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APPROACH TO AUTOMATION OF FIELD DIAGNOSIS DATA INTERPRETATION FOR LOCALIZATION OF PITTING IN THE PIPELINE WALL

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ABSTRACT

The development of pipeline systems of hydrocarbon transportation and their ageing cause the need for the creation of a contactless system for express-diagnostics of pre-breaking conditions. Low-contrasting physical responses from the damaged pipeline sections are localized by the methods of interpretation of an anomalous magnetic field. The authors consider the problem of limiting automation of interpretation procedure with the estimation of the expert's role decrease. Despite the commercial attractiveness of the idea of automation, one cannot ignore the paradox in a possible solution of the problem: any automation is based on a particular model but this model is developed with the application of experience of a particular expert.

Keywords: pipeline, interpretation, diagnostics, magnetic field, workstation, model, functional, minimization

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1. INTRODUCTION

Being developed for over 50 years, gas and oil pipelines represent an extensive element of transport infrastructure which has no competitors in the field of oil and gas products transportation. The pipeline, like any space-distributed system, has a multicomponent character. The construction of this object from the supplier area to the consumer location requires many years, which determines the significant role of exogenous factors in the dynamics of pipelines. The system of supply pipelines interacts with all elements of the modern landscape and geological substratum as well, crossing the regions with different geological structures and geodynamic regimes; this includes:

variability of soil’s bearing capacity;

complicated relief of modern landscape, causing anomalous load on local sections of the pipeline;

nonzero kinematics of geological fracturing elements.

The complex interaction of components of natural and man-caused landscape with the trunk pipeline, combined with neglect of pipeline regulation standards, leads to a limited period of trouble-free operation of the trunk-line. On average, it varies from three to five years in tectonically inactive regions, after which the system of measures to reduce the risk of development of pre-breakthrough conditions becomes relevant. Usually, this system includes in-line diagnostics with subsequent prospecting, defectoscopy and the final stage of forming by a complex of repair procedures.

At present, more than 50% of existing pipeline systems have been in operation for more than five years. These systems’ total extent of thousands of kilometers requires the development of rapid technology of field diagnostic that determines the role of detailed estimation and repair procedures for internal diagnostics and subsequent actions. The research of the methods of pipeline primary estimation has been conducted for over 25 years and includes the application of the following approaches: implementation of first environmental standards, electrochemical and electromagnetic methods of electrical prospecting, swallow seismic methods, remote sensing. Among these approaches, the method of multiband magnetometric control involving using magnetometer-gradiometers based on the adjusted ferroprobe sensor is preferable [1]. Technologically, this method is reduced to the registration of specific anomalies during magnetometric registration, when the operator moves along the earth's surface following the axis of the pipeline, the upper edge of which is placed at a depth of 0.8-1.5 m [2].

The result of the measurements is paradoxical. Theoretically, the magnetic response of the unknown defect in the pipeline wall is inaccessible for the operator, since this response is concentrated in the relatively small vicinity of the mentioned defect. In practice, the presence of dispersion fields in combination with the phenomenon of corrosion and the appearance of the anode-cathode pair on the pipe create the macroscopic anomalous effect. This effect appeared during contactless measurements in the form of low-contrast distortion of the morphology of magnetic induction vector components and space-related gradients of these components, which requires the implementation of interpretation techniques. Some research groups develop their own methods of qualitative and quantitative interpretation based on the expert (visual and empirical) analysis. The specificity of production (conveyor) problems requires the parametric (physical and mathematical) confirmation of expert estimations. Finally, the development of this aspect should approach the stage of creation of an automated parameterized system for interpretation of contactless pipeline diagnostics results. This formulation of the problem is contradictory: satisfying production needs, it does not consider, first, expert estimations predominant in modern geophysics and, second, the need for expert verification of any computer reconstructions prescribed in the standards of oil and gas companies. Nevertheless, ignoring common sense, managers pursue the attractive idea of total automation, which causes the industrial problem of the development of scientific and technical basis of a workstation for diagnosticians (WSD).

2. METHODS: GENERAL APPROACH TO AUTOMATION

Inequality WSD development is a complex multicomponent problem in the field of information support in the pipeline control system. WSD includes a set of heterogeneous components starting from the operator and hardware complex and ending with the procedure of expert conclusion, therefore, the problem of automation assumes scientifically-intensive structural-technological and mathematical-algorithmic solutions. These solutions should be integrated into a universal hardware unit and an optimized software shell with a consistent and concise user interface. Without formal consideration, the concept of WSD is focused on the following aims:

elimination of the distinction between direct and indirect observations;

minimization of the time spent on real-time processing of observations;

objectivity of expert estimations including parameterization of estimation of pre-breakthrough risk;

analysis of quality of original and final data from the localization of forecast errors to the criterial sorting of information in specialized databases;

dialogue with a user of any qualification level due to limiting automation of specialized transformations and the concealment of intermediate stages of analysis.

Within such context, WSD allows the application of pattern recognition elements, primary expert solutions, intellectual access of the user to the key elements of the survey, targets estimation of which assumes an increased level of responsibility (Fig.1). Against this background, the modern advances in information technology offer a relatively formalized class of approaches, including computational, visualization, software and management components. Their development is the subject of the first stage of WSD progress, while at the second stage, they require the program and technological complex improvement based on the use of accumulated statistics on investigated objects (defects in pipelines).

The key element of the first stage of WSD development is software, organized in the form of modular architecture (Fig. 1,a), in which there are elements of general and special purpose. The modules of general purpose include the units of the operating system and additional standard software. The general-purpose units are based on the following duties:

calculation of parameters (original and secondary);

visualization of data (graphs, tables);

configuration of calculation (main software);

management of database and protection of its information;

rapid analysis;

administration tools.

During processing, the execution of WSD software is realized in the interaction with the operator at all stages of analysis and diagnosis of information. The distribution of functions between software and operator is shown in Fig.1,b, according to which the transformation of information at the stages of primary and secondary processing is performed automatically by WSD software. The configuration, analysis of information and decision-making on the result of processing are executed at the expert evaluation level by a particular operator when determining the stage of processing. Operator estimation is related to the analysis of graphical and physical parameters, the sum of which forms the characteristic of pipeline analyzed section.

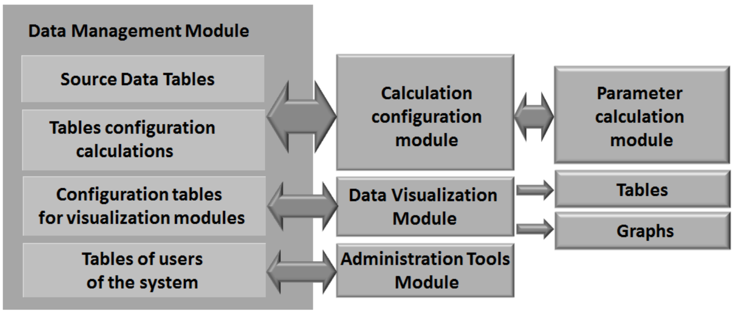
The mechanism of operator's interaction with WSD software includes return cycle with the secondary processing using improved conditions (algorithms, weight coefficients etc.). The sequence of operator actions has constant structure and includes preparatory operations, analysis of information, output of intermediate results, formulation of the problem for a detailed study of the object, reanalysis of information on the basis of a detailed study for verification of object condition, presenting an opinion to a commission of experts. The preparatory works are focused on the standard operating procedure considering a priori information about the object (defects in the pipeline wall), model approximations, converting to working formats, and data sorting. The stage of information analysis includes the following problem solutions: localization of anomalous zones on magnetic parameters, classification of such zones by risk level, localization of pipeline sections with an anomalous strain-stress field. The operator has the opportunity to change processing parameters which affect the classification of the anomalous zone in order to correct the level of risk. After classification, the operator starts the system of rapid analysis for selected pipeline section to get the set of weight coefficients. The application of these coefficients in the processing of the initial database is meant for the exact selection of the pipeline section element with anomalous strain and stress. The accuracy of operation is defined by the completeness of the applied database of defects or previously identified magnetic anomalies. The final stage of the output of expert opinion includes:

recording parameters of dangerous anomalous zones associated with a database object for further observation;

recording the position of detected defects in the database;

record the position of defects which are considered unconfirmed ones during detailed estimations;

writing final report.



a. functional links of modules;

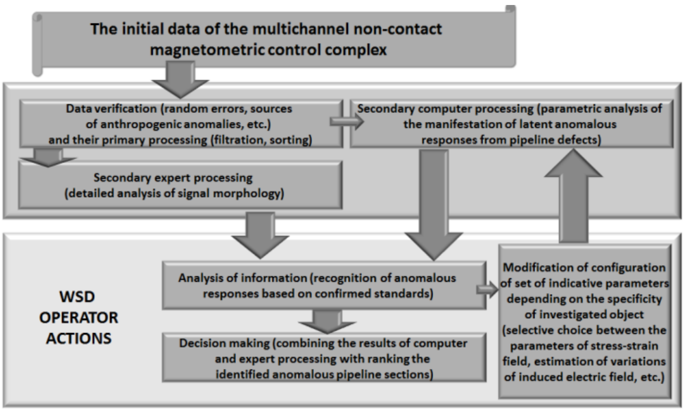


Figure 1. The modular structure of WSD:

b. distribution of functions between the software and the operator.

In the considered processing chain, the main question is related to the high degree of expert involvement including manual operations and visual estimations during data set processing. Statistical generalization of the level of operator utilization demonstrates that the main part of the operations is data analysis (about 50%), registration of the intermediate result (approximately 20%) and re-analysis (about 20%). It is important to formulate the basic requirements for the operator's qualification, including knowledge of the theory of magnetic fields, knowledge of algorithms for analysis and signal processing, the ability to visually find and evaluate magnetic anomalies in primary and secondary information arrays. At the second stage of the WSD development, one has to reduce the level of expert participation to at least 40%. Theoretically, the key aspect of this reduction is proper management of statistical and physico-mathematical modeling.

3. RESULTS: GENERAL PRESENTATION OF THE MODEL

In this part, we suggest proceeding from the discussion of the standard terminology in the areas, where the model presentations are understood as mathematical, physical and physic-mathematical descriptions of natural-technical systems. Mathematically speaking [3], a model is an interpretation of a formalized language, where formalized language is described as an artificial language characterized by precise rules for constructing expressions and their understanding. It is accepted to divide the models into mathematical and computational, where the former have a more general character since they are oriented toward approximate characterization of objects and phenomena of the external world by means of the mathematical symbol. Computational models are of particular interest as elements of the solution of routine problems that lead to the numerical solution of abstract mathematical or applied problems. From the physical point of view [4], a model is characterized as the image of some object or phenomenon, formed based on the theory of similarity and analysis of dimensions. The theory of similarity is based on the idea of physical processes' similarity, phenomena or systems in the case of proportionality of their characteristic parameters in "similar moments of time in similar points of space". The main element of the similarity theory is the analysis of dimensions, the main requirement of which is the invariable validity of the equation reflecting the investigated dependence for any change in the units of quantities included in this equation (this is equivalent to the requirement of equality of dimensions of the right- and left-hand sides of the equation).

Generally speaking, a model in our problem is an extremely simplified equivalent of an initially heterogeneous and anisotropic natural-technical system with complex morphology, the degree of simplification of which is focused on the description of properties and/or dynamics of this system in quantitative, semi-quantitative or qualitative form. In the engineering-geological area, including modeling in contactless diagnostics of pipeline conditions with mentioned simplification, it is necessary to develop the model of response (the element of mathematical geology, Fig.2), the probabilistic (stochastic) model, the model of "black box".

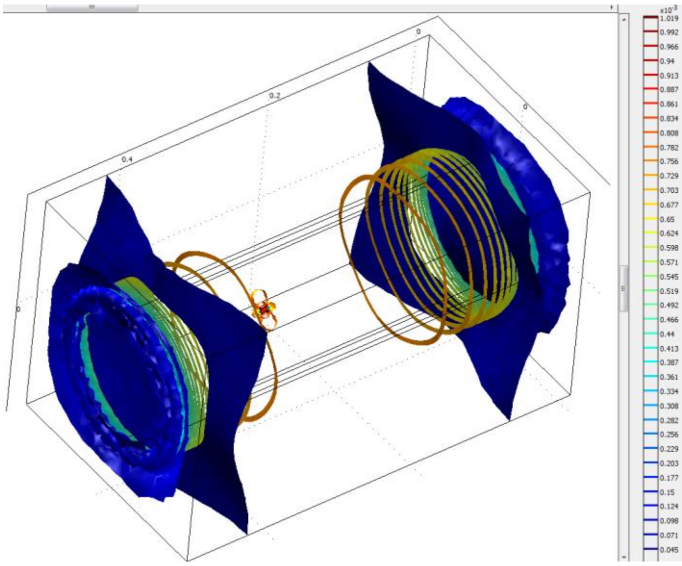


Figure 2. The model of the 3D-structure of the magnetic field (modulus of magnetic induction vector, Tl) for the local section of pipeline and small corrosion pitting in its wall placed between welded joins. One can see the structure of the magnetic response of pitting is similar to the response of dipole.

In the system of the multiband magnetometric signal, the response model implies the existence of additive components with deterministic morphology. These components uniquely correspond to the desired object (external or internal defect in the pipeline wall) and are described by a narrow class of analytic functions. The probabilistic model is reduced to the empirical representation of the statistical nature of the relationship between the morphostructure of initial magnetometric signal and the physico-geometric parameters of wall defects in the pipeline. The model of "black box" describes the problem of WSD development where WSD masks the results of field measurements and their parametric recalculations. These recalculations in the structure of "black box" are realized in the automated mode and should be converted into an expert opinion on the degree of the risk of pre-breakthrough state of the investigated pipeline at the output.

4. DISCUSSION: THE MODEL OF "BLACK BOX" AS A MODEL OF WSD

In the described form, the model of WSD goes back to the solution of the problem in the development of automated control system (ACS) where the operator's actions are not automatized and supposed to be unrelated to the expert's functions: these actions are connected with generalization and target designation. The ACS concept is not applicable for engineering geophysics, which is responsible for contact and non-contact monitoring of the pipeline condition: the role of the expert is decisive throughout the project, from the stage of field journal measurement records and to the stage of the report output and graphical and parametrical generalization. Automation is assigned to [5, 6]:

individual items in the process measurement;

implementation of relative converters for data transfer in processing by specialized hardware-software products;

properly algorithmized parametric processing and data accumulation under taxonomy determined by expert opinion.

As part of the solution of the industrial problem, there are improper attempts to extend the application of automation to other stages of WSD development. For example, during contactless field measurements by automated equipment, where the role of operator is reduced to traveling along pipeline and simultaneous record updating, all the standards of magnetic survey (measurements of gridding points, orientation of magnetometer sensor at each picket, measurements by variation station together with survey along the profile, implementation of three measurements at each picket) are violated. As a result, the structure of measured signals becomes more complicated, but in fact, there is empirical dependence between the morphostructure of this signal and the parameters of the defect in the pipeline wall (Fig.3). This allows us to consider the magnetometric signal as a set of responses in the conditionally potential field which is a subject of qualitative and quantitative interpretation for localization of defects and their ranking.

Highest possible automation can be manifested in the form of expert evaluations as an algorithmic component of WSD. Such tendency contradicts the normative documentation and the actual state of the problem in modern geophysics. Nevertheless, we consider the possible ways of its implementation and related problems.

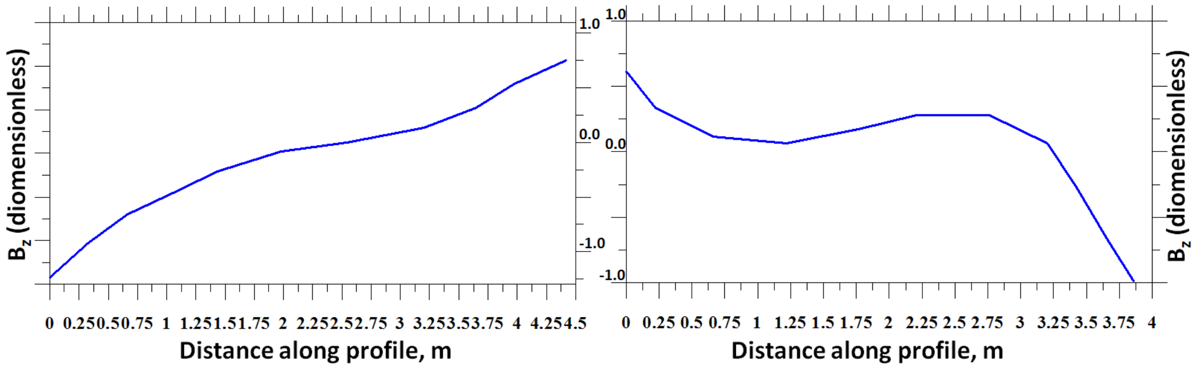


Figure 3. Accumulated reference functions (vertical component of magnetic induction vector) applied for correlation pattern recognition (vertical axis stands for dimensionless reference function, horizontal axis stands for meters along the profile).

At present, the development of neural networks (NN) is one of the trends in the analysis and processing of experimental measurements. Without speculating about artificial intelligence [7], let's note there is no single concept of NN as a developed analytical description or numerical estimation based on particular algorithms: NN architecture depends on a particular applied problem in hand. These problems include [8, 9] clustering of a set of measured signals, approximation of continuous and smooth functions, generalization of analysis of original data, optimization of data and their compression, forecast as a result of classification and pattern recognition. Any mentioned element includes such a basic concept as "perceptron", which is a model for the comprehension and processing of incoming unsorted information in the human brain. From the point of view of applied psychology, the primary perception of arbitrary information in consciousness is based on a set of conditioned and unconditioned reflexes, as well as on a set of reference images discovered as a result of life experience. Neglecting unconditioned reflexes, the main condition for perceptron execution is training which is provided by expert participation. The training system is based on constructing some target function, which has extremum corresponding to the solution of a set of equations related to numerical modeling, including the model of NN mentioned above. The simplest target function is a discriminant one

$$\Psi = \sum_j \lambda_j \psi_j \quad , \qquad (1)$$

where is an average of statistical expectations of j-th detection of compared groups, are the numerical coefficients, derived from the system of linear equations

$$\left[\sigma^2\right]\cdot[\lambda]=[D]. \quad (2)$$

In equation (2), the first factor of the left-hand side represents the covariance matrix of multidimensional analyzed sample, the right-hand side includes the vector of differences of probabilistic averages of compared groups. Geometrically, the function (1) has the form of hyperplane applied for separation of two reference and arbitrary compared samples, using which one can test the hypothesis of small or significant difference of two multidimensional averages from each other.

Another, more complicated learning process is represented by the methods of linear programming focused on approaching the extremum of the linear target function, similar to (1), $\Omega(x)=\sum_j b_j x_j$ with two kinds of restrictions. These restrictions have the form of equations like $\sum_i c_{ij}x_j = b_i$ or the form of inequalities $\sum_j c_{ij}x_j \geq b_i$, for $x_j \geq 0$. Geometrically, linear programming is reduced to specifying the finite region in conditional parametric space limited by polyhedron in view of the indicated restrictions, where the maximum of the objective function is detected.

The linear criterion gives a physically correct result only if the simulated system is highly uniform. For example, in the case of discriminant analysis, linear hyperplane optimally divides the part of the analyzed sample, similar to the reference one, from the non-perspective part of the original sample only if both compared samples can be taken as homogeneous. From the physical point of view, this statement indicates that the homogeneous sample of some detection (measured signal, physical field, calculated parameter) is a set of responses (low-contrast anomalies) from latent objects or processes which have approximately the same genesis. Statistically, this assumption should be confirmed by the single-mode distribution function $F_X(x)=\mathrm{P}(X\leq x)\equiv \mathrm{P}^X((-\infty,x])$ of compared samples. In fact, field or laboratory experiment gives distribution functions as an approximation of empirically accumulated distribution histograms $\tilde{f}(x)=\frac{n_i}{n\cdot\Delta a},\ n_i=\ \sum_{j=1}^{n} 1_{\{x_j\in(a_{i-1},a_i]\}},\ \Delta a_i=$ that have multimode structures due to real heterogeneous natural and natural-technical systems. Thus, the linear model of training with the use of heterogeneous experimental samples gives a physically incorrect result with the fuzzy level of error and requires expert participation.

When the linear approach to training is debatable, there is a logical choice of the nonlinear solution of the problem, probably, in the plane of nonlinear programming. Depending on the characteristics of the problem, the nonlinear objective function is either maximized ("concave" approximation) or minimized ("convex" approximation). The intermediate result is represented by an approximation of objective function with a set of concave and convex functions. According to [10], the formal formulation of the problem of non-linear programming is similar to finding the extremum of the objective function in multidimensional parametric space $x \in E^n$ for linear or nonlinear constraints which have the form of inequalities $g_j(x)\geq 0,\ j=r+1,\ldots,p$ and equalities $h_j(x)=0,\ j=1,\ldots,r$. For example, one can consider the trial-and-error technique used in geophysics for the solution of the inverse problem of potential theory. The initial information includes the experimentally-measured signal and model of geological heterogeneity in the form of a body of simplest geometry with structural relation and physical characteristic (magnetization) averaged in volume. Thus, on the one hand, there is a geological hypothesis, described by finite number n of physical-geometric properties

$G^{(0)} = \{g_1^{(0)}, \ldots, g_n^{(0)}\}$ and, on the other hand, there is an experimental signal $U_{\exp}(x, y)$, as well as the model signal $U_{\text{mod}}(x, y)$ derived from the geological hypothesis deduced at the level of deterministic computing technology. It is required to transform the parameters of the geological hypothesis in such a way as to provide the minimum difference between the model signal and the experimental signal. Such formulation is equivalent to consideration of quadratic residual functional $\Phi = \sum_{i=1}^{m}\left(U_{\exp}(x_i, y_i) - U_{\text{mod}}(x_i, y_i, G)\right)^2$ with the iterative search for its minimum arising at i-th iteration under the condition of the ultimate closeness of the physical-geometric conditions $G^{(k)} = \{g_1^{(k)}, \ldots, g_n^{(k)}\}$ of the geological hypothesis to the parameters of real geological environment in the vicinity of which the geophysical signal was measured. Gradient method of steepest descent is, among others, a suitable method to solve such a problem when the discovering of physical-geometric conditions of the model is algorithmically associated with the transition from the i-th iteration to $i+1-$ st according to the following equation:

$$G^{(i+1)} = G^{(i)} - \eta_i \cdot \text{grad}\left(\Phi\left(G^{(i)}\right)\right). \tag{3}$$

Here, the quadratic residual functional is transformed to the form $\Phi = \Phi\left[G^{(0)} - \eta \cdot \text{grad}\left(F\left(G^{(0)}\right)\right)\right]$ where the coefficients are derived from the solution of the equation $\mathrm{d}\,\Phi / \mathrm{d}\,\eta = 0$. When trying to reduce (3) in numerical form, one has to provide the solution of the direct problem of the potential theory when the set of physic-geometric parameters of the initial model is explicitly associated with the signal derived by computer-simulation. The structure of the graph of residual quadratic functional Φ depending on the iteration index k has nonlinear character and contains a set of alternating minima and maxima approaching the regional minimum. Unlimited growth of iteration index corresponds to the uncontrolled transition from the regional minimum of residual functional to its regional maximum. In this part, we face the fundamental problem of the theory of nonlinear programming, consisting in the fundamental impossibility of distinguishing the local minimum of objective function Φ from its regional minimum. There is a single way to find an optimal solution. It is the application of expert evaluation with an excessive volume of iterative selection, in which it is possible to find the position of the "regional" minimum of quadratic residual functional and corresponding optimal values $G^{(k)} = \{g_1^{(k)}, \ldots, g_n^{(k)}\}$ of the physic-geometric parameters of the model.

5. CONCLUSION

One has to pay attention to the features of a possible automated solution for the expert evaluation of geophysical monitoring results:

1. Both training methods, linear and nonlinear, are executed under hard limiting conditions that formally have the form of equalities and/or inequalities. The procedure of constraint qualification is not automatized and depends on the expert;

2. Training methods are complicated by errors of fitting which are often multicomponent and sometimes have no quantitative estimation. Verification of the results of the trial-and-error method in solving applied problems is often based on an expert's experience in the industry and intuition;

3. The reference object (model) is the basis of training that compares the model with investigated object, phenomenon or process of different nature. The formation of both the image of the reference object and the dimension of characteristic parameters supposes the creation of databases, their continuous development and depends on expert.

4. According to items 1-3, there is a single optimal solution of the problem of WSD development in the form of a system of centralized accumulation of experimental data and their network distribution for step-by-step interpretation by particular experts. The experts make the qualitative and quantitative interpretation using the response model and the probabilistic model of a searched object with subsequent network collection of expert conclusions when they generalize their database of the parameters of the mentioned object.

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