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AHP BASED MULTI-CRITERIA FUNCTION ANALYSIS AS A TRIZ TOOL FOR COMPLEX TECHNICAL SYSTEMS

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Abstract

This paper presents a modified component importance analysis as a TRIZ tool for complex technical systems modelling and evaluation. A marine diesel fuel injector is used as an example of a complex technical system. The necessity for further development of the function analysis as an effective TRIZ tool is highlighted. Some of the problems encountered in modelling complex technical systems is pointed out. A multi-criteria function analysis with weighted criteria of component importance based on the Analytical Hierarchy Process (AHP) is introduced and the basic criteria for a system component performance and quality evaluation are presented. Results of analyses are presented using weighted criteria and classic function analysis is presented with equal weights.

Keywords: function analysis, importance analysis, complex system, system modelling, weighted criteria, Analytical Hierarchy Process, AHP, multi-criteria analysis.

1. Introduction

Function analysis is a TRIZ tool derived from the theory of systems used at the stage of mapping and assessing a problem [1]. This analysis is also utilized for identifying a key problem in the process of solving inventive problems [2, 3, 4]. Function analysis primarily aims at:

- understanding problems by identifying the relationships between components of the system and of the supersystem and modelling these;
- Finding the existing and potential problems related to system functionality;
- Identifying problems that can be resolved with other TRIZ tools;
- Optimization of the system operation by reducing the number of components while preserving system functionality;
- Modification of existing patents to find patentable solutions having the same functionality

The steps of the function analysis process are as follows [2]:

1. Deconstructing a system and supersystem, namely the isolation of components of the system and components of the supersystem, with which the analysed system interacts.
2. Identifying interactions and indicating them in a relationship matrix.
3. Defining the individual functions for each component, subject to interactions.
4. Determining the direction of each identified function of the components of a system or supersystem.
5. Determining of the type of interaction for each identified function of a system's or supersystem's components.

6. Create a ranking of identified problems based on each component's negative impact on the obtained total value of the system (functionality, efficiency, quality).

This paper is focused on the last step of the function analysis process. The ranking of identified problems is normally created by mutual comparison of individual problems associated the operation of each component of the system [5, 6]. An example of such a variant-based assessment has been presented in section 3.1 of this paper. It is possible for several criteria to be considered, which can then be aggregated; however, this approach does not take into account the ranks of individual criteria and hence the importance of the use of individual rankings for the established criteria. To illustrate the solution to this problem we may determine the final ranking as a weighted average of assessments from individual rankings [7]. However, there remains a matter of indicating weights for particular criteria.

According to the authors, the application of AHP method is a valuable tool for determining the weights of individual criteria, individual rankings and, the aggregated ranking. This method is advantageous as it is possible to quickly determine the importance of criteria and of individual problems in the analysed system. In addition, not only the mutual relation such as "more important" and "less important" is assessed, but also the degree of mutual ratio of importance is expressed on the scale of the intensity. With the above in mind, the authors have attempted to adapt the AHP methodology for the implementation of the latter stage of the function analysis, as shown in the example of the fuel injector in this paper.

2. AHP as a tool for multi-criteria decision-making

The AHP method, developed in 1970 by Thomas L. Saaty, is one of the multi-criteria methods of hierarchical decision problem analysis. It allows the deconstruction of a complex decision problem and result in a ranking for the finite set of alternatives, w_i, according to selected importance criteria, k_i [8]. Figure 1 shows an example hierarchical structure of a decision making process (according to the AHP) for a problem of ordering five analysed alternatives in terms of six different criteria.

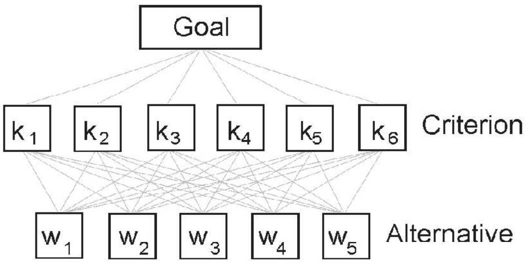

Fig. 1. Example hierarchical structure of a decision making process according to the AHP

After creating a hierarchical problem model by means of the AHP method and pairwise comparison [7], criteria relevance is determined as a level of their dominance relation (Table 1). The range of the allowed dominance levels is between 1 and 9. The relative alternative relevance index - criterion k_i superiority to criterion k_j – is expressed by a_{ij} according to the formula:

$$a_{ij} = \frac{e_i}{e_j}, \quad i, j = 1,2..n \tag{1}$$

where: e_i – absolute criterion rank k_i,

e_j – absolute criterion rank k_j,

while $a_{ij} \in \{1,2...9\}$.

Table 1

The fundamental scale used in AHP [9]

Importance on an absolute scale	**Definition**	**Explanation**
1	Equal importance	Two activities equally contribute to the objective
3	Moderate importance on one over another	Experience and judgment moderately favour one activity over another
5	Essential or strong importance	Experience and judgment strongly favour one activity over another
7	Very strong importance	An activity is strongly favoured and its dominance demonstrated in practice
9	Extreme importance	The evidence favouring one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values	When compromise is needed

Coefficients, a_{ij}, of the relation between criteria, e_i, are grouped in square matrix **A**, while $a_{ij} = \frac{1}{a_{ji}}$ for i,j=1,2…n. Table 2 presents an example of comparison matrix **A** with a weight coefficients vector.

Table 2

Example comparison matrix **A** with a weight coefficients vector [8]

Criterion	k_1	k_2	k_3	k_4		w_i
k_1	1	3	1/5	3		w_1
k_2	1/3	1	1/9	1		w_2
k_3	5	9	1	1/7		w_3
k_4	1/3	1	7	1		w_4

With regard to the fact that the i-th verse of the comparison matrix is the i-th column reciprocity (i=1, 2…, n), a relation is established:

$$\mathbf{A}\vec{\mathbf{w}} = n\vec{\mathbf{w}} \qquad (2)$$

where: $\vec{w}$ – is a column vector with elements $w_1, w_2 \dots w_n$.

The elements of the eigenvector $\vec{\mathbf{w}}$ represent weight coefficients and the priorities of particular hierarchical structure components. The elements describe the estimated share in the superior aim achievement; therefore, they express the preferences associated with the elements by the decision-maker. Using comparison matrix **A** and unit matrix **I**, we can calculate an unknown vector ***w*** by means of the system of equations:

$$(\mathbf{A} - n\mathbf{I})\vec{\mathbf{w}} = 0 \qquad (3)$$

To solve the system of equations, we can use Horner's scheme or an iterative method [8]. The system has a non-zero solution only if *n* is the principal eigenvalue of matrix **A**. With regard to a specific construction of matrix **A** it is the only non-zero principal eigenvalue. The task can be expressed as the following system of equations:

$$\mathbf{A}\vec{\mathbf{w}} = l_{\max}\vec{\mathbf{w}} \quad (4)$$

where: $l_{\max}$ – is the maximum principal eigenvalue for the comparison matrix the order n.

Table 3 shows an example of the vector of the alternatives ranks. The elements of the eigenvector in matrix **A** represent weight coefficients – priorities according to subsequent elements at each level of the hierarchy. Data on global preferences, taken from evaluators, are normalized to estimate weight coefficients for the criteria as their relative share in achieving the main aim which is a synthetic criterion. In Saaty's method, the required evaluation consistency is a prerequisite, expressed by the consistency index C_I of a comparison matrix whose value should not exceed 0,1. The consistency index describes the preservation of the transitive relation of the components dominance and evaluation credibility; obtained from experts or decision-makers.

Table 3

Example vector of alternatives ranks [8]

Alternative	**W**
Choice A	0,123
Choice B	0,323
Choice C	0,143
Choice D	0,232
Choice E	0,279
∑	1,00

Coefficient C_I is given by:

$$C_I = \frac{l_{\max} - n}{n-1} \quad (5)$$

In the case of full evaluation of the consistency of dominance $l_{\max} = n$ and $C_I = 0$. Coefficient C_I is calculated with reference to random index R_I, which is a mean value of C_I for a large number of randomly generated comparison matrices (Table 4).

Table 4

Values of random index R_I [9]

n	2	3	4	5	6	7	8	9	10
R_I	0	0,52	0,89	1,11	1,25	1,35	1,4	1,45	1,49

As a result of dividing index C_I by random index values ratio C_R (consistency ratio) is obtained.

$$C_R = \frac{C_I}{R_I} \qquad (6)$$

The value of the consistency ratio not exceeding 0,1 means that the mutual parameter comparisons satisfy the consistency condition [9]. In the case when $C_R > 0,1$ the process of mutual relation evaluation between alternatives and/or criteria must be repeated.

The grades aggregation in the AHP method is executed by means of an additive usability function which synthesizes the criteria shares (weights) and values of the fulfilled objective fractional function by means of each criterion. The pairwise comparison of alternative results in the relative valuation of alternative shares in terms of the main aim achievement.

3. TRIZ-based function analysis

3.1. Analysed system

The subject of analysis is the marine diesel engine fuel injector. It is an object that is designed to feed the fuel at the correct pressure to the combustion chamber and to spray it properly [10, 11]. The cross-section of the analysed object and the critical components are shown in Figure 2. The main components of the system are: 1 – retaining nut, 2 – nozzle body, 3 – needle valve, 4 – nozzle cap nut, 5 – intermediate spindle, 6 – spring, 7 – O-ring, 8 – dowel pin, 9 – adjusting nut and washer, 10 – injector body.

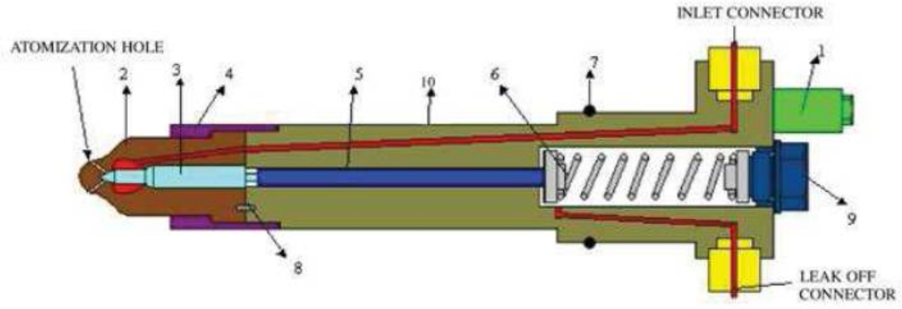

Fig. 2. Object of analysis and their components [13]

For the purposes of this analysis, the most important components of the supersystem were identified: engine block, high-pressure pipe / inlet connector, drain pipe / leak off connector, combustion chamber, fuel oil and the operator / maintenance engineer.

3.2. System modelling

The system has been modelled according to TRIZ rules. A matrix of interactions has been built as shown in table 5, this was used to develop a component-function diagram shown in figure 3. This diagram shows the components of the system and of the supersystem, as well as indicating and describing their inter-relationships (direct contact). For each relationship, the direction of impact and the type were indicated. We have considered following the types of impact: positive, harmful (red arrows) and potentially insufficient (an arrow with a dotted line).

Table 5

Matrix of interactions

Component name	Components of the system										Supersystem				
	Retaining nut	Nozzle body	Needle valve	Nozzle cap nut	Intermediate spindle	Spring	O-ring	Dowel pin	Adjusting nut and washer	Injector body	Engine block	High pressure pipe	Drain pipe / leak off	Combustion chamber	Fuel oil
Retaining nut	x									x	x				
Nozzle body		x	x	x				x		x					x
Needle valve		x	x		x										x
Nozzle cap nut		x		x						x				x	
Intermediate spindle			x		x	x				x					
Spring					x	x			x	x					
O-ring							x			x	x			x	
Dowel pin		x						x		x					
Adjusting nut and washer						x			x	x					
Injector body	x	x		x	x	x	x	x	x	x	x	x	x		x
Engine block	x							x		x	x				
High pressure pipe / inlet connector										x		x			x
Drain pipe / leak off connector										x			x		x
Combustion chamber				x				x						x	x
Fuel oil		x	x							x		x	x	x	x
Operator / maintenance engineer	x								x						

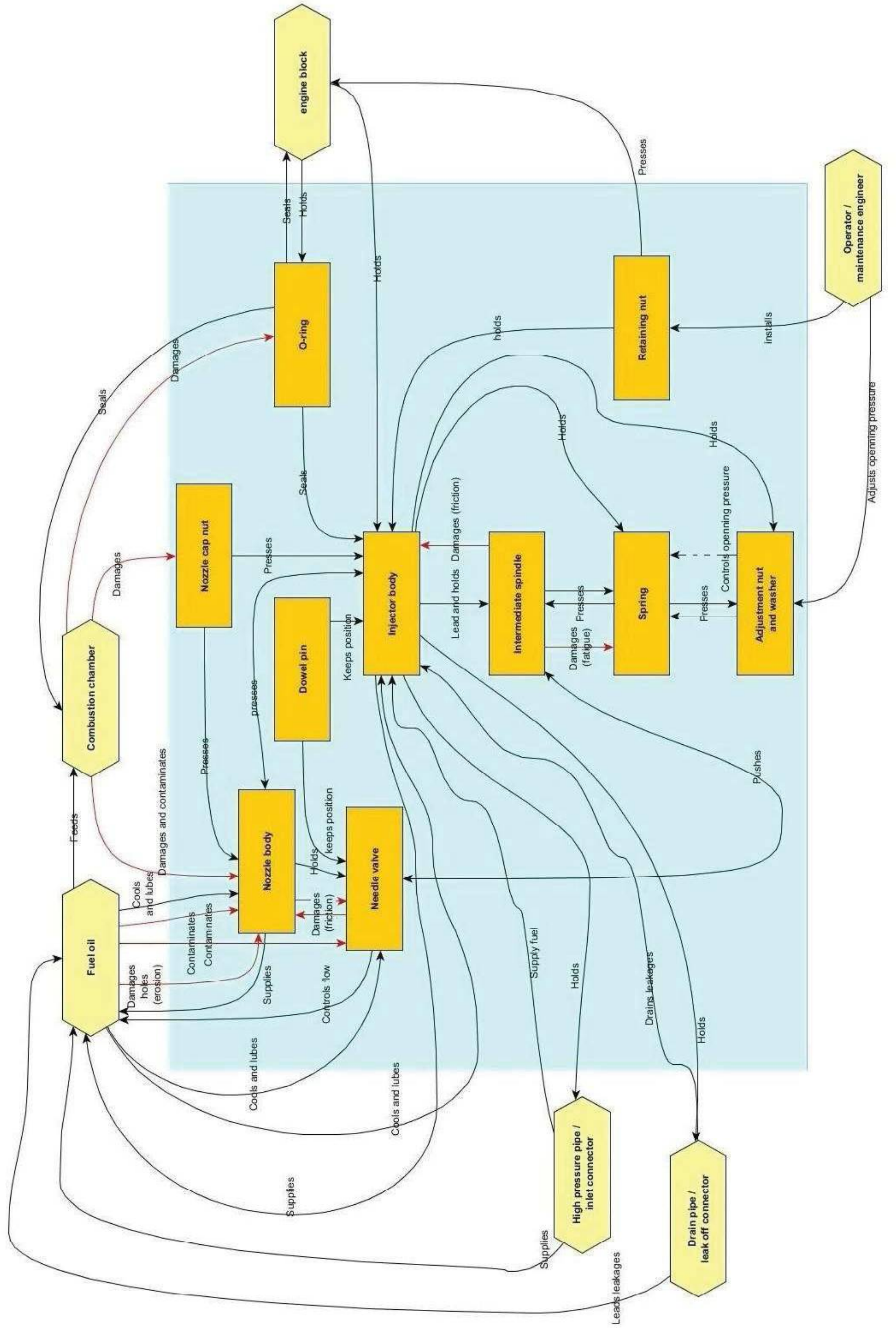

Fig. 3. Function model of the analysed system

4. Problem ranking

4.1. Single criterion analysis

For the analysed system, we have listed problems related to improper operation of particular components, then they have been compared mutually and summed their importance. The mutual relations have been classified as +1 when the given identified problem is more critical or correct (reliable and safe) achieving the objective function, and classified as -1, when it is less important, and 0, when problems are equally important. A summary of problems is presented in table 6. Generic analysis was carried out on the basis of expert opinions to present the methodology in this article [11, 12]. The first column also indicates denotations of individual problems, which will be used below in the paper.

Table 6

Comparative matrix of problems

Identified problem	Atomization holes are damaged by fuel erosion	Atomization holes are contaminated by carbon deposits from combustion	Needle valve stacked in nozzle due to fuel contamination	Excessive wear of precision pair (needle valve + nozzle body) due to	Contamination of the nozzle cap nut	Damage of the O-ring	Excessive injector body wear due to friction	Broken spring	Total score	Rank
R_h - Atomization holes are damaged by fuel erosion	0	+1	-1	+1	+1	+1	+1	-1	3	3
R_d - Atomization holes are contaminated by carbon deposits from combustion chamber	-1	0	-1	-1	+1	-1	+1	-1	-3	6
R_i - Needle valve stacked in nozzle due to fuel contamination	+1	+1	0	+1	+1	+1	+1	0	+6	1,2
R_f - Excessive wear of precision pair (needle valve + nozzle body) due to fuel contamination	-1	+1	-1	0	+1	-1	+1	-1	-1	5
C - Contamination of the nozzle cap nut	-1	-1	-1	-1	0	-1	0	-1	-6	7,8
O - Damage of the O-ring	-1	+1	-1	+1	+1	0	+1	-1	+1	4
B - Excessive injector body wear due to friction	-1	-1	-1	-1	0	-1	0	-1	-6	7,8
S - Broken spring	+1	+1	0	+1	+1	+1	+1	0	+6	1,2

The analysis showed that the potentially most important problems are: spring breakage and needle valve stacking in the nozzle due to fuel contamination, subsequently: atomization holes damaged by fuel erosion, O-ring damage and excessive wearing of precision pair.

4.2. AHP-based problem ranking

For the object analysis of the fuel oil injector, three importance criteria have been taken into account: safety, costs effectiveness and reliability. The criteria have been selected in a way that allow for the unification of their mutual evaluation. These characteristics were matched for the evaluation process with a goal of maximise:

1. Safety – understood as an inverse proportion of negative consequences for the system operation, connected with component failure – greater safety means lesser hazard for the staff, environment and the system itself.
2. Cost effectiveness – understood as a characteristic inversely proportional to system repair costs (spare parts, work force and system operation interruption costs) connected with the failure of a given component. Greater cost effectiveness means smaller restoration costs.
3. Reliability – certainty that the system will operate despite failure of a given component – greater reliability is connected with longer periods in between the planned maintenance work.

The mutual verbal evaluation of relations between criteria are created on the basis of the opinions given by specialists of the operation of technical systems. A mutual relevance matrix with generic data for the analysed criteria that has been created is presented in Table 7. The comparisons were prepared with the use of the fundamental scale applied for the AHP method described in section 2.

Table 7

Mutual relevance matrix for the analysed criteria

Parameters	Safety	Cost effectiveness	Reliability
Safety	1	3	6
Cost effectiveness	1/3	1	3
Reliability	1/6	1/3	1

C_I=0,0091 C_R= 0,0174 l_{max}=3,0181

After normalizing the matrix presented in Table 7, criteria relevance coefficients were obtained. These are shown in Table 8.

Table 8

Importance criteria relevance

Parameters	Sum	Weight	*A*
Safety	1,4999	0,6548	0,9821
Cost effectiveness	4,3333	0,2499	1,0828
Reliability	10,0000	0,0953	0,9530

It can be seen that in this case the parameter for safety equals over 65% of relevance, cost effectiveness 24%, while reliability is less than 10%.

The consistency ratio CR for the matrix equals 0,0174 and this allows the assumption that the matrix is consistent (value CR < 0,1 is required). The analysis can be continued.

The obtained results correlate with a common sense interpretation where safety is the most significant and reliability can be considered less important if the repair or component exchange costs are not high.

In the next step of the analysis, the relevance of the system components has been evaluated with regard to their influence on safe, low cost and reliable system operation. The relative mutual relations matrix of particular components according to the safety criterion is shown in Table 9. The comparisons were prepared with the use of the fundamental scale applied for the AHP method described in section 2. The following notations have been assumed (Table 6): Rh - atomization holes are damaged by fuel erosion, Rd - atomization holes are contaminated by carbon deposits from combustion chamber; Ri - needle valve stacked in nozzle due to fuel contamination; Rf - excessive wear of precision pair (needle valve + nozzle body) due to fuel contamination; C - contamination of the nozzle cap nut; O - damage of the O-ring; B - excessive injector body wear due to friction; S - broken spring. Consistency ratio C_R for the input data equals 0,0180 and it allows for the assumption that the matrix is consistent.

Table 9

Relative mutual relations matrix according to the criterion *safety*

Safety	R_h	R_d	R_i	R_f	C	O	B	S
R_h	1	1/4	2	1/3	1/5	1/2	1/5	2
R_d	4	1	5	2	1/2	3	1/2	5
R_i	1/2	1/5	1	1/4	1/6	1/3	1/6	1
R_f	3	1/2	4	1	1/3	2	1/3	4
C	5	2	6	3	1	4	1	6
O	2	1/3	3	1/2	1/4	1	1/4	3
B	5	2	6	3	1	4	1	6
S	1/2	1/5	1	1/4	1/6	1/3	1/6	1

C_I=0,0252 C_R=0,0180 l_{max}=8,1765

Table 10 presents the relative mutual relations matrix of particular components according to the cost effectiveness criterion. The comparisons were prepared with the use of the fundamental scale applied for the AHP method described in section 2. Consistency ratio C_R for the input data equals 0,0068 and it allows for the assumption that the matrix is consistent.

Table 10

Relative mutual relations matrix according to the criterion *cost effectiveness*

Costs	Rh	Rd	Ri	Rf	C	O	B	S
R_h	1	1	1	1	3	4	1/2	2
R_d	1	1	1	1	3	4	1/2	2
R_i	1	1	1	1	3	4	1/2	2
R_f	1	1	1	1	3	4	1/2	2
C	1/3	1/3	1/3	1/3	1	2	1/4	1/2
O	1/4	1/4	1/4	1/4	1/2	1	1/5	1/3
B	2	2	2	2	4	5	1	3
S	1/2	1/2	1/2	1/2	2	3	1/3	1

C_I=0,0095 C_R=0,0068 l_{max}=8,0665

Table 11 presents a relative mutual relations matrix of particular components according to the criterion reliability. The comparisons were prepared with the use of the fundamental scale applied for the AHP method described in section 2. Consistency ratio C_R for the input data equals 0,0122 and it allows for the assumption that the matrix is consistent.

Table 11

Relative mutual relations matrix of components according to the criterion *reliability*

Reliability	R_h	R_d	R_i	R_f	C	O	B	S
R_h	1	1	1	1	6	3	9	3
R_d	1	1	1	1	6	3	9	3
R_i	1	1	1	1	6	3	9	3
R_f	1	1	1	1	6	3	9	3
C	1/6	1/6	1/6	1/6	1	1/3	3	1/3
O	1/3	1/3	1/3	1/3	3	1	6	1
B	1/9	1/9	1/9	1/9	1/3	1/6	1	1/6
S	1/3	1/3	1/3	1/3	3	1	6	1

C_I: 0,0171 C_R: 0,0122 l_{max}=8,1194

After normalizing matrices 4-6, relevance parameters, of given components, were obtained according to the selected criteria as shown in Table 12. The following notations have been assumed: Rh - atomization holes are damaged by fuel erosion, Rd - atomization holes are contaminated by carbon deposits from combustion chamber; Ri - needle valve stacked in nozzle due to fuel contamination; Rf - excessive wear of precision pair (needle valve + nozzle body) due to fuel contamination; C - contamination of the nozzle cap nut; O - damage of the O-ring; B - excessive injector body wear due to friction; S - broken spring.

Table 12

Components relevance according to the selected criteria

Criteria preferences	Safety	Costs	Reliability
R_h	0,0492	0,1444	0,1989
R_d	0,1722	0,1444	0,1989
R_i	0,0324	0,1444	0,1989
R_f	0,1139	0,1444	0,1989
C	0,2624	0,0520	0,0332
O	0,0750	0,0351	0,0769
B	0,2624	0,2527	0,0176
S	0,0324	0,0824	0,0769

It should be noticed that according to the criterion ‘safety’, B and C (with over 26% relevance) are the most significant system components/problems as well as R_d and R_f (over 17% and 11% relevance relatively). The influence of other components on the system operational safety is relatively little – below 7%. According to the criterion ‘cost effectiveness’, B (with over 25% relevance) is the most significant system component. According to the criterion ‘reliability’ nozzle body and needle: R_h, R_d, R_i and R_f (with over 19% relevance) are the most significant system components/problems.

The last part of the analysis is to indicate an aggregated measure describing the system components relevance, considering all the criteria simultaneously. Table 13 shows the multi-criteria ranking of the components importance.

Table 13

Multicriteria ranking of components importance considering all the criteria

Alternatives rankings with structure	Safety	Costs	Reliability	Result	Rank
R_h	0,0322	0,0361	0,0190	0,0873	5
R_d	0,1128	0,0361	0,0190	0,1678	3
R_i	0,0212	0,0361	0,0190	0,0763	6
R_f	0,0746	0,0361	0,0190	0,1296	2
C	0,1718	0,0130	0,0032	0,1880	2
O	0,0491	0,0088	0,0073	0,0652	7
B	0,1718	0,0631	0,0017	0,2366	1
S	0,0212	0,0206	0,0073	0,0491	8

The aggregated relevance evaluation shows that B and C, with a relevance over 23% and 18% respectively, are the most significant system components, considering all the criteria.

5. Discussion

Summary of the results obtained, for each criterion, indicates convergence of the safety criterion grades (assessments). In the presented single-criterion analysis the assessment was based on the consequences of problems during the proper use of the object. The following notations have been assumed (Table 6): Rh - atomization holes are damaged by fuel erosion, Rd - atomization holes are contaminated by carbon deposits from combustion chamber; Ri - needle valve stacked in nozzle due to fuel contamination; Rf - excessive wear of precision pair (needle valve + nozzle body) due to fuel contamination; C - contamination of the nozzle cap nut; O - damage of the O-ring; B - excessive injector body wear due to friction; S - broken spring. Figure 4 shows the ranking of individual problems for the particular criteria in the AHP method and in the single criterion analysis. In order to compare the used methods, the values for the single-criterion analysis shown in figure 4 were determined after normalization and re-scaling to the total score range of <0.0; 2.5> from table 6.

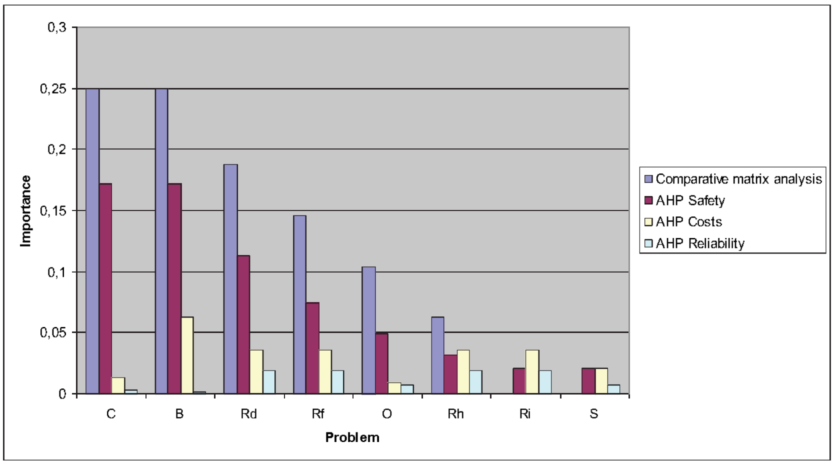

Fig. 4. The importance of individual problems in terms of single criterion

In view of varying weights of the individual criteria and varying partial rankings, the final ranking obtained in the analysis based on the comparison matrix and final ranking from the AHP method differ significantly (Figure 5).

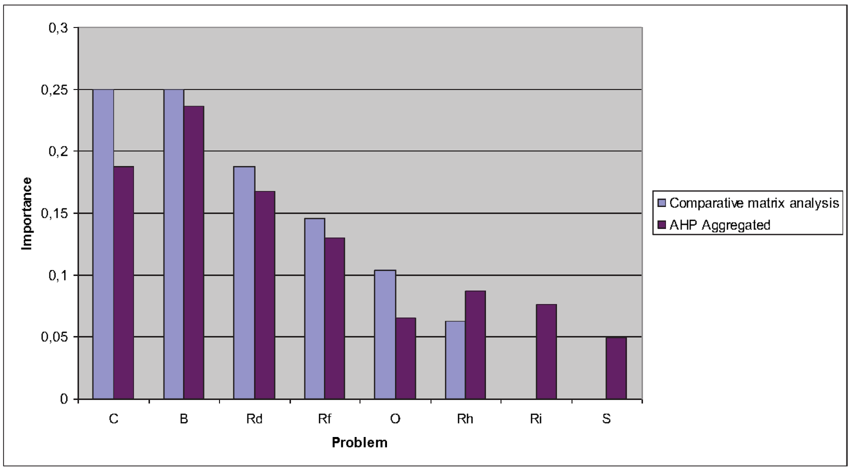

Fig. 5. The final importance of individual problems as determined with different methods

6. Final conclusions

Utilization of AHP as a tool for evaluating problems in the TRIZ function analysis is advantageous owing to simultaneous determination of criteria ranking and problem ranking. Moreover, the method allows one to change the severity of interrelationships of each problem, which increases the suitability of such an approach for analysis of complex systems with varying the severity of effects of hazards associated with the operation of the given system.

The article presents an analysis for safety, reliability and cost effectiveness criteria. The number of criteria can be arbitrarily increased depending on the purpose and scope of the performed function analysis [14]. For the example given the following issues could also have been analysed: availability of spare parts, system repair time, and ergonomics of operation or even aesthetic values for the user of the system.

Using the AHP method requires the calculation of the consistency ratio C_R every time which makes it possible to simultaneously evaluate the mutual relations matrix obtained on the basis of expert opinions. In addition, for calculating the consistency ratio C_R, average expert opinions are considered [7]. When CR is too high, obviously there are some conflicts in the analysed data which can be corrected at the start.

AHP analysis can be used to associate the quality parameters of the system performance (defined by experts) with quantitative parameters based on statistics or measurements. With the results obtained, it is possible to use additional TRIZ tools to solve problems having the highest rank, including through [2, 15, 16]:

- application of inventive principles and 76 inventive standards;
- conducting an in-depth analysis of the causes of the problem using root conflict analysis (RCA+) or cause and effect chain analysis (CECA) and then application of ARIZ algorithm to solve the problem;
- the use of the directory of physical, chemical and geometric phenomena to achieve the desired function of the system if the problem cannot be solved with common scientific principles;
- analysis of resources and system trimming (removing selected components and sharing the functions of other components without lowering of overall functionality, quality and efficiency of the system).

As the proposed analysis might be perceived as more difficult than the comparative matrix, to make the whole analysis easier the AHP analysis can be supported by a computer software. There are many computer programmes and on-line tools available, some of them are free of charge, e.g. Super Decisions (https://www.superdecisions.com/) or 123AHP (http://www.123ahp.com).

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