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COMPUTER AND INFORMATION NETWORKS AND SYSTEMS

MANUFACTURING AUTOMATION

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RULES OF EXPERT SYSTEM FOR SAFETY MONITORING: CHECKING ON COMPLETENESS AND CONSISTENCY

В.М. Рувінська, А.С. Тройніна, Є.Л. Беркович, О.О. Біловзоров. **Правила експертної системи моніторингу: перевірка на повноту і несуперечливість**. Стаття присвячена дослідженню підходів до побудови експертних систем моніторингу. Метою дослідження є скорочення часу і трудомісткості розробки і поліпшення якості баз знань експертних систем для моніторингу на основі візуалізації й інтелектуальної обробки правил. Розроблено модель візуалізації й структуризації правил експертних систем для моніторингу на основі І/АБО-графа, метод перевірки правил експертних систем моніторингу на суперечливість з використанням задачі SAT, метод перевірки правил експертних систем на повноту за допомогою «інверсних» правил. На цій основі запропоновано методику розробки експертних систем, що не є універсальною, а розрахована на системи моніторингу. Створено редактор правил і використано його при розробці бази знань для моніторингу виконання вимог щодо безпечної експлуатації електроустановок.
Ключові слова: експертна система, моніторинг, візуалізація, І/АБО-граф, суперечливість, повнота, редактор правил.

V.M. Ruvinskaya, A.S. Troynina, E.L. Berkovich, O.O. Bilovzorov. **Rules of expert system for safety monitoring: checking on completeness and consistency.** This paper researches approaches for building monitoring expert systems. Aim of the research is to reduce the time, the development man-hours and to improve the knowledge base quality of monitoring expert systems based on visualization and rules intelligent processing. Simplifying means not only less time for the rules base development, but also complexity level decrease that results in errors reduction. Model for monitoring rules visualization and structuring based on AND/OR-graph is developed; also methods for rules validation both of inconsistency using SAT problem and completeness using so called "inverse" rules are proposed. The technique for monitoring expert systems development on the basis of the proposed model and methods is created. Rules editor is established based on the proposed technique and is used to develop the knowledge base for monitoring the safe operation with electrical equipment.
Keywords: expert systems, monitoring, visualization, AND/OR-graph, consistency, completeness, rules editor.

Introduction. Nowadays it is expected that the process of monitoring is the observation of object (the obtaining, accumulation, storage and reporting of monitoring objects), as well as the evaluation of the data, recording the most important parameters and providing the information to the decision mak-

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er. This approach extends the concept of information monitoring. Hence, modern monitoring systems should be equipped with units performing data analysis for the conclusions drawn about the situations.

Expert systems (ES) based on the production model of knowledge [1] are more suitable for monitoring analysis, since they allow to describe the situations arising in the systems for which the monitoring is carried out [2].

For example, we monitor the security of performance of works on electrical installations. Work in existing electrical installations requires from personnel to perform the certain safety rules [3]. One of the rules says: if the number of employees in the team less than two and the type of work is the switching devices and location are especially dangerous, consequently it is impossible to carry out the work. In this case, the *situation* "It is impossible to carry out the work" took place. Thus, the rules in the conclusions contained the *situation*, and in the *premises* — the conditions under which this situation arises. In general, the *premises* are the *states* of some entities. For example, the entity is the degree of danger of location, and the *states* of the entity are: not dangerous location, location with high risk, extremely dangerous location.

In this paper, methods for construction of monitoring systems are considered with an example of an expert system for monitoring the implementation of the requirements for the safe operations with electrical equipment and making decisions about the admissibility of such works. Results which presented are summarized and can be applied to other monitoring systems.

Literature review. ES are designed for so-called non-formalized problems, which typically have features such as inaccuracy, ambiguity, incompleteness and contradictory in input data.

While creating a knowledge base (KB) it is necessary to determine whether there is enough fully represented knowledge for the subject area. The system is called complete if in it for any formula F is provable F or its negation $\overline{F}$. Otherwise the system contains improvable clauses (clauses which can neither be proved nor disproved by means of the system itself), and is called incomplete. Under the completeness (incompleteness) it is understood the sufficiency (insufficiency) of knowledge to solve problems properly using ES. In [4] the completeness noted as an important feature of the formal system. A set of axioms is considered to be complete if it can be used to prove or disprove any well-formed formulas. In [5] the notion of incompleteness suggests the impossibility of obtaining results with some sets of input data. The following types of incompleteness were considered: the missing facts, missing rules, unattainable goals, unclaimed facts, unrelated segments of knowledge. In [6] in the case of inductive construction of an expert system rules (based on examples) incompleteness assumes absence in training set properties of representation, that is, the availability of sufficient number of examples to represent the entire universal set, not just its separate classes.

It is also necessary to help the ES developer to determine whether the rules have contradictions. Contradictory is the most serious mistake in the ES. If the system contains rules which make contradictory conclusions the competing hypotheses may appear, and the final recommendations will depend on rules selection strategy (by the way of conflicts resolution). As a result, the system can't make the conclusions that were expected by expert or don't come to any decision.

It is also necessary to help the developer of ES to determine whether the rules have contradictions. The system is inconsistent if there is such a statement F that F and $\overline{F}$ can be proved from the system. I.G. Pospelov proposed dividing contradictions into two types: external and internal conflicts. The external conflicts are between the productions and the world model; they have natural analogues in scientific theories. The internal conflicts in the production system are undesirable in the ES [5]. The first can be eliminated by restricting the world model, the second need rules modification. Pospelov also provided a method for revealing the internal conflicts in the rules on the basis of the dynamic description of ES.

Methods for static and dynamic anomalies detection in knowledge field and knowledge base of an integrated expert system by means of joint processing uncertain, imprecise and fuzzy knowledge were proposed in [7]. In order to detect anomaly violations of integrity and static inconsistencies it was developed a method in which the internal representation of knowledge is based on the decision tables.

All considered works involves the analysis of the rules incompleteness and consistency for all types of ES. However, if you narrow down the types of EC for which the rules are created, it is possible to improve the existing methods and create the new ones. Therefore, it is relevant to create specialized methods taking into account the specific applications, for example monitoring ES, along with universal ones for definition of rules of completeness and consistency.

Aim of the Research is to reduce the time and the development man-hours, as well as to decrease errors in the rules and improve the quality of knowledge bases for monitoring ES based on visualization and intelligent rules processing.

Main Body.

Construction and visualization of AND/OR-graph for monitoring ES.

One of the challenges in creating ES is that when a large number of rules knowledge base becomes unreadable it is difficult to design, debug and maintain such knowledge base. Solutions to this problem can be different. Firstly, it is usage of such models of knowledge representation as frames, semantic networks and others. Secondly, in the case where the rules are perfectly suitable for the subject area it is necessary to simplify the different ways to work with the rules themselves. For example, for ES diagnostic it is convenient to represent the rules in form of decision tree and visualize them in such way. Similarly, for the rules of ES monitoring it is necessary to create a way for their visualization.

We proposed to use rules as knowledge representation. And rules premises are connected with each other by means of “AND” or “OR” relationships. So for monitoring rules visualization it is suitable to use the structure known as AND/OR-graph [8]. AND/OR-graph is a directed graph without cycles, all vertices are divided into three disjoint classes "and"- vertices, "or"-vertices, the end (or target) vertices [9].

AND/OR-graph is regarded as a basis for logical inference, however, we propose to apply it for rules visualization, and for their interactive processing that means viewing rules as well as the ability to type-in and to correct them graphically.

To facilitate the construction of AND/OR-graph it is proposed to divide the rules for the monitoring system into groups so that all the rules of one group can have the same conclusion. For example in an expert system for safe working on electrical installations we can build a group for which conclusion is a single parameter — "it is impossible to carry out the work." With large number of rules in group it is appropriate to divide the group into subgroups for easy visualization. We have divided the rules for safe working on electrical installations into five subgroups depending on described objects and their states: "orders and arrangements", "staff briefing", "external conditions", "work with metering devices", "the use of protective devices", "work in the buffer zone of electrical networks" [10].

The proposed graph of ES monitoring rules consists of two types of nodes (Fig. 1):

— the first type of nodes corresponds to the premises of the rules, i.e., entity states. All of nodes for the states of the same entity (usually mutually exclusive) we offer to place visually on the same row;

— the second type of nodes corresponds to the rules conclusions, but as a conclusions of all the rules of one group is the same text that indicates the overrun of the monitored parameter, the graph has a single node of this type. Each rules group (subgroup) is displayed as a separate graph.

We receive graph using arrows connecting the nodes for premises with conclusion node in accordance with the rules. This graph has one root and several premises chains each for one rule. Moreover, each arrow has a weight which means the number of rule. The arrow can have few weights so we have a multi-graph.

Fig. 1 shows an example of the AND/OR-graph for the rules of subgroup "Rules that depend on external conditions" of monitoring expert system which was designed for the safe operations with electrical equipment. These rules were developed on the basis of normative acts on technical exploitation of electrical equipment. Within this subgroup there are five rules under which the work in electrical installations cannot be performed:

— if the area is extremely dangerous, work type is commutation and number of employees < 2;

— if the area is extremely dangerous, work type is commutation, number of employees ≥ 2 and there are no two employees, that one of them has qualification ≥ 2 and the other has qualification ≥ 3;

— if the area is with high risk, work type is commutation and qualification of each team employee < 3;

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— if the area is extremely dangerous or with high risk, the work is high-rise and the number of employees < 2;

— if the area is not dangerous, work type is reading from metering devices, U > 1000V and qualification of each team employee < 3.

As a result of such rules visualization presented in the form of AND/OR-graph using a rule editor it is easier for knowledge engineer and expert to analyze and identify inconsistencies and errors, fix them in text form and directly in the graph (it is possible to convert from one type of rules presentation into the other). The system provides the ability to convert rules from one form to another. Also, such graph can be analyzed and optimized using the methods of graph theory and mathematical logic.

Checking the rules of expert system for consistency.

For checking rules for inconsistency it is proposed to use AND/OR-graph and solution of satisfiability problem for Boolean formulas (SATisfiability problem — SAT) [11].

The input data to the problem SAT is a Boolean formula consisting of variable names, logical constants, parentheses and logical operations, in particular, AND, OR, and NOT. The challenge is to find the answer to the question: is it possible to assign the variables that occur in formula the value FALSE and/or TRUE so that formula becomes true? So you need to determine whether the formula is true for at least one specific set of variables. If for some values of variables formula is TRUE, then the Boolean formula is feasible, otherwise it is not (Fig. 2).

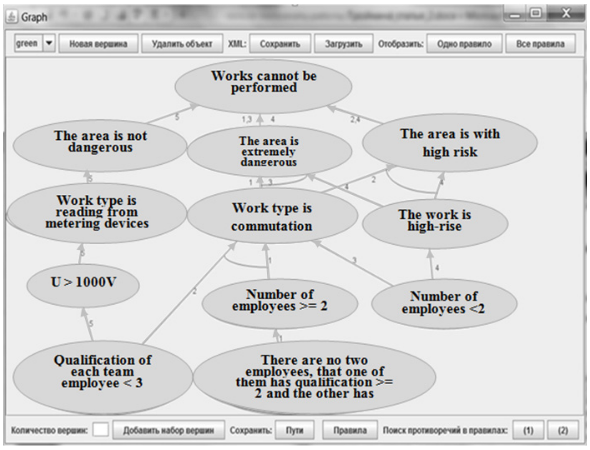

Fig. 1. Rules presentation in form of AND/OR-graph

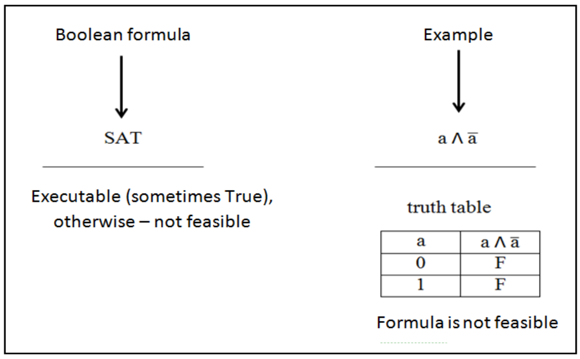

Fig. 2 The task of SAT problem for Boolean functions

According to one of the classifications the Boolean SAT problem is divided into two types: k-SAT and unlimited SAT. The problem is k-SAT on condition that formula is k-conjunctive normal form. Conjunctive normal form is called k-conjunctive normal form when each disjunction contains exactly k literals. In our case we'll bring to the SAT rules' premises, and number of them in rules is not the same, therefore, we have so-called non-restricted SAT.

For expert and knowledge engineer when writing rules it is important to eliminate contradictions within each rule, as well as conflicts between rules.

It is proposed method for checking the monitoring rules for contradictoriness (Fig. 3), which includes three stages of verification. p_i (i=1, 2, …, k) mean rules' premises.

Step 1. To check the so-called "internal" contradictions ("internal" means that check is providing within each rule, but not between the rules) of all the subgroup rules bring the formula $p_1 \vee p_2 \vee \cdots \vee p_k$ as input to SAT problem. If the result of solving the problem is FALSE, it means that all parts of the disjunction normal form (DNF) for any values of variables occurring in them are false, i.e. each subgroup's rule contains within itself the contradiction, namely the contradicting each other premises. An example of such a set of rules is shown on Fig. 4 (example 1). The conclusion is next: no rule in subgroup will ever work, so ES will never give the verdict that the monitored parameter is outside the permissible, every rule has to be corrected. And general check on contradictoriness is finished.

If the result of problem SAT is TRUE, it means that at least one rule in the subgroup contains no contradictions, so the further verification is needed.

Step 2. To check each rule for the "internal" contradictions bring conjunctions of rules' premises p_i, $i = 1, 2, ..., k$ of the form $p_1 \vee p_2 \vee \cdots \vee p_k \to \overline{w}$ alternately to the SAT.

If the result of solving the problem for certain rule is FALSE, it indicates that the rule contains a contradiction, namely, conjunction contains both x and NOT x for some variable x (Fig. 4, example 1). Such a rule is never fulfilled, it is necessary to either correct it or remove it from the system. If at least one rule is controversial, a general check for contradictoriness is finished.

Step 3: To check the contradictoriness between the rules bring to the SAT the left side of the formula $\overline{p_1 \vee p_2 \vee ... \vee p_k} \leftrightarrow w$, namely, $\overline{p_1 \vee p_2 \vee ... \vee p_k}$. This is equivalent to the statement that parameter of the system is normal.

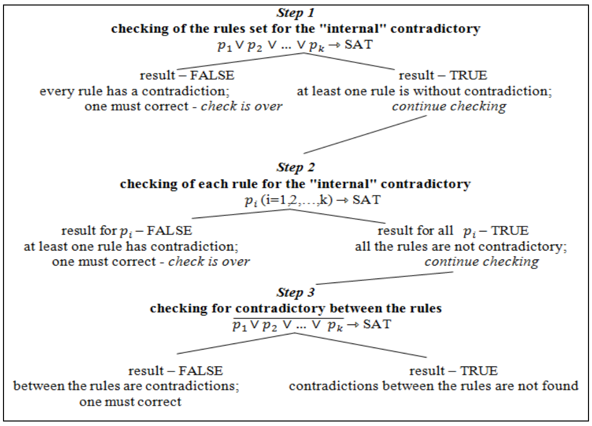

Fig. 3. Method of verification the base of monitoring rules on contradictory

EXAMPLE 1	EXAMPLE 2	EXAMPLE 3
Rule If U>1000V and U≤1000V, the works can not be performed	**Rules** If U>1000V, the works can not be performed If U≤1000V, the works can not be performed	**Rules** If U>1000V and a team is less than 3 persons, the works can not be performed If U≤1000V, the works can not be performed If team is greater or equal than 3 employees, the works can not be performed
a - U>1000V	**a** - U>1000V	**a** - U>1000V **b** – team is greater or equal than 3 employees
boolean formula	**"inverse" boolean formula**	**"inverse" boolean formula**
$a \wedge \bar{a} \to$ SAT	$\overline{a \wedge \bar{a}} \to$ SAT	$\overline{ab \vee \bar{a} \vee \bar{b}} = \overline{ab \vee a\bar{b}} \to$ SAT
always = FALSE	**always = FALSE**	**always = FALSE**
The rule will never execute, remove from the system.	A rules set is meaningless; you can never perform the work.	A rule set is meaningless; you can never perform the work.

Fig. 4. Verification of rules for contradictories, examples

If the result of solving the problem is FALSE, it means that the formula $p_1 \vee p_2 \vee ... \vee p_k$ is always true, and it's possible that at least one pair of members of the disjunction are some variable x and its negation, for example, formula $p_1 \vee p_2 \vee ... p_i \vee \overline{p_i} \vee ... \vee p_k$ is always true, because it is always true $p_i \vee \overline{p_i}$. This, in turn, suggests that at least two rules are in a subgroup contradictory.

In terms of ES the result FALSE says that parameters are always beyond the norm, and under no premises ES rules will not give out messages that the monitored parameter is normal. Thus, the reason is that there are conflicting premises in different rules (Fig. 4, example 2).

Similar case if contradict each other more than two rules (Fig. 4, example 3). For example, $ab \vee \overline{a} \vee \overline{b} = ab \vee \overline{ab}$. Then, if we bring the formula $\overline{ab \vee \overline{ab}}$ to the SAT, we never get TRUE, indicating that the contradictory is in 3 rules.

Checking the rules of an expert system for completeness.

To verify the completeness of monitoring rules it is proposed to use Boolean formulas corresponding to a set of rules and automatic addition of opposite by meaning rule set ("inverse"), that determines in which cases the opposite conclusion takes place. An expert observes and estimates these opposite rules.

Why is the "inverse" set of rules needed to check for completeness? The development phase of the expert system rule set can be incomplete. It is necessary to ask the expert: "What do *you* know that

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does not know the program yet?" and that the expert should answer this question, we need to give him an opportunity to look at the rule base from different angles of view. We can provide two points of view for monitoring:

— the conditions under which the monitored parameter is outside the permissible;

— the conditions under which the monitored parameter is normal.

It is noteworthy that we can automatically get one point of view from another. And then the expert can see AND/OR-graphs from two points of view, and based on these views he can find out that maybe there are not enough rules or in some rules conditions are not fully defined.

In the resulting "inversed" AND/OR-graph vertices correspond such premises for which parameter is normal. If one or more rules of the “inverse” rule set for the expert is seemed to be incorrect, he can add to the original rules an additional one or remove incorrect one (Fig. 5).

Thus, the method of checking the completeness of monitoring rules based on the construction of "inverse" rule set from the original set consists of the following steps:

Step 1. Automatically conversion of the initial AND/OR-graph to the Boolean expression formula $p_1 \vee p_2 \vee \cdots \vee p_k \leftrightarrow \overline{w}$.

Step 2. Construction of "inverse" formula $\overline{p_1 \vee p_2 \vee \cdots \vee p_k}$ and automatically conversion it to DNF and then to "inverse" set of rules:

$$p_1' \to \mathrm{w}\,,$$
$$p_2' \to \mathrm{w}\,,$$
$$\ldots$$
$$p_l' \to \mathrm{w}\,.$$

Step 3. Automatically construction of "inverse" rule set AND/OR-graph.

Step 4. Received AND/OR-graph is presented for consideration to the expert who supplements initial set of rules with new knowledge on the basis of "inverse" rules.

Steps 1…4 are repeated iteratively until the expert makes sure that the rules are satisfactory.

The present method makes it possible to look at the rules from a different perspective, to see the inaccuracies and tells expert or knowledge engineer how to optimize the rules.

Fig. 6 shows an example of validation for completeness of the rules concerning to safe work with electrical installations.

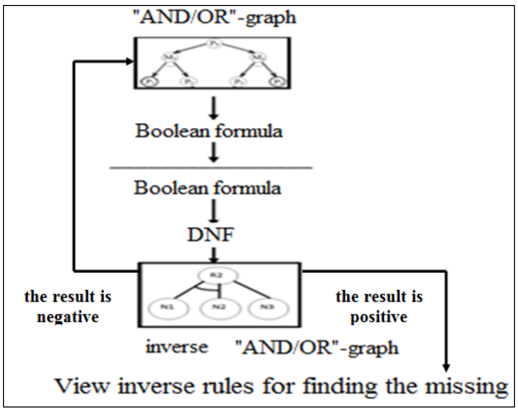

Fig.5. Stages for checking the rules' completeness

Boolean formula for the rules that depend on external conditions
(the works cannot be performed)

$$ade \vee ad\bar{e}\bar{f} \vee cdg \vee \bar{b}hig \vee cje \vee aje$$

Boolean formula for inverse rules
(the works can be performed)

$$\overline{ade \vee ad\bar{e}\bar{f} \vee cdg \vee \bar{b}hig \vee cje \vee aje}$$

One of the inverse rules after conversion to DNF

$$b\bar{h} \vee b\bar{\imath} \vee b\bar{g} = b(\bar{h} \vee \bar{\imath} \vee \bar{g})$$

where

b – the premises without high danger

h – the type of works - obtaining the metering devices indications

i - U>1000v

g - qualification of each employee <3

The inverse rule in English

If the premises are not in high danger and the works type is not obtaining the metering devices indications or U<=1000v or qualification of some of employee is >=3 then the works can be performed

Incompleteness

There are no rules about other work types and U<1000v

Fig. 6. Checking the rules of an expert system for completeness

Using the proposed method for checking the completeness of the rules, it was detected that while building the rules, depending on external conditions, not all work types were considered (for example, the assembly/disassembly of equipment etc.). This mistake should be corrected.

Results. For the verification and validation of an expert system completeness and consistency the it is developed a knowledge editor that implements the ability to create an AND/OR-graph for expert rules.

To create a knowledge editor the following problems are solved:

— The tools for visualizing the graphs and working with them interactively are explored. These tools can be used to make the expert rules in the form of graph. For the graphics part (the graph elements, their interactive changes, displaying) a simple but convenient library JGraphX [12] is chosen.

— The adding and editing of the AND/OR-graph components are developed.

— The graph saving and readout are developed.

— Converting the AND/OR-graph to text rules is developed.

— The possibility of checking the rules inconsistency on the basis of the SAT task is developed. This eliminates several factors concerning the rules. Thus it can be checked whether ES always gives only one of the possible sequences and never the other (opposite).

— The feature checking the rules completeness showing the user the so-called “opposite” rules is implemented, i.e. rules that determine in which cases the sequence opposite to the initial is performed.

The program main window is shown on Fig. 1. The main functions of the system are: "New node", "Add a set of nodes", "Delete object", "Save" to keep the information about the graph in an XML file, "Save the rules" in text form, "Download" button is designed for reading the stored file and building the graph. The user can display one or all of the selected rules with the help of the buttons "One rule" and "All rules", "Inconsistencies search" in the rules.

Conclusions. The result of the research is proposing the ways for visualizing monitoring ES rules, testing their inconsistency and incompleteness. And on the basis of such approaches the knowledge editor for monitoring expert systems is designed, in which are implemented:

— the possibility to create and edit the AND/OR-graph for expert systems rules, visualizing the rules for easy viewing and analysis using the methods of graph theory and mathematical logic;

— the presentation of expert rules in text form that is easy to be read;

— checking the inconsistency and incompleteness of expert system rules.

To test the effectiveness of the proposed methods, experiments were conducted on the basis of the student’s work for developing of monitoring ES in different areas. The experimental group of students used the developed rule editor, the control group developed ES without it. As a result, median and mode for students’ marks in experimental group was 4 and for the control 3, and this result is true with statistical significance of 95%. So it was drawn a conclusion that such a result is associated with the proposed rule editor.

It was created five groups containing 37 rules of ES for safe working on electrical installations. Created expert system is used for dispatcher who organize the work with electrical equipment and it reduces the number of errors in decision-making by an average 5 %.

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