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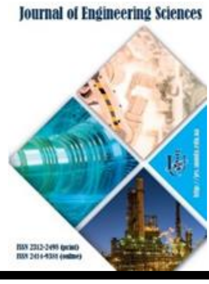

Optimal Management in the Operation of Complex Technical Systems

Dyadyura K.[1][0000-0002-7575-9711], Oborskyi G.[1][0000-0002-5682-4768], Prokopovych I.[1][0000-0002-8059-6507], Khamitov V.[1][0009-0005-3494-8304], Holubiev M.[2][0000-0002-6647-4335]

[1] Odesa Polytechnic National University, 1, Shevchenka Ave., 65044 Odesa, Ukraine;
[2] National University of Life and Environmental Science of Ukraine, 15, Heroiv Oborony St., 03041 Kyiv, Ukraine

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***Corresponding email:**
i.v.prokopovich@op.edu.ua

Abstract. Developing a cost management system for a complex technical system (CTS) at the stages of its life cycle is a modern trend aimed at creating sustainable cooperation ties based on requirements, including those of manufacturers and consumers. The article explores the concept of a complex technical system. The principles and properties of a complex technical system were described. A model of a procedure for checking the operability of a complex technical system with an arbitrary distribution of the time of independent manifestation of a failure was proposed for the example of compressor station equipment. Models of operation of complex technical systems based on information about their state were considered. It was also shown how to optimize maintenance decisions for these systems in terms of the minimum average unit cost and how reliable this ensures. Additionally, proof of the existence of an optimal verification strategy was given. An algorithm for determining the moments of verification was developed to ensure the minimum cost. The methods of collecting, processing, and effectively using information for making decisions about the technical condition of complex products and the possibility of further exploitation were improved based on selecting informative diagnostic features and constructing models that comprehensively consider the maximum and current level of their parameters. This allowed for the quality of the final products to be ensured. The practical use of the proposed methods of diagnosis and forecasting made it possible to increase the actual CTS resource by 1.5–2.0 times. This also increased the productivity of the technological process by 1.6 times due to the reduction of the number of stops for maintenance for replacement, adjustments, and sub-adjustments. As a result, the value of the lack of basic production was reduced from 1.2 % to 0.8 %, and the cost of manufacturing products was decreased by 1.2–2.0 times.

Keywords: standardization, quality assurance, optimum tolerance design, industrial growth, quality control, reliability indicator, product lifecycle management.

1 Introduction

The long-term success of an organization depends on many factors, from constantly evaluating and updating its offerings to optimizing its processes. Innovative development of manufacturing companies in modern conditions takes place in the paradigm of the new industrial order – “Industry 4.0” and “Industry 5.0” [1], which involves a large-scale digital transformation of business processes and products of companies, the establishment and optimization of information exchange between elements of the business environment (the main business and related, as well as the main production and suppliers) within the framework of the concept of “extended enterprise of the future”. The modern trend is the development of supply chains, which includes not only the optimization of logistics but also the development of suppliers of various levels to optimize a single production or provision of services process. This is especially pronounced in the engineering industry [2], where large enterprises set additional requirements for suppliers in terms of improving production systems to optimize the production cycle in terms of cost (pricing), timing, and quality [3]. Another significant trend in the development of large companies is their transition to managing products, production, and infrastructure based on the life cycle management [4] of both the product and production, including equipment and auxiliary means of production

[5]. This allows for managing both the costs (in terms of life cycle costs) and the technical and operational parameters of products and production [6].

Machine-building products for industrial and technical purposes, used in various technological processes to manufacture other products (end products) or provide services, will be considered independently functioning multifunctional and multi-element complex technical systems (CTS).

STS includes three main interconnected heterogeneous components - a complex of technical means, software, and operational personnel. The characteristics of such CTS are determined by the type, composition, and quality of many elements and subsystems that interact and are combined into a system to perform a particular function. The greater the number of elements and subsystems, the connections between them, and the states they can be, the more complex the technical system.

In turn, the design, manufacture, and intended use of CTS are also carried out by multifunctional and multi-element CTS.

The development of a system for managing the life cycle of equipment (Figure 1) and the cost of the life cycle of equipment is a modern trend aimed at creating sustainable cooperative ties between manufacturers and operators of technical systems.

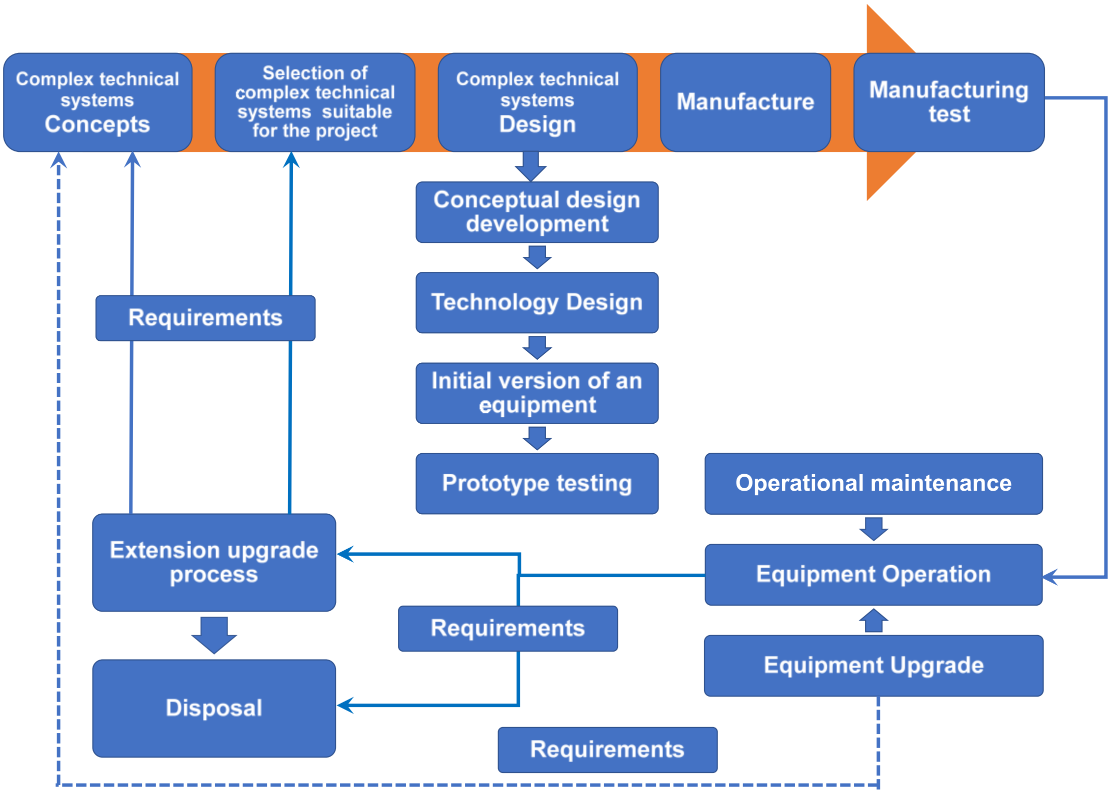

Figure 1 – The life cycle of CTS

Equipment's life cycle cost management involves mutually beneficial cost reduction for participants in the equipment operation process, which involves changing the design, production technology and repairs (recovery), operating modes, and methods of utilization or life extension. In doing so, organizations of all types and sizes face external and internal factors and influences that make it unclear whether they will achieve their goals. Risk management is iterative and assists organizations in developing strategies, achieving goals, and making informed decisions.

The effectiveness of the functioning of the life cycle processes of CTS, in contrast to the life cycle of ordinary systems, is related mainly to the presence of appropriate objective management laws that can take into account the conditions and changes of the internal (transformation of resources into products) and external (source of resources for enterprises) environment. The basis for modeling the processes of the life cycle of CTS is the assumption:

– desired transformations of a set of operand inputs (transformation objects) into a set of operand outputs are achieved by targeted actions of material, energy, and informational types;

– technical systems and the environment carry out these three actions during transformation.

The criterion for optimal management of the life cycle processes of CTS, as opposed to the life cycle of ordinary systems, is a set of technical and economic parameters, and the limitation is the internal environment of the enterprise and the strategic goals and objectives of its development.

Three states are possible during the development of objects of the life cycle system.

1. The requirements of one of the life cycle processes are more significant than the capabilities of another. This

is because the internal development of one of the life cycle processes, which is supported by the connection with the external environment, increases its needs and continuously increases the requirements. As a result, a new additional connection can be formed, which affects the life cycle processes and helps increase its capabilities.

2. The requirements of one of the life cycle processes are equal or identical to the capabilities of another process. In this case, an equilibrium state occurs between neighboring life cycle processes.

3. The requirements of one of the life cycle processes are less than the capabilities of the other. In this case, anticipatory development occurs. Simultaneously, with the help of the connection of the life cycle process with the external environment, the requirements increase, and the system of processes again strives for a state of equilibrium.

2 Literature Review

Risk management of equipment operation, both in the technical aspect (equipment readiness, identification of pre-emergency modes of operation) and in the organizational aspect (reduction of repair and maintenance periods, increasing the transparency of value chains, improving the quality of repairs and maintenance) are associated with economic performance and professional reputation, and environmental, safety and social outcomes [7, 8]. Therefore, risk management effectively helps organizations perform well in the face of uncertainty. As is known [9], the system of operation of technical devices for various purposes depends on the principles for determining the duration of their use and the choice of a program for managing the current state.

This research aims to examine the operation models of complex technical systems (CTS), which are based on initial quantitative information about their state.

Complex systems are used as an umbrella term covering many disciplines, including transportation, physics, non-linear dynamics, biology, computer science, astronomy, sociology, economics, and others. Complex technical systems are systems whose behavior is challenging to model due to complex dependencies between their parts or complex interactions between a given system and the environment [10–13]. A complex technical system is a rich-functional, rich-component system that includes three fully functional components – technical means, software, and operational personnel (Figure 2). In this figure, “data processing algorithm” means software that includes artificial intelligence, machine learning, and the Internet of Things.

Special characteristics serve as the basis for the study of systems in relation to the subject area or the specific interaction of the system and the environment.

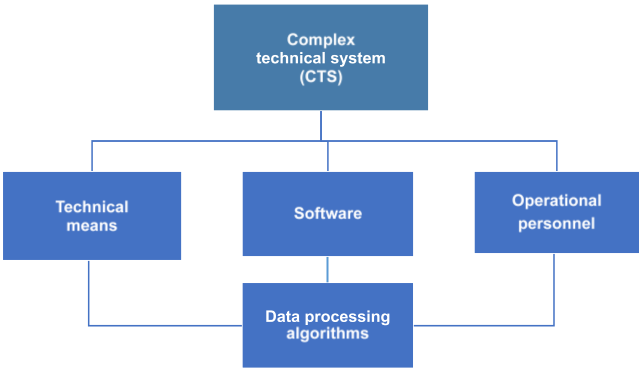

Figure 2 – Components of CTS

Modern CTS differs from pre-existing CTS by the inclusion of an information computer and telecommunications component. Therefore, modern CTS can be designated by the term “complex information and technical systems”, which essentially corresponds to these systems, but this term has not found wide application. Therefore, we will talk about CTS, considering the presence of the information component in these systems as the main one. On the whole, the study of complex technical systems is of interdisciplinary significance. Qualitatively, new emergent properties characterize CTS. One of these properties is manifested in the fact that, due to a particular structural redundancy, failures of individual elements or misalignment of the parameters of some subsystems do not lead to the failure of the entire system but only worsen the quality of functioning. It is assumed that when monitoring the devices, the values of the parameters characterizing their wear or misalignment or the state (working, not working) of the complex, which has a certain degree of redundancy, are known. The following decisions are made based on the results of the control:

– do not interfere with the operation of the system until the next moment of control;

– to restore (adjust) the system until its parameter goes beyond the permissible limits;

– to carry out emergency recovery (replacement, adjustment);

– appoint the moment for the next control.

The decisions taken in this case must be, in a certain sense, the best, optimal. We will be interested in optimizing these solutions according to the criterion of the minimum average specific time spent on maintenance of a system or a complex of systems. Simultaneously, we should also be interested in the system’s reliability (complex), which is ensured during application. Modern production ensures high stability of CTS’s characteristics (parameters) during operation. In practice, this should lead to the fact that the parameters will change in some narrow “corridor”.

Physically, such a change in parameters is explained by “hard” electrical or mechanical connections in the technical system [14, 15].

Currently, the following negative factors are observed that complicate the operation process and lead to an increase in the cost of the life cycle of operation of such CTS as compressor station equipment [16, 17]:

– non-transparency of some stages of the life cycle due to the imperfection of the supplier management system and the lack of a real-time equipment condition identification system;

– lack of interest of suppliers of equipment and services in the timely and high-quality performance of work;

– imperfection of the system for identifying pre-emergency situations for the timely withdrawal of equipment for repair/maintenance;

– the existence of losses due to the operation of equipment with reduced efficiency when approaching the limiting time between failures (before major repairs).

The goal, which is to increase the efficiency and reduce the risks of operating the compressor station equipment, can be achieved by solving the following tasks:

– creation of information tools for identifying the state and technical and economic indicators of equipment functioning in real-time;

– creation of analytical tools (based on qualified simulation models of equipment and competencies of the personnel of participants in the operation process) to identify pre-failure conditions and make management decisions in the field of operation (selection of the operating mode and parameters, maintenance, and repair planning, decisions to extend the operation life).

3 Research Methodology

The diagnostic algorithm is further built based on the approach generally accepted in cybernetics using state observers (adequate and qualified equipment models). It can be called the control of the state of the system complete if it is carried out based on a discrete measurement of the defining parameters of the system at the moments t_n $(n = 0, 1, 2, \ldots)$.

It can be observed a particular sequence of random variables $X_1, X_2, \ldots, X_n$ [8–10]. Let’s call the function $\varphi(X_1, X_2, \ldots, X_n)$, which takes the values $0, 1, 2, \ldots$ stopping rule (observations). It will be assumed that if $\varphi(X_1, X_2, \ldots, X_n) = m \quad (X_1 = x_1, X_2 = x_2, \ldots, X_m = x_m)$, then the observation process ends at the *m*-th step.

If $\varphi(X_1, X_2, \ldots, X_n) = 0$, which means that a decision has been made not to observe random variables. Note that the entries $x_1, x_2, \ldots, x_{n-1}$ refer to already observed increments (implementations of random variables $X_1, X_2, \ldots, X_{n-1}$), and if we have not observed an increment, then we consider it random and denoted by the symbol *X*. For example, if the last observation ended at the moment t_{n-1}, then the increment of the process $S(t)$ from t_{n-1} to t_n is denoted by X_n (Figure 3).

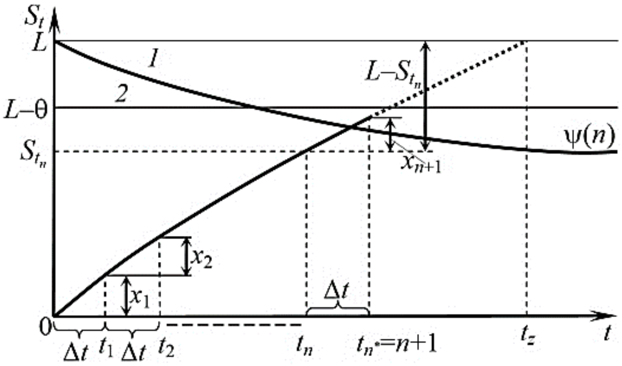

Figure 3 – Implementation of a monotonically increasing random process $S(t)$

Further, for simplicity, we will assume that all random variables X_n $(n = 1, 2, \ldots)$ have the same distribution. Let us now introduce the following optimization criterion:

$$y_{n+1}(X_1, \ldots, x_n, X_{n+1}) = \begin{cases} \frac{C}{t_{n+1}}, \ t_{n+1} \le t_Z; \\ \frac{C+A}{t_{n+1}}, \ \ t_{n+1} \ge t_Z. \end{cases} \quad (1)$$

This entry is explained as follows: observing the process $S(t)$ up to the moment t_n, we then decide what average unit costs we will have if we stop the process at the moment t_n, where C is the average cost of returning the process to zero at $S(t_{n+1}) < L$, and $C + A$ are the average costs of its return to zero at $S(t_{n+1}) \ge L$, where L is the allowable limit of the process change $S(t)$, where t_Z is the moment of exit of the process $S(t)$ for level L. The numerator of the fraction on the right side of (1) is random, then we will look for the optimal rule φ^* minimizing the average unit costs, i.e., it can be obtained $\min_{\varphi^*}\{M[y_{n+1}(x_1, \ \ldots, x_n, X_{n+1})]\}$.

Let’s write the expression for the average unit costs:

$$\begin{aligned} M[y_{n+1}(x_1, \ \ldots, x_n, X_{n+1})] &= \frac{C}{t_{n+1}} \cdot P\{X_{n+1} < L - S(t_n)\} + \left(\frac{C}{t_{n+1}} + \frac{A}{t_{n+1}}\right) \times \\ \times [1 - P\{X_{n+1} < L - S(t_n)\}] &= \frac{C}{t_{n+1}} + \frac{A}{t_{n+1}} \cdot [1 - P\{X_{n+1} < L - S(t_n)\}]. \end{aligned} \quad (2)$$

$M[y_{n+1}(x_1, \ \ldots, x_n, X_{n+1})] \le y_{n+1}(x_1, \ \ldots, x_n, X_{n+1})$ occurs if the observation process is stopped no later than the moment φ^*, i.e.,

$$n \le \varphi^*(x_1, \ x_2, \ \ldots, x_n), \quad (3)$$

if

$$1 - P\{X_{n+1} < L - S(t_n)\} \le \frac{C}{A_n}. \quad (4)$$

Substituting (4) into (2) ensures the statement is true.

$M[y_{n+1}(x_1, \ \ldots, x_n, X_{n+1})] \ge y_{n+1}(x_1, \ \ldots, x_n, X_{n+1})$ occurs if the observation process is stopped no earlier than the moment φ^*, i.e.,

$$n \geq \varphi^*(x_1, x_2, \dots, x_n) \quad (5)$$

if

$$1 - P\{X_{n+1} < L - S(t_n)\} \geq \frac{C}{A_n}. \quad (6)$$

Substituting expression (6) into (2), the converse statement is also valid.

It assumed that n^* can be n such that the equality sign in (3) and (5) holds. Then,

$$\varphi^*(x_1, \dots, x_n, X_{n+1}) = n^*. \quad (7)$$

Indeed, in the case under consideration, all the conditions of the optimal lemma proved in [18] are satisfied, whence it follows that statement (7) is true and n^* should be sought as the largest n for which expression (4) is still valid.

Let's find from (4) the equation of the curve of optimal anticipatory tolerance (curve 1 in Figure 3). From (4), it can be found:

$$F[L - S(t_n)] \geq 1 - \frac{C}{A_n}. \quad (8)$$

Taking the inverse function of F on both sides of the equality, the following can be obtained

$$L - S(t_n) \geq F^{-1}\left(1 - \frac{C}{A_n}\right) \quad (9)$$

or

$$S(t_n) \leq L - F^{-1}\left(1 - \frac{C}{A_n}\right) = n. \quad (10)$$

Optimal control consists of adjusting the parameter $S(t)$ at the first intersection of the curve (10). In Figure 3, straight line 2 replaces curve 1 to reduce the amount of memory when controlling many parameters.

The equation of straight line 2 is written as $S_t = L - \theta$, where θ is often in the range of 0.6–1.0 of the tolerance.

The parameter is considered the lower limit of losses during the operation of the CTS. This indicator is determined considering all possible checks.

If the moment $t = 0$ the functioning of the CTS begins, the uptime of which has the distribution $F(x)$. Then, it is assumed that the failure that has appeared in the system manifests itself independently after a random time t_Z, distributed according to the law $G(x)$. The maintenance strategy is as follows: at time $t = 0$, a sequence of health checks is assigned at moments t_n $(n = 1, 2, \dots)$. If the moment t_K is established as a result of checking that the CTS is operational, no recovery has been carried out, and the CTS continues to function.

If the CTS failed at the time t_{K-1}, but by the next check time t_K the failure did not appear, then as a result of the k-th check, it will be detected with a probability of 1. If after the failure at the time t_{K-1} time of its manifestation $\varepsilon \leq t_k - t_{k-1}$, then at the moment $t_{k-1} + \varepsilon$ this failure is detected independently.

Once a failure is detected, system maintenance is terminated. Each system health check costs C_1 units of cost, and for a unit of CTS downtime in a latent failure state, the loss is C_2.

It can be assumed that checks occur instantly and do not worsen the probabilistic characteristics of the CTS. The challenge will be to determine the optimal timing of the audits. Optimality here is understood in the sense of minimizing the total average cost of maintaining the CTS associated with the checks and latent failures. The cost of operating compressor station equipment directly affects the efficiency of production processes [18].

4 Results

CTS with redundancy in reliability is being investigated [11, 12]. The model of the online diagnostic system shown in Figure 4 allows the analysis of the current state of the equipment, like a CTS, and the prediction of the operation parameters based on both statistical data and continuous modeling of equipment behavior.

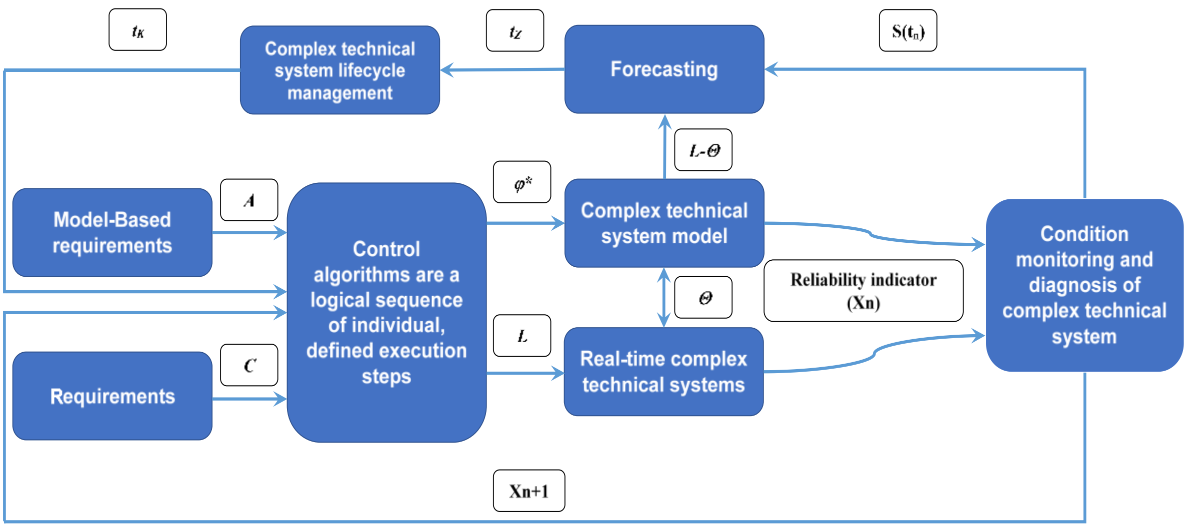

Figure 4 – Implementation of control and diagnostics based on the state observer (real-time models)

In addition to forecasting and managing risks and reliability, the proposed complex system makes it possible to assess and predict the life cycle cost of compressor station equipment operation, depending on the performance and risks of managing the equipment fleet.

The control system described above implements the following main functions:

– monitoring, collection, and storage of information (with the possible creation of an electronic passport for a piece of equipment) on the operating modes and operating parameters of compressor station equipment;

– analysis of information and implementation of operational and long-term corrective technical measures in order to improve the efficiency of equipment operation;

– implementation of organizational measures in the field of optimizing the interaction between participants in the operation of compressor station equipment (creation of an “extended enterprise”);

– the creation of a unified, transparent information environment for participants in the operation of compressor station equipment in order to optimize the planning processes for equipment maintenance and repair;

– implementation of predictive diagnostics of the state of equipment of compressor stations in order to create a unified database of decisions on the application of equipment operating modes;

– create the basis for the transition to repairs and maintenance of equipment of compressor stations “on condition” while considering the requirements of regulations in the field of industrial safety.

Figure 5 shows an approximate model for managing the operation of compressor station equipment from the criterion of “cost (availability) – efficiency”.

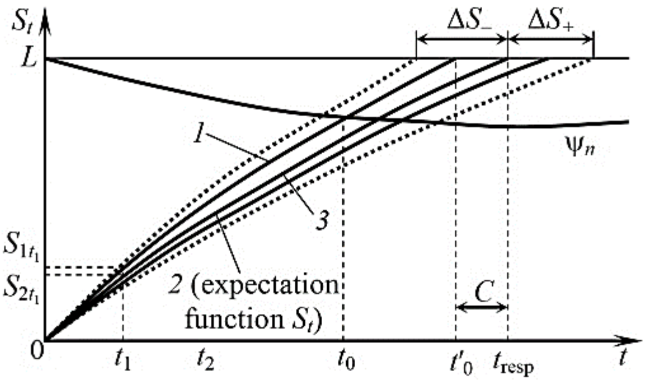

Figure 5 – Approximate model of control

To assign the adjustment torque (Figure 5) when monitoring each implementation of the parameter S_t, it can be guided by the following rule:

– assign parameter adjustment at $t_0^{'} - C - \Delta S_1$ $(0 < \Delta S_1 \le \Delta S_-)$ if the values of the implementation of the parameter S_t at all measurement points were above the expectation function;

– assign the parameter adjustment at the moment $t_0^{'} - C + \Delta S_3$ $(0 < \Delta S_3 \le \Delta S_+)$, and it is possible that $\Delta S_- \ne \Delta S_+$ if the implementation of the parameter S_t, the measured points were below the expectation function.

Curves 1 and 3 are observed parameter changes; curve 2 is the function of the mathematical expectation of parameter change; t_0 is the moment of optimal adjustment, determined using the second method according to the algorithm (4) – moment of intersection of curves 1 and *n*; *C* is the proactive adjustment time of the parameter, selected from the operating experience of a particular equipment; $t_0^{'}$ is the moment of adjustment by the approximate method using curve 2; ΔS_- is the distance between the moment t_{resp} and the moment of crossing the left border of the “corridor”, within which all realizations of the process S_t are located, with the level *L*; ΔS_+ is a similar distance for the right boundary of the S_t process; $S_{1t_1} - S_{2t_2}$ is the difference between the values of the observed parameter (implementation – curve 1) and the value of the mathematical expectation function (curve 2) at the moment t_1.

The corrections ΔS_1 and ΔS_2 are found experimentally for each process S_t. In practice, when observing the first realization, one can “work” with it as a “mathematical expectation function” when obtaining the second realization, taking the average realization, and so on. Naturally, the method’s efficiency (regarding labor costs and the predicted number of failures of parameter values going beyond level *L*) will increase as the number of implementations grows. In order to estimate the accuracy of the described approximate method for adjusting the parameter, it is necessary to apply the optimal adjustment rule (4) to the process S_t.

A study of the technical condition was carried out for the screw compressor station. In the experimental part, research was carried out on the level of vibrations. Measurements of the total vibration level were carried out using the Vibroport device. The characteristic spectrum of compressor vibration results at 5 points, where the measurements were made, is presented in Figure 6.

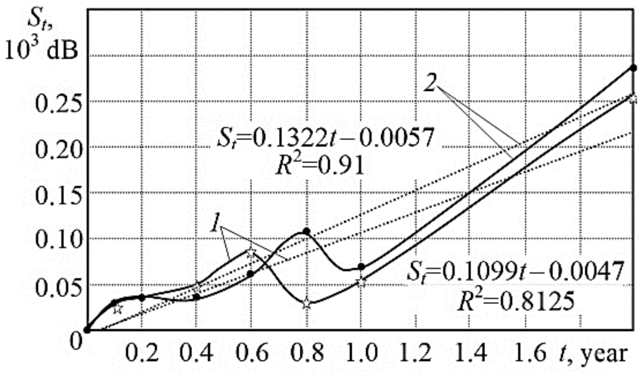

Figure 6 – The results of the parameter adjustment at the moment of compressor station operation based on vibration measurement if the implementation values of the parameter S_t at all measurement points were below (line 1) or above (line 2) the expectation function

This mainly applies to bearings. At the same time, different types of bearings used in the compressor generate vibrations at the same frequencies. Analysis of research results shows that the vibration spectrum of the compressor unit is relatively narrow and is limited to the range of 800 Hz. The research results show that, naturally, as in any rotary machine, oscillations at the reverse frequency and doubled reverse frequency significantly contribute to the vibration level.

The frequency component reacts to the instability of the shaft of the compressor and the drive, to the defect of the rolling bearing bodies, and, in the case of a screw compressor, is generated by the known shaft of the multiplier. These harmonics are superimposed on the basic amplitude-frequency characteristic (frequency characteristic), which characterizes the dependence on the frequency of the amplitude of the oscillations of the main units of the installation. By changing the frequency response of these units in the desired direction, the vibroacoustic characteristics of the installation can be changed. According to the analysis of this information, a forecast of compliance with the requirements during the operation of this compressor equipment was made.

To assess the quality of the research results, the Fisher test was used at the significance level of α=0.05. The significance of the estimates of the model coefficients is checked using the Student's test with a confidence probability of 0.95 and the degrees of freedom $\nu_1 = 5$ and $\nu_2 = 9$. The sample correlation coefficient was 0.962–0.988. The coefficient of determination is 94.5 %. The average relative error of approximation does not exceed 5.0 %.

Preliminary results of the simulation carried out for special cases of the process S_t showed that with the optimal method of 100 observed and controlled implementations, on average, going beyond the level is anticipated in 95 cases and with an approximate one in 60–80 cases.

5 Discussion

The joint interaction of CTS life cycle processes, including design, manufacture, and operation, can be presented as an open system. The stationary state of such a CTS is ensured by material, energy, and information flows that act within the process system and under the conditions of interacting with the external environment.

When setting the task of synergistic modeling, it is assumed that the design, manufacturing, and operation processes are characterized by the duration t (execution time) and the corresponding production functions. At the same time, if the number of resources during the execution of the process does not change, then the intensity will be a constant value. If the number of resources acquires different values, then the duration of the process can be different; accordingly, the variable will be the intensity. In an environment of increasing global competition and rapid adaptation to ever-changing market demands, companies try to be competitive through cost-effectiveness, constantly seeking models and methods for assessing investments and improvement opportunities to understand how to prioritize different actions and options [19]. Effective product lifecycle management involves leveraging digital technologies across the entire ecosystem to optimize processes, eliminate complexity, and ensure seamless data flow across functional areas [20–22]. Integrating digital streams that include strategic interoperability of enterprise platforms such as CAD/CAM/CAE/PDM/PLM and others supports the collaborative creation, management, distribution, and definition of products.

As new technologies emerge and consumer preferences change, the stages of product lifecycle management may shift towards using artificial intelligence and machine learning [23]. Thanks to artificial intelligence, machine learning, or the Internet of Things, companies can collect and analyze data more efficiently at every stage [24]. This will enhance the company's ability to optimize productivity and reduce costs in the future. The pursuit of technology also creates opportunities for better communication. Product development and management are becoming increasingly tighter, with cross-functional teams working together to bring products to market [25, 26]. To support this trend, new methods and approaches are being developed that allow instantaneous strategic decisions to be made in real-time [27–29]. These tools continue to make it easy for team members to collaborate regardless of location. As consumers become more environmentally conscious, companies can respond more to sustainability demands [30–32]. Product lifecycle management systems can support this trend by providing tools to measure and manage sustainability throughout the product lifecycle, from design to end-of-life disposal. This includes smart, scalable ways to measure waste or environmental impact [33, 34]. It also means smarter and cleaner ways to transfer products throughout their life cycle or to consumers. The key is to ensure strategic alignment between stakeholders and set (and continuously manage) appropriate expectations. When making strategic and tactical decisions, it should be considered multiple goals and rely on complex and sometimes contradictory criteria. The disadvantage of the existing models of life cycle processes in cases where complex technical products are designed and manufactured to order (a limited number of products of the same type) is their fragmentary nature, the inconsistency of the results and the inability to reflect the most general, fundamental non-linear regularities of the organizational and technical mechanism of a sequential the formation of emergent properties in the period from the justification of their development to the end of operation and further disposal.

6 Conclusions

The proposed approach makes it possible to identify the characteristic signs of malfunctions and automatically obtain logical expressions describing the malfunctions of a complex technical system using the example of compressor station equipment. The algorithm provides an opportunity to analyze information about faults, represented by many signs, reducing the time needed to develop technical diagnostic programs and improving their quality. Practical implementation of troubleshooting programs based on the resulting logical expressions is possible in universal and specialized information devices that are part of the diagnostic tools for complex systems. Life cycle management of compressor station equipment includes:

– equipment operation efficiency management (maintenance of equipment efficiency at the highest possible level);

– cost management at the stages of the operation life cycle;

– management and coordination of interaction with suppliers at the life cycle stages, the operators of which are third-party organizations.

The methods of collecting, processing, and effectively using information for making decisions about the technical condition of complex products and the possibility of their further exploitation to ensure the quality of the finished final products have been improved based on the selection of informative diagnostic features and the construction of models that comprehensively consider the maximum and current level of their parameters.

Practical use enterprises of the proposed methods of diagnosis and forecasting made it possible to increase the actual resource of CTS by 1.5–2.0 times, to increase the productivity of the technological process by 1.6 times (due to the reduction of the number of stops for maintenance for replacement, adjustments, and sub-adjustments), to reduce the value of the lack of basic production from 1.2 % to 0.8 %, and to reduce the cost of manufacturing products by 1.2–2.0 times.

Further research is related to improving the control system for CTS at the stages of their life cycle, considering the interoperability of their constituent components.

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