Section 2. Intelligent systems and data analysis

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METHOD OF ASSESSING AND FORECASTING THE TECHNICAL STATE OF COMPLEX SYSTEMS OF CRITICAL APPLICATION BASED ON PRECEDENTS

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Abstract. *A method of assessing and forecasting the technical condition of complex critical application systems based on precedents has been developed. When presenting a precedent in the form of a set of parameters with specific values and decisions, the following are taken into account: parameters describing the precedent; risk assessment, probability of failure and assessment of damage from failure of complex systems; recommendations of the decision-maker; assessments of working capacity (partial or full); refined estimates of parameters of the technical condition of complex systems; the predicted values of the parameters of the technical state of complex systems are specified. An information intelligent system for assessing and forecasting the technical condition of complex systems of critical application has been developed using the method of reasoning based on precedents (CBR) and a decision-making strategy has been developed for finding equipment failures based on established assessments of their technical condition. To check the performance, the simulation of the full cycle of functioning of the information intelligent evaluation system, forecasting the probability (risk) of failures of complex systems was carried out using the example of a ship's power plant. The obtained values of probability (risk) estimates of subsystems, components, elements and their mutual relations, which do not contradict expert assessments, testify to the effectiveness of diagnostics, evaluation and forecasting of the technical state of complex systems, taking into account full and partial failures of performance. Taking into account partial (full) equipment failures of complex systems of critical application will allow making decisions aimed at pre-failure maintenance of systems, ensuring operational efficiency, and, therefore, increasing the efficiency of their operation. The sequence of decision-making using the proposed information intelligent system with a CBR cycle, which takes into account the operations of data processing and structuring according to precedents, within the framework of the functioning of the developed software, ensures the operation of the information intelligent system with incomplete information. The results of calculating the efficiency of the operation of complex systems of critical application, taking into account the partial failures of the equipment and carrying out its pre-failure* *maintenance, took into account that the efficiency is determined by the probability of maintaining the system's operability.*

Keywords: *model, method, simulation, algorithm, software, intelligent, method of reasoning based on precedents, diagnosis, evaluation, prediction, decision maker, complex technical system, ship power plant.*

1. Introduction.

One of the main causes of man-made accidents associated with complex technical systems (CTS) used in transport, aviation, energy, etc., remains failures during the operation of system equipment. Thus, from the analysis of the results of the operation of ships, it follows that, despite the measures to ensure the safety of navigation, the number of accidents at sea remains high. The main one of the many causes of accidents is CTS failure. In this regard, such CTS belong to complex systems of critical application (KA).

Complex technical short-circuit systems are hierarchical structures with a non-trivial internal structure, multi-functional numerous subsystems, components, elements and complex connections between them, which are in various states of failure. A characteristic feature of the operation of the short-circuit system is uncertainty during operation, incompleteness of information in the data characterizing the technical condition (TC) of the systems. In connection with the increase in requirements for the safety and reliability of expensive shipboard CTS short-circuits, their effectiveness depends significantly on the need to increase the time and resources of operation. Increasing the effective operation of the CTS can be achieved by applying the results of the development of models and methods of diagnosis, assessment and forecasting of the TC of complex systems and their use in intelligent information systems (IIS), which allow evaluating and forecasting the TC based on the results of diagnostics.

Well-known methods of evaluating and forecasting TC of complex systems, which are implemented in IIS: reasoning based on precedents; analogies; systemic; heuristics for optimization tasks (genetic algorithm, artificial immune networks, annealing method, methods of swarm intelligence, including ant algorithms); structural mapping taking into account precedents for OWL ontologies. A number of the listed methods have disadvantages: high growth of algorithmic and computational complexity during application; the need to implement non-trivial stages of pre-processing of various data; lack of effective opportunities for visual interpretation of results. A general disadvantage is the large dimension of the number of possible problems for further use during decision-making.

Increasing the efficiency of the operation of short-circuit short-circuit systems by applying the results of model development and methods of diagnosis, assessment and forecasting of complex system systems, taking into account partial and complete failures of their equipment, is an urgent scientific task.

2. Comparative analysis of models and methods of intellectualization of assessment and forecasting of the technical condition of complex critical application systems.

The development of conceptual models and methods of evaluation of TCs of complex short-circuit systems requires taking into account the possibility of continuing the operation of CTS in conditions of partial failure of operation with a plurality of scenarios of their development [1]. This approach helps to increase the efficiency of operation of the CTS by increasing the period of productive work before scheduled maintenance and restoration measures.

The measure of man-made accidents is the risk of equipment failure with consequences determined by the level and period of operation of the CTS [2]. Risk analysis is associated with the process of risk assessment of failures - it is the identification of hazards with an assessment based on the criteria of acceptable risk of failure with qualitative and quantitative results and with the transfer of hazards to the level of measurable categories [3].

When assessing the risk of CTS failures, the following should be taken into account: hierarchy, topology and variety of equipment, which differs in terms of physical principles, parameters and modes of operation; functional state; operating conditions under uncertainties; results of diagnosis of TC; difficulties in obtaining statistical and expert data on failures [3, 4, 5, 6, 7]. Only the OREDA database and the service method for safety assessment of CTS [8] are available sources of statistics for risk assessments of failures, for example, of ship's CTS.

Known methods of assessing the risk of CTS failures differ in the methods of obtaining the probability and losses from failures [9].

Assessments of the risk of CTS failures within the framework of the technocratic concept are performed using methods that are divided into deterministic, probabilistic, expert assessments under conditions of uncertainty, combined, performed based on the results of diagnosing complex system TCs.

Advantages of the probabilistic method: accident scenarios and consequences of failures are analyzed; interdependencies between CTS equipment regarding failures are taken into account in an explicit form; the possibility of quantifying the impact of uncertainty on risk assessments; ranking of security flaws and issues. However, it follows from the literature that models based on probabilistic approaches to estimating the risk of shipboard CTS failures are used in a limited way, allowing to obtain approximate estimates of the risk of failures without a sufficient amount of objective information. The most common methods of assessing failure risk indicators are expert methods. However, the disadvantages of such methods are associated with the high complexity of selecting experts with the necessary qualifications and the subjectivity of their assessments.

The significant advantages of the Bayesian trust network (BTN) method make it a promising application for risk assessments of CTS failures. Cognitive simulation modeling technology is also used in models for assessing the risk of equipment failure from the point of view of its significance and criticality for the operation of the CTS [10, 11].

The method of fuzzy probabilistic modeling is used to construct the relationship between the actual resource and the probability of CTS failure [12, 13]. However, the availability of fuzzy logic apparatus standards does not solve the problem of numerical evaluations of the risk of CTS failures. This is due to the fact that the standards formulate criteria without models, which are necessary for the comparative analysis of options for assessing the risk of CTS failures. From the conducted analysis of models and methods, it follows that, despite a number of advantages, they cannot be used in their original form as conceptual models, methods for assessing the risk of CTS failures due to a narrow industry focus. Most of the models and methods are based on the assumption of operation of the CTS equipment in standard modes, without taking into account their partial failures. However, the application of the results of the development of information technologies is possible to solve many of the listed problems for assessing the risk of CTS failures [14, 15, 16]. The level of safety, for example, of ship's CTS, is largely determined by the quality of TC forecasting based on the results of risk assessments of their equipment failures [17, 18]. Forecasting, as well as diagnosis of TC, should take into account the specifics of CTS, which are operated under uncertain, extreme impacts, with insensitivity to incomplete data on the equipment and their interconnections, partial or complete failures [7, 12, 17]. TC forecasting can be carried out using machine learning methods based on specified indicators of the TC functioning [19], but this approach can be applied when only binary TC is taken into account. PHM (Prognostic Health Management) [20] is a promising forecasting method for calculating the remaining service life of CTS.

The analysis of models and methods of forecasting showed that changes in the TC of ship CTS are difficult to predict. This is due to the following reasons: lack of qualitative and quantitative expert data on system reliability; dynamics of operating conditions; human factor [21].

Known models and methods of TC forecasting based on deterministic and formalized statistical models are not universal. There are no opportunities to fully account for the specifics of the functioning of system equipment, especially in conditions of uncertainty of the effects on the CTS of various external or internal factors. An important drawback is that similar models and methods are not recommended for shipboard CTS because they do not meet the requirements of the International Convention for the Safety of Life at Sea SOLAS-74, the provisions of the International Safety Management Code. A significant shortcoming of models and methods of forecasting CTS is that they have not been tested by long-term practical use.

Structural models based on mechanisms and methods of artificial intelligence have a significant advantage for adequate forecasting of CTS failure risk assessments [22]. Similar models make it possible to predict the risk of CTS failures using mechanisms for identifying implicit dependencies between input and output data samples, supporting various learning algorithms. This has a significant advantage for CTS when evaluating and forecasting scenarios of loss of working capacity containing hundreds of criteria and indicators. The possible solution of problems is also connected with the development and development of complexes of problem-oriented programs [15, 23, 24]. At the same time, the role of methods based on modern software for evaluating and forecasting complex systems' TC is growing. Ensuring the guaranteed safety of the operation of the CTS due to the timely and prompt prevention of the transition of normal situations to critical, emergency or emergency situations is the basis of the failure risk management strategy [1, 25]. Such a strategy is based on a systematic analysis of the multifactorial risk of failure, its reliable assessment in different modes of operation of CTS and forecasting of their TC during the period of operation [4].

The analysis of publications, regulatory materials on assessments and forecasting of the risk of failure of various types of CTS showed that the existing diversity of models and methods requires the removal of complex and significant uncertainties, the improvement of the accuracy of assessments and forecasts. Many models and methods take into account the operation of CTS equipment in standard modes, without taking into account partial failures of performance, and are based on engineering, expert and other approaches with complex and expensive calculations, which limits wide application and has a narrow focus of models and methods.

Thus, in order to ensure the efficiency of operation of CTS, the tasks of development and development of new models, methods and their algorithms, implemented in the form of complexes of problem-oriented programs for evaluation and forecasting of TC systems, remain relevant.

3. Comparative analysis of information intelligent systems for diagnosis, assessment and forecasting of the technical condition of complex critical application systems

Traditionally, information intelligent systems are understood as interactive computer systems that help a decision-maker to use information, a complex of mathematical and heuristic models and methods to solve poorly structured or difficult to formalize problems [26]. The efficiency of IIS functioning affects the efficiency of CTS operation throughout the entire period of their life cycle. IIS is united by the general method of forming alternatives of management decisions in CTS, determining the consequences of their implementation and justifying the choice of an acceptable management decision [27]. The IIS includes: data sources and model, model database and software subsystem, which consists of database management systems (DBMS), model database (SBM) and user interface. The main tasks that are solved in the IIS are data entry, storage and analysis.

Main functionality of IIS:

• gathering the necessary information from various data sources;

• transformation of collected information into a single data format;

• generating requests to the data warehouse, processing them, searching for information, forming and providing information in a format convenient for analysis and decision-making.

The IIS should have a web client-side interface or be completely web-oriented [28]. IIC data storage can be built on different types of DBMS, but given the web orientation and the increasing share of cloud technologies on the market, it is better to rely on web-oriented DBMS MySQL and PostgreSQL, as well as on specialized cloud DBMS - MS Azure. Data sources come from the information system of the operational level from a special database and contain engineering and data from external sources. The data model is built on the basis of: data sources and repositories; operational staff and data showcase; metadata. The database of models provides analysis in IIS. Almost all DBMSs have OLAP extensions in one form or another, therefore operationally, the analytical part of IIS is considered ready already by choosing the type of DBMS for the data warehouse. When building a data repository, the task of building a mechanism for working with metadata to describe the data structure in the database is relevant. The design and construction of the metadata tree is carried out by IIS developers. The classification at the conceptual level distinguishes managed IISs: by messages (Communication-Driven DSS); by data (Data-Driven DSS); documents (Document-Driven DSS); knowledge (Knowledge-Driven DSS); models (Model-Driven DSS). The classification of architecture can be as follows: functional; independent data stores; two-level and three-level data warehouses. Depending on the type of data these systems work with, IIS can be conditionally divided into operational and strategic. OLAP and Data Mining are two components of the decision support process. Data operations are carried out by OLAP - a machine that implements the concept of operational analytical processing. According to the method of data storage, MOLAP, ROLAP and HOLAP are distinguished. Depending on the location of OLAP machines, OLAP clients and OLAP servers are distinguished. The OLAP client builds a multidimensional cube based on the raw data (to obtain the necessary sections - reports) and calculates on the client PC, while the OLAP server receives the request, calculates and stores the aggregate data on the server, issuing the results. Cubes and other analytical reporting must be configured. IIS classification is also carried out by levels (initial, medium, higher) and by level of distribution (concentrated, distributed) [29].

IIS uses various methods for analysis and development of proposals: information search; intelligent data analysis; knowledge search in the database; reasoning based on precedents; simulation modeling; evolutionary computing and genetic algorithms; neural networks; situational analysis; cognitive modeling, etc. The use of artificial intelligence in IIC will allow to expand the functionality of the system, increase the operational efficiency and reliability of the CTS.

One of the most important functions of the IIS software is the evaluation of the possible results of the decisions made and the prediction of the TC of the CTS [30]. The choice of the applied specific IIS forecasting method remains with the system developer. Most often, factographic methods are used in software as the least dependent on subjective factors. In conditions of weakly formalized initial data, expert methods are used, but with limitations associated with the availability of a sufficient number of experts.

As it follows from [4, 7], during the functioning of the CTS, adverse impact and factors (AI and AF) can disable individual subsystems, components, and also affect the performance of the systems. Incidents and disasters are usually difficult to predict or unpredictable (for example, personnel errors, natural disasters, etc.). Their influence can have consequences of varying degrees of severity - up to the complete destruction of the CTS [31]. The development of IIC for managing the risk of equipment failures in order to ensure the survivability of shipboard CTS in case of AI and AF is a promising direction in ensuring the safety of CTS [25]. Such IISs can be implemented both in the form of individual stand-alone solutions and in the form of modules that complement the necessary functionality of ready-made general purpose management and decision-making systems. They make it possible to quickly make decisions at the stage of eliminating the consequences of AI and AF, to ensure the reliability of the CTS, thanks to the ability to identify, analyze and assess the existing risks of failure of the CTS equipment [25, 31].

Therefore, most IISs are developed to solve a specific task or a general class of tasks, and also targeting different types of users. The development of IIS to manage the risk of failures in order to ensure the survivability of the CTS in the conditions of incompleteness and uncertainty of the information received in the presence of unpredictable AI and AF is one of the promising directions for the effective and reliable operation of subsystems, components, elements and the CTS as a whole.

The main concept of IIS is to solve classic problems arising in the field of unstructured and poorly formalized CTS [32]. These problems include the impossibility of obtaining complete and objective information for making rational decisions, as well as the need to use subjective and heuristic information. Additional challenges are the presence of uncertainties in the initial data and even ambiguity in the process of finding the optimal solution. In addition, the solution in such cases must interact with the user in the form of dialogue or other forms of communication between a human and a machine system.

Given these factors, there is a need to abandon traditional algorithmic methods and management and decision-making models. Instead, it is necessary to move to the use of technologies of intelligent systems.

IISs must implement the scheme: assessment - forecast - decision - action. IIS provides a decision maker with an analysis of the problem to be solved. The main functions of IIS are assessment, forecasting of events, self-learning and adaptation, work from the knowledge base (including formation, structuring, storage, as well as content of the database), formation of decisions and their implementation.

The following methods implemented in IIS are known [33, 34]:

- analogy and system;
- heuristics for optimization tasks (genetic algorithm, artificial immune networks, annealing method, methods of swarm intelligence, including ant algorithms);
- reasoning based on precedents (nearest neighbor, extraction of precedents based on decision trees, precedents based on knowledge, taking into account the application of precedent);
- structural mapping based on precedents based on OWL ontologies.

IISs are often created based on a combination of artificial intelligence systems using the knowledge and technologies of expert systems, machine learning, and agents [33, 35]. To automate the risk assessment process and predict possible failures, machine learning is widely used (analysis of large volumes of data, detection of patterns and trends, modeling and simulation of systems). However, the use of a large amount of data is associated with limitations in failure risk assessments, possible errors that lead to incorrect forecasts.

The well-known method of structural mapping has the following advantages: the possibility of formalizing the nature of multi-linked hierarchical interactions between CTS equipment operating in stochastic conditions; flexibility of implementation of the production approach to the formation of the knowledge base in IIS; convenience of software implementation taking into account the object-oriented approach. Most of the models that make it possible to obtain new knowledge on the basis of existing ones can be reduced to production models. The disadvantage of such models is a shallow representation of the problem area, which affects the flexibility of forming user dialog requests with the expert system [33].

BTN can be used for IIS in multi-equipment CTS to model the relationships between various factors and their uncertainties, providing a structured framework for assessing the risk of failure under uncertainty and helping the decision maker to prioritize the accepted. In the IIS, methods of reasoning based on precedents can be used to evaluate and forecast the TC of the CTS in order to generalize and apply the accumulated experience [36]. When operating CTS associated with uncertainty, the use of a precedent approach simplifies the decision-making process. Advantages of the method: the ability to learn based on experience; versatility; ability to work with incomplete or unstructured data; flexibility in adapting to new situations.

Stages of Case-based Reasoning (CBR) - method cycle (Fig. 1):

1. Capturing precedents from the library of precedents (LP).
2. Indexing (for quick search of similar cases).
3. Finding the most suitable precedents for a new task.
4. Review and adaptation (modification for the current task).
5. Assessment of suitability, retention and implementation.

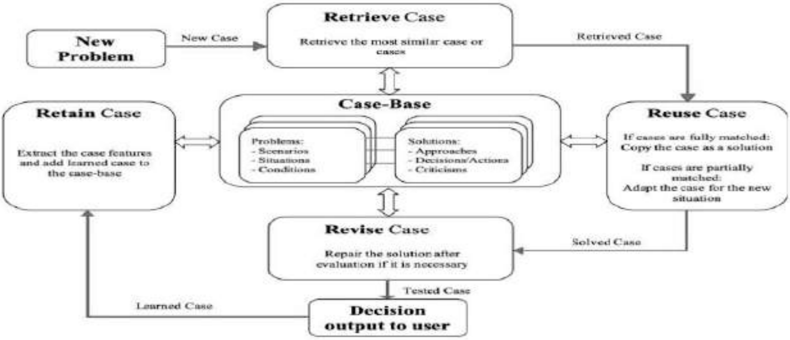

Figure 1. *Case-based Reasoning cycle [36]*

Classic IIC architecture (Fig. 2):

• provides justification of alternatives based on models and methods using expert assessments;

• includes decision-making methods under conditions of uncertainty with modeling of problematic decision-making situations;

• contains knowledge base - a set of rules for choosing appropriate models and decision-making methods for justifying alternatives depending on the specific implementation of the elements of the task;

• contains a database for storing information;

• carries out multidimensional analysis of tasks and generation of analytical reports using the OLAP server.

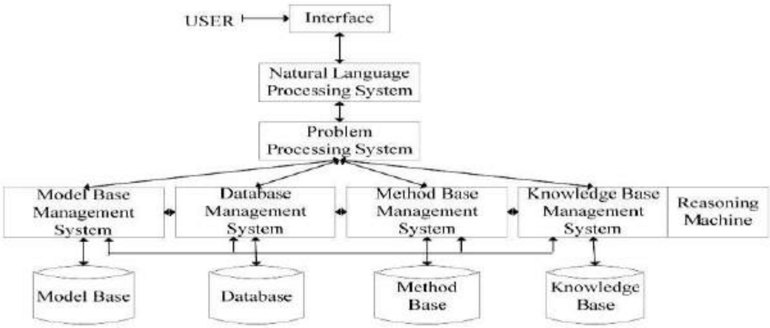

***Figure** 2. Architecture of IIS*

Currently, the implementation of artificial intelligence technologies continues to improve the efficiency of operation of the CTS. Thus, in accordance with the requirements of the Maritime Shipping Register, all ships must be equipped with systems based on artificial intelligence technology [17]. For this, algorithmic and software tools are needed, which provide assessment and forecasting of TC systems, adequate to the set goal [14, 37]. An example of the use of IIS is the PHM method, which covers the entire process from data collection to the use of decision-making results. Information about the status of the CTS received in real time is used to evaluate the IIS TC. The following can be used for vehicle modeling: fault tree analysis; event tree analysis; Bayesian trust networks. BTN is preferred as a tool for assessing the risk of CTS failures.

Crystal Info (Seagate Info) - IIS, based on a flexible technology of data access and data processing, is used among the software complexes that solve decision-making tasks. Open OLAP technology allows integration of multidimensional OLAP data from disparate sources (Crystal Info, Crystal Holos, Hyperion Essbase, OLE DB for OLAP providers (Microsoft SQL Server OLAP Services and Applix TM 1, IBM DB 2 OLAP Services and Informix MetaCube). All OLAP sources can be presented within a single interface. For many years, researchers have been working on the creation of IIS for various purposes, but there are problems, from the point of view of efficiency, of knowledge formalization in CTS, which need to be solved:

- increasing the objectivity and reliability of the decisions made in the presence of uncertainties in the evaluation tasks, forecasting the risk of failures;
- accounting for the factors of incompleteness, ambiguity and inconsistency of source information (data and knowledge) and rules;
- provision and processing of various types of knowledge, data and models, development of relevant databases, databases and models;
- collection, storage and accumulation of declarative, expert information about the problem industry in the database and knowledge base, library of precedents;
- increasing the accuracy of evaluations of CTS vehicles on the basis of new models, methods, algorithms, software invariant to the subject area for evaluations, forecasting the risk of failures in order to identify signs of the pre-failure state of the equipment at an early stage of development;
- the application of adequate and technically feasible formal models for solving the tasks, taking into account the structural, functional, informational and subject features of the CTS.

4. Development of a method of reasoning based on precedents of the technical state of complex critical application systems

The development of a method of reasoning based on precedents of the technical state of complex systems of critical application includes the following stages:

1. Presentation of a precedent set of parameters with specific values and solutions.
2. Entering the data of vehicle diagnostics of a complex short-circuit system into the IIS of evaluation and forecasting of a vehicle of a complex system.
3. Obtaining evaluation data and forecasting of the vehicle of a complex short-circuit system.
4. Transmission of assessment data and TC forecasting of a complex system to decision maker system.

IIS can be implemented both in the form of individual stand-alone solutions and in the form of modules that supplement the necessary functionality of ready-made management and decision-making systems of general purpose. They will make it possible to quickly make decisions at the stage of eliminating the consequences of adverse effects and impressive factors, to ensure the efficiency of the operation of ship's CTS thanks to the possibility of evaluating and forecasting their TC [34].

The construction of the IIS is based on the formulation of the decision-making task in general:

$$N = f(F, G, A, FR, SG, P, C, PC, NS) \tag{1}$$

where *F*- is the number of failures of FE (functional elements) and FC (functional components) of the CTS;

G -– sets of set goals;

A - is a set of possible alternatives;

FR - equal sets of FE and FC CTS failures;

SG, P, C - a set of characteristics, advantages, criteria for ensuring the reliability of FE and FC CTS;

RS - set of principles of coordination of evaluation of alternatives taking into account individual criteria;

NS - necessary solution to the problem

The development and research of IIS using CBR, with the aim of increasing the effectiveness of the implementation of learning mechanisms and adaptation to the specifics of the problem environment for the relevant specific applications, as well as increasing the effectiveness of decision-making in ODA based on the results of evaluation, forecasting of TC of complex systems is relevant.

Such development and research was carried out taking into account: partial and complete failures of FE and FC performance; a precedent model of knowledge based on a vehicle dynamics model from a serviceable state to complete failure. The TC dynamics model takes into account cause-and-effect relationships and the hierarchical structure of the TC, which consists of: elements (E); components (C); subsystems (S).

The description of the problematic situation during the operation of the CTS consists in the consequences of partial or complete loss of FE and FC of a complex system.

When using the method of reasoning based on precedents for the representation of precedents, a fairly simple parametric representation, i.e. presentation of a precedent in the form of a set of parameters with specific values and decisions (estimates, TC forecasts and recommendations to the person making the decision):

$$CASE = \left(R, P, D, W^{f}_{\vartheta_{S(C,E)_{n(m)}}}, W^{f}_{\omega_{I_{S(C)_{a(z)}}}}, RE, FS, RF, FF, DR\right), \quad (2)$$

where *R,P,D* are parameters (risk, probability, loss) describing the precedent;

$R\left\{R_{S(C,E)_{n(m)}}, R_{I_{S(C)_{a(z)}}}\right\}$ - sets of FE and FC CTS failure risk assessments and a decision maker recommendations;

$P\left\{P_{S(C,E)_{n(m)}}, P_{I_{S(C)_{a(z)}}}\right\}$ - sets of FE and FC CTS failure probability estimates and a decision maker recommendations;

$D\left\{D_{S(C,E)_{n(m)}}, D_{I_{S(C)_{a(z)}}}\right\}$ - sets of estimates of losses from failures of FE and FC CTS and recommendations of a decision maker;

$W^{f}_{\upsilon_{S(C,E)_{n(m)}}}$ - assessments of working capacity (partial or full) of FE and recommendations of a decision maker;

$W^{f}_{\omega_{I_{S(C)_{a(z)}}}}$ - evaluations of the operational capacity (partial or full) of the FC and recommendations of the decision maker:

RE – sets of refined specific estimates of parameters of TC FE and FC CTS, decision-making ($re_1,..re_N \in RE$);

FS - saving a set of refined estimates of parameters of TC FE and FC CTS, adopted decisions;

RF - sets of refined certain predicted values of parameters of TC FE and FC of CTS decision-making ($rf_1,..rf_N \in RF$);

FF - preservation of a set of refined forecasted values of TC parameters FE and FC of TC, adopted decisions;

DR - diagnosis and recommendations of a decision maker [38]

$$R_{s(c,e)_{n(m)}} = \{r_{s(c,e)_{n(m)}} \mid s(c,e) = \overline{1, S(C,E)}, n_{s(c,e)} = \overline{1, N_{S(C,E)}}, m_{s(c)} = \overline{1, M_{S(C)}}\}, \quad (3)$$

$$R_{I_{s(c)_{a(z)}}} = \{r_{i_{s(c)_{a(z)}}} \mid i_{s(c)} = \overline{1, I_{S(C)}}, a = \overline{1, A}, z = \overline{1, Z}\},$$

where $r_{s(c,e)_{n(m)}}$ - is the risk of failures of FE CTS;

$r_{i_{s(c)_{a(z)}}}$ - the risk of FC CTS failures;

$n_{s(c,e)}$ - FE number in CTS;

$m_{s(c)}$ - the number of the hierarchical level of FC CTS;

$N_{S(C,E)}$ - number of FE CTS;

$M_{S(C)}$ - the number of hierarchical levels of FC CTS;

S, C, E – FE CTS;

I_S, I_C – FC CTS;

n, m – number, hierarchical level in the CTS;

a – number of intercomponent communication;

z - is the number of intersystem communication.

A - the number of intercomponent connections;

Z - is the number of intersystem connections

$$P_{S(C,E)_{n(m)}} \cdot \lambda(t)_{S(C,E)_{n(m)}} = \frac{\alpha_{S(C,E)_{n(m)}} \cdot \exp(-\alpha_{S(C,E)_{n(m)}} \cdot T_{S(C,E)_{n(m)}})}{\exp(-\alpha_{S(C,E)_{n(m)}} \cdot T_{S(C,E)_{n(m)}})} = \alpha_{S(C,E)_{n(m)}}, \quad (4)$$

$$P_{I_{S(C)_{a(z)}}} \cdot \lambda_{I_{S(C)_{a(z)}}}(t) = \frac{\alpha_{I_{S(C)_{a(z)}}} \cdot \exp(-\alpha_{I_{S(C)_{a(z)}}} \cdot T_{I_{S(C)_{a(z)}}})}{\exp(-\alpha_{I_{S(C)_{a(z)}}} \cdot T_{I_{S(C)_{a(z)}}})} = \alpha_{I_{S(C)_{a(z)}}}$$

where λ - is the intensity of failures;

α – distribution parameter, $\alpha \approx 1/(T_o)\hat{}$, (T*o*) – estimate of average service life before failure

Quantitative assessment of damage from failure $n(m,e)$ - subsystem, component, element to determine the risk of failure:

$$D_{S(C,E)_{n(m)}} = \{d_{s(c,e)_{n(m)}} \mid s(c,e) = \overline{1, S(C,E)}, n = \overline{1, N}, m = \overline{1, M}\}, \qquad (5)$$

where $d_{s(c)_{n(m)}}$ - losses from failure of FE CTS

Quantitative assessment of losses from failure $a(z)$ - FC determination of the risk of failure:

$$D_{I_{S(C)_{a(z)}}} = \{d_{I_{s(c)_{a(z)}}} \mid i_{s(c)} = \overline{1, I_{S(C)}}, a = \overline{1, A, z} = \overline{1, Z}\}, \qquad (6)$$

where $d_{i_{s(c)_{a(z)}}}$ - is the loss from failure FC

Performance of FE at different degrees of its loss:

$$W^{f}_{\upsilon_{S(C,E)_{n(m)}}} = \{W_f^{<n_{s(c)}, m_{s(c)}>} \mid f = \overline{0,1}; n_{s(c,e)} = \overline{1, N_{S(C,E)}}; m_{s(c)} = \overline{1, M_{S(C)}}\} \qquad (7)$$

Functional capacity of FC at different degrees of its loss:

$$W^{f}_{\omega_{I_{S(C)_{a(z)}}}} = \{W_f^{<a,z>} \mid f = \overline{0,1}; a = \overline{1, A}; z = \overline{1, Z};\} \qquad (8)$$

In the process of functioning of FE CTS in emergency scenarios, taking into account Harrington's generalized desirability function, they can be in one of the following TC [38]: 0 - 0.2 - the level of risk and consequences are minimal, which do not affect the operation of CTS (RMi); 0.2 - 0.37 - the level of risk is acceptable and the consequences are insignificant, allowing the operation of the CTS without repair (RA); 0.37 – 0.63 – the level of risk is maximum, the consequences are significant, but allowing the operation of the CTS during repair work (RMa); 0.63 - 1.0 - the level of risk is critical, the consequences are catastrophic, preventing the operation of the CTS (RC). Taking into account [39] for the hierarchical structure of CTS, TC transitions are possible in the form of a TC matrix (Fig. 3). In Fig. 3, ke, kc, ks are the weight (significance) coefficients of an element, component, subsystem in the structures of the CTS.

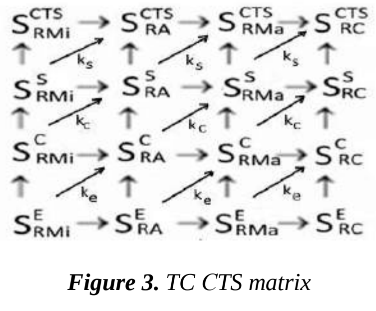

Figure 3. *TC CTS matrix*

The construction of the method is based on: presentation of a precedent set of parameters with specific values and solutions; obtaining assessment data and forecasting of complex system vehicles; formation of recommendations to ensure the efficiency of operation of CTS equipment.

5. Designing an information intelligent system of diagnostics, assessment and forecasting of the technical condition of complex critical application systems

Methods of finding solutions in IIS based on precedents are an approach based on the use of analogies with previously solved problems to find and adapt solutions to new situations. Similar methods include the stages that make up the CBR cycle:

1. Capturing precedents from the library of precedents (LP).
2. Indexing (organization of precedents to find similar cases).
3. Finding the most suitable precedents for a new task.
4. Adaptation (modification of the found precedent to match the current task).
5. Evaluation and implementation (checking the adapted solution for its suitability and, if necessary, implementation).

Advantages of the method of reasoning based on precedents: adaptability; work with incomplete information; versatility; learning Case studies can be presented in ways including text description, diagrams, tables, prototypes and use case scenarios, modeling through UML. Each of these methods can be effective depending on the context and goals of the project.

The method of presenting precedents is implemented as follows. In the proposed CBR cycle (Fig. 4) to support the exchange of knowledge, a set of input parameters of the diagnosed TC and an array of ontologies that represent a structured description of the domain area of the ship CTS are received at the initial block of task formation.

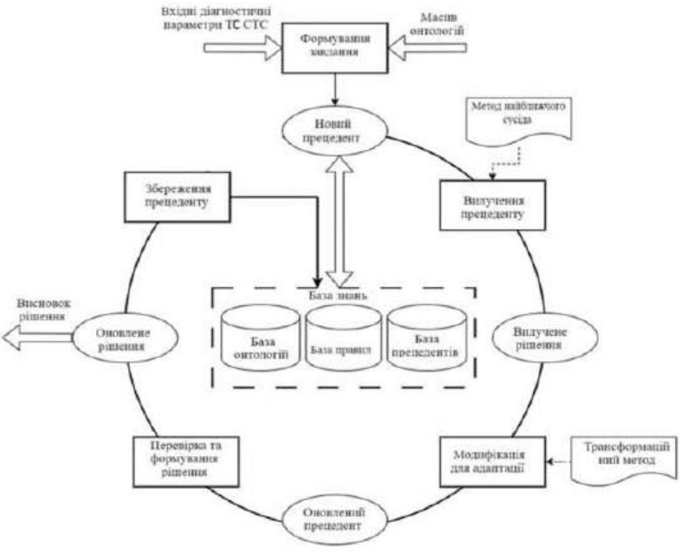

Figure 4. *The structure of the CBR cycle*

As a result, the structure of the object of a new precedent is generated and content is extracted, which is performed using the nearest neighbor method based on the results of the assessment of the degree of similarity (closeness) of the analyzed scenario with the TC and taking into account the data in the knowledge base. Based on the implementation of this procedure, a solution object is formed, which can be changed for its targeted adaptation, taking into account all aspects of the scenarios of partial and complete failures of the FE and FC CTS using the transformation method [40]. The updated precedent is checked for logical inconsistency taking into account the use of predicative products using the Hermit ontological method of constructing a logical conclusion [40].The decision obtained as a result of the performed actions is exported as a separate object containing recommendations for the decision-maker and metadata. After that, the precedent is stored in the basis of precedents, which is a component of the knowledge base (Fig. 4). The decision-making sequence (Fig. 5) using the proposed CBR cycle, taking into account data processing and structuring operations regarding precedents within the framework of the application software system, is carried out as follows.

Figure 5. *Decision-making sequence diagram*

When the software system is started, the main form of the user interface is initialized, in which the possibility of importing input data for task formation is provided. Then the control parameters and configuration options for the operation of all modules involved in the information processing cycle are set, including the data processing (DPMod), precedent extraction (PEMod) and adaptation (AMod) modules. Next, a request is made to transfer the generated data arrays to DPMod, in which data processing procedures are performed step by step (including checking for consistency and splitting into fragments), forming a collection for storing precedents taking into account metadata (such as a short text description of the target, its identifier, date of formation and some statistical indicators). After that, a request is made to obtain a specific PEMod precedent, in which actions from the metric evaluation based on the nearest neighbors method are performed. The resulting result is sent to DPMod as a collection based on an associative array.

After checking and verifying the results, DPMod sends the formed collection to AMod for the purpose of carrying out the adaptation procedure. For this, the method of transformation is used, taking into account the comparison of the precedent with a set of rules, the logical products of compliance are taken into account. As a result, the updated collection of precedents is sent to DPMod to form a list of final decisions and their validation. To output results in the form of text records and graphical representation, the resulting solution in serialized form (in json format) is sent to the main form of the interface. This is necessary for further initialization of the process of sending case data, saving them in the knowledge base, and issuing an informational message to the user about the transaction results. For the formation of precedents, a simple parametric representation is sufficient, i.e. presentation of a precedent in the form of a set of parameters with specific values and a decision (diagnosis and recommendations of the person making the decision).

Different methods of extracting precedents and their modifications are known. The most common methods are: determination of the nearest neighbor (NN - Nearest Neighbor) [41]; extraction of precedents based on decision trees; obtaining precedents based on knowledge [34]; extraction of precedents taking into account their application. The listed methods use a variety of metrics.

From the main metrics, the method of determining the nearest neighbor was used, which allows you to easily calculate the degree of similarity of the current problem situation and precedents with LP. The method of determining the nearest neighbor uses a simple coordinate-by-coordinate comparison of the current situation with a precedent, where each parameter of the description of precedents is perceived as one of the coordinates. The DCT distance between the point corresponding to the current situation and the point corresponding to the precedent is determined. The effectiveness of the nearest neighbor method depends on the choice of metric. If the precedent C and the current problem situation T are given in an n-dimensional property space, then the degree of similarity or closeness S(C,T) of the precedent C and the current situation T can be determined using one of the metrics defining the distance between two points x_i^C and x_i^T, in particular, the Euclidean distance:

$$D_{CT} = \sqrt{\sum_{i=1}^{n}(x_i^C - x_i^T)^2} \tag{9}$$

To determine the similarity degree value (SIM), the maximum distance Dmax in the selected metric is calculated using the limits of the parameter ranges to describe the precedents. After that, the value of the degree of similarity is determined, using the limit of the ranges of parameters to describe the initial and final precedents, i = 1, ..., n. The value of the degree of similarity can be calculated as follows:

$$SIM = 1 - D_{CT} / D_{max} \tag{10}$$

6. Implementation of an information intelligent system of diagnostics, assessment and forecasting of the technical condition of complex critical application systems

The implementation of IIS with CBR (Fig. 6) connects the developed models and the method of diagnosing a vehicle with a database, a knowledge base, an expert system containing calculation, experimental, as well as data obtained by experts during the operation of the vehicle. The development of the software structure began with a schematic presentation of the main interacting modules of the IIS. The structural diagram of modules and relationships (Fig. 6) reflects a visual representation of the interaction of FE and FC in IIS.

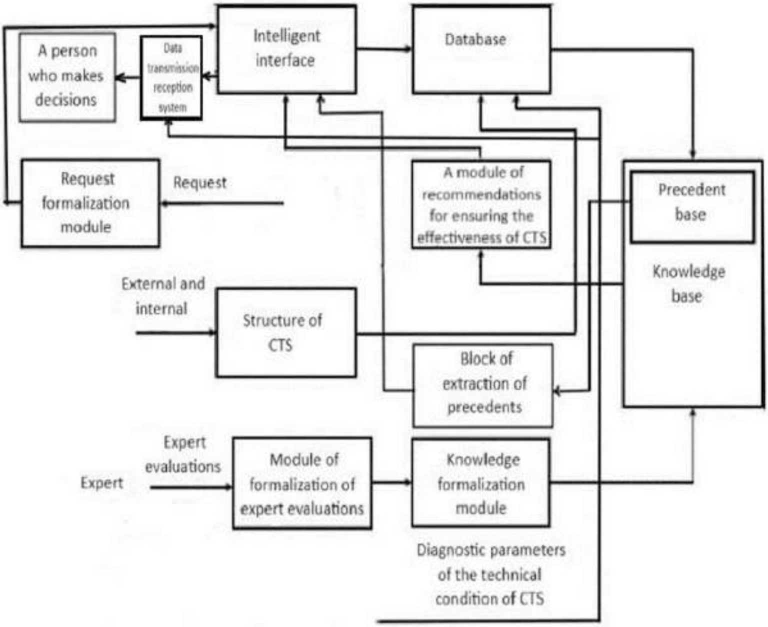

Figure 6. *Structural diagram of the implementation of the method of reasoning based on precedents for evaluating and forecasting the TC of a complex short-circuit system*

During the development of the IIS, a ship's power plant was chosen as an object of evaluation and forecasting of the vehicle. When assessing the reliability of the ship's power plant, it was taken into account that the CTS is characterized by a large number of parameters that are diagnosed, which differ in informativeness and the degree of availability when there is insufficient information for the evaluation of the TC, as well as specific and diverse operating conditions with uncertainty. The cores of IIS are: DB; a knowledge base with methods for calculating reliability indicators (risks and failure probabilities) and a set of decisive rules for choosing appropriate decision-making methods; the model of intellectualization of evaluation of TC FE and FC CTS.IIS includes: interface module knowledge base with a library of precedents and a knowledge base; request formalization module; a module of recommendations for ensuring the effectiveness of the CTS; libraries of ship CTS structural diagrams; module of formalization of expert evaluations; knowledge formalization module. The implementation of the developed strategy in IIS is ensured by purposeful actions in accordance with decision support for finding FE and FC failures based on the established estimates of their TC. The model base is known as production, in relation to the implementation of its software functionality, it is object-oriented. The developed knowledge base is represented by rules obtained on the basis of intellectual data analysis (a multi-level hierarchical structure of the tree of the knowledge base), expert evaluations, the results of the application of models of diagnostics of complex system vehicles, which functions according to the developed sequence of decision-making (Fig. 5) and taking into account the vehicle matrix of the vehicle control system (Fig. 3).

Upon request, the entire list of data and expert evaluations are sent to the knowledge base from the database. As a result, evaluations of TC subsystems, components, elements and their mutual relations are formed at the output of the knowledge base. The vehicle evaluations are sent to the module of recommendations for ensuring the effective operation of the vehicle and then the person who makes decisions for the vehicle management of the complex system. The database contains: DB of CTS structures; database of failure risk criteria; Database of vehicles of complex systems; Database of degradation processes; Database of measures to reduce the risk of CTS failures. The library of precedents consists of LP of incidents and BP of emergency situations. Diagnosis of a problematic situation - complete or partial failure of equipment and their mutual connections of the CTS is carried out by modeling their diagnosis based on data on the risk (probability) of failures, as well as on losses from failures. Taking into account the diagnostic data, the established assessment of the vehicle of a complex system is entered into the LP knowledge base, and recommendations are formed for the decision-making of a decision maker. Based on the results of the evaluations, the TC of a complex system is forecasted. The output may include a list of actions taken, additional comments, and references to other precedents. The hierarchical structure of the key program logic of fragments of data processing modules according to precedents and considerations is shown in Fig. 7. To form the level of abstractions and ensure polymorphism when implementing the behavior of objects implementing different stages of data processing, three interfaces have been implemented. IData – formation of the path to the location of the input data set, initialization of data structures and collections, transformation of data into a single normalized view with a check for missing rows, setting of the structure. IOntology - storage of structures of attributes, classes and relationships, formation of the composition of the structure of the ontology with its verification and validation. IPRecedent - operation with the properties of scenarios of situations, problems and solutions, as well as the formation of the process of creating a precedent, its preservation and serialization, checking for logical consistency.

Each has a different implementation of the logger() method of providing processes for logging the intermediate results of performing computational operations over time. The DataLoader class implements the IData interface, performing contact with loading data into the system and operations of forming precedent collections, checking data integrity, performing the necessary transformations, filtering and aggregation, as well as setting the structure and issuing messages based on the results of the performed actions in the status bar. The OntologyMaker class implements the IOntology interface, operating with a partial collection of ontologies of a dynamic array for aggregating individual elements of the ontology and is designed to form the logical base of the system structure when building each individual precedent, providing visualization of the ontology in a graph-oriented form.

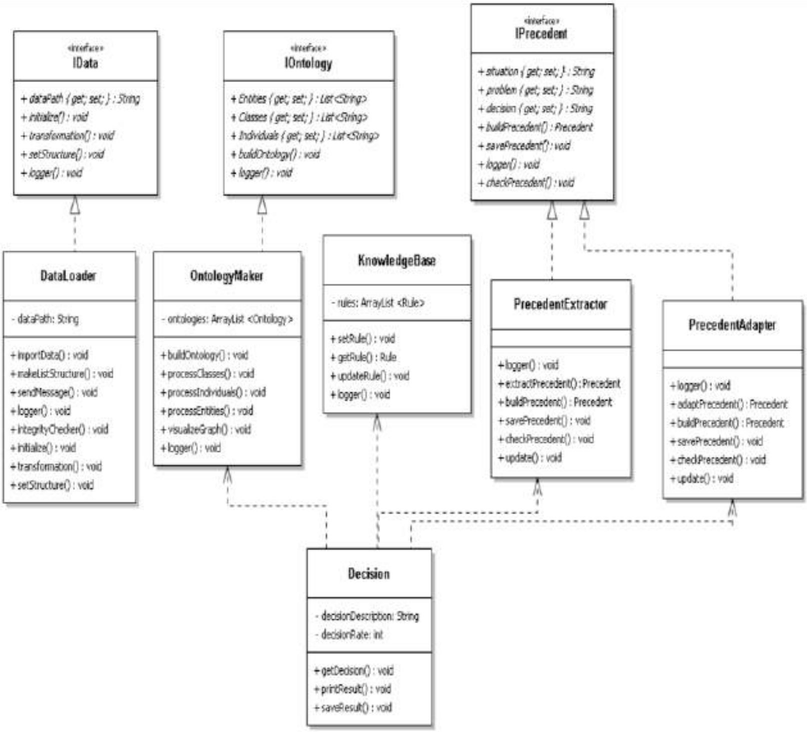

Figure 7. *Hierarchical structure of the key program logic of fragments of data processing modules regarding precedents and considerations*

The PrecedentExtractor and PrecedentAdapter classes implement the IPrecedent interface, overriding the precedent data management methods for use in the extraction and adaptation procedures performed in the extractPrecedent() and adaptPrecedent() methods, respectively, resulting in a Precedent object. The

KnowledgeBase class is separately implemented for the implementation of CRUD operations on rule management. Based on the use of instances of data classes, a Decision object is formed, the state of which is described using the private properties decisionDescription and decisionRate, and the behavior is expressed using public methods of forming the decision object, its output and saving the results. The Visual Studio development environment, the .NET 4.7 framework, the technology for creating WinForms graphic interfaces, as well as functional libraries supporting Hermit ontologies and working with JSON were used for the software implementation of IIS with the CBR cycle [42]. The interface of the main form of the software system with the control tab of the process of creating precedents within the framework of the proposed CBR cycle for evaluation and forecasting of the TC, using the example of the ship's CTS, is shown in Fig. 8.

Figure 8. *The interface of the main form of the software system with the tab for managing the process of creating precedents*

The main menu is provided for navigation between the processes of connecting data sources and the knowledge base (item File), management and processing of data (item Data processing), the selection of computing operations and their implementation (item Operations), configuration of system modules and settings for its operation (item Settings), issuance of reference information on the operation of the system (item Help).

The functionality supports data manipulation from precedents, ontologies, rules and decisions. A separate graphic widget is provided for the hierarchical representation of the structure of ship CTS and their FE and FC in the form of a tree of nodes. Data entry by precedents is carried out through the appropriate text field, options are provided for providing a detailed description of the parameters, building a summary cross-table of all values of the ship's CTS and their equipment, as well as forms for extracting, adapting and validating (checking) compiled precedents.

The formation of a table displaying the obtained results according to precedents with an assessment of their degree of similarity, a description and a short set of typical recommendations has been implemented. For ease of management, a separate component for quick table navigation with CRUD operations and search is provided. The means of visualization of the most priority options for adaptation of precedents for a specific scenario of CTS operation, which is considered after performing all analytical procedures, have been introduced. The possibility of local saving of visualization results in pdf and csv formats, respectively, has been implemented. The results of assessments of the risk of failures of the subsystems of the studied ship's power plant, formed taking into account the compiled precedents, are shown in fig. 9.

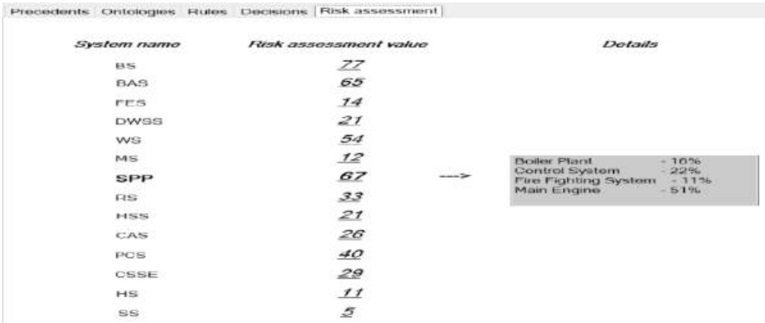

Figure 9. *The interface of the risk assessment form for the analyzed subsystems of the ship's power plant*

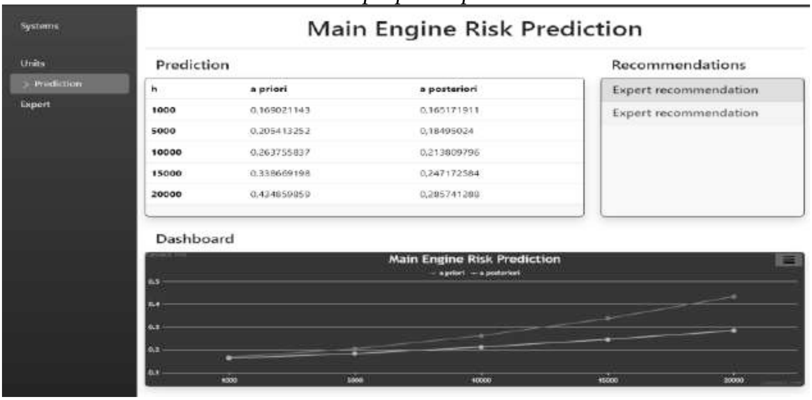

Figure 10. *Main Engine subsystem failure risk prediction block*

The results of forecasting the risk of failures FE and FC of the ship's power plant, for example, for the Main Engine subsystem can be seen in the block of the interface for viewing the risk of failures when navigating to the Predictions web page (Fig. 10). A block for displaying a priori and a posteriori values of the risk of Main Engine failures and a widget for displaying the dependence of the values of predicted a priori and a posteriori risk of Main Engine failures are provided. The user interface of the viewing module of the output of the obtained results according to the generated system solution is shown in Fig. 11. Support for navigating decision scenarios has been implemented, as well as data presentation components for decisions, causes of violations, consequences of scenarios for further system operation, and a list of recommended actions to improve the performance of the CTS. There are options for opening a log file for viewing the intermediate stages of computing operations and calculations, as well as saving the results of the database.

To control the process of building a fault tree model, components for setting the parameters of node construction methods, tree graph visualization algorithms, graphical representations, and report generation have been developed. The functionality of building a decision tree, viewing its structure, and adding to the model in the editor mode are provided.

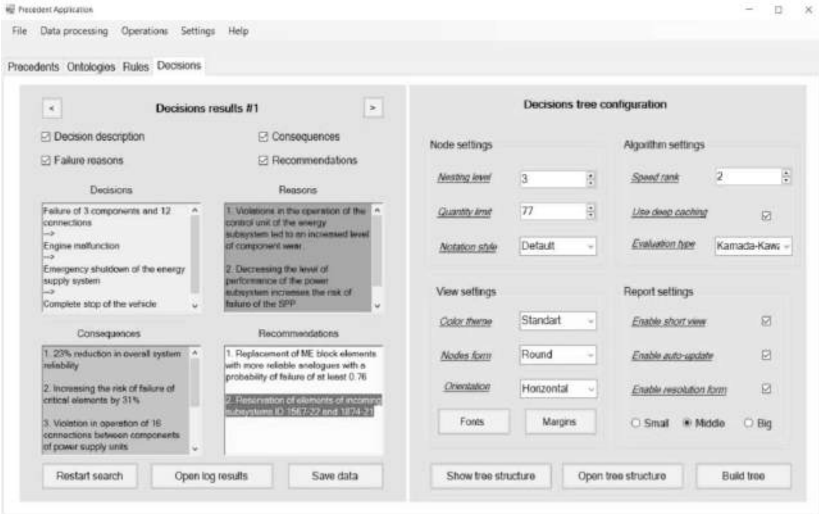

Figure 11. *User interface*

The disadvantage of the method of precedents with a CBR cycle is an increase in the time of searching for the nearest precedents. Therefore, a comparative analysis of the time of searching for the closest precedent was carried out depending on the size of the precedent database, taking into account data caching when initializing the data structure as an associative array collection. The graph showing the time of determining the TC of a complex system from the number of precedents is shown in Fig. 12. The time spent on the closest precedent for 10,000 precedents in the knowledge base was about 370 ms. The first closest precedent out of 5000 precedents was obtained in about 50ms. With the increase in the number of precedents in the library of precedents, the time to determine the TC of a complex system increases, but it does not significantly affect the total time spent on evaluating the TC of the subsystems of the studied ship's power plant. Despite such a shortcoming, research has shown the possibilities of applying the method of reasoning based on CBR precedents and its appropriate use for decision-making in real operating conditions. The developed IIS has high performance.

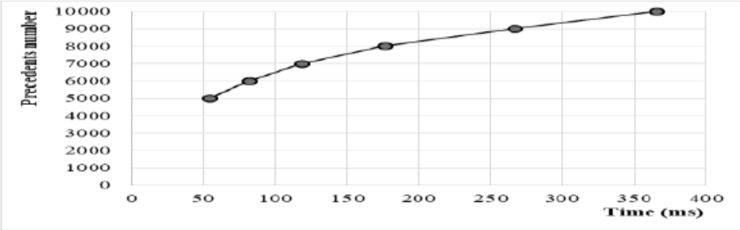

Figure 12. *Time to determine the TS of a complex system depending on the size of the precedent base*

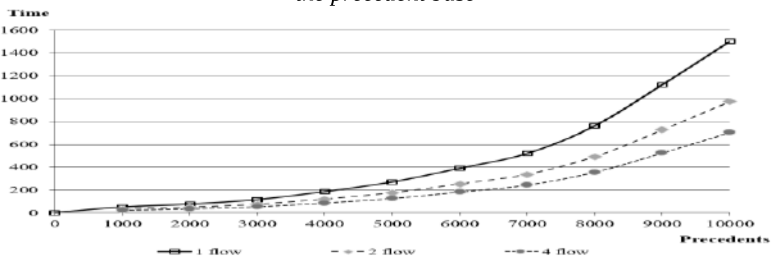

Figure 13. *Execution time of computational processes based on the number of formed precedents*

In order to estimate the time spent on the formation of the knowledge base as part of the implementation of the proposed method with the help of the developed IIS, a comparison of the execution time of computing processes was carried out when starting the system in the following modes: single-threaded; two-flow; four-flow (Fig. 13). It should be noted the general exponential nature of the dependence of the time of execution of computational processes of estimations and forecasting of TC of a ship's power plant on the number of precedents in the knowledge base.

Thanks to the distributed computing mode, it becomes possible to reduce time costs by up to 28% when using two data streams isolated from each other, and up to 42% in the case of dividing the computing load into four separate data streams. The presented interface of the main form of the software system with the tab for managing the process of creating precedents implements the functionality of determining the serviceability of the IIS with the CBR cycle and the implementation of the functions embedded in it.

Taking into account partial and complete failures of the ship's CTS short-circuit equipment in the IIS will allow the decision-maker to make decisions aimed at pre-failure maintenance of complex systems, and thereby extend the service life of the systems, which means increasing the efficiency of their operation.

7. Conclusion

Thus, the development and research of IIS with CBR was carried out, intended for effective evaluation and forecasting of TC of complex short-circuit systems by ensuring the speed of operation of IIS.

The effective functioning of IIS with CBR is based on the use of the method of reasoning based on precedents. IIS with CBR consists of: interface module; database with library of precedents and database; request formalization module; a module of recommendations for ensuring the effectiveness of the CTS; CTS structural scheme libraries; modules of formalization of expert assessments and formalization of knowledge. Experimental studies of IIS for evaluation and forecasting of TC of complex systems showed that the time spent for the closest precedent to be found in the database of 10,000 precedents was about 370 ms.

The sequence of decision-making, using the proposed IIS system with a CBR cycle, which takes into account the operations of data processing and structuring according to precedents within the framework of the functioning of the developed application software system, has high speed, provides work with incomplete information, versatility and learning with decision-making support. Thanks to the distributed computing mode, it becomes possible to reduce time costs by up to 28% when using two data streams isolated from each other, and up to 42% in the case of dividing the computing load into four separate data streams. In the operation of the proposed IIS, partial and complete failure of subsystems, components, elements and their mutual connections in the CTS of the circuit are taken into account. Increasing the efficiency of operation of the CTS is ensured by the speed of evaluation and forecasting of the TC, as well as by the actions of the decision-maker aimed at making decisions regarding the pre-failure maintenance of the equipment of complex systems in the early stages of the development of failures. The design of the IIS was carried out to ensure the efficiency of the CTS operation using the method of reasoning based on precedents. The design of IIS with CBR connects the developed models and methods of diagnosis, assessment and forecasting of TC of complex short-circuit systems with an expert system containing calculation, experimental, as well as data obtained by experts during the operation of CTS. The cores of IIS are: database; a knowledge base with a library of precedents, with methods for calculating probability indicators, failure risks and a set of decisive rules for decision-making; request formalization module; a module of recommendations for ensuring the effectiveness of the CTS; CTS structural scheme libraries; module of formalization of expert evaluations; knowledge formalization module. The implementation of the developed strategy in the IIS is ensured by purposeful actions in accordance with decision-making to find equipment failures based on the established evaluations of their TCs. In order to check the performance, a simulation of the full cycle of the IIS evaluation, risk prediction (probability) of CTS failures was carried out using the example of a ship's power plant using the developed knowledge base. The received assessments of the risks (probabilities) of failures of subsystems, components, and elements of their mutual relations, which do not contradict expert assessments, testify to the effectiveness of diagnostics, assessment and forecasting of complex systems, taking into account their partial and complete failures.

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МЕТОД ОЦІНКИ ТА ПРОГНОЗУВАННЯ ТЕХНІЧНОГО СТАНУ СКЛАДНИХ СИСТЕМ КРИТИЧНОГО ЗАСТОСУВАННЯ НА ОСНОВІ ПРЕЦЕДЕНТІВ

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Анотація. *Розроблено метод оцінки та прогнозування технічного стану складних систем критичного застосування на основе на основі прецедентів. При поданні прецеденту у вигляді набору параметрів з конкретними значеннями та рішеннями враховано: параметри, що описують прецедент; оцінки ризику, ймовірності відмов та оцінки збитків від відмов складних систем; рекомендації особи, яка приймає рішення; оцінки працездатності (часткової або повної); уточнені оцінки параметрів технічного стану складних систем; уточнені прогнозовані значення параметрів технічного стану складних систем. Розроблено інформаційну інтелектуальну систему оцінки та прогнозування технічного стану складних систем критичного застосування з використанням методу міркувань на основі прецедентів (CBR) та розроблено стратегію прийняття рішень щодо пошуку відмов обладнання на основі встановлених оцінок їх технічного стану. Для перевірки працездатності було здійснено моделювання повного циклу функціонування інформаційної інтелектуальної системи оцінювання, прогнозування ймовірності (ризику) відмов складних систем на прикладі суднової енергетичної установки. Отримані значення оцінок ймовірностей (ризиків) підсистем, компонентів, елементів та їх взаємних зв'язків, що не суперечать експертним оцінкам, свідчать про ефективність діагностики, оцінки та прогнозування технічного стану складних систем, враховуючи повні та часткові відмови працездатності. Врахування часткових (повних) відмов обладнання складних систем критичного застосування дозволить приймати рішення, спрямовані на передвідмовне обслуговування систем, забезпечити працездатність, підвищувати ефективність їх експлуатації. Послідовність прийняття рішень з використанням запропонованої інформаційної інтелектуальної системи з CBR циклом, що враховує операції обробки та структуризації даних за прецедентами, в рамках функціонування розробленого програмного забезпечення, забезпечує роботу інформаційної інтелектуальної системи з неповною інформацією.*

Ключові слова*: метод, моделювання, алгоритм, програмне забезпечення, інтелектуальна, метод міркувань на основі прецедентів, діагностика, оцінка, прогнозування, особа, яка приймає рішення, складна технічна система, суднова енергетична установка.*