Uncertainty Evaluation in the Expert System of Evolutionary Management of a Multistage Technological Process

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Abstract. The paper considers an approach to constructing an expert system to support decision-making in evolution management of multistage technological processes under conditions of uncertainty. There one can find a procedure and principles for expert systems (ES) design which applies evidence theory methods. The paper also describes an ES developed in CLIPS environment and an interface which has a CLIPS core and starts the inference engine.

1. Introduction

Many modern continuous multistage technological processes are potentially dangerous, as an equipment failure leads to dire consequences. Managing such technological processes, one should timely and immediately deal with two interconnected issues: failure diagnostics and detection of the technological process stages featuring the equipment which is inefficient in emergency. The second problem is solved within the framework of the evolution management system of a multistage technological process [8]. A decision on inefficient operation of a technological process stage is made on the basis of the diagnostic variables which are either measured directly, or calculated on grounds of the mathematical simulation results.

The diagnostic variables values violating the limits defined by the process procedure are a sign of some stage of the technological process working inefficiently in emergency. Technological process monitoring and control are the responsibility of the process control operator, who should, on grounds of the current values of the diagnostic variables, recognize a dangerous situation and make the decision to eliminate it. In most cases, this is performed successfully. However, the uncertainty of the data on a technological process can cause emergencies when the operator is unable to find the true reason causing the deviation of the diagnostic variables, and makes wrong decisions. The most vivid example is the Sayano-Shushenskaya power station accident. Uncertainty of such emergencies is not statistical. Lately they have started to apply methods based on the logic of non-monotonic reasoning [2, 3] to create expert systems which support decision-making related to such situations. We consider an approach to evaluation and analysis of uncertainty and inaccuracy within the framework of possibility theory for developing expert systems intended for managing multistage technological processes.

2. Uncertainty accounting on basis of Dempster-Shafter belief structures

Here they consider a hierarchic (two-level) procedure of failure diagnostics and search for the inefficient stage of the production process [8, 9]. At the first level, the search space is reduced to separate production stages (technological process chains), and then, at the second level, we solve the problem of tracing the failure down to some element of the processing equipment in a certain chain of the technological process. Let us call $X = \{x_i\}$ a set of diagnostic variables, while $C = \{c_j\}$ will be a set of technological chains. As already mentioned, a sign of possible equipment failure is the diagnostic variable violating the acceptable technological limits. This fact will be named a diagnostic variable violation (DVV). Let us call $P = \{p_i\}$ a set of logical variables. The value of the logical variable $p_i = 1$ corresponds to a DVV emerging on the i - th variable, while $p_i = 0$ corresponds to the absence of a DVV. Each DVV indicates a fault in one or several technological chains. Taking into account the agreed notation, the input data for finding the equipment failure can be presented with the following diagnostic matrix:

$$\begin{array}{ccccc} & c_1 & c_2 & \dots & c_r \\ x_1 & \mu_{11} & \mu_{12} & \dots & \mu_{1r} \\ x_2 & \mu_{21} & \mu_{22} & \dots & \mu_{2r} \\ \dots & \dots & \dots & \dots & \dots \\ x_n & \mu_{n1} & \mu_{n2} & \dots & \mu_{nr} \end{array},$$

where μ_{ij} defines the degree of impact of the i-th variable on the operational capability of the j-th chain, this capability being defined expertly. Each value of the logical variable $p_i = 1$ induces an expertly-defined set of technological chains C_i

$$C_i = \{(c_j, \mu_i(c_j) \neq 0)\}, c_j \in C,\ C_i \subset C,\ C_i \neq \varnothing \ .$$

Here c_j are the chains where failures might cause violation of limits on the i - th diagnostic variable; $\mu_i(c_j)$ is the membership degree of the element c_j in the set C_i (it corresponds to the expert's level of confidence (adjusted to the range [0; 1]) in the presence of a DVV source on the j-th variable in the chain c_j). At the first stage, the problem of recognition comprises matching the values of the diagnostic variables and the faulty or inefficient stage of the technological process (technological chain).

Applying Dempster-Shafter theory (DST) helps to assign the common measure of probability to the subsets of the set of the faulty technological chains [10, 12]. It is necessary for of several reasons. The first one is the ambiguity of the solution of the expert classification task, when the expert is unable to define the degree of characteristicity of the given DVV for one particular chain. Second, the results of DVV presence detection itself may be inaccurate. Third, it is required for setting the common confidence level for all the diagnostic procedures.

The fundamental notion of DST is [12] the frame of discernment, defined as the complete set of mutually exclusive events. In our case, the set $C = \{c_j\}$ is the frame of discernment. The empty set Ø is identified as an impossible event. Let us denote as A some subset of the set C, including the empty set Ø and the set C itself. The power set will be denoted as $\{ A | A \subseteq C \}$. A real number $m(A)$ called base probability may be assigned to each set A. DST considers not all the sets of the frame of discernment [5], but only those having nonzero base probabilities – so-called focal elements of belief function *Bel*. Thus, any set C_i, induced by the logical variable $p_i = 1$, is a focal element. Any subset A_i of the set C_i is a focal element, as long as it has nonzero base probability. Belief function $Bel(A_i)$ is calculated for the set A_i as the sum of all the base probabilities of the elements which comprise the set A_i

$$Bel(A_i) = \sum_{B \subseteq A_i} m(A_j) \ .$$

As a rule, in case of a potential emergency there is registered some DVV set $P^* = \{p_i \mid p_i = 1\}$. Should this happen, the facts of various DVV being registered are considered as independent evidences of failures in the technological process. In order to unite various evidences [5, 6], one should calculate orthogonal sums of base probabilities defined for each of the evidences. To achieve this, one should apply Dempster's rule [10], according to which the orthogonal sums are defined by the following expression:

$$m_1 \oplus m_2(A) = \frac{1}{1 - m(\varnothing)} * \sum_{Y \cap Z = A} m_1(Y) * m_2(Z),$$

where A and B is focal elements distributed on the trust frame generated by different evidences. The probability measure for the empty set is

$$m(\varnothing) = \sum_{Y \cap Z = \varnothing} m_1(Y) * m_2(Z).$$

Dempster's rule is associative and commutative, thus allowing one to unite, in a similar fashion, even more evidences.

New base probabilities provide the foundation for computing belief and plausibility functions for all the hypotheses in question, thus allowing one to use all available information while searching for faulty or inefficient technological chains, to reduce the number of suspected objects by eliminating some of them and to redistribute the evaluations of possible failures for a separate technological chain or for many chains.

3. Uncertainty accounting in an expert system with production rules

A software product was developed in order to implement the above-described uncertainty accounting procedure based on Dempster-Shafter belief structures. This product represents an application software package developed and functioning in CLIPS environment [14] and using external application programs.

The developed prototype of a diagnostic type expert system (ES) enables the expert production engineer to detect failures of the equipment applied in multistage production processes. The engineer makes the decision on a failure occurring in one or other unit of production equipment on the basis of the current values of the diagnostic variables or, in terms of ES, the facts.

Facts are the principle form of information representation in CLIPS. As a rule, some unordered facts are applied, which provide an opportunity to abstract away from their structure. Such facts are described in the built-in object-oriented COOL language with the help of deftemplate construction.

The diagnostic ES is based on a set of production rules and operates according to the "question-answer" principle. Production rules let "keep" the expert's experience in the ES knowledge database (KD). ES developer must write a set of rules which, when applied together, let solve the issues arising at the facility. Rules are entered into CLIPS with defrule structure.

The set of rules depends on fulfillment of the conditions which, in their turn, are activated by facts. Facts and production rules are crucial for ES successful operation. An important feature of CLIPS is the inference engine which actually decides which rules must be executed in the presence of the available facts. In addition, CLIPS supports a procedural tool, or application of the functions which are set with deffunction structure.

The major drawback of CLIPS environment is the absence of the graphical interface which is familiar to everyone because of Windows OS, because API CLIPS uses C++ functions which let one work only in text mode (console input-output). However, the open source code of API CLIPS functions, which were written in C++ [1], enabled the developers to integrate CLIPS core successfully into their own application. The integration of CLIPS into the application written in C# was performed in Visual Studio environment. In order to achieve this, they used CLIPSNet library [14]. Thus, the integration task was reduced to arranging an interface between Windows application and CLIPS core.

A trial model of an ES was constructed as a Windows Forms application in Visual Studio 2015 environment. In order to organize the interface between the expert and CLIPS core, "on the part" of Windows Forms there were used standard components .NET Framework 4.5.2:

TableLayoutPanel, FlowLayoutPanel, Button, Label;

while on the part of CLIPS there were embedded API functions:

public bool LoadFromResource (string A_0, string A_1);

public void Reset();
public long Run().

The developed prototype of an expert system of evolutionary control of a multistage production process includes a data management unit, a knowledge base management unit and an information model control unit (figure1). The data management unit includes the tools that enable one to edit electronic spreadsheets describing technological links and diagnostic variables for the purposes of one or other production. The knowledge base management unit contains the tools for describing the production rules, for knowledge base creation and setting up a dialog with the operator in a natural language. The information model control unit ensures interaction between the data management units and the knowledge base, and also with the external environment.

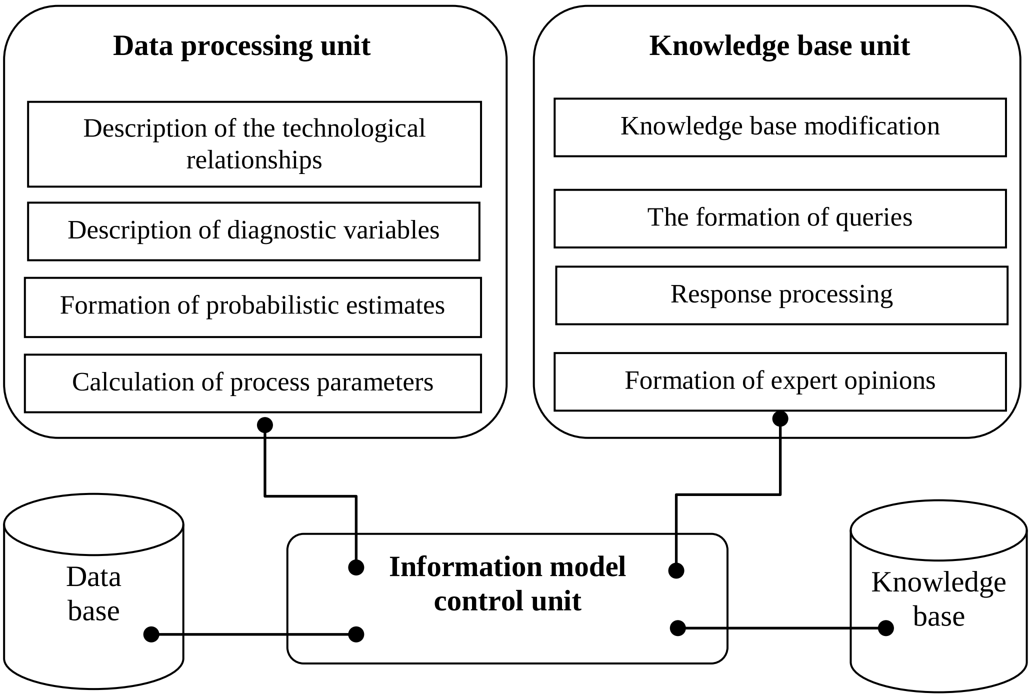

Figure 1. Structure diagram of the expert system.

While operating, ES monitors the current values of the diagnostic variables, coming in from the external environment at certain time intervals. If the values of these variables do not correspond to the standard ones, the two-level mechanism of failure detection of the production equipment described in Sec. 1 starts working.

An interface window of the application is used to start the ES and to detect failures in the stated technological chain of the production. After “Start” button is pressed, the ES starts a dialog with the technology expert who supplies the ES operation area with new facts by choosing one of the options (yes/no), thus activating the corresponding production rules. This way the application organizes an interface with CLIPS core, starting the inference engine with the present set of facts and production rules. As a result of this dialog, the ES forms its expert judgment on the failure causing the malfunction. This judgment is offered to the process control operator for further analysis.

4. Conclusion

In order to check the efficiency of the developed system, it was tested by analyzing the defects of a centrifugal blower. Fig. 2 shows the operation of a diagnostic system which applies the Boolean method at 10% belief threshold and not more that 5% of data noise contamination. Here icons S0 – S8 codes indicated a faulty device blower. S1-pressure sensor fault. S* indicates no fault.

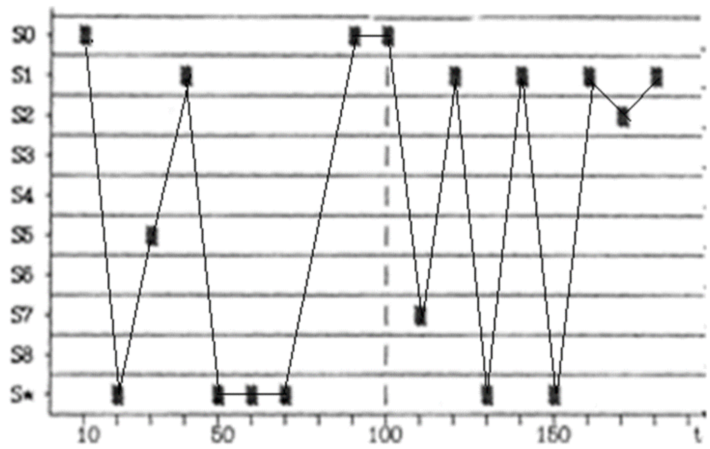

Figure 2. The results of the model experiment with the use of the Boolean calculus.

The figure demonstrates that, under normal operation of the system, the noise in the measurements causes diagnosis instability. At the 100th step we introduced a defect into the system; this defect was presented by 70% of confidence in pressure sensor failure. When the failure is introduced, the right diagnosis appears sporadically.

Fig. 3 shows ES operation diagram based on the above-suggested procedure in presence of the same input data.

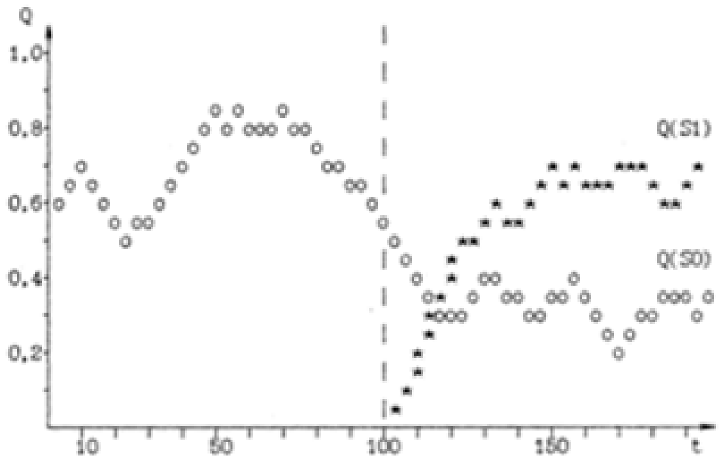

Figure 3. The results of the model experiments using the theory of Dempster - Schafer.

The diagram shows how evaluation of plausibility of diagnostic hypotheses Q changes before and after the failure is introduced, ensuring stable correct diagnosis. Plausibility evaluations of alternative hypotheses are not shown, as their values are below the noise level.

The suggested procedure of uncertainty accounting and principles for expert systems (ES) design, which are intended to support decision-making in evolution management of multistage technological processes, thus allow one:

- to ensure sequential analysis of the state of health of a processing facility, including tracing the trouble source down to the initial failure level;
- to apply, within their structure, interval diagnostic models of the process, in order to account for the data physical uncertainty and to combine the results of analytic and expert analysis of the equipment unit state;
- to perform the analysis of faulty and inefficient production subsystems with the help of ES and according to the suggested procedure of uncertainty accounting, which allows reducing the required time and resources of the diagnostic procedures.

5. References

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Acknowledgments

The paper is developed with the financial support of RFBR (project № 17-07-01339).