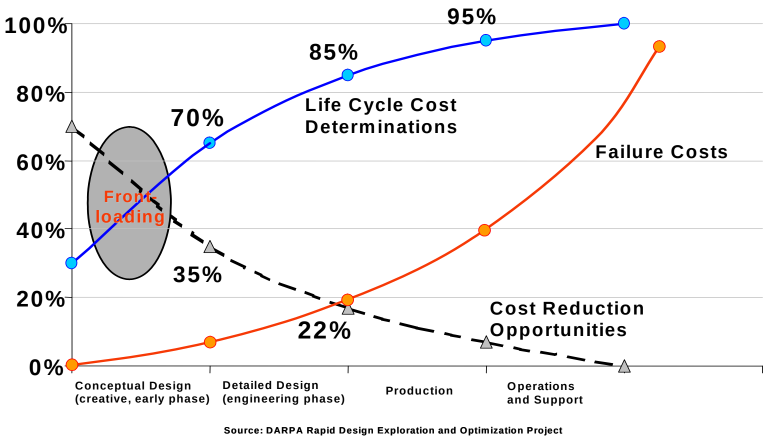

Figure 1: Frontloading

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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 [1], when the costs of modifications are low and the chance to reduce expenses is high.

Design criteria have a primary role throughout the whole design process. Formalizing the requirements takes place in the early phase. After specifying the criteria, they need to be categorized and the connections among them have to be defined (modelling). The resulting network clearly shows the interactions, influences and conflicts among the criteria. During the assessment of this requirement system various automated algorithms can be applied to support design decisions.

Product requirements can be grouped according to several criteria. The most important ones are the following:

- qualitative and quantitative
- internal and external
- explicit and implicit
- functional and non-functional

Qualitative requirements mean the product characteristics that cannot be described (i.e. do not make sense) with numerical value or parameters, e.g. aesthetic or waterproof, while quantitative requirements mean the product characteristics that can be described with numbers, such as equations or inequations.

External requirements are set by the customer or any other person outside the company, e.g. laws, TÜV regulations, whereas internal ones are given by the designer. Normally, internal requirements mean a company-specific directive, which refers to the certain product (shipping, storing requirements, etc.).

Explicit requirements are the unambiguous ones, the precise fulfilment of which is a basic condition of the design process. Implicit requirements can be originated from the laws of natural sciences and their boundary conditions.

The list of requirements primarily focuses on the functional and non-functional requirements of the product. Functional requirements tell "what" the product should know that will help the user solve a particular problem. Non-functional requirements tell how, how well or in what quality the system should provide a possibility or a group of possibilities. They are extremely important in terms of the success of the system. They can refer to the system as a whole, to certain parts of it or to specific functional requirements (e.g. qualitative, safety requirements).

In general terms, System Engineering (SE) deals with systems as the synergy of individuals, products and processes [2]. The task of SE is to transform design criteria into the design process, the method of which is Requirements Analysis (RA). According to SE, from a technical point of view requirements can be categorized in the following way:

- *User requirements*: requirements set by users.
- *Functional requirements*: include the necessary tasks, errands and activities, which characterise the operation of a system on the highest level.
- *Performance requirements*: specify the measurable value of the fulfilment of functions.
- *Design requirements*: criteria that are related to function development or the integration of already existing functions.
- *Originated requirements*: requirements on a lower level transformed from those on a higher level (e.g. the lightness of a product can be originated from a requirement that is quick and has a large range)
- *Allocated requirements*: lower level criteria derived from requirements of the highest level (e.g. mass of a certain unit calculated from the total mass allowed).

All these requirements can be grouped from a completely different point of view, if the accuracy of criteria definition is our main focus [3]. 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.

FUZZY METHOD FOR EVALUATING DESIGN CRITERIA

Several methods and software based on these are available to model criteria (Kläger, Rzehorz, Langlotz, Gebauer, Franke, Weber – Malmqvist, Das Kano-Modell, FMEA). The future development of the requirement-based design methods and their application has the following hindrances:

- It is difficult to write algorithms for the creative steps of design. Although the latter phases of design are based on these steps, they cannot be described with the use of even the most modern CAD systems.
- The continuous monitoring of design criteria changes is critical throughout the whole design process. It cannot be described with a static model how the requirements broaden as a result of a real-time iteration process, or how they are redefined in the development project. Therefore, the requirements cannot be attached directly to E-BOM.
- All steps of the design process have to be identified before completing the list of design criteria. It takes such a complex, fully comprehensive knowledge that the applied systems usually do not own.
- In many cases design criteria are vague or inaccurate at the beginning of the design process.
- The used design systems are not included in criteria management.
- Criteria are usually unrealistic.
- Requirements and specifications often vary.

The remaining part of the article introduces the application of fuzzy logic on different requirements grouped according to their accuracy. This method can perfectly be used for managing some parts of the above difficulties.

The previous section highlighted the fact that the design requirements are not always accurate and in many cases cannot be expressed with numbers. For these problems fuzzy logic is the best solution of all mathematical methods. Fuzzy logic is the logic of fuzzy sets. In this logic it can be defined with fuzzy membership functions how much a unit is member of the fuzzy set. As opposed to the traditional set theory, here particular membership can be defined on the basis of the blurred boundary of the fuzzy sets. The application of fuzzy logic has the following advantages:

- Possibility of managing vaguely defined criteria.
- Defining fuzzy sets and relating membership function is similar to schemes used in human thinking.
- Algorithms can be defined for fuzzy method without any difficulty, thus it can easily be implemented in digital design environment.

Since fuzzy logic also manages inaccurate cases, mixed quantitative/subjective and, under certain conditions, purely subjective criteria can be transferred into the design environment. In the next section the application of fuzzy logic will be demonstrated through two exceptionally complex design projects, in which the design requirements are of different accuracy.

SAMPLE TASKS FOR SUPPORTING MULTI-CRITERIAL DESIGN DECISIONS

In this section the application of fuzzy logic for supporting different design decisions is introduced through sample tasks taken from two complex design projects. The task in both projects was of such complexity that proper answers for the requirements could only be given with the help of digital Mock-ups and virtual simulations carried out on them.

One of the projects was the design of a unit of a fusion powerplant (ITER). Namely, the task was to design the components and the operations related to European tritium breading unit. Several special standards and regulations regarding the environment had to be taken into consideration throughout the project. The group of complex requirements provides numerous examples for the application of fuzzy-based assessment in practice.

The other project was making all engineering documentation of an electric car [5]. The car already had the power train system and axles designed, the body, the chassis and all necessary auxiliary units were newly designed (Figure 2). Besides, a number of virtual simulations were made in order to test DMU in as a wide range as possible. The simulations

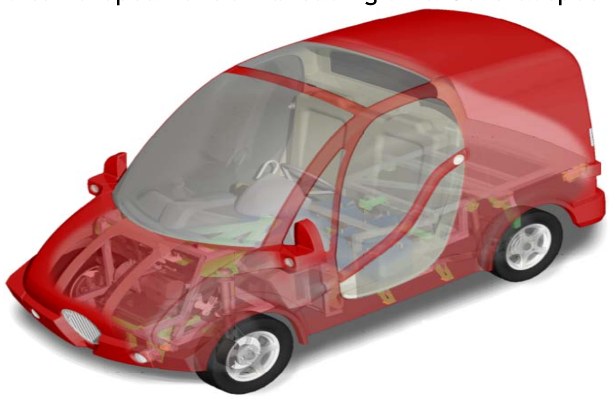

Figure 2. Digital Mock-Up of electric car

included FEA-, multi body- and CFD (Computational Fluid Dynamics) simulations, and ergonomic-, surface continuity tests. Also several photorendered images were made of the virtual product in different phases of the design work. As this was a project of the vehicle industry, many subjective criteria were present, the assessment of which would have been difficult without the fuzzy method.

Purely quantitative, numerical criteria

This kind of criteria is the most common in product design. It specifies that a certain number or a value range has to be corresponded with. Accordingly, two different types of fuzzy membership function can be applied to evaluate requirements.

In the first example the technical solutions for alignment of the two main blocks of the tritium breading unit have to be evaluated. The margin with which the two blocks have to be positioned is so narrow compared to the dimensions of the structure that the tolerance can only be zero in the percentage of the main dimensions. Therefore, only those solutions can be used which at least theoretically ensures absolutely accurate positioning (in practice no such solution is available due to the inaccuracies occurring during production). The fuzzy membership function can be given as follows (Figure 3).

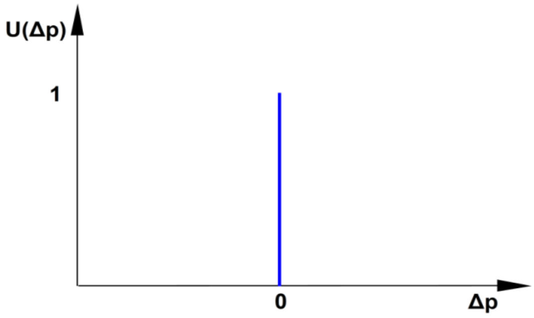

Figure 3. Fuzzy membership function to evaluate the position - U(Δp)

Δp: difference from the required position

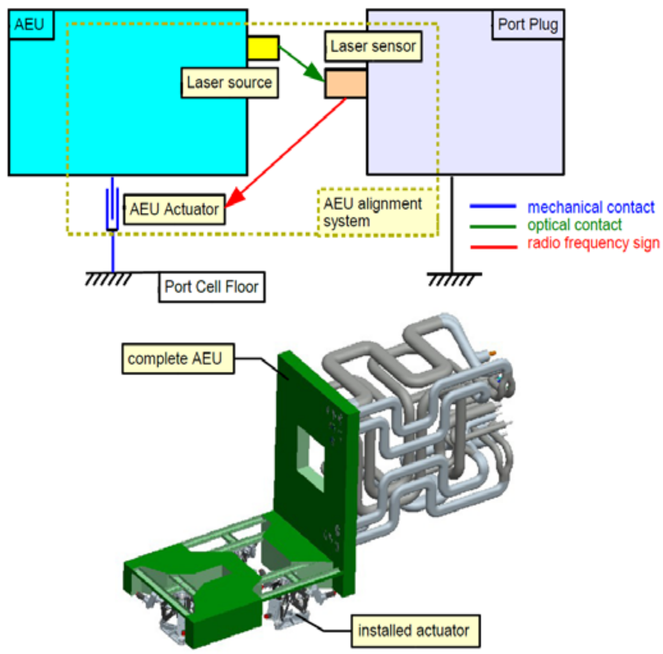

Figure 4. Selected positioning system

In this case every technical solution the misalignment of which does not correspond to the value given by the function, is ignored, i.e. is excluded from the set of acceptable solutions. In the current project a laser measuring based adaptive controlled positioning system was selected (Figure 4).

A typical requirement for specifying a value range is the one referring to the allowed total mass of a vehicle. Here the mass range into which the total mass should fit can clearly be defined.

Purely quantitative, textual criteria

A typical example of the above features is the type of applicable components. For the fusion power plant, the remote control of the necessary procedures was solved with the installation of an industrial robot. However, only an articulated industrial robot, which has at least 6 degrees of freedom, can make the required movements that are significantly limited in space (welding robots used in automotive industry are of this type). Therefore, the assessment of the robot type itself was the initial step at the first evaluation of the robots available in commercial trade. The relating fuzzy membership function has the same shape as the previous one.

Mixed quantitative/subjective, reference-based criteria

A standard referring to a certain design parameter is a typical example of the reference-based design specification. The above mentioned requirement referring to total mass exemplifies such criteria clearly (Figure 5).

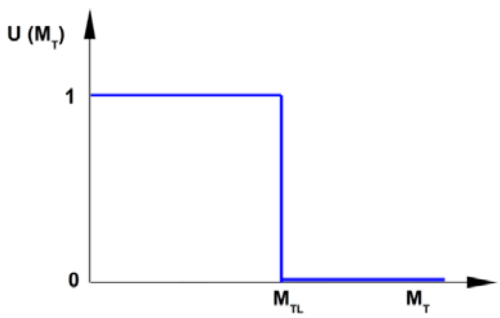

Figure 5. Fuzzy membership function to evaluate the total mass - U(M_T)

M_T: total mass, M_{TL}: allowable total mass

Mixed quantitative/subjective, relative criteria

Opposed to reference-based criteria, relative criteria do not compare the given parameter to a generally accepted and universally interpretable reference base, but to an arbitrarily selected reference, e.g. a former version of a product or a parameter or parameter range defined by a competitive solution. In what extent a certain parameter exceeds a reference value can also be an important viewpoint when evaluating relative criteria.

The final evaluation of the remote handle maintenance system of the fusion powerplant project exemplifies the assessment of relative criteria perfectly. In this case the total duration of procedures was compared with the procedures performed with direct human interference. Since the specialist can only enter the working area 10 days after the shutdown due to the fading of the neutron radiation, the reference in the evaluating function is this time (Figure 6).

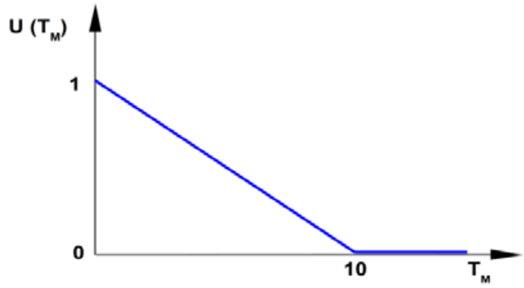

Figure 6. Fuzzy membership function to evaluate the maintenance system - $U(T_M)$ T_M: maintenance time [days]

Purely subjective criteria

It is difficult to assess this kind of criteria with mathematical means in unique cases, as the person setting the requirement has a significant influence on the evaluation of the requirement. Therefore, the person himself also has to be taken into consideration when defining the membership function. However, in the presence of a proper number of people, with considering statistic principles, a fuzzy membership function which models the sum of subjective criteria can be applied. It was one of the purposes in the electric car project to design a simple driver's area without setting options, which would mean an even ergonomically acceptable compromise to most of the drivers (Figure 7).

Figure 7. Study for steering wheel positions in the conceptual phase of the design

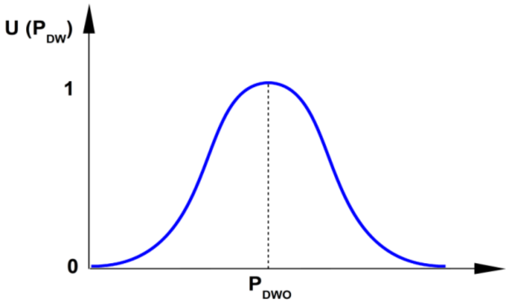

Figure 8. Fuzzy membership function to evaluate the position of the steering wheel - $U(P_{DW})$. P_{DW}: position of the steering wheel, P_{DWO}: optimal position of the steering wheel

The convenience of the layout is basically influenced by the position of the steering wheel. The results of evaluating the steering wheel positions in terms of convenience follow Gauss distribution, if the necessary number of samples is provided and if they represent the users precisely. The selection of the steering wheel position which is expectedly considered convenient by most of the drivers can be ensured with a fuzzy membership function of the following shape (Figure 8).

Purely subjective, non-specifiable criteria

Since no specification is available mathematical modelling is not possible. A good example of a non-specifiable criterion is the requirement for aesthetic appearance.

❖ CASE STUDY: CALCULATING THE UTILIZATION RATIO IN A LINEAR DRIVE SYSTEM

The next section introduces the fuzzy method for evaluating the servo motor utilization ratio in a linear motion system (Figure 8.). During the design of a linear motion system the selected servo motor must be evaluated from more aspects, like power, size, inertia ratio and utilization ratio. The proper evaluation of the utilization ratio helps to avoid selecting a motor too big for the given task, which leads to oversizing.

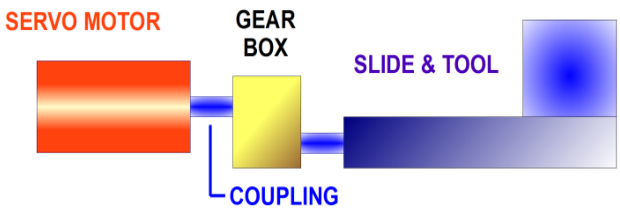

Figure 8. The arrangement of the linear drive system

The utilization ratio (U_R) is calculated as the ratio of the required acceleration torque at the motor side (T_{aM}) and the maximum torque of the motor (T_{mM}):

$$UR = \frac{T_{aM}}{T_{mM}}$$

The acceleration torque is calculated based on the required torque for constant velocity movement (T_{CL}), the required acceleration torque at the load side (T_{aL}) and the ratio of the applied gearbox (i_{GB}):

$$T_{aM} = T_{CL} + \frac{T_{aL}}{i_{GB}}$$

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The required torque for constant velocity movement is the power of the moved mass (m_L) and the gravity acceleration (g):

$$T_{CL} = m_L \cdot g$$

The calculation of the acceleration torque above is based on the following values: the speed of the motor (v_M), the time of the acceleration (t_a), the inertia of the motor (I_M), the calculated load inertia at the motor side (I_{RL}) and the efficiencies of the gearbox and the guide (η_{GB}, η_G):

$$T_{aL} = v_M \cdot \frac{2 \cdot \pi}{t_a} \cdot \left(I_M + \frac{I_{RL}}{\eta_{GB} \cdot \eta_G} \right)$$

The calculated inertia related to the moved mass (m_L), ratio of the guide (DPR_G) and the inertias of the gearbox and the coupling (I_{GB}, I_C):

$$I_{RL} = \left(\frac{m_L \cdot DPR_G}{2 \cdot \pi} \right)^2 + I_{GB} + I_C$$

The calculated utilization ratio can be handled as a mixed quantitative/subjective relative criteria, where value 1 marks the optimal utilization and values beyond 20 mean oversizing. The concerning fuzzy membership function is displayed in Figure 9.

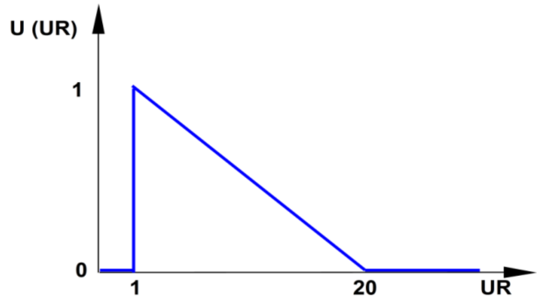

Figure 9. The fuzzy membership function for evaluation of the utilization ratio - U(UR)

❖ CONCLUSION - SUMMARY

It is a tendency in today's design projects that the design has to be made within the shortest design time possible and with a criteria system more complex than ever. Although digital mock-ups and the virtual tests carried out on them help engineers, the evaluation of the results also needs remarkable energy and time. Therefore, it is essential to apply an evaluation method which can make numerous automatic design decisions based on requirements of different accuracy with minimal human interference. The application of fuzzy logic, already gaining ground in other fields of engineering, can be the solution for making difficult design decisions.

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