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MULTI-CRITERIA DESIGN OF MECHANICAL SYSTEM BY USING VISUAL INTERACTIVE ANALYSIS TOOL

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Abstract

Nowadays, to design any mechanical system the engineer needs to analyse and evaluate among many criteria such as production cost, geometry, manufacturing technology, etc., which forms the terminology of multi-criteria design. In this paper, the design based on the product lifecycle management concept was proposed. A Visual Interactive Analysis Tool (VIAT) was used to deal with a model based multi-objective optimization including many parameters-variables, constraints and objective functions or criteria in the design process. In virtue of VIAT, both of engineer and related experts in the concerned system are able to perform analysis and evaluation, if there are inconsistencies, they can discuss openly before making a decision on the design option for the object. VIAT is a practical and user-friendly tool for the multi-criteria design of the mechanical system.

Keywords: Mechanical system, Multi-criteria design, Multi-objective optimization, Product lifecycle management, Visual interactive analysis tool.

1. **Introduction**

Up to the present moment, all kind of mechanical systems (equipment, tools, etc.) have played a crucial role in our life. In fact, it has still been a big challenge for every engineer and expert in the field to design them. Currently, the design might be carried out by one of the following manners [1-3]:

- Conventional method: first it needs to select technical parameters based on mainly experience, and then check them whether they comply with the requirements or not. In practice, this manner is the most commonly used due to the limitation of budget and manpower for design at many institutions and small companies, however, if the design based on experience is not suitable in the manufacturing process, manufacturers will be very confused in looking for the alternatives.
- Design based on single-objective optimization: it focuses mostly on optimizing a particular demand of the client such as production cost, or geometry, or productivity, etc. Nevertheless, if the client requires those criteria simultaneously, this manner will not meet the requirements.
- Design based on multi-objective optimization or multi-criteria design: it focuses on optimizing multi-criteria, for instance simultaneously production cost, geometry, and productivity; thus, this manner seems to be the best option for design engineers, though it has not been common-used yet in practice rather than at research institutions and very large companies. The reason is generally due to the fact that currently there is not a practical and user-friendly tool used for multi-criteria design.

On the other hand, the design organization, i.e., the way how to unite numerous experts in the mechanical system, is also a concerning topic. Frankly speaking, it is truly useful for the creation of any product if there are contributions of knowledge and experience from different professionals or experts. However, it is actually hard to settle them work together because every expert owns different conception, bias, and view on the significance of technical factor. Statnikov et al. [4] explained that even sometimes their opinions on the same fact might be contradictory. According to Saaksvuori and Immonen [5], the idea of united experts for a good reason can be carried out by using the product lifecycle management concept. Doing so, if there are inconsistencies among experts, they will be described by a mathematical model based on multi-objective optimization and the resultant mutually-agreed solution will relieve these issues. As a result of that, the objective of this paper is to propose the idea of product lifecycle management with the aim to deal with the multi-criteria design of the mechanical system. Besides, a visual interactive analysis method is used for the solution search and decision-making process occurred smoothly.

2. Multi-Criteria Design Solutions for Mechanical System

Traditional approach

When the design is carried out by the traditional approach, a chief engineer needs to acquire concept, knowledge, experience and useful data from other members in the design team especially experts, as shown in Fig. 1. Based on this, he develops a mathematical model based multi-objective optimization including parameters-variables, constraints and criteria or objective functions. To deal with this problem, he first has to determine weight coefficients of objective functions depending on

criteria significance. Then, all of the objective functions are converted into an equivalent single-objective function by mean of numerous techniques such as weighted minimax (maximin), compromise programming, weighted Sum, modified Tchebychev, weighted product, exponentially weighted sum, etc. The terminology "convolution" presents the above-mentioned conversion technique in a general form, for instance, in case of weighted minimax (maximin) method $convolution = \max_i \alpha_i \left[\Phi_i(\mathbf{x}) - \Phi_i^0 \right], i = 1..M$, for weighted sum method convolution $= \sum_{i=1}^{M} \alpha_i \Phi_i(\mathbf{x})$, and for weighted product method $convolution = \prod_{i=1}^{M} \left[\Phi_i(\mathbf{x}) \right]^{\alpha_i}$, etc.

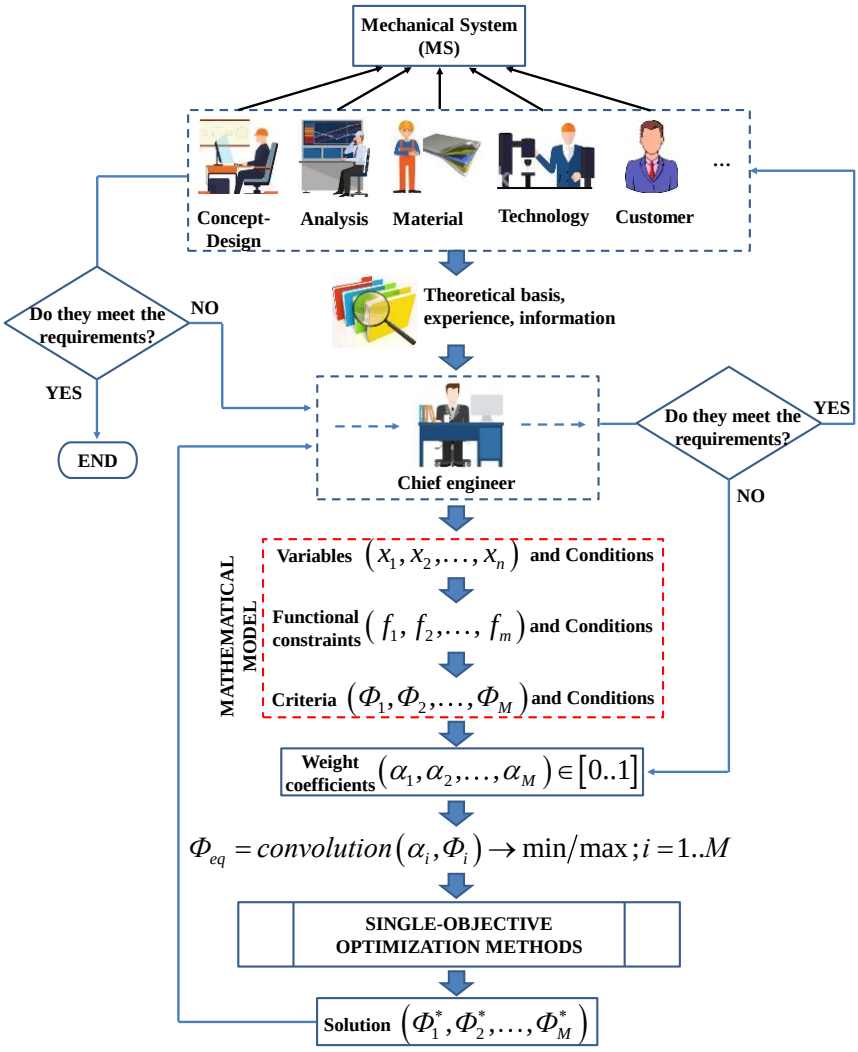

Fig. 1. Scheme of multi-criteria design based on traditional approach.

On the other hand, in order to find the extreme (min-max) of the equivalent function, several methods can be used including direct search-descent methods, genetic algorithms, particle swarm, etc., [1, 6]. By using these methods, the result of the single-objective optimization can be obtained, and consequently, values of initial objective functions $\left(\Phi_1^*, \Phi_2^*, \ldots, \Phi_M^*\right)$ can be pointed out. At this moment, the engineer has to analyse whether these values comply with the requirements or not; if not, he could modify the weight coefficients of objective functions and make a calculation again up to the moment that there are desirable solutions; if yes, he would send the results to experts in every field related to the concerned mechanical system to analyse thoroughly. With feedback from the experts, he needs to correct the model or conduct another optimal solution search.

An approach based on product lifecycle management concept

Since the traditional approach presents several drawbacks, a multi-criteria design based on the product lifecycle management concept can be used, as the illustration is given in Fig. 2. Looking into this figure, right at the first step every issue in the lifecycle of the mechanical system is specified, arranged and given to an expert in the field. Doing so, the system is studied by all of the related experts properly and consistently [7].

Unlike the previous approach, the model based multi-objective optimization is developed openly by the experts instead of the chief engineer on his own. Then, a Visual Interactive Analysis Method (VIAM) is applied; indeed VIAM in the form of software tool allows them to examine the parameter space that expressed in determined ranges and existence tendency of valid solutions. At the same time, they are also aware of constraints and objective functions or criteria of the concerned mechanical system [8, 9].

It is important to note that by this approach to define parameter space, constraints and objective functions is not a simple task at the beginning due to varieties of experts' views on the same fact. The virtue of VIAM is that when the experts modify any determined range, the corresponding output results will yield automatically and almost instantly.

If the outcome does not comply with the experts' requirement, by using the software tool they could keep adjusting the ranges up to the moment that there are a valid result and the process finishes. Notably, all of these occur in real-time in front of the experts, consequently, all of them together analyse the results in the discussion before making a decision. In case there is no mutually agreed solution, the tool would let them know, which criteria or determined range of parameter and constraints are the reason for solution nonexistence.

Afterwards, in the dialogue, each of them needs to analyse thoroughly in accordance with all of the data such as valid ranges in order to decide whether to keep his opinion on criteria significance or change it. Besides, the tool is also able to plot interactive graphs to illustrate the relation of criteria and parameter or others, which efficiently support the experts in the analysis process. Definitely, the VIAM tool provides a piece of useful information about design object that helps the experts to make a decision.

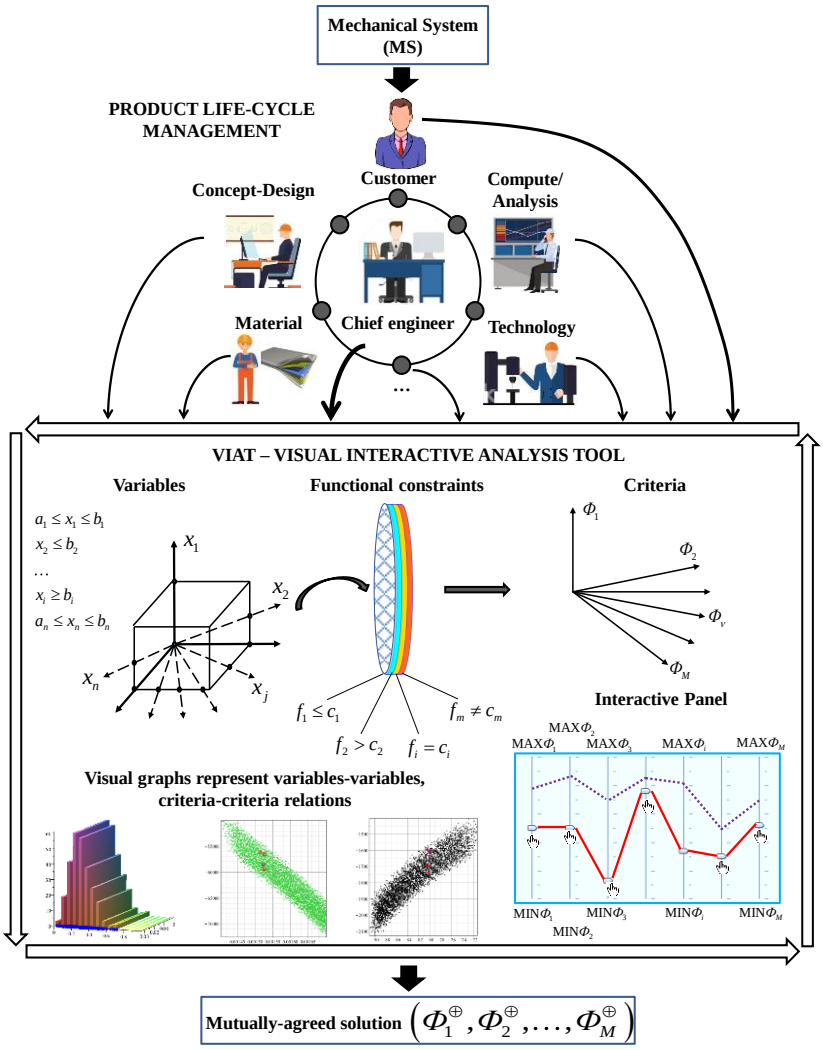

Fig. 2. Scheme of multi-criteria design based on product lifecycle management concept.

3. Toolkit for Multi-Criteria Analysis

Podinovskaya and Podinovski [10] and Podinovski [11] proposed to illustrate a multi-criteria design based on the product lifecycle management concept, an algorithm scheme on the basis of successive concession method and the parameters space investigation method [4]. This approach is named as a visual interactive analysis method or VIAM. The difference between VIAM and successive concession method is an interactive panel. This panel shows data on a feasible range of objective functions and mutual influence among them, thus, the expert could select the appropriate design solution. Besides, VIAM is more effective than the parameter space investigation method because the latter requires a lot of test-points (thousand, even million), which in turn it is time-consuming.

3.1. Details on the algorithm

The main idea is to use the single-objective optimization techniques as a device to find valid solutions. The detailed steps in the solution search are described in Figure 3. Looking into this figure, the model {1} is the first step, hence, it is necessary to optimize the vector $\langle \mathbf{\Phi} \rangle$ of M criteria with the parameter vector $\langle \mathbf{x} \rangle$, as well as the constraints $\langle \mathbf{f} \rangle$ (where, $\mathbf{x} = \{x_1, x_2,\ldots, x_N\}$, $\mathbf{f} = \mathbf{f}(\mathbf{x}) = \{f_1(\mathbf{x}), f_2(\mathbf{x}),\ldots, f_K(\mathbf{x})\}$, $\mathbf{\Phi} = \mathbf{\Phi}(\mathbf{x}) = \{\Phi_1(\mathbf{x}), \Phi_2(\mathbf{x}),\ldots, \Phi_M(\mathbf{x})\}$).

The condition of parameter vector $\langle \mathbf{x} \rangle$ is as follows: $a_i \le x_i \le b_i$; $a_j \le x_j$ or $x_k \le b_k$ ($i, j, k \in [1; N]$); while, the condition of constraints $\langle \mathbf{f} \rangle$ is as follows: $f_l(\mathbf{x}) \le 0$; $f_m(\mathbf{x}) = 0$; $f_n(\mathbf{x}) < 0$ or $f_o(\mathbf{x}) \ne 0$ ($l, m, n, o \in [1; K]$). Next step {2} is to use single-objective optimization algorithms [1] to determine the minimum and maximum values or min Φ_i and max Φ_i, respectively, of every objective function, and include these values into an interactive panel. To make it more user-friendly, the optimal trends are provided with top-down order (from MAX to MIN). The function, which needs to be maximized, is assigned with a negative sign. This panel helps the experts to analyse and make a decision on the outcome. In case, the final solution is a vector $\mathbf{\Phi}^{\oplus} = \left\{\Phi_1^{\oplus}, \Phi_2^{\oplus}, \ldots, \Phi_M^{\oplus}\right\}$, i.e., $\Phi_i^{\oplus} \in \left[\mathrm{MIN}\Phi_i; \mathrm{MAX}\Phi_i\right]; i = 1..M$.

Based on the panel in step {2}, the experts define a priority order for criteria or objective functions, for instance in {3}: $\left\{\Phi_1 \mapsto \Phi_2 \mapsto \ldots \Phi_M\right\}$. Accordingly, it needs to optimize firstly the objective function Φ_1 (step {4}) and the optimal value $\mathrm{MIN}\Phi_1$ is used for further steps. However, while setting a goal for Φ_1 is such superior, the obtained solution for other functions might be inferior and out of requirement. In this case, the experts need to adjust the range of Φ_1, and set its value with a threshold $\left[\Phi_1\right] = \mathrm{MIN}\Phi_1 + \Delta E_1$ (with the deviation $\Delta E_1 > 0$). If so, among the obtained solutions that $\Phi_1 \le \left[\Phi_1\right]$, there might be the most favourable option for other objective functions. While searching the optimal value for other objective functions $\min \Phi_i^1$ (i=2…M), it needs to add the constraint $\Phi_1 - \left[\Phi_1\right] \le 0$. Notably, the upper index "1" implies that these are the minimum values of the rest objective functions when the threshold $\left[\Phi_1\right]$ is concerned. Since there is a constraint $\Phi_1 \le \left[\Phi_1\right]$, range values of objective functions are shrunken (Fig. 3), i.e., $\min \Phi_i^1 \ge \mathrm{MIN}\Phi_i$ {5}. Then, the value $\min \Phi_i^1$ (I = 2…M) needs to be studied by the experts, because there might be a situation that these ranges are invalid or they do not comply with the expert requirements. This is an advantage of VIAM that it checks the effect of $\left[\Phi_1\right]$ on all of the rest functions, while the successive concession method only considers how the $\left[\Phi_1\right]$ influences on Φ_2. If so, the threshold $\left[\Phi_1\right]$ needs to be modified again to resolve the step {5}. While, in the case that these values $\min \Phi_i^1$ comply with the requirement, similarly the experts

set a threshold $[\Phi_2] = \min \Phi_2^1 + \Delta E_2$ for the objective function Φ_2 (with the deviation $\Delta E_2 > 0$) with the goal to optimize the succeeding functions (step {6}).

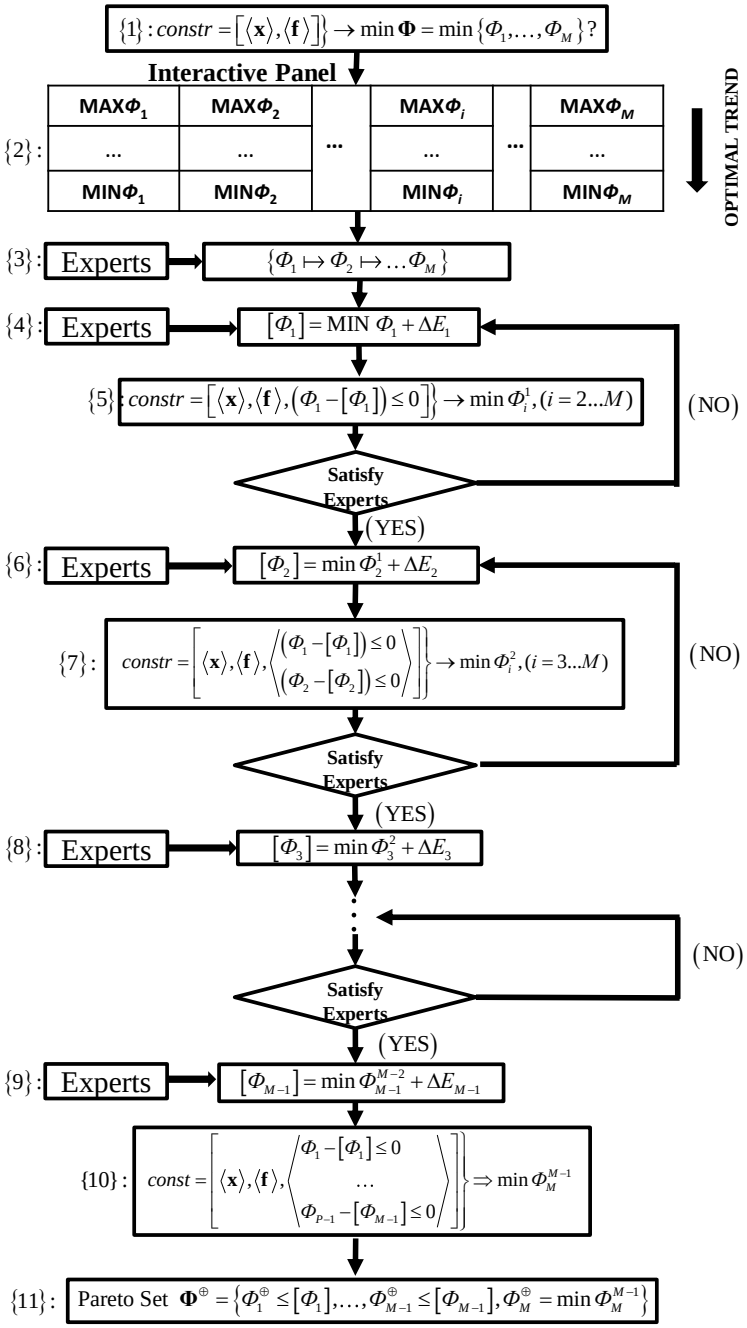

Fig. 3. Algorithm of visual interactive analysis method.

While searching the optimal value for other objective functions $\min \Phi_i^2$ (i=3…M), it needs to add two constraints $\begin{cases} (\Phi_1 - [\Phi_1] \le 0) \\ (\Phi_2 - [\Phi_2] \le 0) \end{cases}$ (step {7}). By the same manner, the experts set a threshold $[\Phi_3] = \min \Phi_3^2 + \Delta E_3$ (step {8}), and so on there are a series of thresholds $[\Phi_1], [\Phi_2], ..., [\Phi_{M-1}]$ for the first (M-1) criteria (step {9}). Based on (M-1) constraints of the corresponding threshold and necessity of minimizing M^{th} criterion, eventually, the mutually-agreed solution with a desirable priority order can be achieved (step {10}). The obtained result $\mathbf{\Phi}^{\oplus} = \{\Phi_1^{\oplus}, \Phi_2^{\oplus}, \ldots, \Phi_M^{\oplus}\}$ is the best mutually-agreed solution ({11}), which means that there is no better solution for all of the functions simultaneously.

It is important to note that currently there are plenty of the single-objective optimization methods available, hence, which one being effectively used in VIAM depends on the mathematical model of particular objects.

3.2. Example of an interactive panel with four criteria

Based on the algorithm VIAM, it is possible to determine Visual interactive analysis tool or VIAT, which is a computing application built in C++, MATLAB, MAPLE etc., so that it supports the expert efficiently to have multiple-criteria decision analysis and define the optimal design solution for the mechanical system.

Assumed that there is a model with four criteria or objective functions need to be optimized, and priority order of criteria ($\{\Phi_1 \mapsto \Phi_2 \mapsto \ldots \Phi_4\}$) is considered as shown in Fig. 4. The valid range of objective functions and their optimal trends are defined and illustrated in the interactive panel (Fig. 4).

Bearing in mind that values of objective functions have to be expressed with the right magnitudes and units that allow experts to study and analyse determinedly.

To simplify the nomination, the expert or group of experts or a chief engineer is named as a decision-maker (DM). According to an interactive panel, DM selects a threshold $[\Phi_1]$ for the objective function Φ_1.

This threshold turns into a constraint to define the optimal values of the rest of functions, as it is illustrated in Fig. 5. An influence of Φ_1 on the rest of functions can be observed visually by adjusting the threshold. Thus, DM can easily see the "price to pay" to improve the Φ_1 with a magnitude of ΔE_1. Yet, the panel also shows a new valid range and an inaccessible domain at which, there would be never a valid solution with the threshold $[\Phi_1]$.

If the new range does not comply with the requirements of experts, they can adjust the threshold up to the moment there is a mutually-agreed solution.

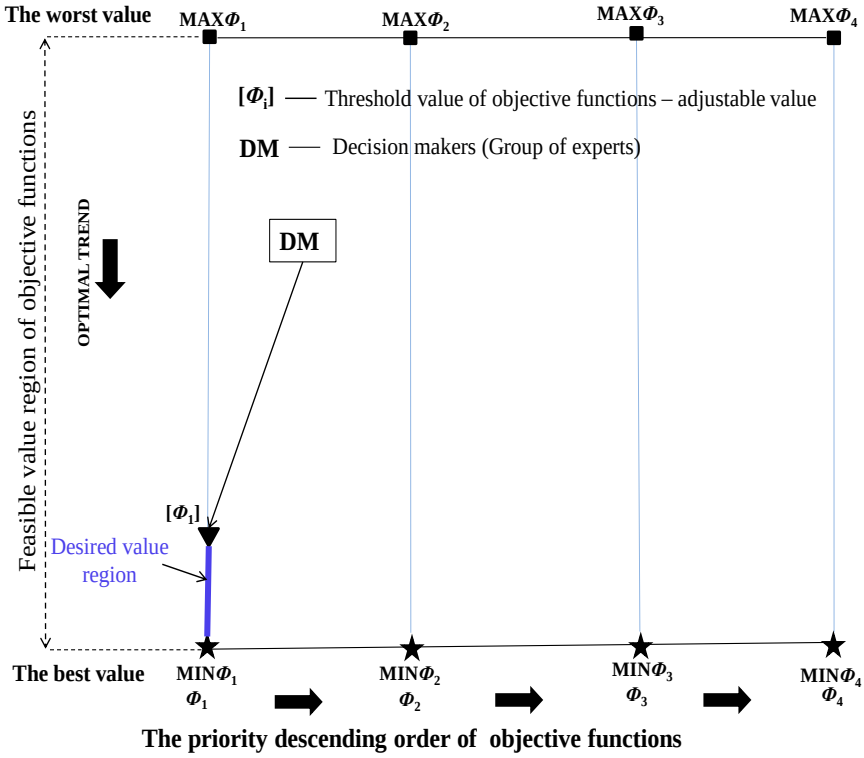

Fig. 4. Interactive panel-step 1.

Based on a valid range for the function Φ_2, DM continues selecting a threshold $[\Phi_2]$ for this function. The threshold $[\Phi_2]$ also turns into a constraint to define the optimal value the functions Φ_3 and Φ_4.

At this moment, a valid range becomes narrower; while an inaccessible domain is expanded, as it can be seen in Fig. 5. Carry on studying, DM picks a threshold $[\Phi_3]$ for the function Φ_3. Here, the optimal value $\min \Phi_4$ can be defined on the basis of the selected thresholds $[\Phi_1]$, $[\Phi_2]$, $[\Phi_3]$, as it can be observed in Fig. 6. Indeed, at this step, the obtained solution is the best mutually-agreed one among experts with respect to the initial concerned priority order, as shown in Fig. 7.

It is evident that at every step there is an intervention of experts to select, adjust and analyse the thresholds. Besides, the adjustment of thresholds points out a mutual influence of one function to another and alteration of the valid range.

Thus, the design object is analysed comprehensively and entirely. Doing so, the final design option is incontrovertibly the most optimal one.

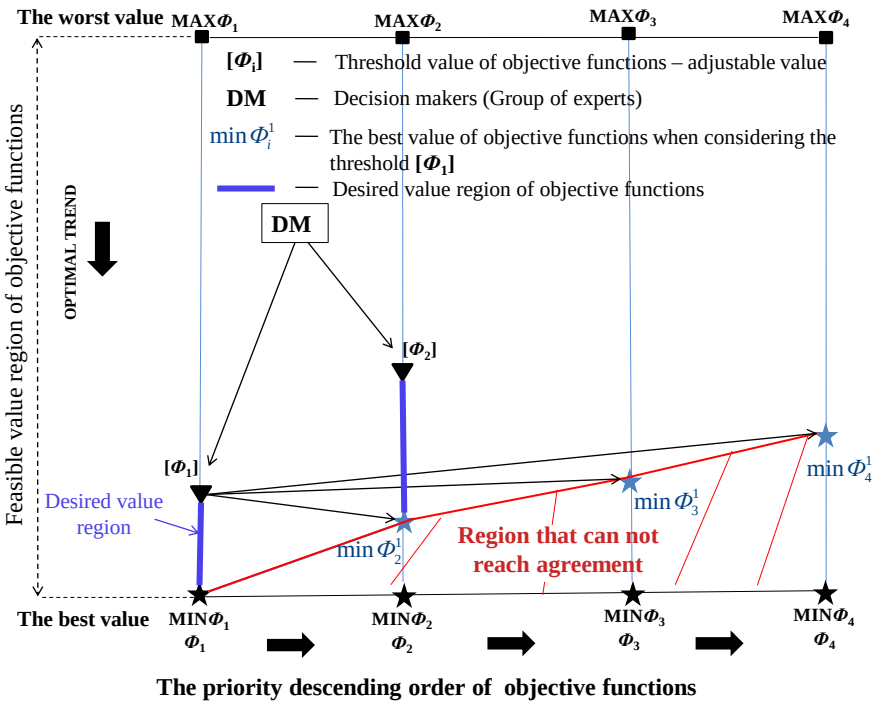

Fig. 5. Interactive panel-step 2.

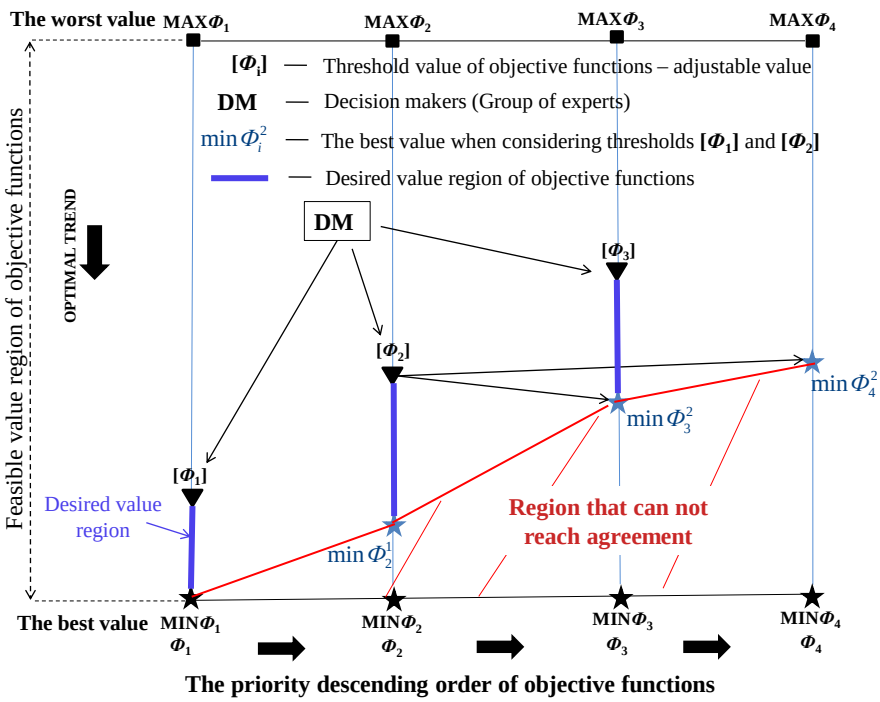

Fig. 6. Interactive panel-step 3.

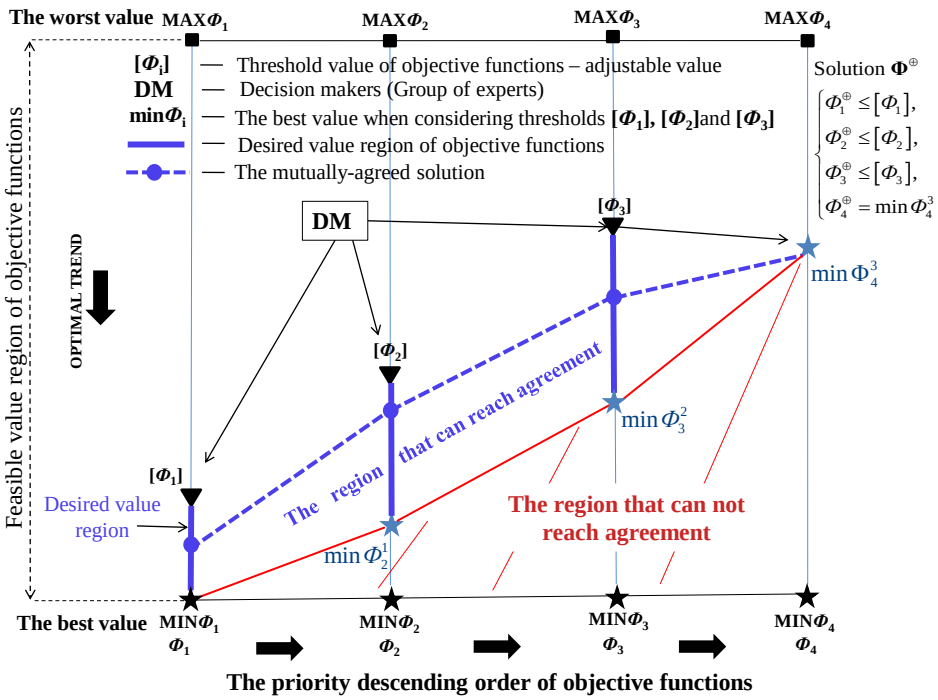

Fig. 7. Interactive panel-step 4.

3.3. VIAT applicability

The benefits of VIAT are the following:

- Provide information on the feasible range of objective functions and their alterations in the feasible solution search;
- Evaluate the "price to pay" to improve a particular function and its effect on the rest of functions;
- Support efficiently a decision-maker to select a suitable threshold of the objective function in the valid range at which, there exists a valid solution.
- Eventually, allow for an automatic determination of mutually-agreed solutions among experts for a multi-criteria design option.

By virtue of VIAT, the authors have found the solution for automation and management of design and production of composite pressure vessel by the winding method [8], multi-criteria design of an innovative frame saw machine [12, 13] and determination of optimal manufacturing modes in the metal cutting process [14].

4. Conclusion

In this paper, a multi-criteria design of the mechanical system was studied. The design based on the product lifecycle management concept was concerned. A Visual Interactive Analysis Method (VIAM) together with a tool named VIAT was used. VIAT has provided a useful database that allows related experts in the mechanical system to analyse conveniently a mutual effect of one objective

function on another. Without any bias and overbearing opinion, they conducted a straightforward discussion and evaluation accurately on the same fact with the utmost aim to define the optimal mutually-agreed solution for the design object. VIAT is actually a very user-friendly tool that makes the multi-criteria design more practical especially for the mechanical system.

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Nomenclatures

a_i	Lower limits for i^{th} parameter
b_i	Upper limit for i^{th} parameter
$f_i=f_i(\mathbf{x})$	i^{th} functional constraints
K	Number of functional constraints
N	Number of parameters
M	Number of criteria

Greek Symbols

ΔE_i	Deviation for i^{th} functional constraints
$\mathbf{x}$	Parameter vector
x_i	i^{th} parameter
$\Phi(x)$	Criteria vector
$\Phi_i = \Phi_i(x)$	i^{th} criterion
$\mathbf{\Phi}^{\oplus}$	Criteria vector in final solution
$\Phi_i^{\oplus}$	i^{th} criterion in final solution
$[\Phi_i]$	Threshold for i^{th} criterion
$Min\ \Phi_i$	Minimum value of ith criterion
$Max\Phi_i$	Maximum values of ith criterion
$\min \Phi_i^k$	Minimum values of ith criterion, when first k thresholds $[\Phi_1]...[\Phi_k], [\Phi_1]$ are concerned

Abbreviations

DM	Decision-Maker
MS	Mechanical System
VIAM	Visual Interactive Analysis Method
VIAT	Visual Interactive Analysis Tool

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