Modeling and computer forecasting of a comprehensive reliability indicator for a fleet of identical gantry cranes*

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Abstract
Portal cranes are the most important elements of the technological infrastructure of modern ports, providing automated cargo movement between ships and the coastal zone. They perform an indispensable function of moving cargo between ships and the coastal zone, guarantee fast and productive handling of containers, various cargoes, bulk materials and other types of products, which directly affects the productivity of logistics processes and the economic sustainability of the port complex. The efficiency of loading and unloading operations in river ports is largely determined by the availability of port cranes. In modern conditions of digitalization, the use of computer technologies for monitoring, modeling and forecasting the technical condition of crane equipment is of particular importance. However, unfortunately, in Ukraine, a significant part (more than 90%) of these cranes are already operated outside the regulatory resource, which increases the risks of downtime and reduces the overall reliability of the cargo transportation process. This article presents a computer model for assessing the reliability of a fleet of identical gantry cranes, which makes it possible to calculate a comprehensive reliability indicator — the availability coefficient. Analysis of the data obtained showed that: when using 1 post, the readiness coefficient of the crane group decreases to a value of 0.53 (0.54) (almost twice), which will lead to the creation of permanent queues in idle time due to repairs and restoration. With an increase in the number of posts, the readiness factor of the fleet increases significantly. The readiness coefficient of a gantry crane is not just a statistical value, but a key indicator of the condition of the fleet and the effectiveness of its management using digital tools. Maintaining a high level of operational readiness requires an integrated approach, including the introduction of monitoring information systems, predictive analytics, and maintenance optimization based on modern computer technology..

Keywords
Analysis of maintenance data, portal crane, ratability, readiness factor

1. Introduction

In today's world, where international trade is a key driver of economic development, seaports are the most important transport hubs and centers of digital transformation. Seaports are not just transshipment points for cargo, but complex information technology complexes that ensure high speed and efficiency of handling containers, bulk and other types of cargo. Seaports are powerful sources of income that significantly replenish the state treasury [1]. Many countries around the world are actively developing their ports, realizing their strategic importance for the economy. For example, Singapore, Rotterdam and Shanghai are the largest ports in the world and make a huge contribution to the economies of their countries.

Moreover, the effect of port development is not limited to direct financial flows. This has a multiplier effect on the economy, stimulating the development of entire regions. Industrial clusters,

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logistics centers, and free trade zones are forming around major ports, which creates new jobs, attracts investment, and promotes infrastructure development.

2. Purpose of the study

The aim of this research is computer-based prediction of a complex reliability indicator for a fleet of identical gantry cranes. This article presents a computer model for assessing the reliability of a fleet of identical gantry cranes, which makes it possible to calculate a comprehensive reliability indicator — the availability coefficient.

3. Overview of results and sources

Gantry cranes are the real "workhorses" of any modern port. They are key elements of the port's technological infrastructure, ensuring a continuous flow of cargo between ships and the coastal area. More than 1,000 gantry cranes are in operation in Ukraine, with more than 90% of the equipment operating beyond its design life [1-6]. In such conditions, real-time digital monitoring and the use of predictive analytics systems are becoming critically important for improving the reliability and safety of crane operations. Thus, the reliability of gantry cranes is not just the desired quality, but also the most important factor in the efficient and trouble–free operation of the entire port, since they are an integral part of technological processes [7-14].

Imagine a situation: a ship with valuable cargo has arrived at the port, but one of the key gantry cranes has failed. This leads to delays, vessel downtime, increased transshipment costs and, ultimately, customer dissatisfaction. That is why such close attention is paid to the reliability of gantry cranes. We present a model for a comprehensive assessment of the reliability of a fleet of identical gantry cranes using modern computer technology. The analysis showed that in the presence of one repair post, the availability coefficient of the crane group decreases to 0.53–0.54, which leads to increased downtime and reduced productivity. The increase in the number of repair posts and the introduction of digital maintenance planning systems can significantly increase availability and reduce downtime.

The reliability of gantry cranes is determined by a variety of factors: the quality of design and manufacture, operating conditions, the skill level of operators and the efficiency of maintenance. An important role is played by the integration of cranes into the overall digital port management system, which ensures logistics optimization, process automation and operational decision-making based on real-time data analysis. The use of high-quality materials and components, compliance with strict production standards, as well as regular inspections and repairs play a crucial role in ensuring long-term and trouble-free operation of cranes.

The conditions in which gantry cranes operate are also of great importance. Exposure to adverse weather conditions (wind, rain, snow) in a particular port can significantly increase the risk of accidents. These factors must be taken into account when planning operations [1-15].

The operator's qualifications also affect the reliability of gantry cranes. Improper operation can lead to overloads and damage to the equipment. Therefore, it is important to conduct regular training and retraining of operators so that they are familiar with the features and rules of safe operation of cranes.

In addition, the integration of gantry cranes into the overall port management system is an important aspect. This makes it possible to optimize logistics, reduce cargo handling time and increase the overall efficiency of the port. For example, information about the condition of cranes can be used to plan the loading of a vessel and distribute tasks between different crews.

Special attention is paid to the problem of the operation of outdated equipment, which is subject to cyclic loads and accumulation of fatigue damage. The use of digital twin technologies, status monitoring and predictive maintenance allows you to identify potential malfunctions before they occur, reducing the risk of accidents and increasing safety.

Regular maintenance is crucial to maintain the reliability of gantry cranes. Regular inspections, lubrication of moving parts, and timely replacement of worn components help prevent breakdowns and accidents. Enterprises using gantry cranes should follow the manufacturers' recommendations and develop their own maintenance schedules.

When choosing a supplier, you must carefully consider their reputation, work experience, and availability of a service network and spare parts. It is important to make sure that the supplier offers not only high-quality equipment, but also comprehensive support throughout the entire life cycle of the crane. This may include staff training, technical support, spare parts supply, and equipment upgrades.

Nevertheless, the analysis of the forces arising in the grab suspension of gantry cranes, which have been in operation for more than 40 years in the conditions of port activity, has so far been insufficiently covered in the scientific literature. Given the steady growth of cargo transshipment volumes on a global scale, this topic is an important research object [2-12].

The increase in transshipment volumes has led to an increase in the load on cranes. In Ukraine, the problem of replacing gantry cranes is acute, as their service life has significantly exceeded the established standards [2-12].

The operation of such cranes under cyclic loads leads to the accumulation of fatigue damage, which increases the risk of breakdowns and accidents. Observations show that a significant number of mechanical failures and accidents may be due to the fact that lifting equipment has exceeded its operational life, but is still subjected to intense cyclic loads [10-14].

A review of the existing literature [1-9] shows that insufficient attention is paid to the reliability of port cranes, which have been operating in marine and river conditions for more than 35 years. A cursory examination of the processes occurring in their metal structures makes it difficult to identify and fix problems before they occur. The operation of faulty cranes carries a high risk of structural failure and accidents, possibly injury or death. Therefore, each crane requires a comprehensive case-by-case analysis [6,9], especially for a fleet of similar machines.

Given the ever-increasing volume of cargo handling around the world, this problem is becoming even more urgent. The ability to predict possible equipment failures is necessary to reduce maintenance costs, reduce downtime, and ensure safety [13-26].

A malfunction of the port lifting equipment can lead to significant disruption of the production processes of local enterprises and negatively affect the daily lives of citizens. Therefore, ensuring the safety of working gantry cranes, especially those whose service life is approaching or exceeding the expected one, is crucial. It is extremely important to carry out careful control based on the level of safety [1-15,26]. It follows from this that the digitalization of the port infrastructure and the introduction of computer technologies in the management of gantry cranes are key factors in improving the efficiency, reliability and safety of seaports. This contributes not only to the sustainable development of the port industry, but also stimulates the economic growth of the regions, providing a multiplier effect on the entire economy.

4. Data and methodology

A reliability study was conducted on five identical 16-ton gantry cranes operating in grapple mode in sea and river ports.

The performance of the cranes under study differed slightly, and the loads handled were identical.

Data encompassing maintenance and repair logs from 2015 to 2022 formed the basis of the analysis. These records, meticulously gathered from port operational logs, crane passports, shift mechanic reports, and other relevant port services, provided comprehensive insights into crane failures. Visual inspections were performed semiannually throughout the observation period, a frequency that could be optimized with the use of advanced condition monitoring techniques such as vibration analysis or oil particle analysis which would allow for proactive maintenance scheduling rather than solely relying on scheduled inspections. This proactive approach could significantly reduce downtime and improve overall reliability. The study employed a reliability analysis framework considering the crane operational lifecycle as an interplay of failures and subsequent repairs.

A key performance indicator, the availability factor (K_g), was used to quantify the reliability [17-16,23]. The availability coefficient represents the likelihood that a facility will be operational at any moment, excluding scheduled maintenance periods when the facility is not meant to be in use.

This coefficient is calculated as the ratio of the duration of effective operation to the total time, which includes both the effective operation time T_w and any unplanned downtime T_p, all measured over the same calendar period.

$$K_g = \frac{T_w}{T_w + T_p} \tag{1}$$

This factor represents the proportion of time the crane is operational and available for use, considering both planned and unplanned downtime. The availability factor calculation should have incorporated the duration of repairs and the inherent downtime associated with the cranes' maintenance schedule (including the time required for visual inspections). Furthermore, a detailed breakdown of failure modes (e.g., mechanical, electrical, hydraulic) would offer valuable insights into the dominant causes of downtime and provide a basis for targeted preventative maintenance strategies, perhaps focusing on specific components with a higher failure rate.

Understanding the availability factor is only the first step. It is important not only to know the figure, but to actively use it to improve the operation of the gantry crane. This requires a comprehensive approach, including an analysis of the causes of downtime, the development and implementation of corrective measures, as well as continuous monitoring of the results.

The availability coefficient characterizes the readiness of an object for its intended use only in relation to its operability at any given time.

The more the crane operates, the more cargo it can handle, which increases the overall productivity of the port.

The readiness coefficient of the gantry crane was not just an abstract number – it represented the well-coordinated work of the entire port staff. From the qualifications of specialists to the timely delivery of spare parts, from an effective planning system to prompt response to unforeseen situations, all these factors together determined the success of the port and its competitiveness in the global market.

Reducing downtime means lower repair and maintenance costs, as well as increased revenue from cargo transshipment.

Optimizing the availability factor of a portal crane is a strategic task for any modern port. A high Kg directly affects throughput, reduces cargo handling time, reduces operating costs and, importantly, increases the safety of the working environment.

A decrease in Kg, on the contrary, signals potential problems that require immediate attention. These may be hidden defects in equipment, inefficient organization of maintenance, insufficient qualifications of personnel, or even problems with the supply of spare parts. Timely identification and elimination of these problems is the key to stable and efficient operation of the port.

This enhanced approach would enable a more granular analysis to identify areas needing improvements in design, maintenance procedures, or operator training. Environmental factors influencing the cranes' performance (such as corrosion due to saltwater exposure or extreme weather conditions) should also be considered to accurately assess and improve operational reliability. Future studies could benefit from incorporating these factors for a more comprehensive and accurate reliability assessment.

The prompt availability of the necessary spare parts and consumables makes it possible to quickly eliminate malfunctions and minimize crane downtime.

We assume that uptime and recovery time after a failure follow an exponential distribution (Fig.1).

Differential equations for the probabilities of states of an object can be composed in the form of a graph of states.

One of the powerful tools for modeling recovery-redundant systems is the use of the theory of Markov processes, namely, the representation of the system as a state graph, along which the "point" moves, reflecting the current state of the system. Each state describes the health of individual components and the system as a whole. Transitions between states are determined by the failure and recovery intensities of the components.

Mathematically, the model of probability state flows is described by a system of differential equations that determine the change in the probability of the system being in each of the possible states over time. Solving this system allows us to determine important reliability indicators such as the probability of failure-free operation, the average time to first failure, and the availability rate.

As before, we assume that the system is in state k when exactly k elements failed simultaneously. Obviously, in this case k = 0, 1, 2,..., n, where n is the total number of elements in the system. A model of flows of probable states of a restorative redundant system (Fig.1) [23].

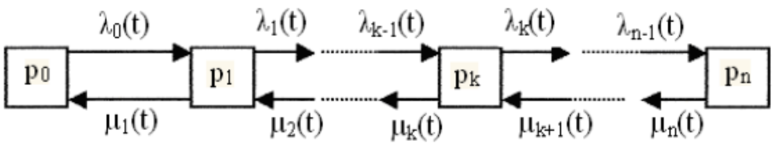


Figure 1: A model of flows of probable states of a restorative redundant system

The probability that the system will remain in state k during the stationary period of its operation is usually called the marginal or final probability. Physically, pk means the fraction of time that the system remains in state k between scheduled repairs

By definition, the random process in question can increase by 1, decrease by 1, or remain the same. Moreover, when taking it, it will be intertwined ergodically, i.e. independent of time.

Under the circumstances, the operation of this system in time can be modeled using the Markov model of the "birth and death" process.

This process can be determined by the number of idle taps i at any given time.

Since the system transitions from one state i to the second j in a finite time, the process can be considered transitive., The process is transitive, the system is homogeneous in the stationary mode of crane operation, since the intensity and probability of transition from one state i to another j does not depend on at what point in time this transition occurred.

Based on the above properties, it can be argued that the process is ergodic Markov random. with the final (time-independent) probabilities P_i of the system remaining in state *i*.

In the stationary mode of operation of the crane, the system is characterized by uniformity, since the abrupt and changeable transitions between different states directly depend on the time at which the transition itself occurs.

In relation to the system under consideration, the final probabilities of p_k are determined by a system of homogeneous algebraic equations [7,23]:

$$\left.\begin{aligned} 0 &= \mu_1 P_1 - \lambda_0 P_0 \\ 0 &= \lambda_{k-1} P_{k-1} + \lambda_{k-1} P_{k+1} - (\lambda_k + \mu_k) P_k \\ 0 &= \lambda_{k-1} P_{N-1} - \mu_N P_N \end{aligned}\right\} \quad (2)$$

The values of the availability coefficient k_g are accepted according to the manufacturer's recommendations or based on operational experience.

However, if you substitute the data of the availability coefficient of a single crane into the time formula, the results obtained will be overestimated.

Therefore, it should be replaced by the fleet factor k_{pp}.

Because, in the definition of this process, the number of idle machines *i* at any given time of operation is *t*.

Because, obviously, this number is the number of working cranes:

$$n_c = \sum_{i=0}^{n-1} (n-1) P_i \quad (3)$$

The average number of operational machines n_p at any given time between repairs is a parameter of a random process. operation of machines.

S - corresponds to the number of non-operational cranes, i.e. those that are in need of repair after failure.

Moreover, the number of operational machines

Then, the coefficient can be written as

$$k_{pp} = \frac{1}{n}\sum_{i=0}^{n-1}(n-1)P_i \quad (4)$$

Average operating time of cranes

$$t_v = T_b\sum_{i=0}^{n-1}(n-1)P_i \quad (5)$$

Where λ - is the total failure rate

μ - the total recovery rate (Fig.1).

In the stationary period of operation, the failure λ and recovery rates μ are constant and equal

$$\lambda = \frac{1}{T_0}$$

$$\mu = \frac{1}{T_v}$$

where is T_0 -the average operating time for failure,

Tv - the average time for the machine to recover

The system is homogeneous during the stationary period of crane operation, since the intensely variable transitions from one state to the next depend on the time at which the transition occurs.

The limiting probabilities of states can be found from the system of equations

$$\left.\begin{aligned} 0 &= \mu_1 P_1 - \lambda_0 P_0 \\ 0 &= \lambda_{k-1} P_{k-1} + \lambda_{i+1} P_{i+1} - (\lambda_i + \mu_i) P_i \\ 0 &= \lambda_{n-1} P_{n-1} - \mu_n P_n \end{aligned}\right\} \quad (6)$$

It is convenient to write the solution of such a system in the form of animals [21-26]:

$$P_i = \frac{\beta_1}{\sum_{i=1}^{n} n} \quad (7)$$

When

$$\beta_i = \begin{cases} 1 & when \quad i = 0 \\ \prod_{k=1}^{i} \frac{\lambda_{k-1}}{\mu_t} & when \quad 0 < i \le n \end{cases} \quad (8)$$

Then the crane readiness coefficients will take the form [21-26] therefore

$$K_g = \frac{1}{\left(\frac{\lambda}{\mu} + 1\right)} \quad (9)$$

therefore (10)

$$\frac{\lambda}{\mu}=\left(\frac{1}{K_g}-1\right)$$

Using formulas, it is possible to find a fairly reliable forecast of the total operating time of a fleet (group) of identical cranes, taking into account their availability coefficients (number of repair posts)

When planning the operation of transshipment complexes, it is necessary to know the probability of the number of idle machines out of the total at any given time between scheduled repairs.

The probability that at any given time, between scheduled repairs, m cars in a fleet of n cars will be operational [23]

$$P(a \geq m)=\sum_{i=0}^{i=n-m} P_i \qquad (11)$$

Where P is determined by the above formulas.

It should be noted that skipping the coefficient K allows us to determine only the minimum * (lower) probability bound. Therefore, it can be used in cases where only this coefficient is known.

If there is information about the patterns of crane equipment failures and the allocation of time required for its restoration, it is advisable to use a more detailed approach described in [15,19-21].

It is noted that the use of the readiness coefficient of a separate crane to assess the fleet leads to an overestimation of the indicators. Therefore, a fleet readiness factor was introduced, taking into account the number of repair posts and the likelihood of maintenance queues. The model takes into account that the number of cranes that are idle at the same time is a random variable, depending on the failure rate and recovery rate.

Probabilistic state flow modeling is a powerful tool for analyzing and optimizing such systems. To solve such systems (6) we can use standard numerical methods for solving equations, which are implemented in the software products EXCEL, MATHCAD, MATHLAB and others.

The analysis of the results allows you to identify bottlenecks in the redundancy structure, evaluate the impact of different recovery strategies on system reliability, and optimize redundancy parameters to achieve the required reliability levels at minimal cost.

After simple transformations we obtain the formula for determining the park availability factor.

$$K_{pm}=P_0\left[1+\sum_{i=1}^{r}\left(\frac{1}{K_g}-1\right)^i \frac{(n-i)!}{[(n-i)-i]!i!}+\sum_{i=r+1}^{n-1}\frac{(n-1)!}{[(n-1)-i]!r!r^{i-r}}\right] \qquad (12)$$

When n - the number of cranes in the fleet:

r - the number of repair crews:

K_g - the readiness coefficient of an individual machine.

It should be noted that the above formula can be used only under the condition of partially limited restoration, when the number of repair posts is less than the number of cranes and a queue for restoration is possible.

In the case of a complete limited recovery, when there is only one post (r=1) [21-27]:

$$K_{pm}^{0} = P_0^0 \left[1 + \sum_{i=1}^{n-1} \left(\frac{1}{K_g} - 1 \right)^i \frac{(n-i)!}{[(n-i)-i]!i!} \right] \tag{13}$$

$$P_0^0 = \frac{1}{\left[1 + \sum_{i=1}^{n} \left(\frac{1}{K_g} - 1 \right)^i \frac{(n-i)!}{[(n-i)-i]!i!} \right]} \tag{14}$$

The obtained dependencies make it possible to predict the probability, the availability coefficient for the crane fleet, over the estimated period,

For the case of unlimited recovery, when there is no queue of machines for recovery [21-27]:

$$K_{pm}^{v} = P^{v} \left[1 + \sum_{i=1}^{n-1} \left(\frac{1}{K_g} - 1 \right)^i \frac{(n-i)!}{[(n-i)-i]!i!} \right] \tag{15}$$

$$P_0^0 = \frac{1}{\left[1 + \sum_{i=1}^{n} \left(\frac{1}{K_g} - 1 \right)^i \frac{n!}{(n-i)!i!} \right]} \tag{16}$$

With these formulas available, it is possible to determine the average number of serviceable machines (n) at any given time between scheduled maintenance and repairs.

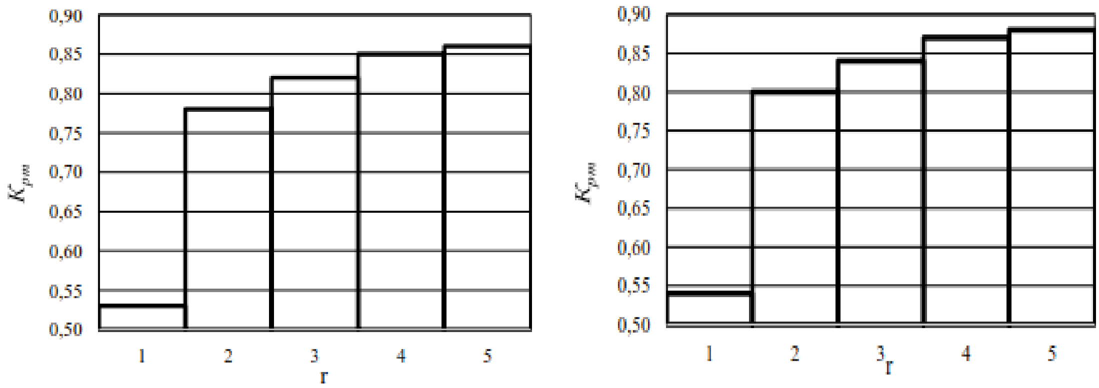
The model of flows of probable states is a mathematical description of the system (12)-(16), can be implemented in Pascal, Piton, etc. environments, used for the analysis of reliability of a wide class of recoverable redundant systems. By varying the model parameters (λ, μ, the number of elements), it is possible to investigate the influence of various factors on the reliability of the system and optimize its structure to meet the specified requirements.

The port authority carefully monitored the condition of all cranes, regularly conducting preventive inspections and repairs. Experienced mechanics and electricians, armed with advanced tools, worked tirelessly to keep the equipment in perfect condition.

However, even with the most careful measures, the availability coefficient could be subject to fluctuations. Unforeseen breakdowns caused by natural wear of parts or exposure to an aggressive marine environment could temporarily disable the crane. In such cases, high-speed crews responded to the accident, eliminating malfunctions with minimal loss of time.

Figure 2 shows the results of calculations using the formula (12), depending on the number of repair posts k for the installation of 5 cranes, with the readiness coefficient of each of them k_g=0,86 (a) and k_g=0,88 (b).

The analysis of **Fig.2** showed that: when using 1 post, the readiness coefficient of a group of cranes decreases to a value of 0.53 (0,54) (almost twice), which will create constant queues in idle time due to repairs and restoration. With an increase in the number of posts, the fleet readiness factor increases significantly. In all cases, the task should be solved taking into account the real cost possibilities for the purchase of equipment, posts and profits from reducing crane downtime due to sudden failures.



a) b)

Figure 2: The dependence of the availability coefficient of the crane fleet kpm on the number of repair posts r and availability coefficients kg=0,86 (a) and kg=0,88 (b).

Regular maintenance and timely repairs necessary to maintain a high availability factor reduce the risk of accidents and accidents.

Awareness of the importance of this indicator and active actions to improve it will lead to significant economic and qualitative results in the use of gantry cranes.

The dependence of the error of the availability coefficients for 5 cranes calculated for the average and Kp values = 0.86...0.87 values is shown in **Fig.3**.

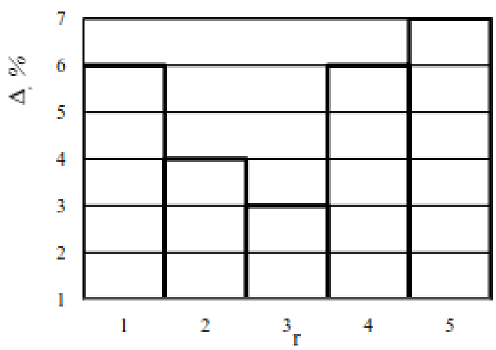


Figure 3: The dependence of the error of the availability coefficients for 5 cranes calculated for the average and Kp values = 0.86...0.87.

Increasing the number of repair posts to 3 or more does not lead to a significant increase in Kpm.

Determining the optimal number of maintenance posts for gantry cranes is an important task that affects the operational availability of equipment and the efficiency of cargo handling in the port. An insufficient number of posts will lead to downtime and service delays, while an excessive number will lead to unjustified investments and inefficient use of resources.

On average, repair posts are recommended — from 2 to 6 — to ensure round-the-clock maintenance and rapid response [23]. However, it is better to check the exact number with the project documentation or specialists, because each installation is individual.

Ultimately, determining the optimal number of repair posts is a difficult task that requires a comprehensive analysis of all these factors.

As you can see, the calculated number of repair posts is within the recommended limits.

The use of mathematical modeling and statistical analysis methods makes it possible to more accurately assess the need for repair posts and optimize the maintenance costs of crane equipment.

It should be noted that the higher the intensity of operation, the higher the need to increase the number of repair posts for prompt troubleshooting.

Highly qualified personnel can perform work faster and more efficiently, which can reduce the need for a large number of repair posts.

Thus, the optimal number of repair posts will vary depending on the specific conditions, however, having at least two posts (current and major repairs) is standard practice.

As can be seen from Fig.3, the calculated values of the availability coefficients for the average and actual values for 5 cranes differ slightly. The error values obtained do not exceed 7%, which is acceptable for practical calculations.

The use of high-quality and reliable components such as motors, gearboxes, brakes and electrical systems increases the overall reliability of the crane.

It should be noted that the introduction of modern automation and control systems can also significantly increase the availability factor. Smart technologies are able to optimize the operation of cranes, minimizing the human factor and increasing the accuracy of operations.

The calculations showed in Fig.3 that with one repair post, the fleet availability coefficient decreases to 0.53, which almost doubles the downtime due to repairs. Increasing the number of repair posts significantly increases the availability factor, reducing the likelihood of downtime and optimizing operating costs.

The use of computer models and reliability analysis methods makes it possible not only to accurately assess the condition of the gantry crane fleet, but also to optimize maintenance resources, which is critically important for improving the efficiency of port complexes.

5. Conclusion

When predicting the reliability of a fleet of equipment, including gantry cranes, it is advisable to use a generalized fleet availability coefficient that reflects the overall condition of all units of equipment. When designing a fleet, it is necessary to take into account economic parameters, including projected maintenance costs and potential profits from operation.

For a fleet of identical cranes, the availability coefficient values can be approximated by the availability coefficient of one crane, provided there are sufficient repair posts to ensure timely maintenance and minimize downtime.

If the crane fleet consists of equipment with different availability coefficients, it is advisable to use an average value, since practice shows that the final indicator will differ slightly.

Thus, the use of a generalized availability coefficient and the use of averaging methods make it possible to effectively model the reliability of a crane fleet, which is important for optimizing resources and improving maintenance efficiency in the context of the digital transformation of industrial enterprises.

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Declaration on Generative AI

The authors have not employed any Generative AI tools.

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