Fuzzy classification of technical condition at life cycle stages of responsible appointment systems

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Abstract. Approaches are considered and models of fuzzy classification of the technical state of systems of responsible design are proposed. For such systems, known performance estimates in the tolerance field are supplemented by the evaluation of the proximity of the parameter to the tolerance boundary and the anomaly state. The offered approach on three criteria is offered to extend on all stages of the life cycle connected with the control of a technical condition. For innovative products, a fuzzy model for estimating the drift of parameters near the primary base model is proposed. The structure of an intellectual decision support system designed to uncover uncertainties in the technical state on the basis of the updated knowledge base is considered.

1. Introduction

The tasks of identification and assessment of technical condition are topical for all technical systems. Failure of on-board automated systems, automation systems for energy, transport and other objects of responsible use leads to catastrophes, significant damage or other losses. The assessment of the technical condition of such responsible appointment systems(RAS) raises increased requirements for uncovering the uncertainty associated with their technical condition. In the article, in addition to the known probabilistic characteristics associated with parametric tolerance control, it is proposed to introduce fuzzy estimates of the technical state at the stages of the life cycle. When creating an innovative SES of the estimation of fuzzy sets characterizing the uncertainty of the type "located in the interval" corresponding to the tolerated parametric control with the lower and upper tolerances, piecewise linear functions and bell-shaped functions are used. Theobtainedestimatescharacterizethedriftoftheparametersneartheprimarybasemodel (Figure 1). For the stages of production and operation of RAS, a model of complex assessments "the level of operability" of parameters by the criteria of closeness of the values of the parameters to the boundaries of tolerance fields and the anomalous behavior of the values of the parameters within the limits of tolerance fields is proposed. Models for estimating fuzzy categories are proposed to be integrated into the intellectual decision support system designed to uncover technical uncertainties based on the updated knowledge base.

2.Fuzzy assessment of the innovative products parameters

The current practice of automated parametric control involves traditional methods of assessing the performance of the product, based on the criteria for the belonging of the values of the parameters to the corresponding tolerance zones. The binary approach does not take into account the boundary conditions of the investigated object in the control of RAS, which are necessary for forecasting potential supernumerary situations. Parametric control and maintenance of the target state of RAS is a complex task with a multitude of states and possible outcomes. The problem of determining the trajectory of the development of basic structures, to which the investigated RAS belongs, is reduced to the localization of the base sample, as a set of functionally necessary and functionally sufficient parameters [1]. The values of the parameters can vary under the influence of various scientific and industrial and social factors. The reaction to the impact is expressed in the form of creating technical and consumer characteristics and changing (drift) parameters (figure 1). Expansion of the scope of application of functionally sufficient parameters, creates the possibility of product diversification for the market.

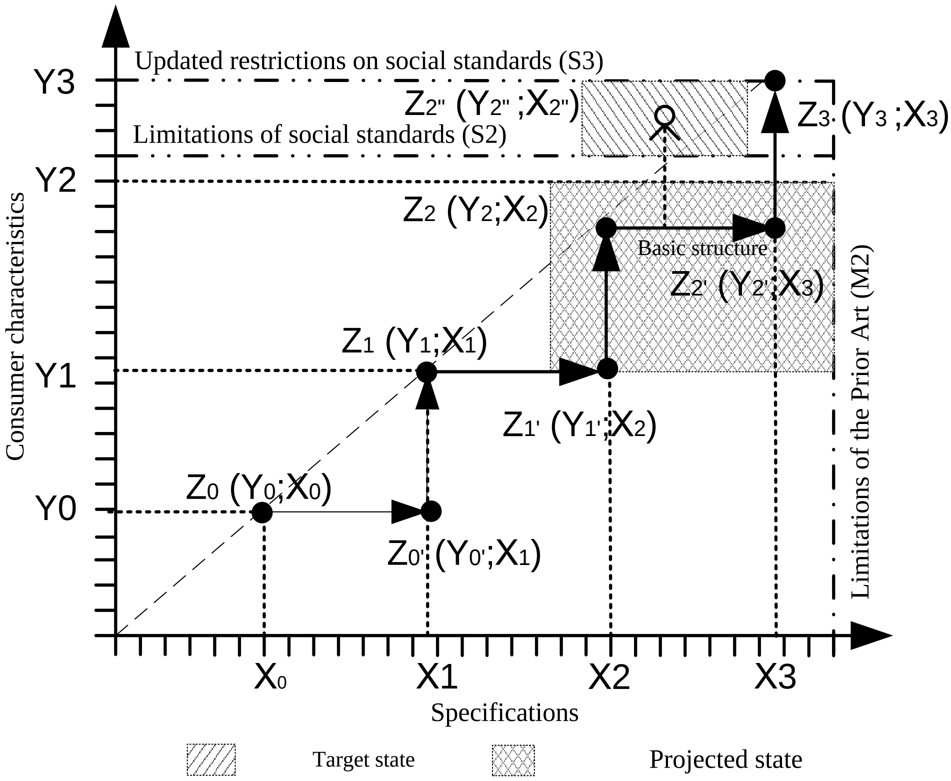

Figure 1. Drift of parameters.

Reaching the values of functionally necessary parameters allows you to stay in the local extremum of the product parameters to determine the technical novelty of the product or the degree of novelty of the product. However, it is difficult to say how the product behaves when performing the objective function under the load of external influencing factors (EIF). Therefore, preliminary tests are designed to identify significant EIF that affect the state of RAS. Features of the design of the basic structures of RAS include an assessment of the achievement of functionally significant (critical) parameters. The use of auxiliary tools presented in the work of Deming [2], in the process of decision-making on the basis of facts, the selection of functionally significant parameters of the RAS is reduced to the search and acceptance for the basis of the existing base sample, from which the developers of the new RAS will be repelled.

The ranking, synthesis and choice of options for the development of new RAS is carried out in the morphological space of parameters obtained by monitoring the reference points in the process of operation. Thus, several potential objects are formed in some neighborhood of the base point. The concept of the base point is based on the notion of a basic model created to solve current problems in the industry. The base sample is the basis for the generally accepted scientific and industrial paradigm existing at the time of its creation. To improve the search process in the space of parameters of a rational structure, within the framework of planned technological development by methods (KAIRYO) and (KAIZEN), it is also advisable to take into account the laws of the development of technical systems proposed by the theory of solutions of inventive problems (TRIZ).

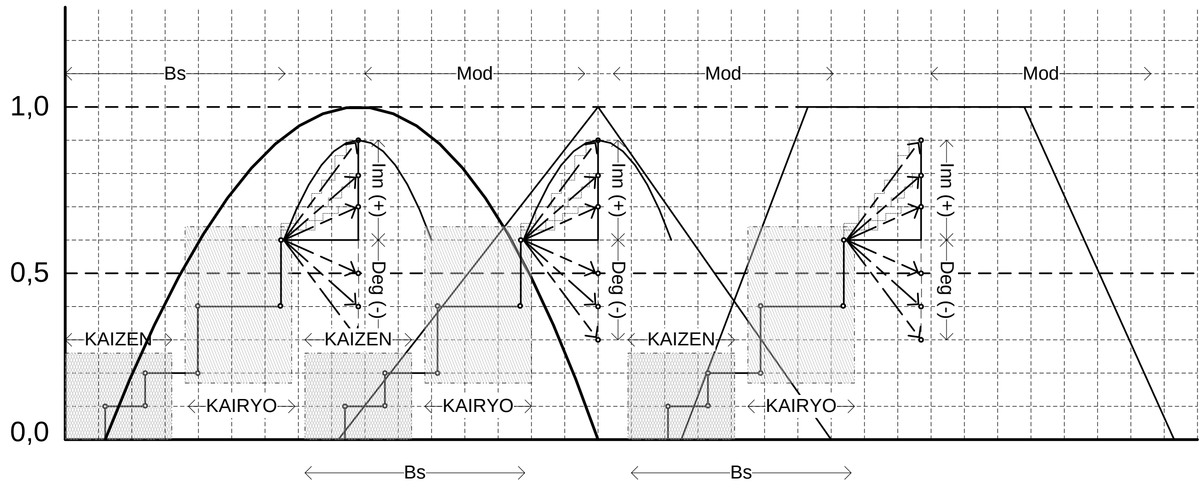

Figure 2. Themembership functions for investigating the drift of the product parameters. BS - area of the basic structure; Mod - zone of modernization; KAIRYO - a zone of technological breakthrough; KAIZEN - zone of continuous improvement; Inn (+) - an area of innovative leap; Deg (-) - zone of moral (artificial) obsolescence.

Different states of the basic structures created under the influence of the EIF reflect the drift of the parameters of the RAS. In cases where the result of parameter control is determined and a point state is required or the result is expressed by a range of values, the membership functions characteristic for solving such problems are used (figure 2).The use of membership functions depends on the expert's opinion and is not formalized. In [3] recommendations are given on the areas of application of membership functions. Following [3], piecewise linear functions are used to specify fuzzy sets characterizing the uncertainty of the type "located in the interval" corresponding to tolerant parametric control with lower and upper tolerances. Z-shaped or S-shaped membership functions are used to specify fuzzy sets characterizing the uncertainty of the "lower tolerance" or "upper tolerance" type, respectively. It is possible to build bell-shaped functions. When there is a lack of information, it is recommended to use piecewise linear membership functions that can be corrected by an expert or in the process of functioning of an intellectual decision support system (IDSS).

3. Fuzzy assessment of technical condition during production and operation

Admission control of parameters is carried out with the help of an automated control system (ACS) in the process of adjustment, technological run, bearer, acceptance and periodic testing, during the products operation. The current practice of automated parametric control involves traditional methods of assessing the performance of the product, based on the criteria for the belonging of the values of the parameters to the corresponding tolerance zones [4].The data on the control of the values of the parameters and the results of the checks come from the ACS on the universal serial bus to the industrial computer that implements the functions of the IDSS.

New results on the creation of the necessary means for automated control systems for mass-produced objectsare presented in [5]. Such systems can be used in preliminary and acceptance tests, as well as during adjustment and adjustment in the production process. Creation of mass-capable objects with specified quality indicators should be provided at all stages of the product life cycle. The formal requirements for the reliability of control that can be made can differ at different stages. The concept of reliability used can be interpreted, depending on the quality requirements, as completeness of control, depth of control (diagnosis), "manufacturer's risk" and "customer risk". The customer in the delivery of products is usually interested in the control of the product as a whole. The developer and the manufacturer, in addition to monitoring the operation, are also interested in the results of diagnosing for debugging design decisions and manufacturing techniques in order to reduce rejection. In this setting, the creation of an ACS for the verification of any electronic product is reduced to the creation of an input driver, a device that reads responses to input influences and decides device, providing a decision on the operability of the product.

The solution to the problem of increasing the efficiency of ACS operation is associated with an increase in the accuracy of estimates of the results of parametric control, the quality of recognition, and the assessment of the technical state of RAS. For the timely detection of pre-existing conditions of RAS and the detection of predispositions to the instability of an operational state in the early stages of defect development, improvement of scientific principles and technical controls is required. A promising way to solve these problems is the development of new models, criteria and algorithms for a deeper evaluation of the technical state of the product, the decisive rules for recognizing the different states of a workable system based on the theory of fuzzy sets [6] and fuzzy logic [7].

To increase the accuracy of estimates of the results of parametric control, three fuzzy classifiers of estimates of the monitored parameters have been developed, which are used in conjunction with the mathematical apparatus of fuzzy logic in the model to obtain complex estimates of the "working capacity" parameters.

As parameters to be more accurately estimated, it is proposed to select the critical parameters of the RAS that characterize the performance of critical elements that have a "fit" rating based on the results of ACS's tolerance control. The initial data for a more accurate estimation of critical parameters are their numerical values. The list of critical parameters is determined in accordance with the guidelines given in [8] and [9].

The construction of the classifier is based on the results of processing expert opinions and analyzing the existing database of the results of previous tests. The choice of the required number of values of linguistic variables is made taking into account the need to ensure a minimum degree of difficulty when using classifiers in the control process and the maximum consistency of expert judgments in their creation.

The input linguistic variables of the model for obtaining complex estimates of the parameters "health level" are: A_1 - "estimation of the state of the parameter by the criterion C_1" and A_2 - "estimation of the state of the parameter by the criterion C_2". As A_1, we will use the qualitative estimation of the state of the parameter "fit" by the criterion of proximity to the boundaries of the tolerance fields, and as A_2 - the qualitative evaluation of the state of the parameter "fit" by the criterion of anomalous behavior of the values within the boundaries of the tolerance fields. " The output linguistic variable is B - "estimation of the state of the parameter by the criterion C_3". The value of B is an estimate of the state of the parameter "fit" according to the complex criterion "level of efficiency." The aggregate of linguistic values of A_1, A_2 and B are presented in table 1.

Table 1. Setting of term sets for variablesA_1, A_2иB.

Designation	Linguistic variable	Term-set
A_1	Evaluation of the parameter by the C_1 criterion	EC_1 – «excellent condition», GC_1 – «good condition», SC_1 – «satisfactory condition», DC_1 – «Dangerous condition», PS_1 – «Pre-failure status».
A_2	Evaluation of the parameter by the C_2 criterion	EC_2 – «excellent condition», GC_2 – «good condition», SC_2 – «satisfactory condition», DC_2 – «Dangerous condition», PS_2 – «Pre-failure status».
B	Evaluation of the parameter by the C_3 criterion	EC_3 – «excellent condition», GC_3 – «good condition», SC_3 – «satisfactory condition», DC_3 – «Dangerous condition», PS_3 – «Pre-failure status».

To form the basis of rules for fuzzy inference systems, you must first determine the input and output linguistic variables. Since different critical parameters can have different values of tolerances, then as a carrier of linguistic variables A_1, A_2 and $B$the unit interval of the real axis [0,1] is chosen. Since finite-dimensional segments of the real axis can be reduced to a segment [0,1] by a simple linear transformation (dividing all values by the maximum value), then the selected segment of unit length (relative scale) has a universal character. To describe subsets of the term set (Table 1), we introduce a system of five membership functions, which are based on triangular membership functions. The choice of the form of the triangular membership function is justified by the following considerations:

- When estimating the parameters of membership functions, only interval limits and the most acceptable parameter values are known. If the researcher does not have more information, then the only acceptable approximation is linear. The triangular membership function is specified by the minimum number of parameters: the minimum value, the modal value, and the maximum value;
- triangular membership functions have low computational complexity, which makes it possible to apply them in situations with a limited time limit for making managerial decisions. In addition, they are widely used in existing applications of fuzzy logic, their reliability and effectiveness are tested by practice.

The numerical value of the input variable x_1 from the interval [0,1] is the distance from the middle of the tolerance field to its edge, the value of x_2 is the rate of change of the parameter, which is the ratio of the difference between the maximum and minimum values of the parameter from all values obtained during various tests the difference in the fixation time of these parameters. The value of y is a numerical estimate of the state of the parameter "fit" according to the complex criterion "level of efficiency".

Thus, the linguistic variable A_1 (A_2, B), defined on the unit segment of the real axis [0,1], with a term-set of values that are described by triangular membership functions, is a five-level fuzzy classifier of the parameterx_1 (x_2, y).Graphically, the set of membership functions of the term set of values of the linguistic variable B is shown in the figure 3.

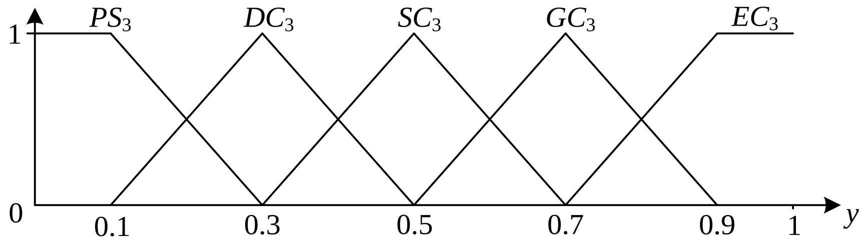

Figure 3. Five-level fuzzy classifier for the parameter y.

As an algorithm of fuzzy logic inference, the Mamdani algorithm was chosen, which makes it possible to significantly reduce the amount of computation that has received the greatest practical application and was appreciated by specialists [10].Let's consider an example of an estimation of a condition of a critical parameter "is good" under the complex criterion "level of working capacity" at a stage of acceptance control at the manufacturing enterprise.Given the above abbreviations and all combinations, the base of fuzzy rules consists of 25 rules:

RULE 1: IF "A_1 is EC_1" AND "A_2 is EC_2", then "B is EC_3";
RULE 2: IF "A_1 is EC_1» AND «A_2 is GC_2», then "B is GC_3»;
RULE 3: IF "A_1 is EC_1» AND «A_2 is SC_2», then "B is SC_3»;
RULE 4: IF "A_1 is EC_1» AND«A_2 is DC_2», then "B is DC_3»;
RULE 5: IF "A_1 is EC_1» AND «A_2 is PS_2», then "B is PS_3»;
RULE 6: IF "A_1 is GC_1» AND «A_2 is EC_2», then "B is GC_3»;
RULE 7: IF "A_1 is GC_1» AND «A_2 is GC_2», then "B is GC_3»;
RULE 8: IF "A_1 is GC_1» AND «A_2 is SC_2», then "B is SC_3»;
RULE 9: IF "A_1 is GC_1» AND «A_2 is DC_2», then "B is DC_3»;
RULE 10: IF "A_1 is GC_1» AND«A_2 is PS_2», then "B is PS_3»;
RULE 11: IF «A_1 is SC_1» AND «A_2 is EC_2», then "B is SC_3»;
RULE 12: IF «A_1 is SC_1» AND «A_2 is GC_2», then "B is SC_3»;
RULE 13: IF «A_1 *is* SC_1» AND «A_2 is SC_2», then "B is SC_3»;
RULE 14: IF «A_1 *is* SC_1» AND «A_2 is DC_2», then "BisDC_3»;
RULE 15: IF «A_1 *is* SC_1» AND «A_2 is PS_2», then "BisPS_3»;
RULE 16: IF «A_1 *is* DC_1» AND «A_2 is EC_2», then "B is DC_3»;
RULE 17: IF «A_1 *is* DC_1» AND «A_2 is GC_2», then "B is DC_3»;
RULE 18: IF «A_1 *is* DC_1» AND «A_2 is SC_2», then "B is DC_3»;
RULE 19: IF «A_1 *is* DC_1» AND «A_2 is DC_2», then "B is DC_3»;
RULE 20: IF «A_1 *is* DC_1» AND «A_2 is PS_2», then "BisPS_3»;
RULE 21: IF «A_1 *is* PS_1» AND «A_2 is EC_2», then "B is PS_3»;
RULE 22: IF «A_1 *is* PS_1» AND «A_2 is GC_2», then "B is PS_3»;
RULE 23: IF «A_1 *is* PS_1» AND «A_2 is SC_2», then "B is PS_3»;
RULE 24: IF «A_1 *is* PS_1» AND «A_2 is DC_2», then "B is PS_3»;
RULE 25: IF «A_1 *is* PS_1» AND «A_2 is PS_2», then "B is PS_3».

Suppose, before the beginning of fuzzification, the numerical values from the interval [0,1] of all input variables of the fuzzy inference system are known, namely,x_1= 0.15 *и*x_2=0.82. The active rules that will be used in the current process of fuzzy inference are:

RULE 4: IF«A_1 is EC_1» AND «A_2 is DC_2», then «B is DC_3»;
RULE 5: IF«A_1 is EC_1» AND «A_2 is PS_2», then «B is PS_3»;
RULE 9: IF«A_1 is GC_1» AND «A_2 is DC_2», then «B is DC_3»;
RULE 10: IF«A_1 is GC_1» AND «A_2 is PS_2», then «B is PS_3».

Further, using the membership functions of all terms of the input linguistic variables $A_1$and A_2, we determine the degree of truth of elementary fuzzy sentences, which are the subwords of active fuzzy rules 4, 5, 9 and 10.For example, for the term EC_1, the membership function formula has the following form:

$$\mu_{EC_1}(x;0.1,0.3)=\begin{cases}1, & x\le 0.1\\ \dfrac{0.3-x}{0.2}, & 0.1\le x\le 0.3,\\ 0, & x\ge 0.3\end{cases} \quad (1)$$

Таким образом, при фаззификации получаем степени истинности элементарных нечетких высказываний:

- «$A_1$is an" excellent condition ", $\mu_{EC_1}(x_1)=0.75$;
- «$A_1$is a" good condition ", $\mu_{GC_1}(x_1)=0.25$;
- «$A_2$is a" dangerous state ", $\mu_{DC_2}(x_2)=0.4$;
- «A_2 is a" pre-failure state", $\mu_{PS_2}(x_2)=0.6$.

Figures 4 and 5 show examples of the fuzzification of input linguistic variables: "estimation of the state of the parameter by the criterion K_1" and "estimation of the state of the parameter by the criterion K_2". The degree of truth of the fuzzy statement is the ordinate of the point of intersection of the graph of the membership of the term and the line *x* equal to the numerical value of the input variable.

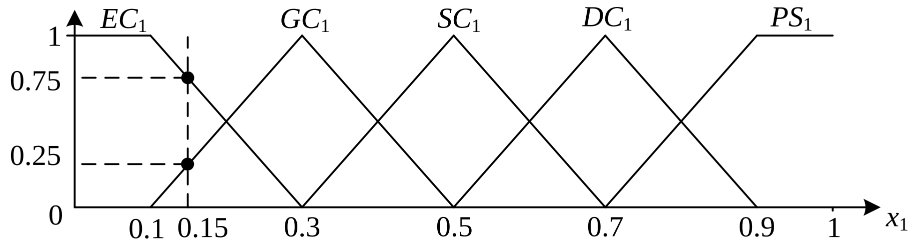

Figure 4. Example of fuzzification of the input linguistic variable "estimation of the state of the parameter by K_1".

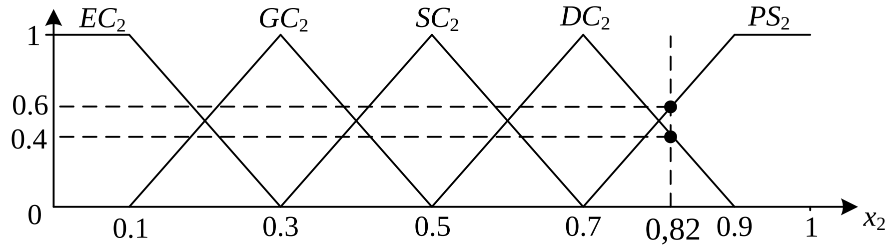

Figure 5. Example of fuzzification of the input linguistic variable "estimation of the state of the parameter by K_2".

At the stage of aggregation of subwords in fuzzy rules (Figure 6), we determine the levels of "clipping" α (the degree of truth conditions) for each of the active fuzzy rules using the min-activation method:

$$\alpha_4=\min\left[\mu_{EC_1}(x_1),\mu_{DC_2}(x_2)\right]=\min(0.75,0.4)=0.4;$$

$$\alpha_5=\min\left[\mu_{EC_1}(x_1),\mu_{PS_2}(x_2)\right]=\min(0.75,0.6)=0.6;$$

$$\alpha_9=\min\left[\mu_{GC_1}(x_1),\mu_{DC_2}(x_2)\right]=\min(0.25,0.4)=0.25;$$

$$\alpha_{10}=\min\left[\mu_{GC_1}(x_1),\mu_{PS_2}(x_2)\right]=\min(0.25,0.6)=0.25.$$

At the stage of activation of conclusions in fuzzy rules (Fig. 4) we find activated ("truncated") membership functions using min-activation: $\mu^{4}_{DC3}(y) = \min\left[\alpha_4, \mu_{DC_3}(y)\right]$;

$$\mu^{5}_{PS3}(y) = \min\left[\alpha_5, \mu_{PS_3}(y)\right];$$

$$\mu^{9}_{DC3}(y) = \min\left[\alpha_9, \mu_{DC_3}(y)\right];$$

$$\mu^{10}_{PS3}(y) = \min\left[\alpha_{10}, \mu_{PS_3}(y)\right].$$

At the stage of accumulation of the conclusions of fuzzy rules (Fig. 4) we find the function of μ_{ACC} (y) belonging to the output linguistic variable B by combining fuzzy sets

$$\mu^{4}_{DC_3}(y), \mu^{5}_{PS_3}(y), \mu^{9}_{DC_3}(y), \mu^{10}_{PS_3}(y)$$

with membership functions by the max-association method:

$$\mu_{ACC}(y) = \mu_{ACC}(y) = \max\left\{\min\left[\mu_{EC_1}(x_1), \mu_{DC_2}(x_2)\right], \min\left[\mu_{EC_1}(x_1), \mu_{PS_2}(x_2)\right], \min\left[\mu_{EC_1}(x_1), \mu_{DC_2}(x_2)\right],\right.$$
$$\left.\min\left[\mu_{EC_1}(x_1), \mu_{PS_2}(x_2)\right]\right\}$$

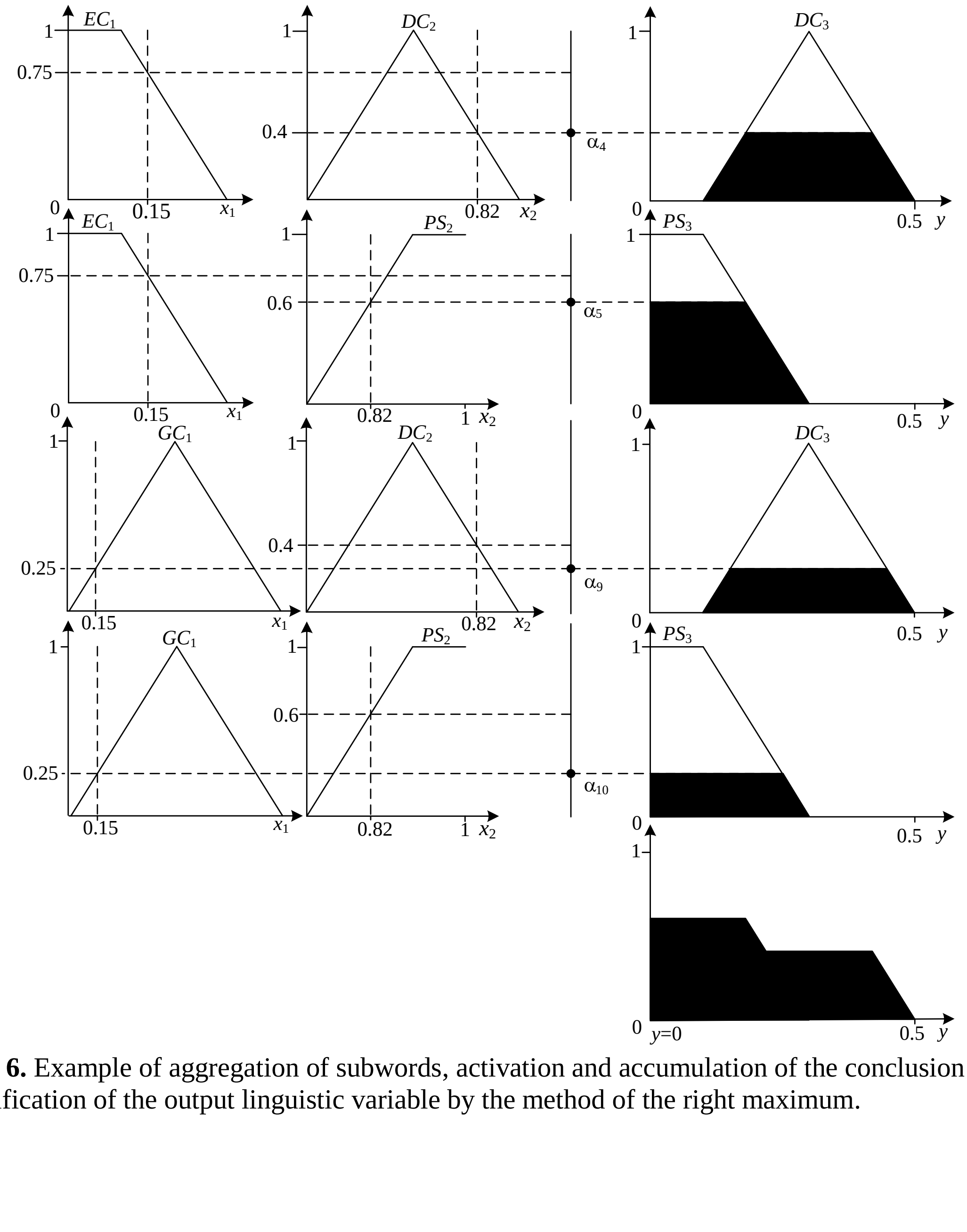

Figure 6. Example of aggregation of subwords, activation and accumulation of the conclusion and defuzzification of the output linguistic variable by the method of the right maximum.

To determine the quantitative value of the output linguistic variable at the stage of defuzzification, we use the method of the left maximum, which consists in choosing the smallest value y that has the highest degree of affinity for the fuzzy set. As a result of the reduction to clarity, a numerical estimate of the state of the parameter "fit" is obtained from the complex criterion "level of efficiency" $y = 0$. The following critical parameters are then evaluated. Having received a set of estimates, the decision-maker selects a possible strategy for further action based on the results of the parametric control, depending on the level of risk of failure in table 2.

Table 2. Possible strategies for decision-making depending on the level of risk of failure.

The level of risk of failure	The criterion of the level of risk of failure	Possible strategies for decision-making
Acceptable	$\exists y \in Y : 0.7 < y \leq 0.9$	The decision on acceptance of the product with a regular complete set of spare parts, tools and accessories is made
Border	$\exists y \in Y : 0.35 < y \leq 0.7$	The decision on acceptance of the product with the changed complete set of spare parts, tools and accessories is made
Unacceptable	$\exists y \in Y : 0 \leq y \leq 0.35$	The decision on acceptance of the product is not accepted. A program for the implementation of preventive measures and subsequent decision-making is being developed

4. Modeling of intellectual decision support system

IDSS (figure 7) carries out the input, processing, storage and exchange of information. Information sources in addition to ACS (measurement data) are: PDM-system (data and knowledge of similar IDSS), accumulating information about the product within the life cycle, decision-maker (data of the conditions for solving the problem), knowledge engineer (new and corrected data and knowledge), a programmer (developed or adjusted software).

To model the desired states in accordance with established market priorities or regulatory terms of reference, it is advisable to use the capabilities of databases on technical solutions or access to knowledge bases. An excellent creative accumulator of non-standard technical solutions is TRIZ, which includes a list of methods and methods for the preventive development of a technical system. Inclusion of a set of typical principles for solving technical contradictions of TRIZ arising in the design of new RAS, taking into account possible WWF, will reduce the time and resources of the development team. Using the laws of the development of technical systems included in the expert knowledge base will create the ability to control the drift of parameters through constructive modernization or artificial aging as separate structural elements and the entire system as a whole. This will have the necessary consumer effect on the sales market. The supplemented fuzzy classification by TRIZ tools will allow not only to determine the technical state and consumer value of the system under study at all stages of the SDS life cycle, but also to promote the development of the potential of this system to a competitive product.

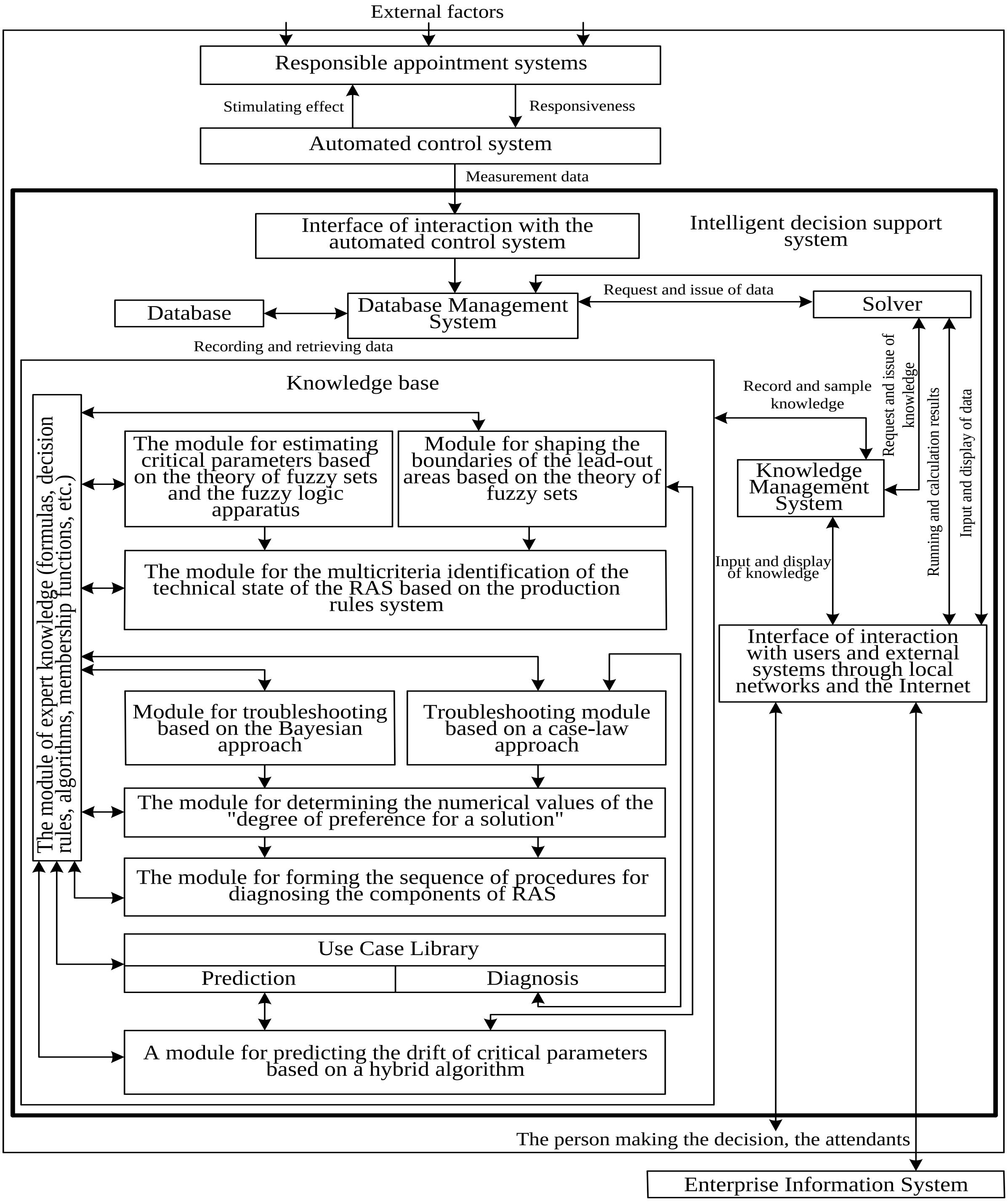

Figure 7. Structure of intellectual decision support system.

5. Conclusion

The proposed methods of fuzzy classification of the technical state at the stages of the life cycle of the systems of responsible use differ from the existing ones in that it allows to control the so-called drift of the functionally significant parameters of the system under study, influenced not only by the factors of the development of scientific and technological progress, the social environment, but also by external factors, having a destructive character. Complemented fuzzy classifications contain membership functions that are applicable to each of the states of a technical system of responsible design that model different stages of its life cycle. Considering the reference to databases on current technical problems of such systems, the principle of continuity is implemented. To do this, we use a supplementary knowledge base with typical solutions of technical contradictions, laws of technical systems development contained in TRIZ. This makes it possible to use the current databases as part of a promising expert knowledge base, which will lead to original solutions for the design of new RAS that meet not only all modern market requirements, but also create an additional competitive advantage.

The proposed model for obtaining complex estimates of the "working capacity" of parameters by the criteria of closeness of the values of the parameters to the boundaries of the tolerance fields and the anomaly of the behavior of the parameter values within the boundaries of the tolerance fields allows us to quickly detect and qualitatively estimate the insufficient availability and dangerous changes in the critical parameters of the operable RAS. The received evaluations make it possible to take informed decisions aimed at preventing potential failures to prevent emergency and emergency situations in the operation environment, to carry out timely recovery and preventive measures (adjustment, additional adjustment, debugging of the interaction of the component parts within the RAS, etc.) aimed at increase in the availability of work and ensure the stable operation of the RAS, i.e. increase its actual resource.

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