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Improving the Visual Interactive Analysis Method for Automation and Control of the Decision-Making Process in Multi-Criteria Design of Complex Mechanical Systems

Abstract

For multi-criteria design problems of complex mechanical systems with a large number of control parameters, technical constraints, and quality criteria, the search for Pareto solution domain takes quite a lot of time varying from hours to days. In fact, the decision-maker (DM) desires to examine a small number of reasonable Pareto optimal solutions in order to understand the problem itself and control the decision-making in a simple manner. This paper presents the improvement of a visual interaction analysis method or VIAM developed by the authors with the aim of providing a tool for DM to define the optimal and mutually-agreed solutions in the multi-criteria decision making (MCDM). Indeed, VIAM allows for evaluating the distribution domain of the Pareto optimal solutions defined by the genetic algorithm, which supports the DM to set additional thresholds for the objectives to filter the desired solutions and suggest to shrink or expand the threshold to control the search. In case of mutually-agreed solution non-existence, VIAM allows for providing instruction to reestablish the multi-objective problem that new Pareto solution domains can be found as desired by the DM. Based on VIAM, a visual interaction analysis tool or VIAT was developed by means of Matlab. VIAT was then used for the multi-criteria design of slider-crank mechanism for an innovative fruit vegetable washer with three objectives. Comparative study on the obtained results from VIAT with the existing design option and the obtained solution from the traditional method "concession by priority" has shown the effectiveness of the method proposed in this paper. VIAT is actually a very user-friendly tool that makes the multi-criteria design more practical especially for the mechanical system.

Keywords: *automation, decision-making, multi-objective optimization, visual interaction analysis method, trade-off-based method*

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Совершенствование метода визуально-интерактивного анализа для автоматизации и управления процессом принятия решений при многокритериальном проектировании сложных механических систем

При решении сложных задач многокритериальной оптимизации процесс нахождения области Парето-решения часто занимает много времени. В большинстве практических случаев лицо, принимающее решение (ЛПР), желает протестировать небольшое число разумных Парето-вариантов, чтобы облегчить понимание и управление процессом принятия решений. В данной статье рассмотрен метод визуально-интерактивного анализа (Visual Interactive Analysis Method — VIAM), разработанный авторами с целью предоставить ЛПР инструмент для управления процессом поиска рациональных оптимальных вариантов в задаче принятия решений при нескольких критериях. VIAM позволяет экспертам анализировать области Парето-решений, найденных с помощью генетического алгоритма; дает возможность ЛПР устанавливать дополнительные пороговые значения критериев для фильтрации желаемых решений. При необходимости повторно решается многокритериальная задача в целях нахождения новых лучших областей Парето-решений. На основе метода VIAM реализована авторская программа VIAT (Visual Interactive Analysis Tool) на языке MATLAB. VIAT применяется в задаче многокритериальной оптимизации кривошипно-шатунного механизма, использованного в моечной машине нового типа для овощей и фруктов. Сравнение результатов, полученных VIAT и традиционным методом последовательных уступок, показало эффективность метода, предложенного авторами. Необходимо отметить, что VIAM также может быть применен для автоматизации и управления процессом принятия решений в многокритериальных задачах оптимизации широкого спектра других механических конструкций.

Ключевые слова: *автоматизация, принятие решений, многокритериальная оптимизация, визуально-интерактивный анализ, компромисс*

Introduction

Today, multi-objective optimization methods in the field of machine design have evolved immensely around the world to respond to increasingly complex problems such as large scale, highly nonlinearity, large scale, a large number of quality criteria and constraints [1]. This raises the need to consider many aspects of the multi-objective mathematical model simultaneously. In fact, the application of multi-objective algorithms including a priori methodology, progressive methodology, a posteriori methodology, etc allows for having a multi-dimensional Pareto front used for selection of design options based on axiomatic methods or interactive man-machine (IMM) procedures [2—5]. Fig. 1 illustrates the interaction between DM and machine in IMM. DM desires to define the most favourable solution based on selections, while the machine represents an algorithm and search method, in other words the machine itself is an optimization algorithm.

However, in many cases, determination of the rational option from the set of Pareto solutions is not easy, because some of objective functions are contradictory one to another [6]. In this contradiction, the value of one function is considered to deteriorate when the value of another is improved. In other words, there is no simultaneous optimal solution for all of them. Therefore, the multi-objective optimization problem most of the time comes to the choice situation, the decision must trade the advantage of one or several criteria to get that of other criteria. Decision-making techniques, or simply tools that help to make decisions, are an increasingly-evolving field that provide interesting and successful solutions. Over the last few decades, many interactive support systems have appeared on the basis of decision-making methods such as: a visual design method based on Rasmussen's abstraction-aggregation hierarchy [7], decision-making spheres based on the even swap concept [8], PriEsT [9], AHP-GAIA [10], VIDEO [11] etc. One of the most effective decision-making techniques is trade-off-based method, which has been used based on value comparison of objective functions. In general, trade-off means that on the basis of a reference objective function, DM needs to quantify the increment of the rest function to compensate for the reduction of the reference one. Thus, a trade-off can provide an exact search direction for determination of a desirable solution. There are many IMM methods based on the trade-off such as Even Swap method [12], interactive step exchange method based on slope GRIST [13], PROJECT method [14], IMO method driven by evolutionary algorithm (T-IMO-EA) [15] etc. Methods in different classes have their strengths and weaknesses and for that reason different approaches are needed. Overlapping and combinations of classes are possible and some methods can belong to more than one class depending on different interpretations. Selection of the appropriate

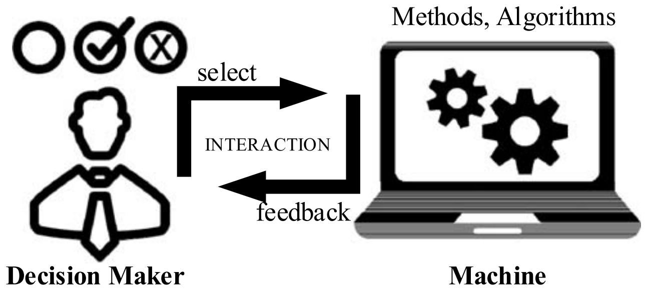


Fig. 1. DM — Machine interaction system

method depends on the size (number of objectives, constraints, and parameters), mathematical models, the need and DM interoperability, computational cost (programs calculation, time consumption), and others. Although there are many interactive methods used for solving the multi-objective optimization problem in case of designing mechanical systems, their disadvantages are following: i) it needs to have intuitive interactive interfaces that requires specialized software programs, leading to problems with software licensing or funding; ii) secondly, in complex mathematical models, it takes a lot of time to determine the Pareto optimal solutions (POS), this may require to purchase supercomputers with fast computing capabilities. When there is a long time-spending, the interaction with the DM becomes inconvenient.

In order to deal with the above mentioned limitations, this paper presents the visual interactive analysis method or VIAM that helps DM to define the optimal and mutually-agreed solutions in MCDM. VIAM allows for evaluating the distribution domain of the POS defined by the genetic algorithm, which in turn supports DM to set additional thresholds for objective function to filter the desired solutions. In case of mutually-agreed solution non-existence, VIAM provides the direction to reestablish the multi-objective problem, so that new Pareto solution domains can be established as desired by the DM. Based on VIAM, a visual interactive analysis tool or VIAT is developed on the basis of Matlab. VIAT is then used for the multi-criteria design of slider-crank mechanism for a new type of fruit vegetable washer with three objectives. Comparative study on the obtained results from VIAT with the initial design plan and the one from the traditional method "concession by priority" is carried out in order to prove the effectiveness of the method proposed in this paper.

The visual interactive analysis method

VIAM has had many remarkable research achievements in the field of multi-criteria design optimization of mechanical systems. It was first developed in 2013 in the doctoral thesis of H. M. Dang (VIAM1) by using parameter space investigation algorithms in combination with single-objective optimization in order to find manufacturing technology solutions for compression cylinders made of composite materials [16]. In 2017, V. B. Phung [17, 18] developed VIAM2 on the basis of a single-objective optimization algorithm and priority selection method for the multi-criteria design of an innovative frame saw machine. While VIAM3 is proposed in this paper, it uses a multi-parameter approach based on concurrent engineering principles to solve the multi-objective optimization problem. VIAM3 allows for automation of solution search without DM waiting. The obtained results can be illustrated visually so that DM can analyze and suggest changes. Then, the search will continue. The visual tool is an objective function diagram that can be easily plotted without the need of complex software. In a nutshell, VIAM3 allows DM to pause the search of Pareto solutions based on quantity and distribution of the solution domain on a visual tool, so that mutually-agreed solutions can be immediately defined in the current Pareto domain. VIAM3 algorithm flowchart is presented in Fig. 2.

{1}: Starting from the multi-objective mathematical model, it needs to *define the bounds of control parameters, technical constraints, and quality criteria or objective functions.* The multi-objective optimization problem is stated as follows:

Problem: generic multi-objective optimization

$$\min_x \left[\Phi(\mathbf{x}) = \Phi_1(\mathbf{x})\Phi_2(\mathbf{x})\ldots\Phi_n(\mathbf{x})\right]^{\mathrm{T}} \ (n \geqslant 2)$$

subject to

$$\boldsymbol{g}(\boldsymbol{x}) \leqslant 0,$$
$$\boldsymbol{h}(\boldsymbol{x}) = 0,$$
$$\boldsymbol{x}_l \leqslant \boldsymbol{x} \leqslant \boldsymbol{x}_u$$

where $\boldsymbol{\Phi}$ is a vector of n objective functions, $\boldsymbol{g}$ and $\boldsymbol{h}$ are inequality and equality constraint vectors, respectively, $\boldsymbol{x}_l$ and $\boldsymbol{x}_u$ are the lower and upper bounds of the design variables, respectively, and $\boldsymbol{x}$ is a vector of design variables.

{2}: *Building a visual interactive graph on parallel coordinate system* by:

— Defining the maximum and minimum achievable values of each objective function (independent of each other) by using single objective optimization algorithms such as genetic algorithm (GA), nonlinear programming, ect.

— Determining the feasible solution domain (FD) of the objective functions by using the parameter space-filling algorithms such as: Sobol sequence, Halton sequence, ect.

— Determining the POS domain by using multi-objective optimization algorithms such as GA-multi-objective, PSO, NGSA, ect.

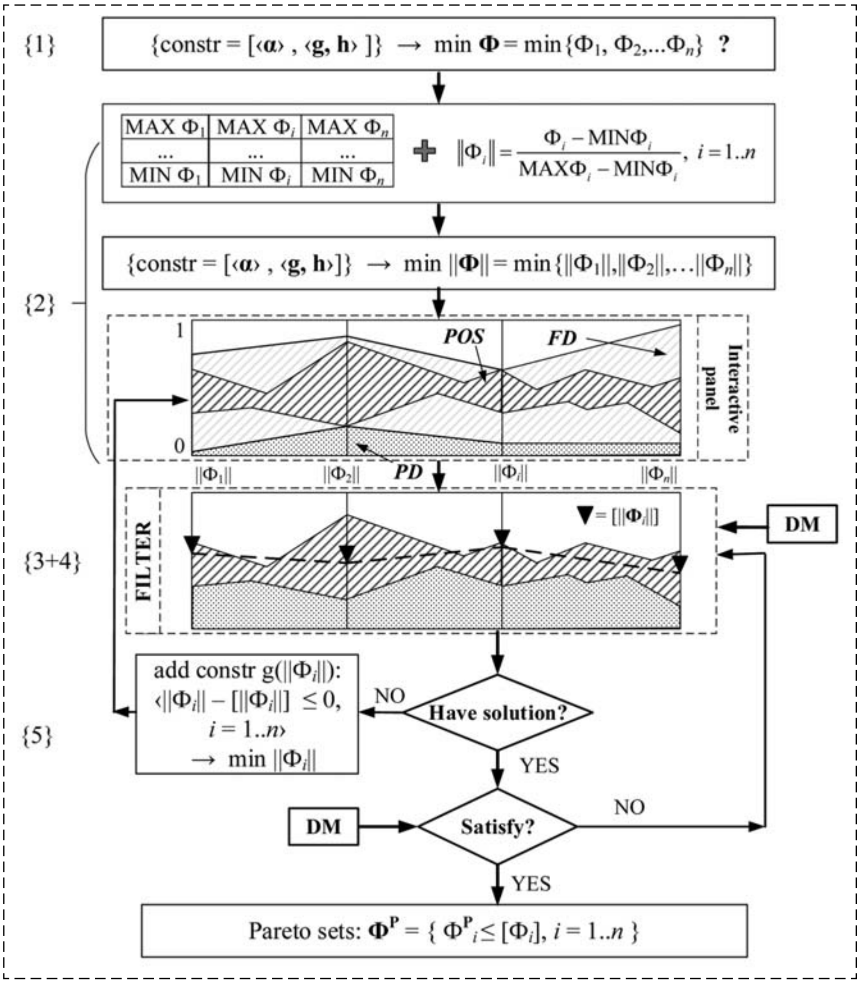


Fig. 2. VIAM3 algorithm flowchart

— Generation and normalization of the POS using formula:

$$\|\Phi_i\| = \frac{\Phi_i - MAX\Phi_i}{MAX\Phi_i - MIN\Phi_i},$$

where $\|\Phi_i\|$ is the i-th normalized objective function: $0 \leqslant \|\Phi_i\| \leqslant 1, \quad i = 1 \ldots n.$

The visual interactive panel in Fig. 3 allows for converting the n-dimensional Pareto space into the 2-dimensional normalized space, and at the same time it helps DM to acquire the conflicts of objective functions thanks to the appearance of the sign "X" among them. This makes a firm basis for the subsequent trade-off decision-making process.

{3}: *DM decides to suspend the POS* search based on quantity and distribution of solutions on the interactive graph with the aim of selecting the mutually-agreed solutions.

{4}: *Setting bounds for objective functions to search solutions.* Threshold rules are established for different types of objective functions, as illustrated in Fig. 4. In the multi-objective optimization problem, the objective functions are distinguished by a narrow (type I) or wide (type II) range of value changes. The best value of objective "type I" is often accompanied by the worst value of objective "type II", which is in compliance with the Pareto principle. It is quite difficult to select all the best values of all objective functions simultaneously, in some cases it is even impossible.

In order to define the mutually-agreed solution, DM needs to use a compromise rule: accept to trade

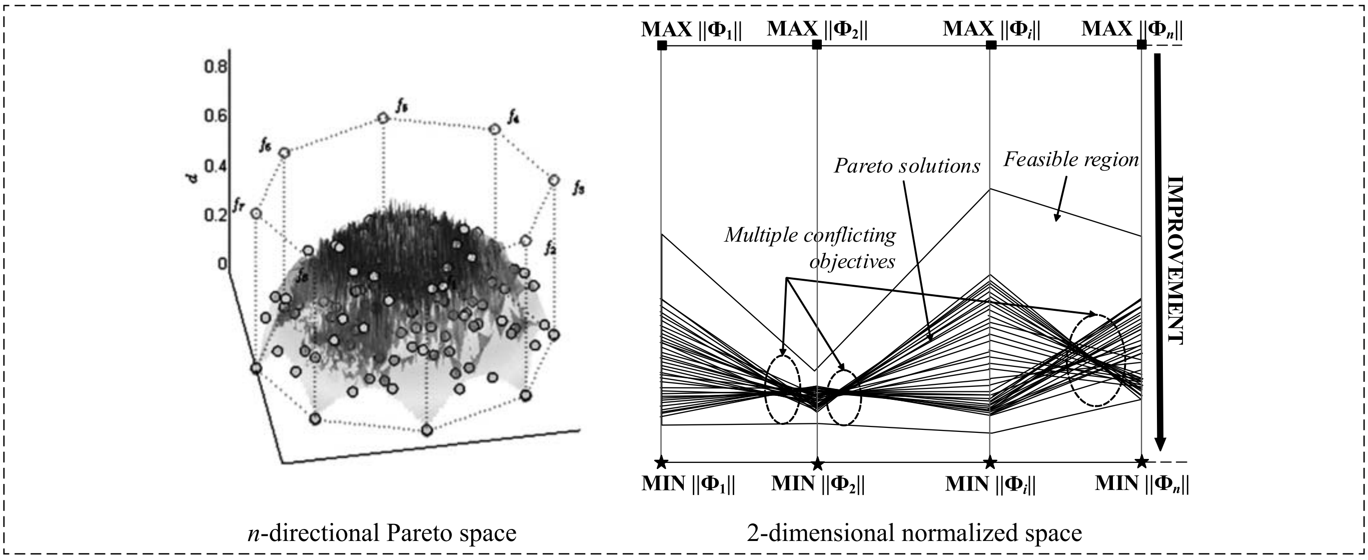
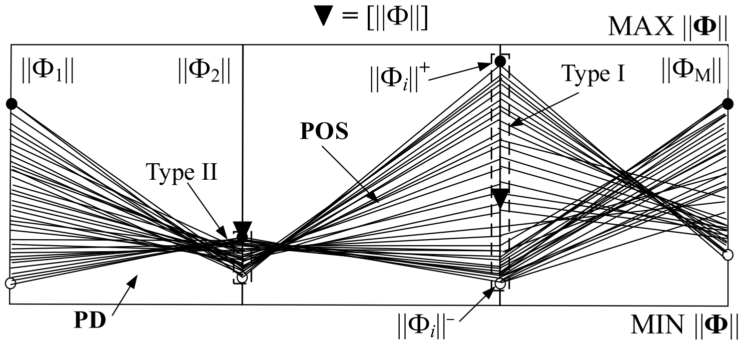


Fig 3. Visual interactive panel



$$\begin{cases} \|\Phi_i\|^{\text{type I}} \Leftrightarrow \|\Phi_i\|^{+} - \|\Phi_i\|^{-} \le 0.2 \\ \|\Phi_i\|^{\text{type II}} \Leftrightarrow \|\Phi_i\|^{+} - \|\Phi_i\|^{-} > 0.2 \end{cases}$$

Fig. 4. Classification of objective functions

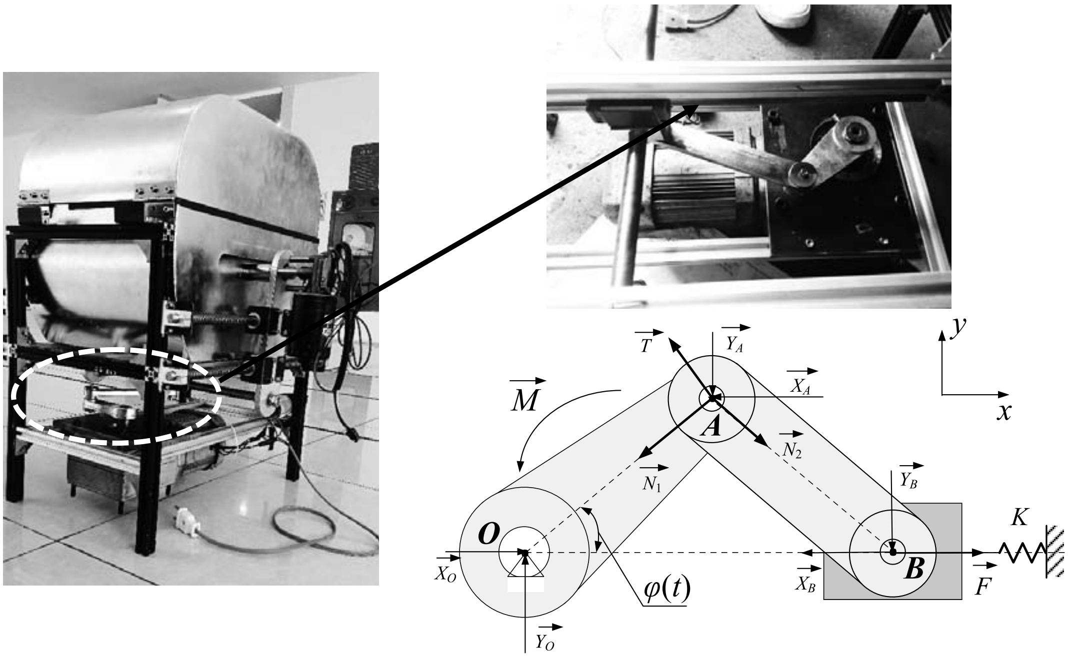


Fig. 5. Existing (*a*) and calculated (*b*) model of SCM used for the fruit vegetable washer:

$X_{O/A/B}$, $Y_{O/A/B}$ — reactions at the joints *O, A, B* along the positive direction on the x— and y-axes, respectively; N_1, N_2 — compression loads at the joint *A* of crankshaft and connecting rod, respectively; *T* — bending force at joint A of crankshaft; $\varphi(t)$ — angle of rotation; *M* — engine torque

the nearly-worst solution $\|\Phi^{+}\|$ of objective "type I" and filter out the best solutions $\|\Phi^{-}\|$ of objective "type II" on the principle of setting the following threshold limit $[\|\Phi_i\|]$:

$$[\|\Phi_i\|] = \begin{bmatrix} [\|\Phi_i\|]^{\text{type I}} = \|\Phi_i\|^{+} \\ [\|\Phi_i\|]^{\text{type II}} = \dfrac{\|\Phi_i\|^{+} + \|\Phi_i\|^{-}}{\zeta}, \quad \zeta \geqslant 2 \end{bmatrix},$$

where ζ — positive real number

{5}: *Pareto filter.* After the thresholds have been established, the process of filtering out the best solution is automatically performed on the basis of checking the *n* constraints $g(\Phi_i)$ of *n* objective functions: $g(\Phi_i) = \|\Phi_i\| - [\|\Phi_i\|] \leqslant 0$ with $i = 1...n$. There are three possibilities:

(*i*) If there exists the solution that the expert agreed mutually, the final option can be concluded immediately;

(*ii*) In case there exist many solutions that are still controversial, it is necessary to tighten the threshold value $[\|\Phi_i\|]^{\text{type II}}$ by increasing the value ζ. Filtering continue until the mutually-agreed solution is achieved;

(*iii*) In case there is no mutually-agreed solution even though all possible $g(\Phi_i)$ constraints have been established, this indicates that the POS does not currently have the most favorable solution. At this point, VIAM3 allows users to reset the original multi-objective problem on the basis of adding constraints $g(\Phi_i)$ with the aim of finding new "better" POS domain than previous one. It is noted that for the objective "type II" the threshold value needs to be loosened: $[\|\Phi_i\|]^{\text{type II}} \geqslant \|\Phi_i\|^{+}$.

DM continues to define the moment to stop the search algorithm when a new POS is eligible to make a decision to choose the mutually-agreed solutions. This process is repeated over and over on the basis of compromise rules {4} until the mutually-agreed options is achieved. In addition, VIAM3 also allows for evaluating the range of the control parameters corresponding to the obtained mutually-agreed solutions, and at the same time correct this range when repeating calculations for determination of additional design options.

Application of VIAM3 in multi-criteria design of transmission system for fruit vegetable washer. Problem statement

Lately, concurrent engineering, which has been widely used, has brought positive effects in engineering, one of which is machine design and manufacture [19]. The advantage of concurrent engineering design engineering is the use of multi-objective mathematical models with the aim of identifying the optimal design options right in the early stages of the design process. Consider an example of concurrent design technique in the multi-objective optimization problem of slider-crank mechanism (SCM) for the fruit vegetable washer, as shown in Fig. 5 [20]. The multi-objective mathematical model consists of 11 control parameters $\boldsymbol{\alpha}$, 3 quality objective function $\boldsymbol{\Phi}(\boldsymbol{\alpha})$, and 16 constraints $\boldsymbol{g}(\boldsymbol{\alpha})$. The aim is to define a set of control parameters which is the detailed size of SCM components $\alpha = \{\alpha_1 ... \alpha_{11}\}$ in order to simultaneously minimize power consumption (Φ_1), structure weight (Φ_2) and dynamic reaction at rotating joints (Φ_3) on the basis of meeting the constraints of structure, technology, and admissible size. Details of the mathematical model are described elsewhere in Ref. [21, 22].

$$\underset{\alpha \in D(\alpha)}{\text{minimize}} : \Phi(\alpha) = \{\Phi_1(\alpha), \ldots, \Phi_3(\alpha)\}$$
$$\text{subject to} : D(\alpha) = \{\alpha \mid g(\alpha) =$$
$$= \{g_1(\alpha), \ldots, g_{16}(\alpha)\} \leqslant 0\} \subset \alpha = R^N$$
$$\alpha_{l\_i} \leqslant \alpha_i \leqslant \alpha_{u\_i},\ i = 1..11$$

Control of decision-making process in multi-criteria design of SCM by using VIAT tool

The VIAM3 proposed in this paper is developed by using the VIAT tool on the Matlab programming language. The interface of VIAT used for dealing with the multi-objective optimization problem of SCM is shown in Fig. 6. While, the decision-making process based on analysis and visual interaction between DM and VIAT is explained in Fig. 7.

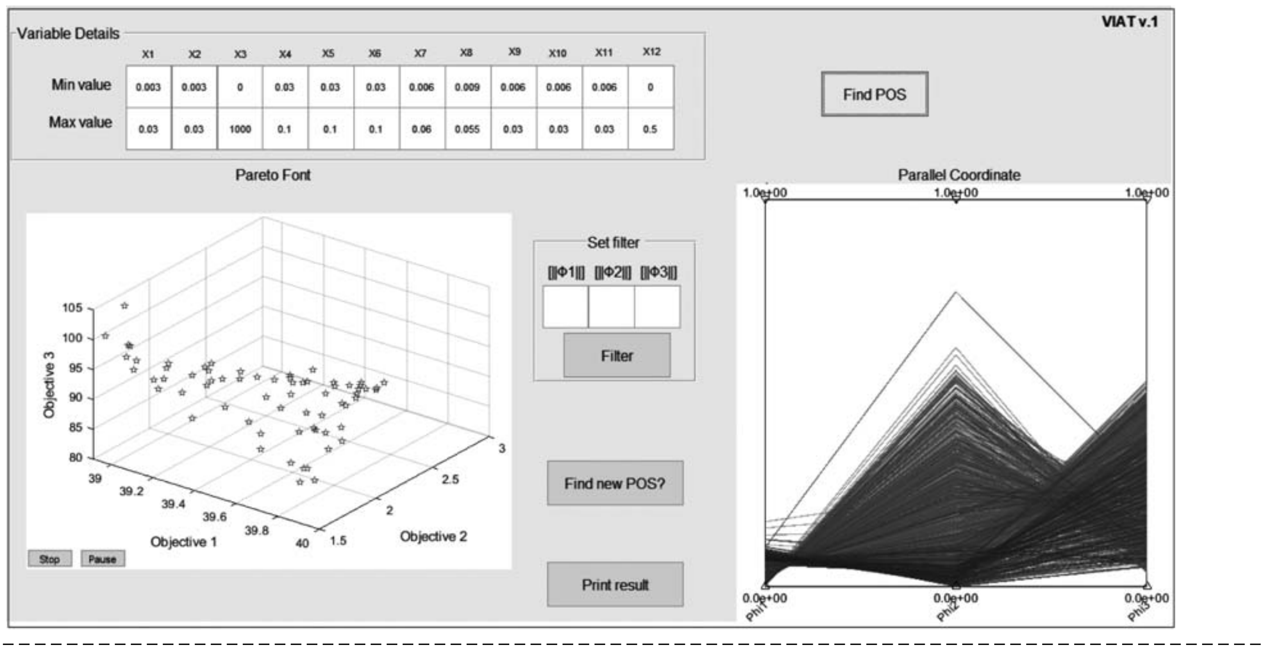


Fig. 6. Interface of VIAT tool

Table 1

Control parameters of SCM according to different methods

Method	α_1	α_2	α_3	α_4	α_5	α_6	α_7	α_8	α_9	α_{10}	α_{11}
S0	0.149	0.079	912.5	0.812	0.518	0.498	0.341	0.17	0.267	0.280	0.190
CP	0.162	0.095	618.5	0.797	0.489	0.436	0.414	0.25	0.204	0.249	0.188
VIAM	0.094	0.044	487.7	0.670	0.472	0.321	0.551	0.25	0.193	0.109	0.196

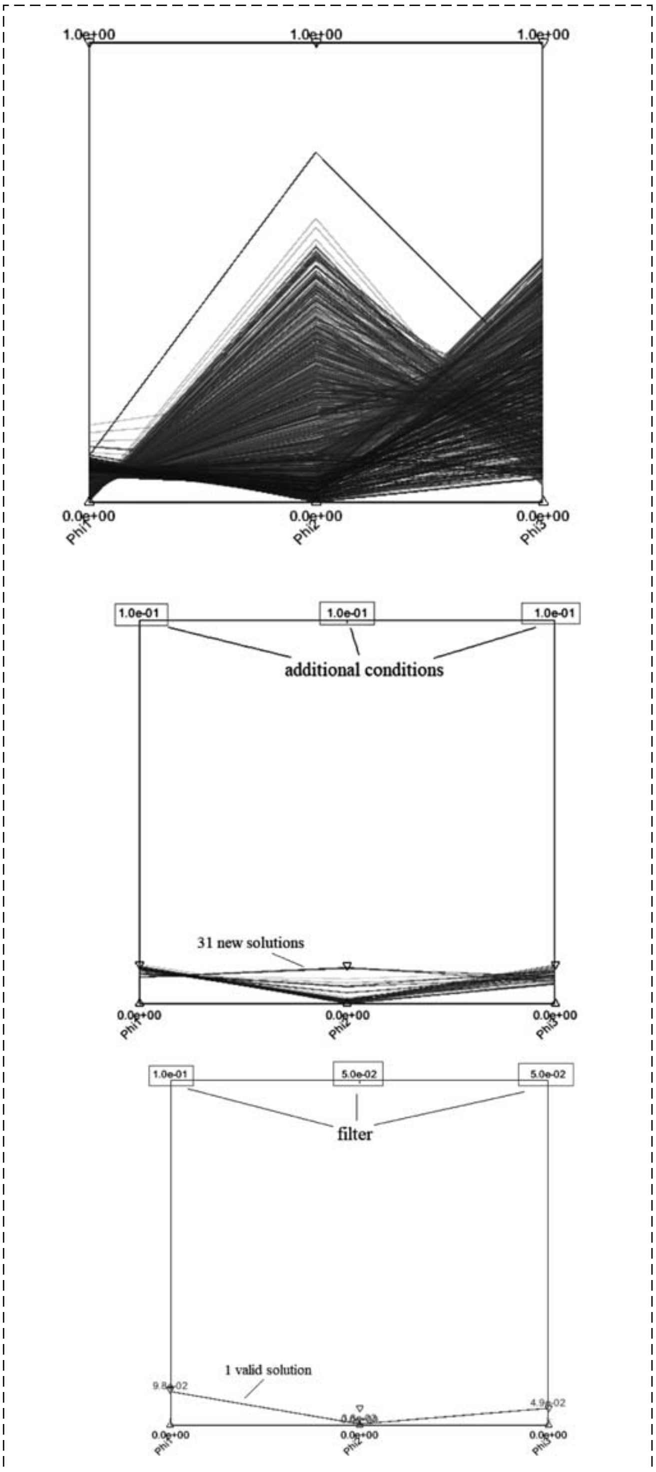


Fig. 7. Decision-making process of DM by using the author's VIAT tool

Results and discussion

The design options of SCM structure (dimensions — control parameters) and values of the objective functions are provided in Table 1 and Table 2 respectively, where: S0 — existing structure of SCM [23], CP — the traditional method "Concession by Priority" [24].

Looking into the graph in Fig. 8, it is seen that the solution obtained by the VIAM3 is the best in terms of two objective functions Φ_2 and Φ_3 (reduce 70.42 % and 32.58 % respectively), but the decrease of Φ_1 (−0.09 %) is the worst in comparison with the solution obtained by the CP (−2.39 %). Albeit being the worst, $\|\Phi_1\|$ — objective function "type I" — is still within the admissible threshold of 0.1. It is observed that the objective values Φ_1 in the solutions are very close one to another. Thus, DM would barely care for this discrepancy. However, it is evident that DM could hardly be aware of the existence of this circumstance, unless they perform the solution search by using the VIAM3. In summary, it comes to the trade-off situation, but what objective function to trade, how much, and what benefit from other objectives are still as a potential research area. Therefore, the VIAM3 promises to make sense in helping DM to make a decision in the design of complex mechanical systems.

The range of the control parameters is specified by expanding the filtering threshold in step 3 (Fig. 7).

Table 2

Comparison of objective functions in SCM design by different methods

Objective functions	S0	CP	VIAM3
Φ_1, W	40.022	39.067	39.988
Comparison Φ_1, %	—	−2.39 %	−0.09 %
Φ_2, Kg	2.497	1.894	0.739
Comparison Φ_2, %	—	−24.14 %	−70.42 %
Φ_3, N	120.8	92.391	81.464
Comparison Φ_3, %	—	−23.53 %	−32.58 %

With the new control parameter domain, as shown in Fig. 9, VIAM3 allows DM for defining more POS in order to find additional design options.

Conclusion

This paper studied the improvement of the visual interactive analysis method (VIAM3) with the aim of providing an automatic tool to control the decision-making process in dealing with multi-objective optimization of mechanism. Based on the evaluation of the distribution domain of Pareto optimal solutions, that defined by GA, if it is required, DM can reorient the search objective, thereby it is possible to reestablish the problem statement and approach to the most favorable solutions. Based on VIAM3, the VIAT automation tool was developed by using Matlab programming language. The effectiveness and validity of the method proposed in this paper was confirmed in the application for multi-objective optimization problem of SCM used in the fruit vegetable washer with three objective functions. Comparing the obtained solution from VIAT with the existing structure and the one from the traditional method "concession by priority", it showed that there is a trade-off of the power reduction (−0.09 %) allows for a significant improvement

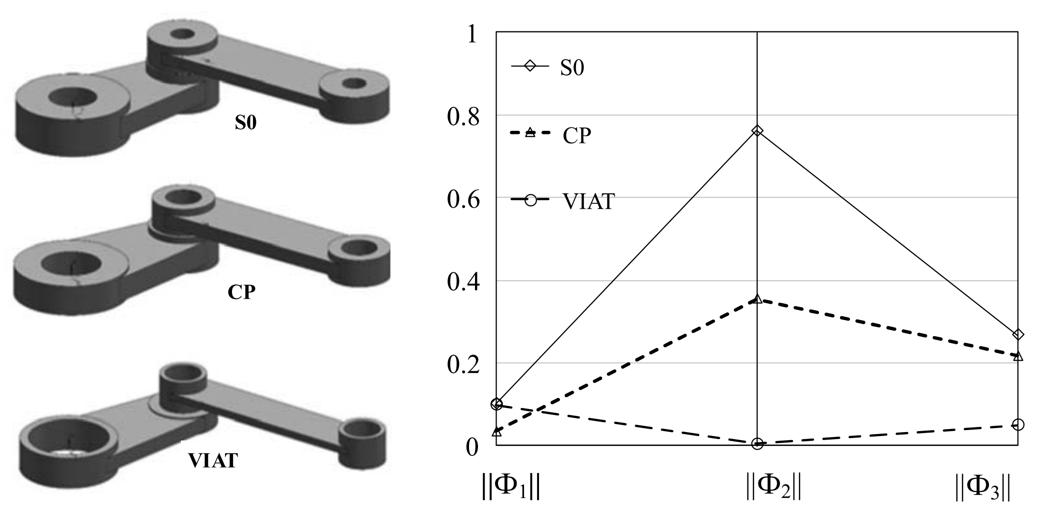


Fig. 8. Comparing the normalization of objective functions on parallel coordinate system and 3D model of SCM corresponding to the obtained solutions

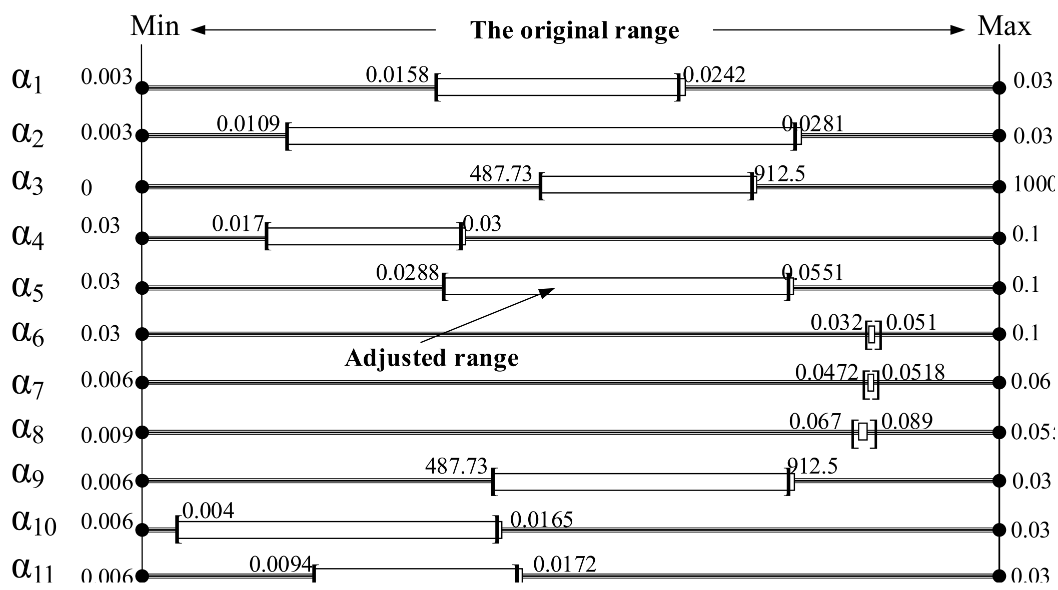


Fig. 9. Range of the control parameter values after expanding the filtering threshold

of the reduction of weight (−70.42 %) and dynamic reaction (−32.58 %) of SCM. Finally, it should be emphasized that the proposed VIAM3 can be widely applicable for the multi-criteria design of other complex mechanical systems.

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