http://doi.org/10.35784/iapgos.3051

received: 18.08.2022 | revised: 06.09.2022 | accepted: 15.09.2022 | available online: 30.09.2022

APPLICATION OF PREDICTIVE MAINTENANCE IN THE PACKAGING PRODUCTION

Bogdan Palchevskiy[1], Lyubov Krestyanpol[2]

[1]Lutsk National Technical University, Faculty of Computer and Information Technologies, Lutsk, Ukraine, [2]Lesya Ukrainka Eastern European National University, Faculty of Foreign Linguistics, Lutsk, Ukraine

Abstract. *To solve the problem of predictive maintenance for packaging manufacturing, we propose a hybrid model that optimizes the maintenance plan. The model is based on monitoring the state of many components of a multi-position automatic packaging machine and makes it possible to predict their future malfunctions and estimate the remaining service life of the equipment. The effectiveness of the proposed solution is demonstrated with the help of a real industrial multi-position machine for the automatic production of film bags and packaging of paste in them. The methodology is based on the analysis of diagnostic information using an expert system.*

Keywords: technological equipment, expert system, monitoring, diagnostics, intelligent control system

ZASTOSOWANIE PREDYKCYJNEJ DIAGNOSTYKI W PRODUKCJI OPAKOWAŃ

Streszczenie. *Aby rozwiązać problem predykcyjnego utrzymania ruchu w produkcji opakowań, proponujemy hybrydowy model optymalizujący plan utrzymania ruchu. Model ten opiera się na monitorowaniu stanu wielu komponentów wielostanowiskowej automatycznej maszyny pakującej i umożliwia przewidywanie ich przyszłych awarii oraz szacowanie pozostałego czasu eksploatacji urządzenia. Skuteczność proponowanego rozwiązania została zademonstrowana na przykładzie rzeczywistej przemysłowej maszyny wielostanowiskowej do automatycznej produkcji torebek foliowych i pakowania w nie pasty. Metodyka opiera się na analizie informacji diagnostycznych z wykorzystaniem systemu eksperckiego.*

Słowa kluczowe: aparatura technologiczna, system ekspertowy, monitoring, diagnostyka, inteligentny system sterowania

Introduction

The change in the technical condition, which is automatically determined by the system, is caused by the appearance and development of defects in parts, nodes and systems of technological equipment [10]. Diagnosis during the operation of technological machines and their maintenance has its own characteristics. Diagnostic methods are divided into two groups:

1. Organoleptic (subjective) methods performed with the help of the performer's sense organs by side effects or using simple technical means, as well as on the basis of expert assessments. Experienced mechanics quickly determine up to 70% of equipment malfunctions and failures using organoleptic methods and the simplest tests.
2. Instrumental (objective) methods, when the measurement of the technical condition parameters is carried out by technical means.

Organoleptic methods allow you to identify by ear the places and nature of abnormal knocks, noise, equipment interruptions, a drop in engine power, its difficulty starting, as well as malfunctions in mechanical gears (rattle, noise). On inspection, you can also establish the places of leakage of oil, water and other technological liquids, the beating of rotating parts, the tension of chain gears, and a decrease in machine performance. When touched, the places and degree of abnormal heating, beating, vibration of parts are established, the viscosity of liquids is changed, and clutch failure, gas leakage and other media, short circuit wiring are determined by smell.

Instrumental methods by the nature of measuring parameters are divided into direct and indirect.

Direct measurement methods are based on direct measurements of the parameters of the technical condition of the equipment. They include kinematic measurements of the relative position and movement of parts (control of gaps in connections, in bearings, deflection of belt and chain gears, resizing of parts due to wear, radial, end and angular displacements of shafts of mechanisms, their inconsistency and non-parallelity), capillary control methods for detecting defects in the structure of parts and assemblies using liquids – penetrants that have a high ability to wet and penetrate through defects (kerosene, paints, or phosphors), ultrasonic search for surface defects, based on the phenomenon of ultrasound waves reflection from an insurmountable obstacle for it (for example, the transition of metal – air).

Indirect measurement methods are based on measuring the values of physical quantities characterizing the technical condition of mechanisms, systems and assemblies of machines (pressure, pressure drop, temperature, temperature difference in the working body of the system, gas consumption, electricity, oil, vibration parameters of the machine components, acceleration during run-up of parts, etc.). They include energy and thermal methods, vibroacoustic (registration of elastic vibrations parameters that occur in mechanisms when parts collide during operation) and pneumohydraulic (time of decrease in air pressure at specified limits of pressure change; relative leakage; absolute leakage) diagnostic methods.

To carry out diagnostics to obtain a complete picture of the state of technological equipment, it is advisable to combine the experience of specialists – experts who will allow to form for the ES a list of production rules based on organoleptic control methods, and the results of current direct and indirect measurements of the machine state during its operation. The creation of an ES for predictive maintenance of equipment in production conditions is carried out in stages.

- At the first stage, data display and the equipment status monitoring is ensured, to do it sensors, actuators, controllers are installed on industrial equipment (in the most important places of equipment). As a result, it becomes possible to collect information. When processing a huge array of unstructured data coming from sensors, filtering and adequate interpretation becomes a priority. Therefore, the creation of a program for information processing is of particular importance.
- The second stage is the creation of algorithms and subroutines based on an understanding of how changing parameters affects the operation of equipment. Here it is necessary to determine the limiting values of the operational parameters, upon reaching which it is necessary to perform certain operations of technological maintenance of equipment. In addition, when creating algorithms, one should consider the availability of organoleptic control data and their relationship with the parameters of the state of the equipment, determined by the results of the analysis of expert responses.

1. Statement of the problem

The aim of the study is to improve the process of diagnosing technological equipment, which allows to increase production efficiency by reducing equipment downtime during repair, to

This work is licensed under a Creative Commons Attribution-ShareAlike 4.0 International License.
Utwór dostępny jest na licencji Creative Commons Uznanie autorstwa – Na tych samych warunkach 4.0 Miedzynarodowe.

reduce production costs by reducing repair costs and restoring equipment. The system of monitoring and diagnosis should provide a combination of the results of organoleptic and instrumental methods for diagnosis and their analysis. To do this, the equipment management system includes an expert system (ES). The system of monitoring and diagnostics using the ES should detect deviations in the early stages of changes in the technical condition and at the same time indicate also the ranked contribution of each technical means to the change in the general technical condition of the equipment. This is achieved by comparing the current state of the equipment with the reference (obtained during modeling), which allows you to choose the direction of searching for sources of emerging problems, as well as to implement predictive maintenance.

In general, most research focuses on the application and optimization of predictive models (mainly public and dedicated manufacturing datasets), but does not consider decision support such as optimization of maintenance planning using predictive models combined with the use of expert systems.

However, in this case, it is necessary to create fundamental approaches to the construction of algorithms for the joint work of organoleptic and instrumental methods for diagnosis and methods for forming the functional structure of the ES software part for a specific type of technological equipment, which is the purpose of this work.

In our work, the model is based on a hybrid approach, that is, the data of the statistical analysis of malfunctions and failures of packaging production equipment components are studied, on the basis of which the selection of sensors characterizing the state of the machine is carried out, and based on various combinations of data on the operation of the machine and its state, an expert system is built allows you to determine the status of the machine and create a schedule for its maintenance.

Such a maintenance system is able to predict its future condition and determine the necessary maintenance measures, based on the current state of the equipment. In this case, the probability of unplanned equipment failure will be minimized.

2. Literature review

Technical equipment is expensive, and its performance can have a huge impact on the production chain. Essentially, any unexpected equipment failure can lead to unintended downtime and costs for the entire production line. Over time, the condition and performance of production machines deteriorates. This eventually causes the machine to fail or malfunction if no maintenance measures are taken [1, 10]. The maintenance can be done in a variety of ways, from conventional approaches such as emergency, preventive, to predictive approaches. The emergency approach is used in the event of a failure that is costly and unpredictable. The preventive approach relies on expert knowledge, that is, on the actual model of system degradation [10]. The predictive approach focuses on maintenance based on the actual state of the equipment. For this, various data obtained from sensors are used.

Many researchers believe that the optimal strategy for maintenance and repair of technological equipment is to perform it according to the actual condition of the equipment using technical diagnostic methods. Existing predictive maintenance research usually focuses on either a predictive model without considering maintenance decisions or maintenance optimization based on known system degradation models [10].

The complexity of machinery involved in modern packaging production has grown rapidly. Thus, it is important to use an effective strategy that coordinates the prediction and detection of malfunctions in the operation of the equipment, and allows the formation of a maintenance schedule to optimize its operation. Consequently, any maintenance activity to be performed in such complex systems must consider not only the individual component, but also the relationships between the various machine components. This creates several problems for the design and implementation of predictive maintenance, namely in data collection, data processing and their interaction with the maintenance process [8].

Predicting the remaining useful life (RUL) of process equipment is a key component. Model-based methods rely solely on the degradation model of the physical structure to a predictive state of equipment performance. Therefore, they are ineffective for equipment with a complex structure, for example, for multi-position technological machines [17]. Methods used for forecasting models include autoregressive integrated moving average (ARIMA) models [14, 20].

The research community has investigated various aspects of maintenance. In the case of traditional maintenance, single-component systems were mainly investigated. Different existing maintenance policies for both single-unit and multi-unit systems are compared here [19]. These approaches mostly consider a single machine or component without paying attention to related machines or components. Thus, the aspect of maintenance of a multicomponent system becomes the focus of various works [3]. In this context, machine equipment with more than one component was considered, for which the main criteria for optimizing technical maintenance of technological equipment were considered, which included the structure of the equipment [18].

However, the requirements of advanced forecasting make traditional data-driven methods impossible for the processing of structurally complex technological machines [11]. To overcome this, a combination of various data on its working and operational parameters of technological equipment is used, which allows for a more accurate assessment of its actual condition. However, all this requires the creation of a principled approach to the construction of algorithms for the joint work of organoleptic and instrumental diagnostic methods for equipment with a complex structure.

Predictive maintenance includes two key components: predictive analytics and equipment maintenance planning.

To analyze data describing the condition of technological equipment, a number of authors used expert systems (ES) for diagnosing complex mechanical systems [9, 12], CNC machines [4], engines [5], and weapons [2]. In order to solve typical problems in the manufacturing process of copper phosphor ball, an expert diagnostic system based on failure tree analysis was built by merging the theory of failure trees and ES. The fault tree model of unqualified quality of production of copper phosphor ball and malfunction of the hydraulic system is highlighted [21]. According to the results of the analysis of numerous works, we note that a good help for diagnosing the technical condition of the equipment in different conditions of its operation can be the determination of zones of fuzzy condition of the equipment [5, 10]. These zones are defined by fixed variables such as "vibration level", "noise level", "heat level", etc., which correlate with terms such as "maintenance required", "faulty condition", "element replacement required", etc. In addition, for each specific type of equipment, the expert himself must set the limiting level of these variables. This is where the ES begins to play the main role.

All ES for the diagnosis of technological equipment in one way or another perform the following generalized functions [2, 4, 5, 9, 12]:

- Determination of the general condition of the equipment.
- Determining the period of occurrence of a malfunction or failure, changes in the state of equipment according to a trend or by an increase in diagnostic parameters.
- Constant monitoring and diagnostics of the condition of the equipment during the entire period of use of the equipment while saving its maintainability.

Packaging manufacturing systems are complex systems of closely interconnected machines and devices that interact and cooperate to achieve common goals. Consequently, any maintenance activity to be performed in such complex systems must consider not only the individual component, but also the dependencies of the various machine components involved.

The main problem that arises when using ES to diagnose technological equipment is the need to combine production rules in one functional software structure based on the results of organoleptic control of the equipment and due to the results obtained by instrumental control methods. Next, it is necessary to form recommendations for forecasting the future state of technological equipment and choosing the type of its maintenance.

The general process of predictive maintenance includes stages.

The first stage is the collection of data for predictive maintenance, which is critical for effective maintenance operations.

The second stage of predictive maintenance is data processing and forecasting. Collected data from facilities or resources is processed to reduce the significant impact on the production chain in the event of their failure. The second step provides a framework to support maintenance decisions.

The third stage in the process is service decision support. This step covers the general aspect of maintenance by helping the operator, in the maintenance engineer, to act on an event that triggers a specific maintenance task.

3. Researches methodology

3.1. The sequence of designing the functional structure of software for diagnosing technological equipment

The process of creating an EC diagnostic system for analyzing the reliability of technological equipment includes the following steps.

1. At the first stage, the decomposition of technological equipment into technological blocks is carried out. All elements included in its composition are determined and potential malfunctions of each element and possible diagnostic signs are identified.
2. The parameters that the information system will control in real time are determined. All parameters can be divided into groups according to the degree of significance:
a) technological parameters controlled by the SAC;
b) direct and indirect parameters of the equipment state, including those related to organoleptic control, a change in the values of which can lead to deviation of the process from the norm or failure.
3. Norms for quantitative parameters are determined considering normative documents (technological regulations, instructions of the manufacturing plant, expert opinion, etc.), as well as expert knowledge. For each malfunction, the possible causes that cause it are revealed. Each fault corresponds to one or more ways to fix it.
4. The nature of the links between diagnostic parameters and malfunctions is determined. For this, cause-and-effect diagrams are built for each failure and malfunction
5. Simplification of the process of building a diagnostic strategy can be achieved using the fault tree analysis (FTA) method, which contributes to a thorough analysis of the causes of failures of technical systems and the development of measures most effective for their elimination [6, 7]. FTA is used to imagine how the functions of technological equipment, its components (mechanisms, nodes, parts) interact with the control system and its software. When analyzing the occurrence of a failure, the failure tree consists of sequences and combinations of violations and malfunctions, which means it is a multi-level graphological structure of causal relationships obtained as a result of tracking dangerous situations in reverse order, in order to identify possible causes of their occurrence (Fig. 1).

When analyzing a fault tree, the contribution of specific processes and their combinations to the occurrence of a failure is determined.

6. A list of possible faulty states of the equipment is formed.
7. Possible dangerous modes on technological equipment associated with violation of normal operating conditions or failure of individual nodes or parts, as a rule, are known in advance. Automatic control devices perceive controlled technological values (temperature, pressure, etc.) and other diagnostic parameters, when reaching the maximum allowable values, a signal is sent. For such situations, a separate rule of this type is created: "If Parameter i = Critical, then Situation = Failure", where "Parameter i" corresponds to a dangerous value. Based on the results of an expert survey, an assessment of the situation in each case is determined according to the rules. Rules are formed and determine the most likely causes of malfunctions and how to eliminate them. The method of expert assessments for each rule created earlier determines one or more reasons.
8. As a result of the research, a software functional structure that consists of the production is developed. The production system is based on the rules and works cyclically. In each product cycle, the rules from the knowledge base are viewed by the rules interpreter in a certain order. If there is a rule, the condition of which, when compared, coincided with some facts from the working memory, then the rule is activated, and its conclusion is added to the working memory. Then the cycle repeats. The choice of ES strategy for decision-making determines the sequence of application of rules for a multi-stage process.

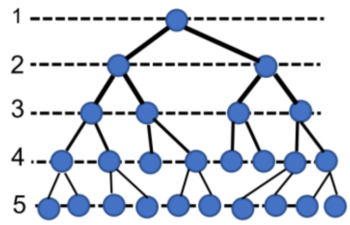

Fig. 1. Conditional scheme of building a tree of faults and malfunctions: 1 – equipment failure, 2 – failures of mechanisms, 3 – failures of components and parts, 4 – events causing failure, 5 – types of impacts

3.2. Methods

The change in the technical state caused by the initiation and development of defects in parts and nodes is determined by the diagnostic system, which allows analyzing various options for complete and partial failures, the operation of devices considering their operating modes, the influence of both the environment and different degrees of wear of parts. The complexity of using logical analysis methods to solve a diagnostic problem (Ishikawa diagram, decision tree, fault tree) is due to the lack of strict formal procedures for their implementation, that sometimes makes it possible to attribute this stage more to heuristics than to science. For analyzing the reliability of technological equipment it is promising to use digital twins that is, virtual prototypes reflecting how a particular technological equipment should work, under the condition that its components – parts, nodes, mechanisms – are fully functional. By comparing the current state of the equipment with a virtual sample, it is possible to identify current and predict future malfunctions and act proactively, eliminating problems before they lead to failure. The digital model can be simplistically represented as a multidimensional surface in the space of operational parameters [12]. For the practical implementation of this approach, it is necessary to form an integral indicator of the technical state of equipment **Y** and establish a functional relationship between it and the set of selected diagnostic parameters specified by vector **X**:

$$Y=F(X) \tag{1}$$

Here, the indicator of the technical condition is understood as a quantitative parameter characterizing the performance of the equipment. The change in this parameter is indicated in the diagram, where it is possible to predict its exit "beyond the permissible limits" in real time using interpolation. This allows you to predict the failure of equipment [14].

4. Experiments and results

4.1. Object of study

As an example, the sources of loss of efficiency for a multi-position automatic machine (MPAM) for packing pastes in doy-pack bags were studied (see Fig. 2b) [15].

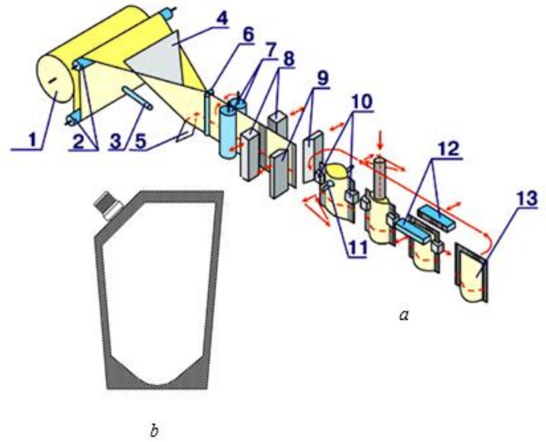

Fig. 2. Technological scheme of packing paste in "doy-pack" bags (a) and a doypack package with cork (b): 1 – laminate roll, 2 – laminate unwinding, 3 – perforator, 4 – pipe forming, 5 – photo sensor, 6,7 – rolls, 8 – longitudinal welding, 9 – cutting, 10 – opening of the package, the 11 cork welding mechanism, 12 – sealing of the package (for packs with a cork, between the cutting mechanism 9 and the mechanism for opening the package 10, the mechanism for cutting off the corner of the pack 9-a, the cork feeding mechanism 9-b and are not shown)

To do this it was considered and recorded in databse of simpl MPAM for the period of time its operation in the real Manufacturing conditions during one year. MPAM performs the following technological transitions: unwinding the laminate from a roll, forming a pipe of it, longitudinal welding of sidewalls to form a package, cutting it off, cutting the corner of the package and welding the cork into it, filling the package and sealing it by welding (Fig. 2a). The results of the study for the MPAM reliability were obtained based on data collection on the duration of its operating state in working conditions and in states of downtime for various reasons.

For data collection and their subsequent analysis, a complex machine is divided into autonomous units. The structure of the MPAM is shown in figure 3.

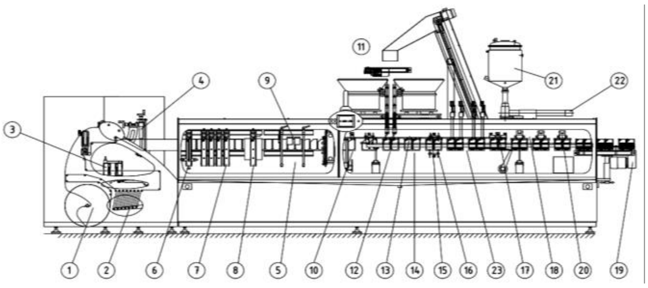

Fig. 3. Multi-position automatic machine (MPAM) for packaging of pastes in "doy-pack" type packs: 1 – laminate roll, 2 – laminate unwinding, 3 – perforator, 4 – forming triangle, 5 – guides, 6 – bottom soldering iron with drive, 7 – mechanism of vertical welding, , 8 – cooling mechanism, 9 – angular stamps, 10 – cutting mechanism (scissor), 11 – cork feeding mechanism, 12 – cork soldering irons, 13 – upper stretcher with tweezers, 14 – lower stretcher with tweezers, 15 – upper suction cups, 16 – lower suction cups, 17 – pack stretching mechanism, 18 – horizontal soldering irons, 19 – conveyor, 20 – cooling mechanism, 21 – tank with product, 22 – dispenser drive, 23 – dispensers (4 pieces) with drive

To analyze the reliability of MPAM as a complex technological equipment, we will limit ourselves to the analysis of the most probable failures only. The duration of downtime in the functioning of MPAM in real production conditions during the year are shown in figure 4.

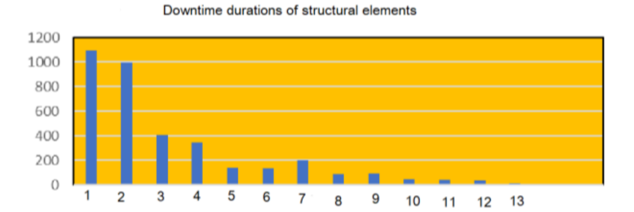

Fig. 4. Ranking of downtime durations of structural elements of MPAM: 1 – broaching mechanism, 2 – cork feeding mechanism, 3 – the cork feeding and inserting mechanism, 4 – cap soldering mechanism, 5 – soldering iron mechanism, 6 – dispenser with nozzle, 7 – cooling mechanism, 8 – vacuum pump, 9 – thermo sensor, 10 – photo sensor, 11 – vibrobunker with a controller, 12 – printer, 13 – scissor mechanism

From the conducted analysis and ranking of downtimes of MPAM structural elements, it follows that the most frequent failures are typical for the mechanisms of stretching the laminate, welding the cork, forming the package and dosing the product [13, 15].

In general, the situation at MPAM depends on a set of factors that are quantified or evaluated qualitatively. To obtain information about the flow state of the technological equipment, it is advisable to install temperature control sensors in the main working areas of the machine, to control the force of moving the laminate per step, the resistance force to the movement of the dispenser piston, a sensor for controlling the viscosity and temperature of the paste, a sensor for electricity consumption, a sensor for the consumption of compressed air, vibration level sensor during machine operation. Next it is necessary to set their normalized values and develop an algorithm for monitoring the interaction of their deviations.

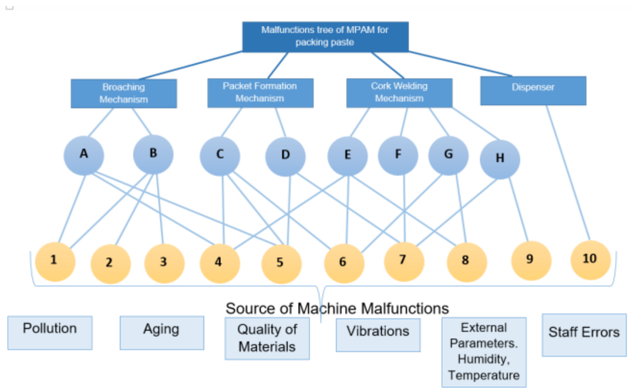

Fig. 5. Malfunctions tree of MPAM for packing paste: Components of the machine that failed: A – stretcher, B – tweezers, C – soldering iron of the package seam, D – package opening mechanism, E – cork soldering iron, F – cork gripping mechanism, G – cork feeding mechanism, H – vibrotank. Machine malfunctions: 1 – laminante tightening, 2 – stretching of the package, 3 – sagging of the package, 4 – burning of the package laminate, 5 – pouring the product, 6 – deformation of the package, 7 – non-installation of the cork, 8 – poor installation of the cork, 9 – jamming of the cork, 10 – dose deviation in the package

In packaging manufacturing, various data are collected during operation. This collected data typically includes data about events, conditions, and transactions. Operational data can include data about a specific process, while event data can collect data about machinery, what has happened to it and what maintenance has been applied to it. Condition data may include the collection of general condition data, i.e. health, and machine condition measurements. In addition, with various sensors such as accelerometers and rain sensors, various signal data such as vibration, temperature, pressure, humidity and climate can be acquired as part of an overall data collection, i.e. events or conditions. In addition to receiving a variety of data from production equipment, tools and systems.

Technological parameters for assessing the state of MPAM, obtained by instrumental control of its state, are given in table 1.

Table 1. Designation of machine condition evaluation parameters

No	Parameter	Characteristics of the parameter
1	t_1	Laminate temperature
2	t_2	corc soldering iron temperature
3	t_3	package soldering iron temperature
4	t_4	paste temperature
5	p_1	laminate pulling force
6	P_2	cork feeding force
7	p_3	paste injection force
8	c	laminate elasticity
9	μ	paste viscosity
10	V	machine vibration level
11	S	noise level at work
12	W	air humidity
13	P	user power of the electric drive
14	Q	consumption of compressed air during operation

The results of a survey of MPAM operators and debuggers, as well as the results of studying and analyzing the relationships between the technological parameters and malfunctions (Fig. 5) were used to form a sequence of production rules in the ES. Information on the identification of components close to failure was obtained by creating an algorithm for the analysis of monitoring results carried out by the ES.

In the data collection process for predictive maintenance, data is usually collected from several sources. In the pre-processing stage, the collected data is cleaned, prepared and formatted as needed to create specific predictive models or general analytical functions [16].

In real conditions, when it is impossible to calculate theoretically the real values of the controlled technological equipment parameters considering its technical condition, it is necessary to provide for the conduct of an educational experiment to obtain reference numerical estimates of the controlled parameters. At the training stage the components of the ES database and knowledge base are filled with reference estimates of the values of parameters and rules that correspond to the specifics of the machine's operation. The reference values of the controlled equipment parameters obtained during the training experiments are used in the future during the operation of the control system and diagnostics of the technological system to ensure its maximum productivity without loss of product quality.

4.2. Results and discussion

Table 2 shows the rules for assessing the state of MPAM, which are used to design the functional structure of ES software. We mark the excess of the specified value of the parameter (see designation in table 1), obtained by the instrumental method, as "+", and its low value as "-".

The procedure for designing the software functional structure for diagnosing a malfunction "Poor/non installation of the cork" is taken as an example from point 7 of table 2 and is illustrated by the following scheme (Fig. 6).

Table 2. Rules for assessing the state of MPAM

No	Evaluation results	Machine malfunctions	Mark in Fig. 5	Reason	Mark in Fig. 7
1	$+t_1$, $-p_1$, -c, +V, +W, +P	laminage tightenning	3	Breakage of the spring of clamped tweezers	4
2	$+t_1$, $+p_1$, -c, +V, +Q	package stretching	5	Incorrect stretcher adjustment	12
3	$+t_1$, $-p_1$, -c, +V, -Q	package sagging	6	Breakage of the clamping tweezers spring	13
				Incorrect stretcher adjustment	14
4	$+t_3$, $+t_2$, $-p_1$, +P	buming the laminate of the package	7	Incorrect temperature adjustment of the package soldering iron	15
				Incorrect temperature adjustment of the cork soldering iron	16
5	$+t_4$, $+p_3$, - μ, -Q	pouring the product	8	Incorrect adjustment of the dispenser	17
				Incorrect adjustment of the paste temperature	18
6	$+t_1$, $+t_2$, $-p_1$, $+p_2$,, +V, -Q	deformation of the package	9	Incorrect temperature adjustment of the package soldering iron	19
				Incorrect temperature adjustment of the cork soldering iron	20
				Incorrect stretcher adjustment	21
				Increased laminate temperature	22
7	$+t_1$, t_2, t_3, $-p_2$, +V, -Q	poor/non installation of the cork	10	Incorrect adjustment of the cork feed force	23
				Exceeded temperature of cork soldering irons and laminate	24
				Incorrect adjustment of the vibrotank	25
				Increased temperature and vibrations in the machine	26
8	$\pm t_4$, $-p_3$, ±μ, -Q, ±W	dose deviation in the package	11	Incorrect regulation of paste temperature and vascosity	27
				Dispenser drive effort	28
				Air humidity	29
				Non-compliance with the specified air pressure in the system	30

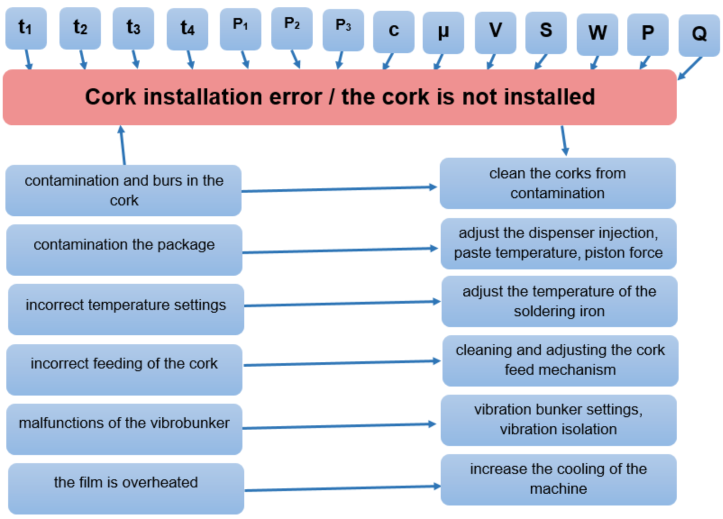

Fig. 6. The scheme of connections when there is the malfunction "Poor/non installation of the cork": temperature (t_1 – laminate, t_2 – cork soldering iron, t_3 – pack soldering iron, t_4 – paste), force (p_1 – laminate pulling, p_2 – cork feeding, p_3 – paste injection), c – laminate elasticity, μ – paste viscosity, V – machine vibration level, S – machine noise level, W – humidity, P – used power of the electric drive, Q – consumption of compressed air during operation

The development of ES for diagnosing MPAM malfunctions was carried out in CLIPS software environment. CLIPS combines 3 programming paradigms: logical, procedural and object-oriented. Clips also provides 3 main formats for presenting information: facts, global variables, and objects. The task of the developed ES is to find the reasons for the breakdown of BPMA mechanisms based on already known defects and malfunctions. Accordingly, using the example of a malfunction "Poor/non installation of the cork", it is possible to determine the reasons for its occurrence: incorrect adjustment of the cork feed force, excessive temperature of the cork or laminate soldering irons, incorrect adjustment of the vibrotank, increased temperature and vibrations in the machine The main task of the developed EC is to identify a malfunction, check the technological parameters, and, as a result, identify the reason of the breakdown. The obtained causes of the malfunction make it possible to select the necessary troubleshooting measures.

The algorithm of work of the EC, which specifies the sequence of application of the developed production rules, is presented in Fig. 7.

Figure 7 shows the ES algorithm, where each circle with a dotted line indicates the index of the question (production rule), and the circle with a solid line indicates the answers that the system displays.

Product rule 1 – the question: "Are there any malfunctions?". The answer "No" goes to the mark 2, which shows the final action – the answer: "The machine is in good working order." The answer "Yes" goes to the production rule with index 3, where a new question is asked: "Is there is laminate tightening malfunction?". The answer "Yes" goes to the choice of the malfunction reason 4 – "Breakage of the spring of clamped tweezers." The answer "No" goes to index 5 which indicates the next malfunction, etc.

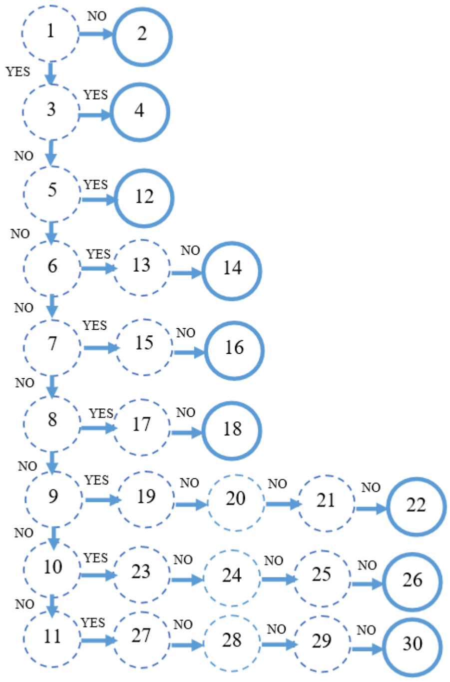

Fig. 7. Algorithm of ES work

The formation of a knowledge base involves entering the questions, in accordance with which the reason of the breakdown is determined, as well as the knowledge that characterizes the malfunctions. The knowledge base also includes additional questions that will be displayed to the user.

In CLIPS, the knowledge base is described as an array of facts of the following form:

```
(deftemplate rule
(multislot if)
(multislot then))
(deffacts knowledge-base
(goal is machine malfunctions)
(legalanswers are yes no)
(rule (if malfunctions is yes) (then type.malfunctions is select))
(rule (if malfunctions is no) (then machine is work))
(question malfunctions is "Is machine malfunctions ?")
(rule (if malfunctions is yes) (then select type.malfunctions))
(rule (if malfunctions is no) (then "Machine is work"))
(question is "Malfunctions is tightening of the film?")
(rule (if type.malfunctions is yes) (then "Breakage of the spring of the clamped tweezers" ))
(rule (if type.malfunctions is no) (then select type.malfunctions ))
```

In addition to the formed array of facts, a rule for conducting a dialogue with the user was also formed to create appropriate changes in the fact base.

```
(defrule ask-question-legalvalues ""
(declare (salience 10))
(legalanswers ? $?answers)
?f1 <- (goal is ?variable)
?f2 <- (question ?variable ? ?text)
(retract ?f1)
(format t "%s " ?text)
(printout t ?answers " ")
(bind ?reply (read))
(if (member (lowcase ?reply) ?answers)
then (assert (variable ?variable ?reply))
(retract ?f2) else (assert (goal is ?variable))))
```

Obviously, in a similar way, the functional structure of all other malfunctions shown in table 2 is carried out.

5. Conclusions

The process of diagnosing technological equipment using ES allows to increase production efficiency by reducing equipment downtime in repair. To do this, the current state of the equipment is tracked by the monitoring system and compared with the reference one, and the decision on the type and timing of specific maintenance is made with the participation of the ES. By comparing the current state of the equipment with a virtual sample, it is possible to predict future malfunctions and act proactively, eliminating problems before they lead to breakage

Using a specific example of MPAM for packing paste into packs, an analysis of the reliability of its components based on annual observation was carried out, the failures and malfunctions of these components were ranked, the most likely malfunctions and processes characterizing the state of the MPAM were determined, and the necessary sensors for monitoring (temperatures in the main working areas of the machine, laminate movement force, resistance force to move the batcher piston, viscosity and paste temperature, fluctuations in the consumption of electricity and compressed air, the level of vibration and noise during operation).

An example of the formation of production rules set for diagnosing a multi-position automatic machine for paste packing and designing the functional structure of software for diagnosing typical malfunctions has been demonstrated.

References

[1] Becker T., Wagner D.: Identification of Key Machines in Complex Production Networks. Procedia CIRP 41, 2016, 69–74 [http://doi.org/10.1016/j.procir.2015.12.006].

[2] Chaoyang G., Fenli G.: Embedded fault diagnosis expert system on weapon equipment. International Journal of Advanced Network, Monitoring and Controls 1(2), 2016, 25–33 [http://doi.org/10.2991/mcei-16.2016.234].

[3] Dekker R. et al.: A review of multi-component maintenance models with economic dependence. Mathematical Methods of Operations Research 45, 1997, 411–435 [http://doi:10.1007/bf01194788].

[4] Erik L. J.: Expert system for diagnosing computer numerically controlled machines: a case-study. Computers in Industry 32(3), 1997, 233–248 [http://doi.org/10.1016/S0166-3615(96)00077-2].

[5] He Q., Li X. Q.: Management of knowledge base of expert system for fault diagnosis of rotating machinery. Applied Mechanics and Materials 44–47, 2010, 2935–2939 [http://doi.org/10.4028/www.scientific.net/AMM.44-47.2935].

[6] IEC 60300-3-1:2003, Dependability management – Part 3-1: Application guide – Analysis techniques for dependability – Guide on methodology.

[7] ISO 17359:2003(E), Condition monitoring and diagnostics of machines – General guidelines.

[8] Lee J., Bagheri B., Kao H.-A.: A Cyber-Physical Systems architecture for Industry 4.0-based manufacturing systems. Manufacturing Letters 3, 2015, 18–23 [http://doi.org/10.1016/j.mfglet.2014.12.001].

[9] Majstorovic V. D.: Expert systems for diagnosis and maintenance: The state-of-the-art. Computers in Industry 15(1–2), 1990, 43–68 [http://doi.org/10.1016/0166-3615(90)90084-3].

[10] Mobley R. K.: An Introduction to Predictive Maintenance. Elsevier Science, 2002.

[11] Mourtzis D., Vlachou E., Milas N.: Industrial Big Data as a Result of IoT Adoption in Manufacturing. Procedia CIRP 55, 2016, 290–295 [http://doi.org/10.1016/j.procir.2016.07.038].

[12] Olatunbosun A., Arulogunol O.: An expert system based equipment diagnostics. Journal of Applied Science, Engineering and Technology 5, 2005, 63–70 [http://doi.org/10.4314/jaset.v5i1.38299].

[13] Palchevskyi B., Krestyanpol L.: The Use of the "Digital Twin" Concept for Proactive Diagnosis of Technological Packaging Systems. Babichev S., Peleshko D., Vynokurova O. (eds): Data Stream Mining & Processing. Communications in Computer and Information Science 1158, Springer, Cham. 2020 [http://doi.org/10.1007/978-3-030-61656-4_29].

[14] Palchevskyi B., Krestyanpol L.: Strategy of Construction of Intellectual Production Systems. IEEE Third International Conference on Data Stream Mining & Processing (DSMP), 2020, 362–365 [http://doi.org/10.1109/DSMP47368.2020.9204190].

[15] Palchevskyi B.: Improving the efficiency of intelectual packaging systems. Technological complexes 15, 2018, 4–14.

[16] Sang G. M., Xu L., de Vrieze P.: Simplifying Big Data analytics systems with a reference architecture. Camarinha-Matos L., Afsarmanesh H., Fornasiero R. (eds): Collaboration in a Data-Rich World. PRO-VE 2017. IFIP Advances in Information and Communication Technology 506. Springer, Cham. [http://doi.org/10.1007/978-3-319-65151-4_23].

[17] Tobon-Mejiaab D. A., Medjahera K., Zerhounia N.: CNC machine tool's wear diagnostic and prognostic by using dynamic Bayesian networks. Mechanical Systems and Signal Processing 28, 2012, 167–182 [http://doi.org/10.1016/j.ymssp.2011.10.018].

[18] Van Horenbeek A., Pintelon L., Muchiri P.: Maintenance optimization models and criteria. International Journal of System Assurance Engineering and Management 1, 2010, 189–200 [http://doi:10.1007/s13198-011-0045-x].

[19] Wang H.: A survey of maintenance policies of deteriorating systems. European Journal of Operational Research.Volume 139(3), 2002, 469–489 [http://doi.org/10.1016/S0377-2217(01)00197-7].

[20] Wu W., Hu J., Zhang J.: Prognostics of Machine Health Condition Using an Improved ARIMA-Based Prediction Method. Second IEEE Conference on Industrial Electronics and Applications ICIEA, 2007, 1062–1067 [http://doi.org/10.1109/iciea.2007.4318571].

[21] Zhang Z., Li Z., Zhao C.: Research on condition monitoring and fault diagnosis of intelligent copper ball production lines based on big data. IET Collaborative Intelligent Manufacturing 4(1), 2022, 45–57 [http://doi.org/10.1049/cim2.12043].

Prof. Bogdan Palchevski
e-mail: bogdan_pal@ukr.net

Doctor of Technical Sciences, professor of the Department of Automation and Computer-integrated Technologies of the Lutsk National Technical University. Academician of the Public Organization National Academy of Sciences of Higher Education of Ukraine. Member of East European Scientific Society. Author of more than 310 scientific papers, 33 patents for 33 patents for inventions et 27 patents for utility models.
Research interests: Automation of food production and packaging processes; Control and diagnostic systems of automatic technological complexes (mechatronic technological systems).

http://orcid.org/0000-0002-4000-4992

Ph.D. Lyubov Krestyanpol
e-mail: lkrestyanpol@gmail.com

Expert of National Agency for Higher Education Quality Assurance (Ukraine).
Member of East European Scientific Society.
Associate Professor of Lesya Ukrainka Eastern European National University.
Author of more than 60 scientific papers, 4 patents for utility models.
Research interests: information and communication technology.

http://orcid.org/0000-0003-3617-7900