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# CONCEPT OF DEVELOPING AN INTELLIGENT SYSTEM FOR CONTROL AND OPERATIONAL DIAGNOSTICS OF TECHNOLOGICAL EQUIPMENT CONDITION

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***Abstract.*** *The authors propose a concept for developing a system of automated monitoring and on-line diagnostics of main technological equipment conditions. Monitoring and diagnostics system should work along with the automated control system. In this case, the effects of the optimal control and operational forecasting of the process equipment will complement each other and enhance the overall efficiency of the system. The proposed technique for developing diagnostic algorithms with the use of intelligent technologies will speed up their development and improve the accuracy of forecasting.*

**Keywords**: diagnostics, automated control system, intelligent system, algorithm, technological object

# KONCEPCJA BUDOWY INTELIGENTNEGO SYSTEMU KONTROLI I DIAGNOSTYKI OPERACYJNEJ STANU TECHNICZNEGO WYPOSAŻENIA

***Streszczenie****. Zaproponowano koncepcję budowy systemu automatycznej kontroli i diagnostyki operacyjnej stanu podstawowego wyposażenia technicznego. System kontroli i diagnostyki powinien działać razem z automatycznym systemem sterowania. Przy tym rezultaty optymalnego sterowania i operacyjnego prognozowania stanu technicznego będą dopełniać się wzajemnie i podwyższać całkowitą efektywność systemu. Proponowana metodyka zastosowania algorytmów diagnostyki z zastosowaniem sztucznej inteligencji znacznie przyspieszy ich opracowanie i podwyższy dokładność prognozy.*

**Słowa kluczowe**: diagnostyka, automatyzowany system sterowania, system inteligentny, algorytm, obiekt technologiczny

## 1. General information about technical diagnostics

Initially the maintenance of technological equipment (TE) to ensure its operational reliability and proper technical conditions was carried out “to failure” [2]. Since the second half of the last century another strategy, scheduled preventive maintenance (SPM), has been successfully applied. However, it becomes obvious that in the market conditions it is necessary to move to a more progressive approach of ensuring the operational reliability of TE, “in accordance with its actual condition” [2]. The transition to this strategy calls for the development of automated monitoring and on-line diagnostics system of TE technical condition (AMODS).

The use of assessment of TE systems in accordance with its actual condition allows improving the efficiency of production by reducing downtime under repair, bringing down production costs on account of reduction in expenditure on repair and post-fault reconditioning of equipment. (see Table 1) [2].

*Table 1. Practical importance of AMODS application*

| Costs | Savings |
|---|---|
| Preliminary research, selection of monitoring points, definition of limit values.<br>Developing a common database of equipment failures.<br>AMODS development | Increase in average time between repairs (increased productivity and reduced maintenance costs).<br>Actual elimination of unexpected failures (increased reliability and productivity).<br>Elimination of excessive consumption of spare parts (replacement of defective parts).<br>Reduction of the number of spare parts (providing warnings of the need to order replacement parts.)<br>Improved safety (reducing the likelihood of unforeseen failures).<br>Increased productivity of production processes. |

The costs of developing AMODS will be significantly reduced if included into the structure of existing automated process control system as a subsystem. In this case, an information application of the existing automated process control system will be used and this will greatly reduce the costs of its development and introduction. At the same time, the effect of the introduction of an advanced automated process control system will increase significantly because in addition to the effects of rapid and optimal process control the effect of rapid diagnostics of TE will be achieved (see Table 1).

Besides, there may be a so-called synergistic effect when the effects of the automated process control system and AMODS are not just added together but multiplied. It results from the mutual influence of process control and TE diagnostics: on the one hand prompt and optimum management of processes has a positive effect on TE, and on the other hand on-line diagnostics can save the condition of TE at the appropriate level, thus improving its controllability.

The AMODS diagnostic functions allow recording the beginning of destructive processes in TE at an early stage. These processes are irreversible, but their development can be monitored and predicted using the method of anticipatory multi-parameter diagnostics (MPD), which at each moment of time generates a complex estimate of monitored parameter trends. [11] The function of forecasting a condition classifies MPD as a proactive diagnostics, which can prevent undesirable developments in controlled equipment with control actions. Control actions include messages to operational staff on necessary actions and control signals for operating mode, up to disconnection of the OT in case of anticipation of destructive processes [11].

Existing methods of monitoring operational characteristics of TE consist in time-consuming periodic inspections of their values during planned supply disconnection performed by qualified personnel. These methods are considered test diagnostics. In case of invalid parameter values such control allows no possibility for timely prevention of reduction of TE operating resources. At the same time, a system of continuous computer monitoring can monitor the rate of TE performance change, predict the time of necessary repairs to extend its safe operation and to prevent the inevitable failure of equipment.

Thus, the combined operation of automated process control system and AMODS can manage processes not only efficiently and optimally, but also safely for TE.

One of the important stages of AMODS development is determining diagnostic features, whose amount and information content should be taken into account in accordance with specifications accepted at the stage of design and installation, performance of prototype objects, and special features of the operating conditions of diagnosed objects. [2]

Diagnostic feature (DF) is an attribute of an object of diagnostics used in accordance with the established procedure for determining the condition of an object. Each type of system of a certain type can be specified as a variety of attributes that characterize its condition. In accordance with their intended purpose, most of DFs can be both diagnostic and attributes of functional use. It is these attributes, that can often be measured directly, and are easier to establish standards and limits. Going beyond such limits indicates a failure or a defect in the functioning of a system [2].

Regularities of changes in DFs over time are generally similar to the regularities of parameter changes of object technical condition. During operation DFs vary from their initial value to the maximum allowable for a certain operating period. By measuring the current value of a DF and comparing it with the attributes of the reference condition of an object, one can determine a technical condition of the object at this moment and predict its subsequent condition. The assortment of DFs and the permissible limits are established by manufacturers and are specified in the technical documentation. Typically, a diagnostic conclusion requires an analysis of a large number of DFs [11].

In general, development of AMODS requires solving the following interrelated tasks:

- to develop a mathematical model of an object under diagnostics, which allows to check working capacity and correctness of functioning on the strength of all the DFs.
- to create a mathematical model of damages and failures, which gives an opportunity to detect damages and failures and identify their causes.
- to build algorithms for diagnostics, which is achieved by selecting a set of elementary inspections to help: a) in the problems of detecting damages and failures to distinguish serviceable or working condition or condition of the proper functioning from its faulty conditions; b) in the problems of looking for damage and failures to distinguish between faulty and inefficient conditions [11].

For solving these problems various mathematical models are used. For example, when creating models which allow testing the functionality and correctness of functioning we use systems of linear and nonlinear equations. For modeling of damages and failures we use topological models in the form of fault trees and graphs of cause-and-effect relationships between the technical conditions and DFs. The models of objects under diagnostics are the basis for constructing algorithms for diagnostics. Construction of diagnostics algorithms consists in selecting of such sets of inspections whose results can distinguish serviceable condition, working condition or condition of the functioning from their opposite conditions, and also to distinguish types of defects between each other [11].

A state of a system is described by a set of features defining it (parameters). Of course, the multitude of defining attributes may vary, especially in connection with the recognition problem. Recognizing conditions of a system means referring it to one of possible diagnoses (classes). The number of diagnoses depends on the objectives and purposes of study [2].

In the majority of problems of technical diagnostics, diagnoses are established in advance, and in these conditions the recognition problem is often called the problem of classification. A set of sequential actions in the recognition process is called a pattern recognition algorithm. An essential part of the recognition process is the selection of diagnosing features (DF) that describe the condition of the system. They should be informative enough to allow the recognition process to be carried out under a selected number of diagnoses. With the collection of statistical data, the list of DFs should refine and improve the decisive rules for recognition of defects [1].

There are two main approaches to the problem of recognition, probabilistic and deterministic. Probabilistic methods require a large amount of background information. Deterministic approaches more succinctly describe the essential aspects of the recognition process, are less dependent on excessive, low-value information, are more in line with the logic of human thinking. However, the deterministic approach requires knowledge of qualitative and quantitative regularities of physical and chemical phenomena going on in the TE, which is not always possible. One of the most important features of the technical diagnostics is to detect faults in the condition of limited information when one needs to be guided by certain principles and rules to make an informed decision.

In these circumstances, the most promising approach may be to use a modern intelligent technology (IT) for problems of pattern recognition. At present the most commonly used in practice ITs are: fuzzy logic, neural networks and neuro-fuzzy network. In our reference [6] we proposed a method for the application of intelligent technology to develop technological process control systems. However, we believe that this technique can be applied to creating systems of diagnostics of process equipment, since the study, development and implementation of processes of technical condition of the diagnosis are necessary to solve the same problems that arise in the research, development and implementation of management processes in general [4].

## 2. The method of application of intelligent technologies in control systems

The Department of Automation and Controls of K. I. Satpayev KazNTU is actively engaged in research and development of hybrid and intelligent control systems of various technological processes, such as [4, 5, 6, 8, 9]. Numerous studies conducted at the department, as well as analysis of recent publications on the subject have shown that IT can be used directly in the development of models for optimal process control, but not a model of the process itself. In other words, the considered technologies enable the immediate development of control algorithms, as opposed to the traditional chain: development of a structure of process model → conducting experimental studies on the object → model identification → optimization problem formulation → selection of optimization method → optimal control algorithm development. The traditional approach involves a long (sometimes several years), expensive and not always successful way of creating a system of optimal control.

The use of IT allows solving analogous problems immediately, and as experience has shown, quite successfully. The fact is that artificial intelligence techniques involve the use of knowledge, experience and intuition of human experts who are familiar with the subject area. In other words, it uses the so-called effect of “ready-made knowledge.” In contrast, the development of a mathematical model (the main component of the system) is the process of creating “new knowledge”, and therefore requires a long enough time to conduct theoretical research, as well as high material and labor costs for pilot studies and model identification.

Moreover, thanks to their long-term work experience, operators-technicians have learned how to control technological processes in optimized modes in different initial situations (and they usually manage to perform well). The transfer of “ready knowledge” from human experts to the knowledge database of an intelligent system greatly simplifies the development of intelligent systems; and their operation eliminates the effect of the “human factor” during process control (under “human factor” we assume such properties of a human body as: fatigue, slow reaction, lack of psychological stability, drowsiness during monotonous work, limited experience of young operators, and other causes).

Using the main idea of work (instead of development of a technological process model, development of a model of its control process), and developing existing IT methods, we propose the following three stage process of creating systems of optimum process control.

At the *first stage*, a priori studies of technological features of the control object based on literature sources, publications in periodicals and production forms and records are carried out. Typically, existing processes have to go through a long phase of research, pilot and industrial tests before they are put into production. It is likely that there remained materials of this research, as well as attempts to develop mathematical models of this process. A thorough analysis of all this information in order to use it in the development of intelligent control systems is required. This is especially important for the possible creation of hybrid control systems (HCS).

At the same stage it is required to analyze the process under study as a control object with the identification of input and output, controlled and uncontrolled, manageable and non-manageable variables. It is necessary to assess the object response rate through different channels, the class of object (continuous or discrete), the degree of completeness of the information about the object's variables, the operating range of variation of variables of the object, etc.

After careful analysis of the available information it is necessary to prepare a structure of the future system of control, which will considerably facilitate further work.

At the *second stage* the model of control process is developed. The main objective of control (analogue of objective function in optimization problems) is determined with the help of experienced experts (practicing operators, technicians or engineers). This objective is generally known and usually experienced operators are striving to achieve it. Then of all types of variables by the method of ranking from the general list are defined those which according to experts are essential to this object (process).

The main objective of the second stage is the compilation of a matrix of planning a full factorial experiment (FFE). A model of a control object (process) is made with the help of a FFE matrix. At the same time, for example, the total number of possible combinations of factors for two input variables for three-level factors is equal to $N=3^2=9$; for three variables $3^3 = 27$, etc.

For example, when there are two input variables, a FFE planning matrix is compiled, which is given in Table 2. Type 2 tables are the foundation for the development of intelligent systems, as they have concentrated many years of experience, knowledge and intuition of human experts in the particular subject area. The quality of the FFE matrix will depend upon efficiency of the entire control system.

The values: 0.0, 0.5, 1.0 mean the minimum, average and maximum values of the input variables $X_1$ and $X_2$. An expert using his experience, knowledge and intuition has to only write down the values of the output variable $Y^э$ (controlling action) in the range from 0.0 to 1.0. Normalization in the range from 0 to 1 of input and output variables is done according to the formula:

$$\bar{x} = \frac{x - x_{\min}}{x_{\max} - x_{\min}}, \tag{1}$$

where: $\bar{x}$ - normalized (from 0 to 1) value of an input or an output variable; x – current value of the variable; $x_{min}$, $x_{max}$ – minimum and maximum value of the variable.

*Table 2. FFE Matrix of Planning*

| Experiment number | X1 | X2 |
|---|---|---|
| 1 | 0,0 | 0,0 |
| 2 | 0,0 | 0,5 |
| 3 | 0,0 | 1,0 |
| 4 | 0.5 | 0,0 |
| 5 | 0.5 | 0,5 |
| 6 | 0.5 | 1,0 |
| 7 | 1,0 | 0,0 |
| 8 | 1,0 | 0,5 |
| 9 | 1,0 | 1,0 |

Drawing up a matrix of experiment planning is much more convenient for experts than making rules of fuzzy productions recommended in all textbooks and publications. At that, an expert needn't invent endless terms ("very much", "very, very little," "quite normal", etc.); he just puts the value of the output (controlling) variable in the range from 0.0 to 1.0. In this case, the FFE matrix of planning can be used for four different methods of control model development: experiment planning, expert systems, neural networks, neuro-fuzzy algorithms.

In contrast to the well-known classical method of experiment planning, compiling a matrix of FFE planning with the help of experts makes this procedure considerably faster and cheaper. Experts carry out so-called "mental experiments" instead of expensive experiments conducted in reality. Besides, it is necessary to keep in mind that active experiments in the conditions of a functioning production process is unrealistic because of the possible emergency situations when the process variables fluctuate from the minimum values to their maximum values, and vice versa. In addition, many enterprises simply do not have opportunities to change the variables according to the FFE Planning Matrix.

It should be emphasized that the output values Yi are actually control variables, so the planning matrix displays a process control model for all scheduled by experts combinations of input variables. For calculation of intermediate values in combinations of input variables (for example, $X_1 = 0.21$ and $X_2 = 0.74$) it is necessary to synthesize a process control model, which is the main task of the second stage.

It should be noted that it is more efficient to use known mathematical relationships identified in the first stage of research along with intelligent models. At the same time, it is necessary to make sure that such dependencies adequately reflect certain physico-chemical regularities of a particular process.

At the *third stage* a study of developed control models is conducted. At this stage the following actions are carried out.

The received models are thoroughly researched and analyzed by their sensitivity, stability and uniqueness. This is achieved by conducting a simulation of a control process with various changes of input variables; constructing the curves of variation of output variables at changing input variables; and performing their analysis with the help of experts.

After completion of investigation of models obtained by different methods, the comparative analysis of their adequacy is carried out. For this purpose the output variables are calculated using models for the values of input variables taken from the FFE planning matrix and compared with the expert estimates. After that a comparison matrix is formed, which allows to calculate the value of modeling errors in different ways. For example, the absolute error in percentage is calculated as follows:

$$\delta = 100\frac{1}{N-1}\sum_{i=1}^{N}|Y^э - Y^p|, \tag{2}$$

where $Y^э$ and $Y^p$ are experimental and calculated values of the output variables respectively.

An absolute error is calculated for the models obtained in four different ways, and then their comparative analysis is performed. The model with the smallest absolute error is considered to be the most appropriate.

The most adequate model is subject to taking tests in simulated conditions of existing production. In this case, the model is fed to the input with actual input variables taken from the measuring apparatus of an industrial unit; and the simulation results (output control variable) are compared with the value of control, which is effectively implemented by an experienced operator-technologist. In case of a satisfactory result of simulation tests, the model is integrated into an industrial controller. Otherwise, everything starts over again – going back to the first stage and improvement of the model parameters.

## 3. Technique of development of intelligent diagnostics algorithms

As it was already mentioned, the above suggested technique of application of intelligent technologies for development of process control systems can be used for TE fault detection tasks. Let us consider the use of intelligent technologies using the example of FFE planning matrix for TE fault identification providing the production of yellow phosphorus in the conditions of Novo-Dzhambulsky Phosphorus Plant (NDPP).

The NDPP technological instructions for the production of yellow phosphorus contains a lot of options for possible malfunction of the TE and considers the ways of their elimination. Let us look at some of them (see Table 3).

There are three different conditions of a technical system [10]:

1) Workable – it is a condition under which the system is able to perform specified functions with parameters, which are set up by technical documentation.
2) Workable, but faulty – it is a condition of a technical system when it is able to perform its main functions, but does not meet all the requirements of technical documentation.
3) Failure – violation of system operation capacity, i.e. a condition when it is unable to perform specified functions.

*Table 3. Possible malfunctions and methods of their liquidation*

| No | Type or symptom of malfunction | Possible causes of malfunctions | Actions of the personnel and ways of malfunction liquidation |
|---|---|---|---|
| … | … | … | … |
| 5 | Increase of temperature under the cover of electric furnace | 1. Stuck of the charge in the boot chutes<br>2. Overexposing slag<br>3. Short electrodes<br>4. Excess of coke in the charge<br>5. Bummer of an electrode | 1. Identify the chute with a frozen charge and "break" it in accordance with instructions<br>2. Drain the slag with a maximum removal of coke<br>3. Switch on electrodes again<br>4. Flush with coke-lean charge<br>5. Act by orders of the shop technologist |
| 6 | Temperature under the cover of furnace is below the limit | 1. High content of $P_2O_5$ in the slag<br>2. Low power of electric furnace | 1. Adjust furnace charge<br>2. If possible, increase power. In case of need close sectoral chute closures without violating the uniform dynamic load of charge on electrodes |
| … | … | … | … |
| 10 | Lowering the water level in the tank of "softened" water | 1. Water leakage due to burn-out of one or more cooling elements | 1. Turn off the electric furnace<br>2. Determine the location of burnout and replace or block the element |
| … | … | … | … |

According to this classification the malfunction Number 6, is likely to be attributed to the second group of conditions of technical systems – "workable, but faulty." Problem Number 10 can be attributed to the third group – "failure". Problem Number 5 is closest to the group of failure, but it has some features of the second group.

The most dangerous for TE are certainly failures. Therefore we shall consider the third group of the technical system conditions in greater detail. Failure is the core concept of the theory of reliability. A failure occurs a result of action on an object by a set of objective and subjective factors. These factors are quite difficult to be fully taken into account [10].

*Classification of failures*:

1. Failures are distinguished by causes as:
   - *Constructional*, caused by deficiencies in design;
   - *Technological*, caused by imperfections or violation of manufacturing technology;
   - *Operational*, caused by improper operation.
2. Failures are distinguished by effect on the performance of a technical system as:
   - *Failures* of elements of the system, causing its malfunction;
   - *Failures* of *elements* of the system, causing its failure.
3. By relations with the failures of other elements:
   - *Dependent failures*;
   - *Independent failures*.
4. By randomness of occurrence:
   - Random (*sudden*);
   - Gradual (*systematic*).

Of course, the classification proposed in [10] (as well as any classification) is conditional as sometimes the problem can be attributed to several of its kinds. For example, the malfunction Number 5 can be attributed both to a group of "failures" and the group "workable, but faulty"; it may be caused by structural as well as operational reasons, and it can occur either suddenly or gradually.

It should also be noted that all of the above problems are of "emergency notification" nature, i.e., they inform that an emergency situation has arisen, but do not allow to predict it. Qualitative (not quantitative) assessment of symptoms and causes of malfunction, do not enable "predicting" the proximity to a particular emergency situation. To forecast it (as noted in all the textbooks on technical diagnostics, as well as by the authors [11]) it is necessary to develop a mathematical model of object diagnostics, a mathematical model of damage and failures, and to build algorithms for diagnostics.

However (as already noted in paragraph 2 of this paper), this approach assumes a long, expensive and not always successful way of developing a system of on-line diagnostics. We use the same method as for developing control systems: i.e. instead of creating mathematical models of diagnostics objects and failure models we immediately begin developing an algorithm for diagnostics using advanced intelligent technologies. The use of IT can solve similar tasks at once, and as experience has shown (e. g., [4, 5, 6, 8, 9]), quite successfully. In other words, the effect of "ready knowledge" derived from human experts would be used in this case.

The basis of the proposed methodology for diagnostics algorithm development is composed by (see Section 2 of this paper) FFE planning matrix instead of the traditional rules of productions. Let us consider the method of producing the FFE planning matrix using the example of diagnosing the problem Number 5.

The fluctuation of temperature in a furnace is quite a "standard" situation, which is controlled by raising or deepening electrodes – "fine adjustment", or switching steps of a transformer – "rough adjustment" explained by the divergence of chemical and physical properties of the loaded charge. However if the temperature exceeds a certain threshold level, and it cannot be reduced by the control system, it means the occurrence of an emergency situation according to the above-mentioned five reasons. In other words it is possible to say that if the change in temperature is compensated to a certain extent by a control action, the technical condition of the furnace is considered normal within the region of the control system (AMODS). At the same time, even if the temperature is still within the limits, but is not governed by the control system that gives a command to lower it, it means that the situation is close to an emergency and it is necessary to move into the sphere of influence of the diagnostics subsystem - AMODS.

In the work [7], we attempted to assess the quality of a newly developed technical system by evaluating its controllability. Here we can use the same criteria for evaluation of the current technical system from the point of view of TE current condition. In other words, we used the current rate of controllability of process equipment as a diagnostic feature (DF). This can be done in the presence of an automated process control system, which allows monitoring and evaluating the effect of input, output and control variables on TE.

Thus, determining the degree of TE controllability allows to evaluate the possibility of occurrence of emergency situations at an early stage. In accordance with the definition of Kalman [3], controllability (elimination of initial displacement) means the ability of a system to have control actions that allow to transfer it from a given initial condition to a desired one within a limited period of time. In the work [7] a profound analysis of numerous methods for determining the controllability of TE is provided, but they are quite complex and require knowledge of the static and dynamic characteristics of the controlled object, which is not always possible. In the work [7] we provided a methodology to assess the degree of controllability of TE which uses knowledge, experience and intuition of operators-technologists along the advanced intelligent technologies.

To determine the degree of current controllability of TE it is suggested to use the following criteria: static evaluation of control channels, assessment of TE inertia, interference immunity, and measurability. Since the criteria for interference immunity measurability of TE change much over the time, they cannot be considered in assessing the overall controllability of TE.

As an example, let us consider a methodology for assessing a degree of controllability of TE for the malfunction Number 5.

In this case, for the static assessment we take the following variables:

- temperature under the electric furnace cover ($X_1$);
- value of penetration of electrodes ($X_2$);
- switching transformer steps since the beginning of temperature increase (X3).

As dynamic estimates we assume the following parameters:

- speed of temperature increase ($X_4$);
- inertia of the object ($X_5$) along the channel "depth of immersion of electrode - temperature in the furnace", this is a reaction time of TE (furnace temperature) for controlling impact (depth of immersion of the electrode).

As an output variable we will assume the overall assessment of controllability (Y).

All of these variables (except for the transformer changing steps) can be normalized using the formula (1), which allows to estimate their values change from minimum to maximum in the range [0 - 1]. $X_3$ variable can have only two values: 1 (there was switching of steps) and 0 (there was no switching of steps).

One should also consider that almost all the criteria and the evaluation of the static and dynamic control channel will vary depending on the furnace capacity. It is therefore necessary to form the FFE planning matrix for each value of power Wi separately.

We can now proceed to the main point – the compilation of production rules or the formation of a knowledge base of experienced on-site operators-technicians or engineers for production of yellow phosphorus at NDPP. For example, the rules may be:

**Rule 1**: "IF THE TEMPERATURE IS MINIMAL" AND "THE IMMERSION IS MINIMUM" AND "THERE WAS NO SWITCHING" AND "THE RATE OF TEMPERATURE INCREASE IS MINIMAL" AND "THE INERTIA OF OBJECT IS LOW" THEN "THE CONTROLLABILITY IS HIGH";

**Rule 2**: "IF THE TEMPERATURE IS MAXIMAL" AND "THE IMMERSION IS MAXIMAL" AND "THERE WAS SWITCHING" AND "THE RATE OF TEMPERATURE INCREASE IS MAXIMAL" AND "THE INERTIA OF OBJECT IS HIGH" THEN "THE CONTROLLABILITY IS LOW";

**Rule 3**: "IF THE TEMPERATURE IS MEDIUM" AND "THE IMMERSION IS MEDIUM" AND "THERE WAS NO SWITCHING" AND "THE RATE OF TEMPERATURE INCREASE IS MEDIUM" AND "THE INERTIA OF OBJECT IS MEDIUM" THEN "THE CONTROLLABILITY IS MEDIUM";

etc.

It is more convenient to present these production rules in a form of FFE planning matrix after conducting so-called "mental experiments" with experts. Then the planning matrix for these three rules will look as follows (see Table 4).

*Table 4. FFE planning matrix+ for the assessment of controllability for Wi power*

| Experiment No. | $X_1$ | $X_2$ | $X_3$ | $X_4$ | $X_5$ | Y |
|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 | 0 | 1 |
| 2 | 1 | 1 | 1 | 1 | 1 | 0 |
| 3 | 0.5 | 0.5 | 0 | 0.5 | 0.5 | 0.5 |

To ensure a full factorial experiment with a three-level assessment of variables: 0; 0.5; and 1.0, the number of experimental points will be equal to: N = $3^5$ = 153. But it is desirable to apply a five-level assessment: 0.0; 0.25; 0.5; 0.75; and 1.0; while the number of points will be equal to N = $5^5$ = 2625. However, this large number of experiments is difficult to implement. In this case one can perform fractional factorial experiment (FrFE) with fewer experimental points [4]. It should be remembered that the accuracy of intelligent models for control systems should be much higher than for a diagnostic subsystem. Therefore, the number of points in FrFE for the diagnostic system can be significantly fewer than that required for the furnace control. But in any case, the more "mental experiments" will be conducted, the more accurate the mental model of the algorithm of diagnosis will be.

The FFE planning matrix can be used for the synthesis of one of the three types of intellectual models: fuzzy, neural network or neuro-fuzzy. There are further studies into the sensitivity, stability, unambiguousness and adequacy of received intellectual models. The best of these three models may be used in developing the AMODS diagnostic subsystem.

Further it is possible to adopt, for example, the following evaluation grading for the degree of closeness of the current condition of TE to the emergency situation (for malfunction Number 5) depending on the evaluation of the degree of controllability:

a) if the value Y is between 0 and 0.25 – the emergency situation occurred;
b) if the value Y is in the range from 0.26 to 0.5 – the situation is prior to emergency;
c) if the value Y is in the range from 0.51 to 0.75 – the emergency situation is likely;
d) if the value Y is in the range from 0.76 to 1.0 – the furnace is in the normal condition.

Depending on the assessment of the degree of furnace controllability, AMODS can make one of the following decisions:

- in the case (d) – no action to be taken;
- in the case (c) – analyzing possible reasons for the decline of controllability: bridging scaffolding in boot chutes; overexposure of slag; short electrodes, excess of coke in the charge; bummer of electrode;
- in the case (b) – depending on the results of analysis making one of the following: identifying the chute with a frozen charge and "breaking" it according to instructions, draining the slag with a maximum removal of coke; switching electrodes on again or providing "flushing" with coke lean charge;
- in the case (a) – acting by the orders of an on-site technologist.

Similarly, one can develop a FFE planning matrix and assess the degree of controllability during the furnace malfunction Number 6. Malfunction Number 10 by this classification [10] can be classified as random (sudden), the causes of which are impossible to predict in advance. The malfunctions of this type are recorded with appropriate sensors, and the reaction to them is stipulated in the technological instructions and can be duplicated on a monitor using an AMODS subsystem.

Thus, the proposed method of estimating the degree of controllability allows predicting the occurrence of accidents at an early stage and preventing them.

## 4. Conclusions

The original methodology for the development of real-time diagnostics intellectual algorithms on the basis of evaluation of process object control level is proposed. This methodology provides application of knowledge, experience and intuitions of technologist operators, given in the form of the planning matrix of Complete Factorial Experiment (CFE). At that the CFE planning matrix is planned by experienced technologist operators in the mode of "mental experiment", thus significantly saving labor costs and material resources.

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