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Statement Networks to Condition Monitoring of the Sealless Pump

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Abstract—**This paper shows an application of multi-layer statement networks to condition monitoring of the sealless magnetic drive pump. In this case, statement networks are computed based on the use of Bayesian probabilities. Moreover, the tool called REx which allows implementing such networks is described. An example of created four-layer network as well as final results of the performed tests shows also.**

Keywords—**diagnostic model, statement network, multi-layer statement network, expert system**

I. INTRODUCTION

The purpose of technical diagnostics is to determine the condition (technical state) of technical objects by using objective methods and resources [7][8]. The technical state st_i of every technical object at a given moment of time t belongs to (usually finite) set of possible states $\{ST\}$ assigned to this object. The simplest set $\{ST\}$ has two main states (generally class of states): $\{st_0$: good; st_1: faulty$\}$. The obtained information about the technical state of the object is called *diagnosis*.

In order to supporting decision-making process *expert* systems are used [1][4][5]. One of the modules of such system is *inference module*. Among the many different inference methods the *statement network* can be used [2][3]. In statement network each node corresponds to statements, and edges describe relationships between the statements. Generally, every statement *s* can be written as a set:

$$s = <c \text{ (the stmt. content)}, v \text{ (the stmt. value)}> \quad (1)$$

The statement content can be declarative sentence, to which is attributed one of the certain values (e.g. *c="the liquid level in the tank is too high"*). While the statement values indicates whether the statement content is true. In such networks, obtaining a stable state between statements values may be based on a statistical model proposed by Bayes. The networks based on such probabilistic model are being called *Bayesian networks* [6]. The Bayesian network is an acyclic directed graph consisting of nodes and directed branches joining nodes, where:

- the nodes represent random variables (e.g. temperature, some features of technical object etc.),
- directed branches represent relationships between the nodes (variables): "*variable A has a direct impact on variable B*",
- each node is linked with table that contains conditional probabilities for all elements of Cartesian products of states of parent nodes and states of the node linked with the table; conditional probability is calculated from the formula:

  $$P(A|B) = P(A,B) / P(B) \quad (2)$$

  where: P(A,B) is the probability of joint occurrence of events A and B,
- the nodes of network have discrete values (e.g. {*yes*, *no*}).

An extension of the statement networks are *multi-layer statement networks* [2][3]. In such networks each layer is a single statement network, wherein the selected nodes can simultaneously belong to several layers. Values of these nodes are calculated with using some methods of aggregation.

During the process of creating the diagnostic model, *Knowledge engineer* makes decisions relating to:

- way of combining statements represented as nodes of the network model,
- determining values of conditional probabilities of each node, thereby assigning the uncertainty of e.g. measurement data,
- defining the weights of each model layer, where weight values may be determined on the basis of expert knowledge (from experience acquired during building the individual layers that represent a selected portion of domain knowledge),
- specifying aggregation method of values of selected nodes that simultaneously belongs to several layers.

The above steps can be the subject of actions to tune network parameters after preliminary validation process.

By using multi-modal statement networks a diagnostic model can be built as:

- a multi-modal networks, where individual layers are treated as modes associated with the individual components of the system,
- a multi-modal networks, where individual layers are treated as modes associated with the various operating aspects of the modelled system, e.g. mode associated with the hydraulic issues and mode associated with the thermodynamic issues,

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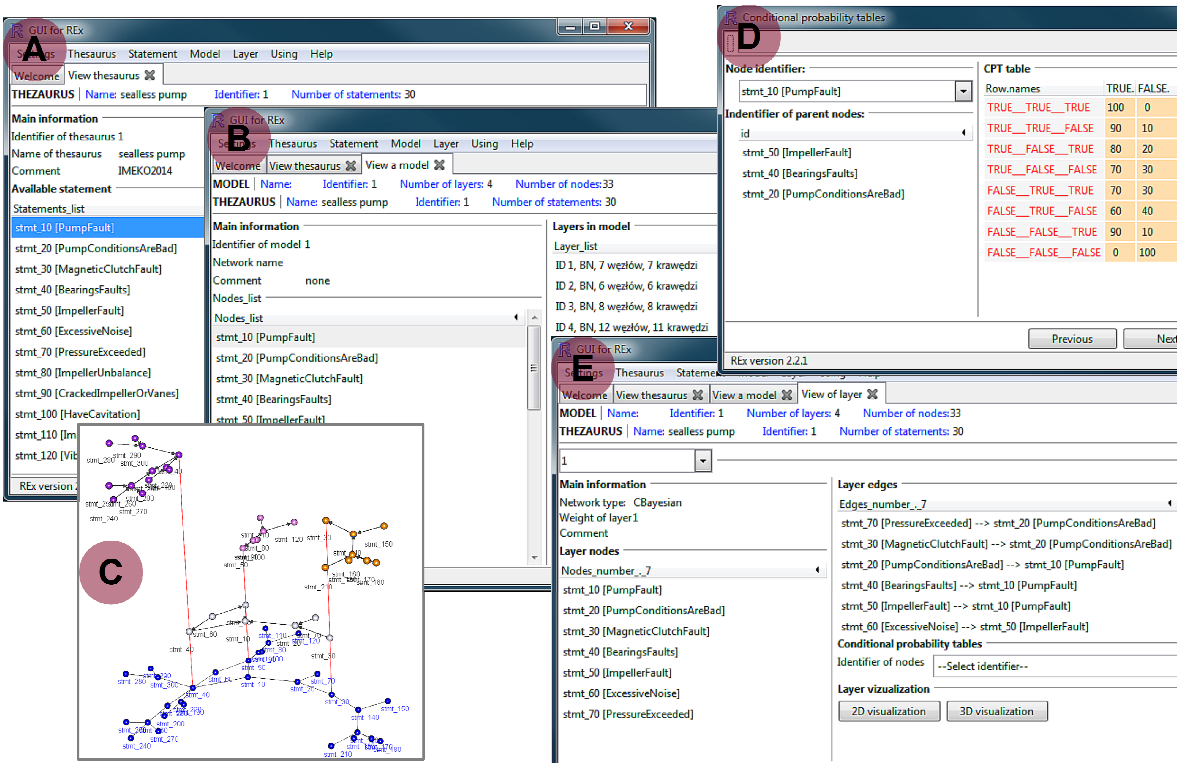
- a multi-layer model, where is defined a one general mode and a set of detailed modes (e.g. associated with the selected operational aspects or associated with the individual components of the system).

Generally, using a multi-layer statement networks in inference process involves the following steps:

1. Defining known values of selected statements.
2. Starting the process of calculating unknown values of others statements (according to the adopted method).
3. Reading values of interesting statements.



THEZAURUS | Name: sealless pump Identifier: 1 Number of statements: 30

Main information

Identifier of thesaurus 1

Name of thesaurus sealless pump

Comment IMEKO2014

Available statement

Statements_list

stmt_10 [PumpFault]
stmt_20 [PumpConditionsAreBad]
stmt_30 [MagneticClutchFault]
stmt_40 [BearingsFaults]
stmt_50 [ImpellerFault]
stmt_60 [ExcessiveNoise]
stmt_70 [PressureExceeded]
stmt_80 [ImpellerUnbalance]
stmt_90 [CrackedImpellerOrVanes]
stmt_100 [HaveCavitation]
stmt_110 [Im
stmt_120 [Vib

REx version

MODEL | Name: Identifier: 1 Number of layers: 4 Number of nodes:33

THEZAURUS | Name: sealless pump Identifier: 1 Number of statements: 30

Main information

Identifier of model 1

Network name

Comment none

Nodes_list

stmt_10 [PumpFault]
stmt_20 [PumpConditionsAreBad]
stmt_30 [MagneticClutchFault]
stmt_40 [BearingsFaults]
stmt_50 [ImpellerFault]

Layers in model

Layer_list

ID 1, BN, 7 węzłów, 7 krawędzi
ID 2, BN, 6 węzłów, 6 krawędzi
ID 3, BN, 8 węzłów, 8 krawędzi
ID 4, BN, 12 węzłów, 11 krawędzi

Node identifier: stmt_10 [PumpFault]

Indentifier of parent nodes:

id
stmt_50 [ImpellerFault]
stmt_40 [BearingsFaults]
stmt_20 [PumpConditionsAreBad]

CPT table

Row.names	TRUE.	FALSE.
TRUE__TRUE__TRUE	100	0
TRUE__TRUE__FALSE	90	10
TRUE__FALSE__TRUE	80	20
TRUE__FALSE__FALSE	70	30
FALSE__TRUE__TRUE	70	30
FALSE__TRUE__FALSE	60	40
FALSE__FALSE__TRUE	90	10
FALSE__FALSE__FALSE	0	100

REx version 2.2.1

MODEL | Name: Identifier: 1 Number of layers: 4 Number of nodes:33

THEZAURUS | Name: sealless pump Identifier: 1 Number of statements: 30

1

Main information

Network type: CBayesian

Weight of layer1

Comment

Layer nodes

Nodes_number_._7

stmt_10 [PumpFault]
stmt_20 [PumpConditionsAreBad]
stmt_30 [MagneticClutchFault]
stmt_40 [BearingsFaults]
stmt_50 [ImpellerFault]
stmt_60 [ExcessiveNoise]
stmt_70 [PressureExceeded]

Layer edges

Edges_number_._7

stmt_70 [PressureExceeded] --> stmt_20 [PumpConditionsAreBad]
stmt_30 [MagneticClutchFault] --> stmt_20 [PumpConditionsAreBad]
stmt_20 [PumpConditionsAreBad] --> stmt_10 [PumpFault]
stmt_40 [BearingsFaults] --> stmt_10 [PumpFault]
stmt_50 [ImpellerFault] --> stmt_10 [PumpFault]
stmt_60 [ExcessiveNoise] --> stmt_50 [ImpellerFault]

Conditional probability tables

Identifier of nodes --Select identifier--

Layer vizualization

Fig. 1. REx Environment: A – Thesaurus view, B – Model view, C – Model 3D view, D – Conditional probability table editor, E – Layer view

II. EXAMPLE OF USE

To build a multi-layer statement network used specialized tools Development Environment REx (Fig. 1, website: `http://ipkm.polsl.pl/index.php?n=Projekty.Rex`). Using this software to building a multi-layer statement network involves the following steps:

1. Creating a set of statements.
2. Creating thesaurus and assign to this thesaurus created statements.
3. Creating a set of single statement network.
   a. Creating nodes and assigning them to statements included in the thesaurus.
   b. Creating edges joining nodes.
   c. Defining tables that contain conditional probabilities (needed for Bayesian model).
4. Creating a multi-layer statement network.

REx system supports i.a. the process of building diagnostic models which can be applied to recognize of technical state of different technical objects. In this paper an example of model building has shown on the base of heat transfer oil hermetic pump which is used to carrier working fluid in the Organic Rankine Cycle of cogeneration plant. The location of the pump has shown in Fig. 2. Also the selected measurements devices used to observe the considered pump have been indicated. Because of the possible influence of other ORC components on the considered pump it has been conceptually separated from the rest and no further interactions e.g. critical states associated with abnormal technical state of other cycle components or control are considered in the paper.

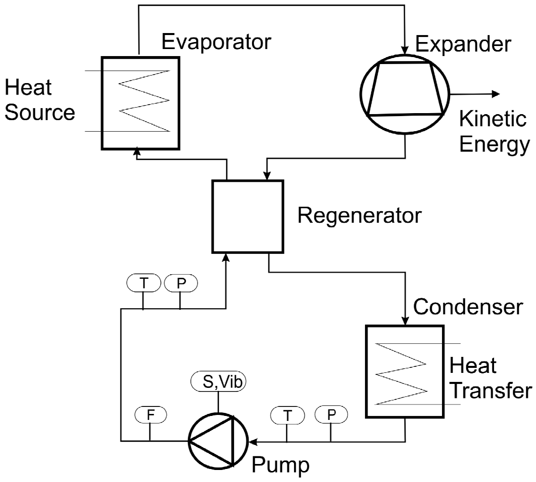


Fig. 2. Organic Rankine Cycle with sealless magnetic drive pump

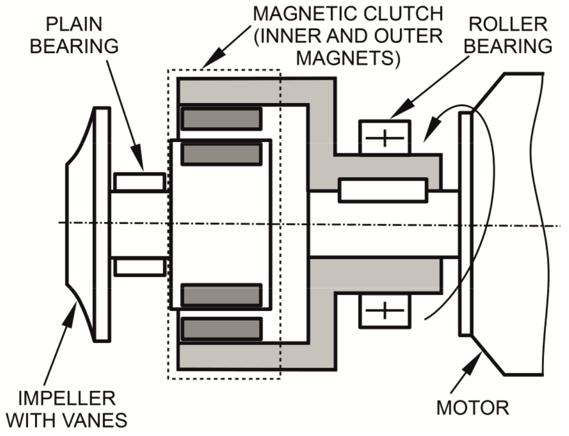
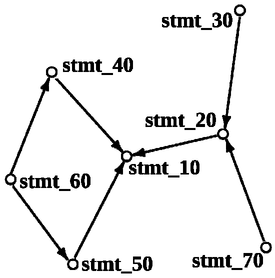


Fig. 3. General form of the sealless magnetic drive pump

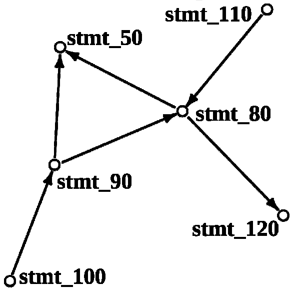
The considered pump belongs to the sealless magnetic drive pumps (Fig. 3) and ensures adequate pressure and flow in the cycle. The pump has driven by asynchronous motor. The input shaft is supported on ball bearings which require periodic lubrication performed by the service. The output shaft is coupled with the input shaft by the magnetic drive. Thus, the transfer of power takes place without contact with the impeller. The shaft of the impeller is supported on massive plain bearings which are directly lubricated by the working fluid.

LAYER 1 – Pump generic



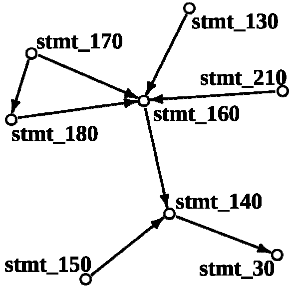
Statements list:
stmt_10 – PumpFault
stmt_20 – PumpConditionsAreBad
stmt_30 – MagneticClutchFault
stmt_40 – BearingsFaults
stmt_50 – ImpellerFault
stmt_60 – ExcessiveNoise
stmt_70 – PressureExceeded

LAYER 2 - Impeller



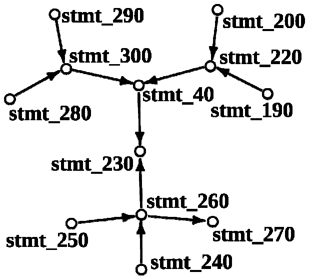
Statements list:
stmt_50 – ImpellerFault
stmt_80 – ImpellerUnbalance
stmt_90 – CrackedImpellerOrVanes
stmt_100 – CavitationOccurs
stmt_110 – ImpellerDeposits
stmt_120 – VibrationSpectrumIsBad

LAYER 3 – Magnetic clutch



Statements list:
stmt_30 – MagneticClutchFault
stmt_130 – PressureDrop
stmt_140 – Decoupling
stmt_150 – TorqueExceeded
stmt_160 – TorqueBelowNominal
stmt_170 – PumpTemperatureExceeded
stmt_180 – ClutchDemagnetized
stmt_210 – RotationalSpeedNormal

LAYER 4 - Bearings



Statements list:
stmt_40 – BearingsFaults
stmt_190 – RotationalSpeedExceeded
stmt_200 – PressureRise
stmt_220 – OverloadPlainBearing
stmt_230 – BearingTemperatureRise
stmt_240 – FlowRateExceeded
stmt_250 – DegradationThermoWorkingFluid
stmt_260 – PlainBearingLackLubrication
stmt_270 – RubbingFrequency
stmt_280 – HigherFrequency
stmt_290 – RollerBearingLackLubrication
stmt_300 – RollerBearingFault

Fig. 4. Four layers of multi-layer statement network for considered sealless pump

Gathering knowledge about the considered object one can find that the manufacturer of the pump points important recommendations regarding proper operation and maintenance. This comprises the need to maintain the adequate operating temperature, which, to high, can lead to demagnetization of the magnetic coupling, or the development of excessive thermal stresses. The second recommendation is also dependent on the temperature of the medium. Third and the last recommendation, concerns to ensure a minimum mass flow rate to ensure proper lubrication of plain bearings.

Information about considered diagnostic domain can be incorporated into REx system via statements and structures of multi-modal network. Statements are the basic elements which are used for the purpose of exchanging information between REx's diagnostic system user and inference system. In the considered example, it is possible to elaborate the subsets of statements which will be recorded in the thesaurus. These statements may describe:

- possible faults of object (based on available diagnostic knowledge),
- critical states of object (based on product documentation e.g. operation and maintenance manual),
- information about observed parameters (based on measuring systems and signal processing).

Also it is possible to define additional auxiliary statements, which can be used to reduce a complexity of diagnostic models. The description of selected exemplary statements defined for the concerned example is listed below:

- Pump is faulty = {Yes, No},
- Impeller unbalance = {Yes, No},
- Pressure limit value is exceeded = {Yes, No},
- Typical high frequency components for ball bearings appear in the spectrum = {Yes, No},
- Angular speed of drive shaft is nominal = {Yes, No}.

Process of designing a diagnostic model is conducted based on elaborated thesaurus. This thesaurus may be considered as a dictionary of available statements. These statements may be used by many domain engineers to develop diagnostic models for complex technical objects, which is especially useful where the domain knowledge about considered object is complex and inaccessible for wide groups of engineers. This approach enables an integration of knowledge from many sources (e.g. domain experts, external data, etc.).

An example of multi-layer network for considered pump has shown in Fig. 4. Diagnostic model was divided into following modes:

- General mode for basic information about pump state (Fig. 4. Layer 1). Nodes which represent general information about pump state and states of some components of this pump, and the general statements that do not require detailed diagnostic knowledge are available on this level;
- Impeller's mode that is related with the technical state of impeller (Fig. 4. Layer 2). The statements represent potential symptoms of impeller faults and statements represent some information about measured signals (e.g. increased values of frequency components associated with the unbalance) are considered in this case;
- Magnetic clutch's mode (Fig. 4. Layer 3);
- Bearing's mode, which contains nodes that represent statements related with technical state of ball and plain bearings (Fig. 4. Layer 4).

Conditional probability tables (CPT) for each statement are defined. Some examples of those tables have shown in Table 1 and Table 2.

TABLE I
EXAMPLE OF THE CONDITIONAL PROBABILITY TABLE (CPT) FOR STATEMENT STMT_10 – PUMPFAULT

stmt_20	stmt_40	stmt_50	stmt_10=T	stmt_10=F
T	T	T	100	0
T	T	F	90	10
T	F	T	80	20
T	F	F	70	30
F	T	T	70	30
F	T	F	60	40
F	F	T	90	10
F	F	F	0	100

TABLE II
EXAMPLE OF THE CONDITIONAL PROBABILITY TABLE (CPT) FOR STATEMENT STMT_80 – IMPELLERUNBALANCE

stmt_90	stmt_110	stmt_80=T	stmt_80=F
T	T	100	0
T	F	30	70
F	T	70	30
F	F	0	100

T – true, F – false

Some results which are obtained from the tests of created four-layer statement network have shown in Table 3. Default values of statements are written in the column "Default". It is assumed that all statement values are presented for the *true* state. The column "Test 1" contains the results of calculations when values (*true* or *false*) of selected independent nodes (**`stmt_20:F`**, **`stmt_60:F`**, **`stmt_120:F`**, **`stmt_150:F`**, **`stmt_160:F`**, **`stmt_190:F`**, **`stmt_230:F`**, **`stmt_250:F`**) are fixed by user for normal operation of the pump. It can be seen that the values of the selected nodes that identify the particular failures (**`stmt_10: 0.064`**, **`stmt_30: 0,027`**, **`stmt_40: 0.224`**, **`stmt_50: 0.097`**) is low.

The column "Test 2" contains results of calculations when values of selected independent nodes (**`stmt_20:F`**, **`stmt_60:T`**, **`stmt_120:T`**, **`stmt_150:F`**, **`stmt_160:T`**, **`stmt_190:T`**, **`stmt_230:T`**, **`stmt_250:F`**) for pump faults. One can observed that the values of the selected nodes that identify the selected failures (**`stmt_10:0,682`**, **`stmt_30:0,377`**, **`stmt_40:0,772`**, **`stmt_50:0,722`**) are high and indicates that fault may affect bearings or impeller. The last two columns contains the results of calculations in the case where it was assumed that all components of the pump are not damaged (column „Test 3"; **`stmt_30:F`**, **`stmt_40:F`**, **`stmt_50:F`**) and when it was assumed that some components of the pump are damaged (column „Test 4"; **`stmt_30:T`**, **`stmt_40:T`**, **`stmt_50:T`**). Values of statements that belong to different layers are determined by aggregation operation; in this case it is an arithmetic average.

TABLE III

DEFAULT VALUES OF STATEMENT AND RESULTS AFTER SETTING THE VALUE FOR SELECTED STATEMENTS (':' – RESULT OF AGGREGATION (MEAN FUNCTION), T– FIXED TRUE, F – FIXED FALSE)

Statement name	Default	Test 1	Test 2	Test 3	Test 4
Layer 1					
stmt_10 - PumpFault	0,640	0,064	0,682	0,090	0,995
stmt_20 - PumpConditionsAreBad	0,525	F	F	0,100	0,950
stmt_30 - MagneticClutchFault	0,500:0,566	0,053:0,027	0,053:0,377	F	T
stmt_40 - BearingsFaults	0,325:0,573	0,050:0,224	0,600:0,772	F	T
stmt_50 - ImpellerFault	0,375:0,416	0,050:0,097	0,700:0,772	F	T
stmt_60 - ExcessiveNoise	0,500	F	T	0,117	0,994
stmt_70 - PressureExceeded	0,500	0,421	0,421	0,500	0,500
Layer 2					
stmt_50 - ImpellerFault	0,456:0,416	0,144:0,097	0,844:0,772	F	T
stmt_80 - ImpellerUnbalance	0,645	0,084	0,940	0,091	0,911
stmt_90 - CrackedImpellerOrVanes	0,450	0,185	0,781	0,050	0,928
stmt_100 - CavitationOccurs	0,500	0,312	0,734	0,217	0,838
stmt_110 - ImpellerDeposits	0,456	0,385	0,643	0,445	0,566
stmt_120 - VibrationSpectrumIsBad	0,445	F	T	0,127	0,825
Layer 3					
stmt_30 - MagneticClutchFault	0,631:0,566	0,000:0,027	0,700:0,377	F	T
stmt_130 - PressureDrop	0,500	0,487	0,488	0,492	0,504
stmt_140 - Decoupling	0,631	0,000	0,700	0,000	1,000
stmt_150 - TorqueExceeded	0,500	F	F	0,132	0,716
stmt_160 - TorqueBelowNominal	0,512	F	T	0,208	0,691
stmt_170 - PumpTemperatureExceeded	0,500	0,256	0,732	0,355	0,585
stmt_180 - ClutchDemagnetized	0,500	0,256	0,732	0,355	0,415
stmt_210 - RotationalSpeedNormal	0,500	0,308	0,683	0,386	0,433
Layer 4					
stmt_40 - BearingsFaults	0,821:0,573	0,398:0,224	0,994:0,772	F	T
stmt_190 - RotationalSpeedExceeded	0,500	F	T	0,143	0,578
stmt_200 - PressureRise	0,500	0,358	0,524	0,143	0,578
stmt_220 - OverloadPlainBearing	0,650	0,230	0,943	0,000	0,208
stmt_230 - BearingTemperatureRise	0,769	F	T	0,400	0,150
stmt_240 - FlowRateExceeded	0,500	0,452	0,523	0,500	0,500
stmt_250 - DegradationThermoWorkingFluid	0,500	F	F	0,500	0,500
stmt_260 - PlainBearingLackLubrication	0,500	0,013	0,142	0,500	0,500
stmt_270 - RubbingFrequency	0,500	0,013	0,142	0,500	0,500
stmt_280 - HigherFrequency	0,500	0,370	0,515	0,195	0,567
stmt_290 - RollerBearingLackLubrication	0,500	0,422	0,509	0,317	0,540
stmt_300 - RollerBearingFault	0,488	0,398	0,511	0,000	0,594

III. CONCLUSIONS

The paper shows an example of multi-layer statement network that can be used to support condition monitoring of selected technical object. Presented example was done with the use of REx Environment which allows to implement this type of networks and conduct their preliminary examination. In the example, four-layer statement network, constructed on the basis of predefined thesaurus with 30 statements, was created. The most difficult stage of network preparation was to elaborate conditional probabilities tables. Proper selection of values of these tables has significant influence on the correct results of inference process. Analysis of the presented results allows concluding that the prepared individual layers create consistent network that works properly.

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