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Simulation Model of Hydraulic System States for Ship Cranes

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Abstract: The aim of this research is to devise a continuous simulation model for predicting ship crane failures to increase their reliability and reduce unplanned downtime during cargo loading and unloading operations. To predict the condition of the hydraulic system, a database from the GALIOT software package was used for carrying out maintenance on cranes at m/v "O" over a period of 120,000 working hours. In the research, fault tree analysis (FTA) was used to identify causal relationships between system failures and basic events, while the Markov mathematical model was used to model the system state and predict transitions between different failure states. A system dynamics simulation model was developed to simulate the behavior of a system using POWERSIM PowerSim Constructor 2.5.d (4002), and regression analysis was performed to analyze the simulation results and understand the relationships between dependent and independent variables. The results show that a model for predicting failures in the hydraulic motors and pumps of ship cranes was developed, and the Markov model makes it possible to estimate the frequency of transitions between states under the condition that the sum of reliability equals one. The simulation model shows high reliability of the cranes and a constant frequency of failures throughout the 120,000 operating hours, while the regression analysis confirms the validity of the simulation model and shows a strong correlation between the analyzed variables. These models are used to improve the planning of ship crane maintenance, reduce unplanned downtime, and predict and promptly detect failures, which overall minimizes maintenance costs and failures.

Keywords: ship cranes; system reliability; fault tree analysis (FTA); Markov model; simulation model; GALIOT software package

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1. Introduction

Designing a bulk carrier requires taking into consideration the type and number of deck cranes to be installed onboard. The cranes should be reliable and have a minimal possibility of failure, while the ship crew and superintendent are expected to predict possible failures and prevent them.

Papers [1–4] are typical papers for this area of research. Special attention is given to researching failures occurring during the exploitation of ship cranes; hence, the paper [1] offers recommendations to avoid unforeseen failures, damages, and breakdowns. Suggestions for proper and timely detection of possible failures and maintenance are also given. The main focus is on safety during cargo operations, maintenance, and the repairing of ship cranes. The literature review reveals additional relevant topics, as shown in the paper [2], dealing with training, reliability, maintenance, handling, control systems, mechanical systems, structural damage, and the inspection of ship cranes.

The Markov chain theory or the reliability model in the paper [3] is used to evaluate associated risks and expenses resulting from delays due to system failures. The Markov model not only evaluates economic consequences (costs) due to crane failures but also helps draw attention to critical aspects during the exploitation of cranes. Some methods that incorporate efficient solutions are a combination of mathematical models obtained from Markov chains and system dynamics, which have been proven to be excellent for monitoring and predicting the system status, as shown in the paper [4].

One of the maintenance decision-making models is the Integrated Maintenance Decision Making Model (IMDMM) for the exploitation of cranes and is based on the concept of the Integrated Decision Making Model [5]. This model aims to improve operational efficiency and crane operation, as well as reduce the risk of gantry crane inefficiency (GCI) on the basis of the digital twins (DT) concept for carrying out maintenance. This paper [5] further evaluates the risk of crane operation based on the Monte Carlo simulation model elaborated using Markov chains, while the IMDMM was used for optimization and supported by optimization algorithms. When endeavoring to meet planning requirements for fuel and lubricating oil systems in terms of maintenance schedules for container cranes (CC) as described in the paper [6], where maintenance planning is of extreme importance and should be aligned with the CC work schedule, with due attention paid to avoiding maintenance activities that interfere with cargo loading and unloading schedules. This paper utilizes the system dynamics modeling method to model system performance and determine the minimum reliability and availability index values, which stem from the schedule for proper container crane maintenance. The aim of many papers addressing this area of research, among which is the paper [7] presenting the crane maintenance model aiming to avoid delays, is maximum safety of the crew who handle ship cranes and tailoring of maintenance to the crew who carry out maintenance works. The primary aim of the paper [7] is based on crane maintenance in ports performed by ship crews, with great reliance on crew education and training, which in turn enables them to solve issues promptly and efficiently.

This working concept (Figure 1) ensures that causes are detected and dealt with while preventing or minimizing the consequences. The primary goal is to elaborate a continuous simulation model with feedback within a given period of time, which would anticipate all system states in a given future time, using the methods and analysis shown in Figure 1.

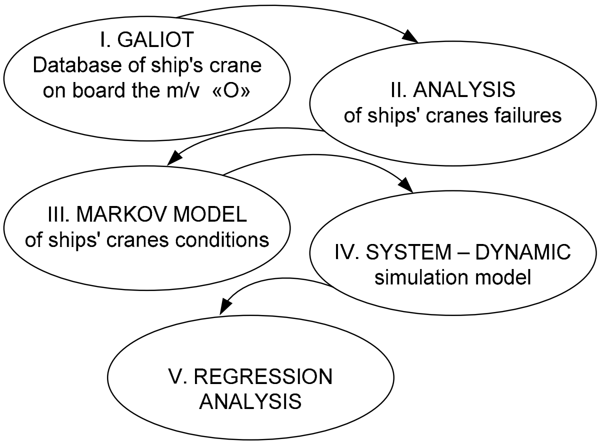


Figure 1. The sequence of methods and analyses used in the paper.

Unlike the previous solutions, this paper includes more methods and analyses (Figure 1), offering a more acceptable solution to defining, monitoring, analyzing, and optimizing preventive maintenance of ship cranes. Besides optimization, education, and training, the derived model also ensures the safety of the crew working on the cranes.

This paper defines and elaborates a system dynamics simulation model capable of anticipating expected ship crane states in the future, thus, preventing major failures or breakdowns of ship cranes. Meeting this goal requires identifying the advantages and quality obtained by implementing the simulation model using the Markov mathematical model, which, in tandem with system dynamics, enables monitoring of ship crane states at any time.

This paper adopted the FTA method utilizing data from the ship crane maintenance software GALIOT to anticipate possible future states of ship crane systems, i.e., states causing breakdowns [8,9]. The FTA method was used as the basis for working out the

Markov model, which, in turn, was used to construe the system dynamics simulation model. The results obtained were analyzed using simulation and regression analysis. The sequence of methods and analyses is shown in Figure 1.

Given that ship cranes operate in harsh environments, there is definitely a need to make timely predictions as to when a failure may occur, thus, ensuring smooth crane operation during loading and unloading operations. A combination of all methods to be used in the paper assisted in providing a quality model and provided better possibilities for further application and upgrades.

2. Methods Analyzing Ship Crane States

Ensuring the best analyses of data collected and defining the states as precisely as possible relied on various methods for deriving a quality simulation model.

2.1. Crane State (Failure) Analysis Using the FTA Method

The FTA method uses deductive analysis, which studies failures and identifies relationships between system failures and top events (i.e., detecting causes of events). It is a system state analysis technique (i.e., unwanted system states), and when applying the FTA method, defining the top event and its cause is of utmost importance.

The majority of failures on ship cranes can be anticipated before they occur and, therefore, prevented. Some failures, however, cannot be foreseen because they are accidental failures and happen during the exploitation of ship cranes.

Fault tree analysis (FTA) is a method for diagnosing and analyzing the safety and reliability of complex ship systems. When using the FTA method, such systems are presented in a diagram to evaluate the reliability of ship cranes while operating.

This paper utilizes the FTA method to construct a diagram, i.e., a fault tree, that models the states causing a top fault, i.e., unwanted breakdown or failure. The fault tree provides a graphic illustration of relationships between events and their impact on the top event. This analysis incorporates a deductive method, which is necessary for ship system reliability models as it monitors the frequency of failures due to top events, i.e., the sequence of events to the very bottom.

Constructing the fault tree requires the following steps:

1. Defining and describing the ship system;
2. Becoming familiar with the limitations of the system and goals;
3. Defining the top event;
4. Utilizing the ship system database, which usually includes a history of the system state from the maintenance program package used to construct the fault tree.

The fault tree consists of an event symbol, logic gates, and symbols for transferring the diagram structure so as to further develop the tree at another location or page. The logic symbols are used to define the interdependence and relationship between events. An example would be the OR gate used if an input event occurs and the AND gate if all the input events occur. If the fault tree is complex, it is divided into several smaller trees that describe the subsystems of the complex ship system, making analysis and interpretation easier.

The paper analyses the target event on the part of a ship crane, involving:

a. failure of the hydraulic engine, and
b. failure of the hydraulic pump.

These two failures in the hydraulic system are analyzed due to their complexity, sensitivity, and key importance in the operation of the ship crane. Every complex ship system, including the hydraulic system, due to the sensitive nature of the components and exposure to the sea environment, is prone to damage and may subsequently cause delays in the ship crane performing unloading and loading operations, including financial losses. A solution to prevent or minimize these losses is given in this paper.

Having analyzed the system and its states and using the FTA method, it becomes an ideal situation to construct the Markov model.

2.2. Markov Mathematical Model

The Markov model is often used to analyze system states as, at any moment, the system can remain in the same state or transit into another state, which is called transition. When using the Markov model, the possibilities of the model are solely dependent on the present state and not on the past states, which is why they are commonly called models "without memory" [4]. The greatest advantage and best use of the Markov model is the possibility of creating a large variety of possible system states.

2.3. System Dynamics Simulation Model

Nowadays, system dynamics has become widespread in science as an efficient simulation tool when combined with simulation software such as PowerSim Constructor 2.5.d (4002) POWERSIM [10–16]. The actions used to elaborate the system dynamics model are given in the following order:

1. Defining the problem;
2. Conceptualization of the system;
3. Constructing the model in the POWERSIM PowerSim Constructor 2.5.d (4002) simulation program;
4. The behavior of the model when changing the initial conditions;
5. Testing the validity of the model;
6. Analysing the obtained results.

The model is described using quantitative and qualitative simulation modeling, leading to the optimization of the dynamic system and the entire process, which is completely based on a mental-verbal model.

System dynamics are utilized in this paper to define the following models for further research:

1. Mental-verbal model;
2. Structural model;
3. Mathematical model;
4. Simulation model using the POWERSIM PowerSim Constructor 2.5.d (4002) computer program.

Modeling the system dynamics was achieved using the visual modeling tool POWERSIM to explore the system further.

2.4. Regression Analysis of the Results Obtained from the System Dynamics Simulation Model

Regression analysis is used to follow up and deduce why the dependent variable is affected by changes in other independent variables or factors [11,12,17]. Regression analysis estimates the relationship between a dependent variable and one or more independent variables, i.e., the regression function. Simple, multiple, linear, and non-linear regressions are used in regression analysis, and in this paper, in particular, a linear regression is used where the regression function is defined with a final number of parameters. The correlation between the two variables is described as:

1. Linear correlation: $y = ax + b$.
2. Curved line correlation: $y = ae^{bx}$.

In regression analysis, the dispersion diagram is used as a goal, and on the basis of the dispersion, a conclusion about the form is made (defines the mathematical function representing the deterministic part of the regression model), the direction (indicates whether the connection is positive or negative), and the strength of the connection (analyses random variables of the regression model).

In this paper, regression analysis was used to explore correlations between variables obtained from the simulation model, i.e., it analyses the relationship between the dependent variable and one or more independent variables, thus, giving the mathematical equation. A linear and exponential correlation was used to determine the relationship between the dependent and independent variables obtained from simulation model data analysis as it best fits the simple regression model.

3. Results and Discussion

3.1. FTA Method for Analyzing Ship Crane Failures

Data from the maintenance program package installed on board was used to describe complex ship systems, including measurement values and system statuses updated daily. For example, the ship crane on board m/v "O" was used, where its top was "SHIP'S CRANE OUT OF ORDER", while a fault tree was constructed for major failures that put the crane out of order.

The ship crane fault tree is divided into two main systems where failures most frequently occur and put the crane out of order. These failures are (1) faults on the hydraulic engine and (2) faults on the hydraulic pump, as shown in Figure 2.

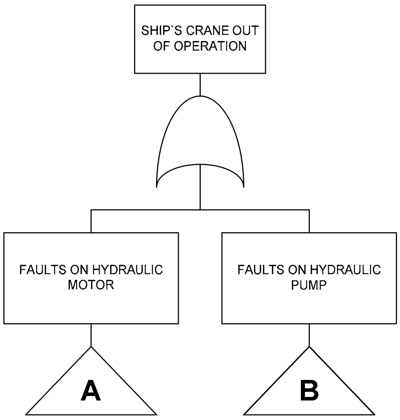


Figure 2. Fault tree for the ship crane.

Frequent failures putting the crane out of order relate to the hydraulic system or the hydraulic motor (Figure 3) and the hydraulic pump (Figure 4), whereas failures rarely occur on the actual crane structure.

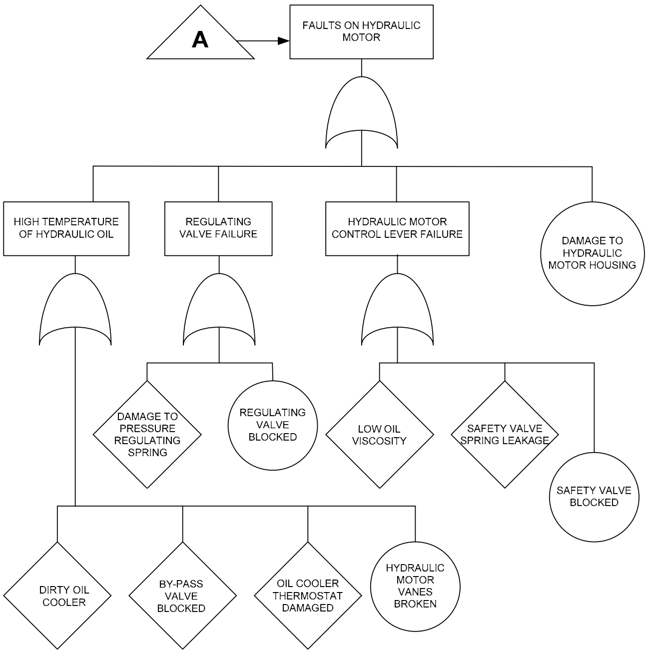


Figure 3. Fault tree for the ship crane hydraulic motor.

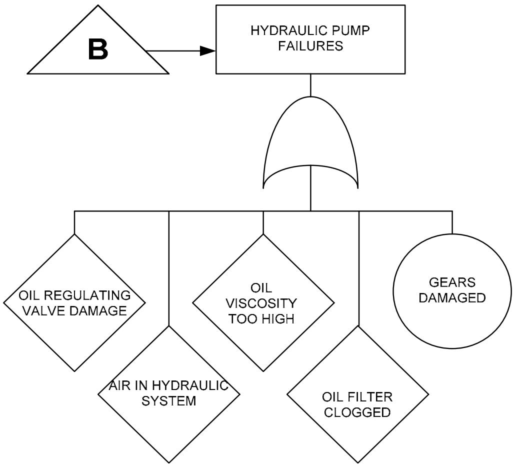


Figure 4. Fault tree for the ship crane hydraulic pump.

On these systems, as shown in Figures 3–5, the faults can be total, when the crane cannot fulfill its required purpose, or partial, when crane operation is compromised.

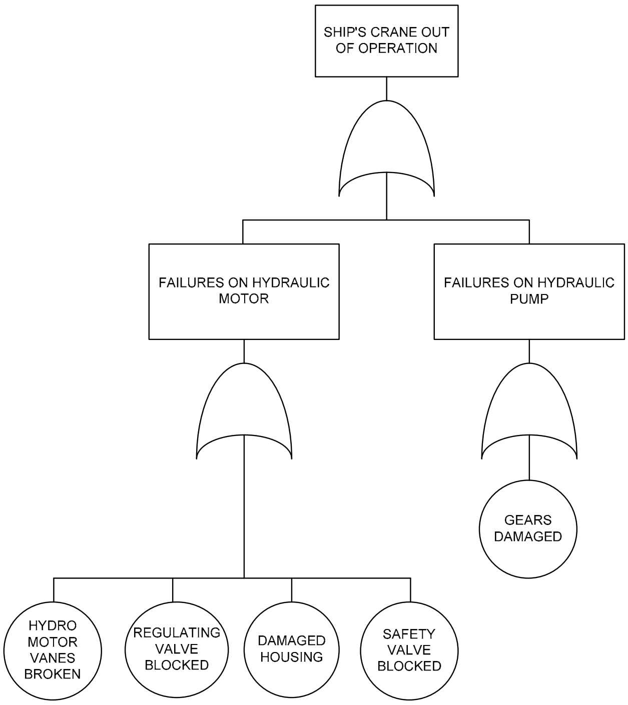


Figure 5. The fault tree with total faults that put the crane out of order.

Figure 3 shows the total faults causing faults on the hydraulic motor and consequently putting the crane out of order. Total faults include:

1. Damage to the hydraulic motor housing;
2. Blocked control valve;
3. Broken hydraulic motor vanes;
4. Blocked safety valve;
5. Damaged hydraulic pump gears.

Figure 4 shows only a particular total fault, i.e., damaged gears, which halted the operation of the entire hydraulic system and the crane itself.

The states mentioned in Figures 2–4 are used to make a fault tree incorporating total faults affecting the top event, i.e., failure of the ship crane (Figure 5).

To work out the mathematical model using Markov chains, the fault tree with a total fault on the ship crane will be used (Figure 5).

3.2. Mathematical Model Described Using the Markov Model

The Markov model was elaborated by defining and analyzing data obtained while monitoring state transition dynamics (from one state to another) of the selected systems on ship cranes over a given period of time.

Marks (0, 1, 2, 3, 4, 5, 6) on the Markov model in Figure 6 have the following meanings:

1. Ship crane state: “in operation”;
2. Out of order state: “control valve blocked”;
3. Out of order state: “vanes on hydraulic motor broken”;
4. Out of order state: “safety valve blocked”;
5. Out of order state: “hydraulic motor housing damaged”;
6. Out of order state: “hydraulic pump gears damaged”;
7. Out of order state: “ship crane out of order”.

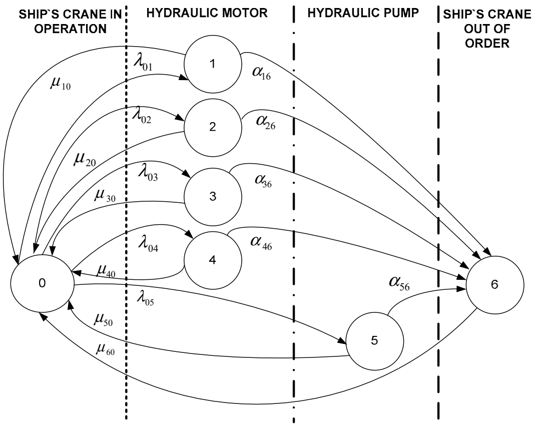


Figure 6. Markov model for ship cranes on m/v “O”.

The frequency of transition from one state to another state until reaching a total fault in the ship crane interrupts unloading operations as well as returning to the state “in operation” (repair) [4,10–12,14].

Frequency of transition from state “0” to “out of operation” (Equation (1)):

$$\lambda 0n = Lam\_0n \quad n = 1, 2, 3, 4, 5 \tag{1}$$

Frequency of transition from “out of order” to “in operation” “0” (Equation (2)):

$$\mu_{n0} = Mu\_n0 \quad n = 1, 2, 3, 4, 5, 6 \tag{2}$$

Frequency of transition from “out of order” to “6”, indicating the ship crane is out of order (Equation (3)):

$$\alpha_{n6} = Alpha\_n6 \quad n = 1, 2, 3, 4, 5 \tag{3}$$

Reliability of the technical system (Equation (4)) [4,8,9]:

$$Rn(t) = \mathrm{e}^{-\lambda_{0n} t} \quad n = 0, 1, 2, 3, 4, 5, 6. \quad \text{where } n = \text{state number} \tag{4}$$

A ship crane is a complex technical system consisting of systems and subsystems, each directly affecting the operation of the crane. Should any of the systems or subsystems fail, the crane is immediately out of order. The paper describes the two most important systems, i.e., the hydraulic motor and hydraulic pump.

Besides the hydraulic motor and pump, the hydraulic system also consists of additional components playing a smaller part in eventual crane failure because they can easily be replaced, or the crane can operate at a reduced capacity. Each "out of operation" state (1–5) directly affects the crane and leads to the crane becoming out of order (6). After repairing the hydraulic system, the ship crane moves from the "out of order" state and returns to the 0 or "in operation" state.

Figure 6 shows the Markov mathematical model with states of ship crane systems and subsystems during exploitation. The Markov mathematical model shows system states in the form of linear differential Equations (4)–(11).

State 0:

$$\begin{aligned}\frac{\mathrm{d}P_0(t)}{dt} &= -(\lambda_{01}+\lambda_{02}+\lambda_{03}+\lambda_{04}+\lambda_{05})\,P_0(t)+\\ &+\mu_{10}P_1(t)+\mu_{20}P_2(t)+\mu_{30}P_3(t)+\mu_{40}P_4(t)+\mu_{50}P_5(t)+\mu_{60}P_6(t)\end{aligned} \tag{5}$$

State 1:

$$\frac{\mathrm{d}P_1(t)}{\mathrm{d}t} = \lambda_{01}P_0(t) - (\mu_{10}+\alpha_{16})P_1(t) \tag{6}$$

State 2:

$$\frac{\mathrm{d}P_2(t)}{\mathrm{d}t} = \lambda_{02}P_0(t) - (\mu_{20}+\alpha_{26})P_2(t) \tag{7}$$

State 3:

$$\frac{\mathrm{d}P_3(t)}{\mathrm{d}t} = \lambda_{03}P_0(t) - (\mu_{30}+\alpha_{36})P_3(t) \tag{8}$$

State 4:

$$\frac{\mathrm{d}P_4(t)}{\mathrm{d}t} = \lambda_{04}P_0(t) - (\mu_{40}+\alpha_{46})P_4(t) \tag{9}$$

State 5:

$$\frac{\mathrm{d}P_5(t)}{\mathrm{d}t} = \lambda_{05}P_0(t) - (\mu_{50}+\alpha_{56})P_5(t) \tag{10}$$

State 6:

$$\frac{\mathrm{d}P_6(t)}{\mathrm{d}t} = \alpha_{16}P_1(t)+\alpha_{26}P_2(t)+\alpha_{36}P_3(t)+\alpha_{46}P_4(t)+\alpha_{56}P_5(t)-\mu_{60}P_6(t) \tag{11}$$

Initial conditions determined at the time t = 0 are given in Equation (12):

$$P_0(0)=1;\quad P_1(0)=0;\quad P_2(0)=0;\quad P_3(0)=0;\quad P_4(0)=0;\quad P_5(0)=0;\quad P_6(0)=0 \tag{12}$$

The condition defined by the identity equation (Equation (13)) must be fulfilled at all times:

$$P_{uk} = P_0+P_1+P_2+P_3+P_4+P_5+P_6 = 1 \tag{13}$$

The stationary solution to the linear differential equations for the system and relating to the Markov model [4,10,11,13] is required (Equation (14)):

$$\frac{dP_n(t)}{dt} = 0; \qquad n = 0,1,2,3,4,5,6 \tag{14}$$

The solution to the Markov model for a stationary process state, representing a system of linear equations with unknown factors, is used to determine probabilities for stationary ship cargo crane states, as shown in Equations (15)–(17).

$$P_0(t) = \frac{\mu_{60}}{\sum\limits_{i=1}^{5}\lambda_{0i}\dfrac{\mu_{60}+\alpha_{i6}}{\mu_{i0}+\alpha_{i6}}} \qquad i=0,1,2,3,4,5 \tag{15}$$

$$P_6(t) = \frac{1}{\mu_{60}}[\alpha_{16}P_1(t)+\alpha_{26}P_2(t)+\alpha_{36}P_3(t)+\alpha_{46}P_4(t)+\alpha_{56}P_5(t)] \tag{16}$$

$$P_j(t) = \frac{\lambda_{0n}P_0(t)}{\mu_{n0}+\alpha_{n6}}; \quad j=0,1,2,3,4,5; \quad n=0,1,2,3,4,5 \tag{17}$$

When using the program package GALIOT [8,9] for the maintenance of a ship diesel engine, the model parameters are calculated, as well as the number of transitions from state into state and time in individual states of a ship crane.

The obtained data are used to calculate mean times:

$\overline{T}_{ij}$—mean time in state i until transitioning to state j.

To calculate the frequency of transitions from state to state, the table containing calculated mean times for individual states of a ship crane is used. The mean time is calculated using the frequency of failures, i.e., the frequency of transitions from state to state. Based on this exponential distribution, the frequencies of failures $\lambda(t)$ or transitions are constant.

The frequency of failures $\lambda(t)$ is constant and is calculated using Equation (18), where the frequency of transitions from the "in operation" state to the "out of order" state (λ_{0n} for n = 1, 2, 3, 4, 5, and 6) is shown (Equation (18)) [4].

$$\lambda(t) = \frac{1}{\overline{T}_{ur}} = \lambda_{0n} \tag{18}$$

The frequency of transitions from any "out of order" state into a "crane out of order" state, given that the failures of these systems halt crane operation when any system is "out of order" $\alpha(t)$ and does not return into the "in operation" state, is calculated using Equation (19) [4,14], where: α_{n6} = 1, 2, 3, 4, and 5.

The frequency of transitions from any "out of order" state into a "crane out of order" state, given that failures in these systems halt crane operations when any system is "out of order" and does not return to the "in operation" state, is calculated using Equation (19), where:

$$\alpha(t) = \frac{1}{\overline{T}_{st}} = \alpha_{n6} \tag{19}$$

Frequency of repair $\mu(t)$ is constant and is calculated using Equation (20) [4]:

$$\mu(t) = \frac{1}{\overline{T}_{uk}} = \mu_{n0} \qquad n = 6 \tag{20}$$

Tsrur_n, or mean time in operation until the system enters state n (number of states n = 1, 2, 3, 4, 5, and 6), is defined based on system reliability (Equation (4)) [4,10–12] and the frequency of system failures λ_{0n}:

$$Tsrur\_n = \overline{T}_{ur\_n} = \int_0^\infty Rn(t)\,\mathrm{d}t \int_0^\infty e^{-\lambda_{0n}t}\mathrm{d}t, \qquad Tsrur\_n \text{ or } \overline{T}_{ur\_n} \tag{21}$$

Table 1 shows the frequency of transitions from state to state in case of a failure λ_{0n}, transition to the state "in operation" μ_{0n}, total failure, crane state "out of order" $\alpha_{\text{n}6}$, and probabilities for each state P on the ship cranes. The values were obtained from the GALIOT program package database for the m/v "O" over a period of 80.000 working hours. Consequently, the scenario accounting for 120.000 working hours for the simulation was given to predict the reliability of the ship cranes in the respective period.

Table 1. Frequency of transitions from state to state in case of failure.

λ_{01}	μ_{10}	λ_{02}	μ_{20}	λ_{03}	μ_{30}	λ_{04}	μ_{40}
0.0000753	0.0147059	0.0000251	0.0066667	0.0000502	0.016	0.0000125	0.02
λ_{05}	μ_{50}	α_{16}	α_{26}	α_{36}	α_{46}	α_{56}	μ_{60}
0.0000125	0.00333	0.0147059	0.0066667	0.016	0.02	0.0333	0.000009
P_0	P_1	P_2	P_3	P_4	P_5	P_6	P_{uk}
0.1	0.0002	0.0001	0.00016	0.00003	0.00019	0.9	1.0

All calculations shown in Table 1 were done using time in operation t_{0n}, time out of operation t_{n0}, and time of transition into ship crane total failure state $t_{\mathrm{n}6}$, where *n* = 1, 2, 3, 4, 5, and 6. When describing the transition from state to state (out of order, in operation, and total failure of ship crane), failures must be random and independent. One of the conditions is that values of time until system failure and time duration of repairs are known. Monitoring over a prolonged period of time indicates that the time values are actually mean times (Equation (22)) to calculate the frequency. This approach is applied in each period, given that components can be renewed [4]:

$$\overline{T}_{0n} = \sum \frac{t_{0n}}{n_{0n}} \tag{22}$$

The same is obtained for the mean time of the "out of order" state (which is the mean time for repairs in the given interval) (Equation (23)) [4]:

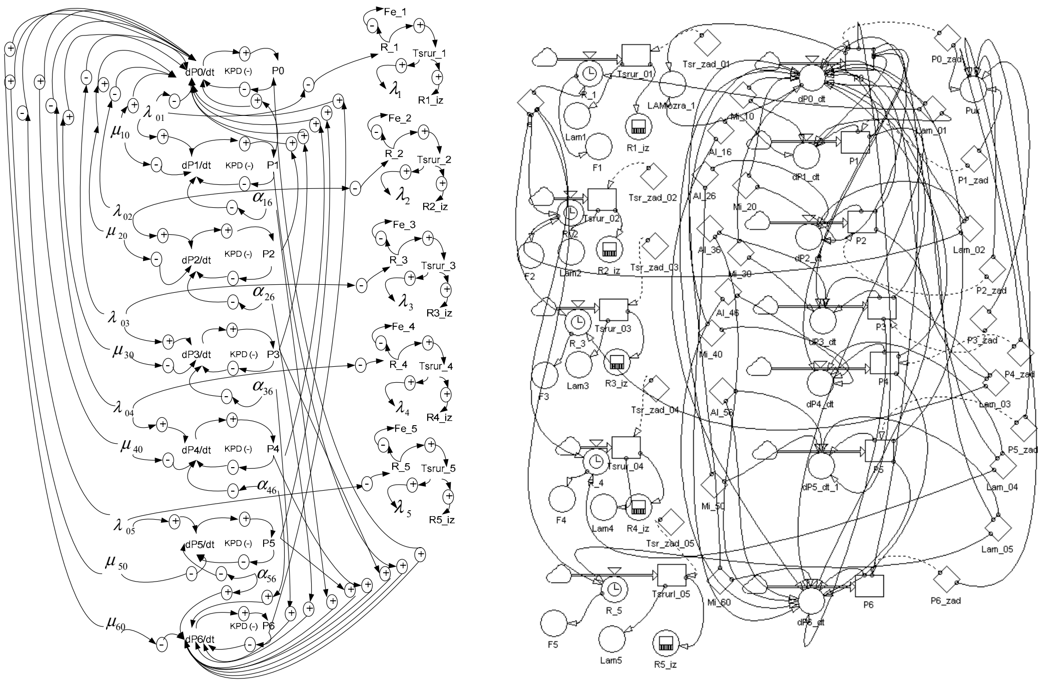
$$\overline{T}_{n6} = \sum \frac{t_{n6}}{n_{n6}} \tag{23}$$

Parameters for frequencies of transitions from one state to another in the Markov model are calculated using data from Table 1 and using the given (for frequency of transitions from state to state) Equations (10)–(14).

The values for individual states are calculated using the Equations (15)–(19).

3.3. System Dynamics Simulation Model for Ship Crane Reliability

By applying the mathematical model described in Markov chains for reliability analysis, a dynamic structural model was devised and presented in Figure 7a. It shows how the reliability of a hydraulic pump and hydraulic motor on crane systems was monitored, given that these two systems are the most crucial systems affecting the reliability of ship cranes, and they are liable to failure caused by the aggressive environment in which they operate [15,16].



(**a**) (**b**)

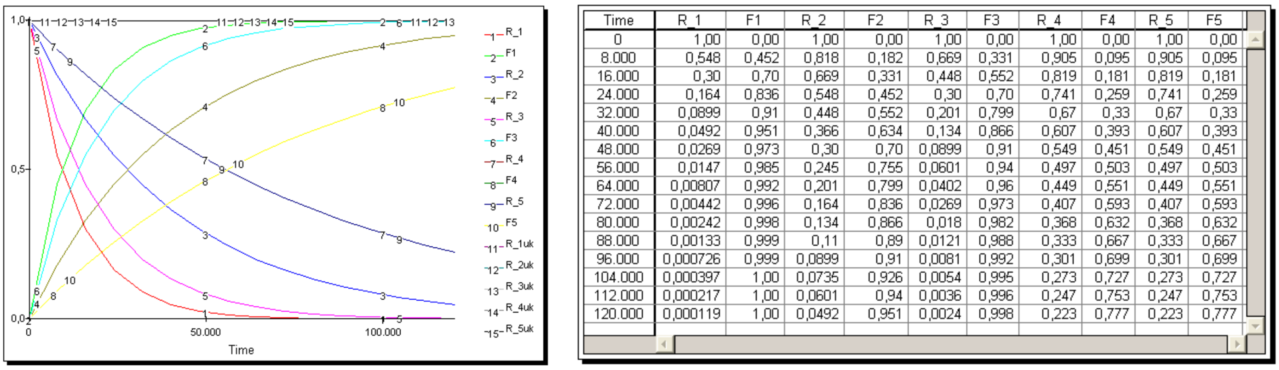
Figure 7. (**a**) System dynamics qualitative structural model of ship crane reliability on m/v "O"; (**b**) structural system dynamics ship crane reliability model on m/v "O".

Figure 7b shows the structural system for the dynamic ship crane reliability model on board the m/v "O" in POWERSIM symbols for states: in operation, out of order, control valve blocked, hydraulic motor vanes broken, safety valve blocked, hydraulic motor housing damaged, hydraulic pump gears damaged, and ship cranes out of operation.

3.4. Analysis of Obtained Results

For this research paper, the initial parameters were taken from the program package GALIOT [8] database for cranes on board the m/v "O", for a period of 10 years and inserted into the mathematical model construed by using the Markov chains. The initial parameters obtained were used to construct the system dynamics simulation model in the POWERSIM simulation program. For simulation purposes, the time scenario of the system state during 120.000 working hours was used.

Figure 8a shows the reliability functions R_1, R_2, R_3, R_4, and R_5 for each state, unreliability functions F1, F2, F3, F4, and F5, and the condition to be satisfied at all times during monitoring R_1uk, R_2uk, R_3uk, R_4uk, and R_5uk, the sum of probable states must be 1 at all times.



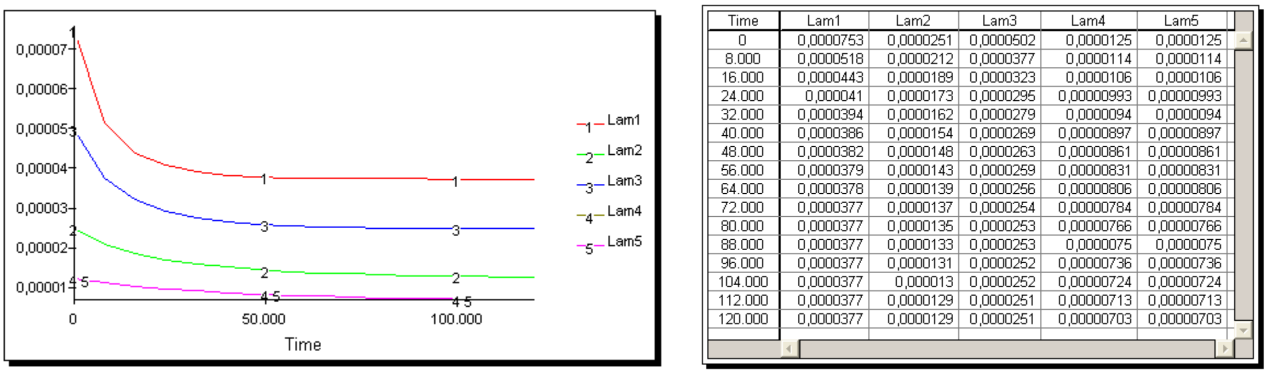
Time	R_1	F1	R_2	F2	R_3	F3	R_4	F4	R_5	F5
0	1,00	0,00	1,00	0,00	1,00	0,00	1,00	0,00	1,00	0,00
8.000	0,548	0,452	0,818	0,182	0,669	0,331	0,905	0,095	0,905	0,095
16.000	0,30	0,70	0,669	0,331	0,448	0,552	0,819	0,181	0,819	0,181
24.000	0,164	0,836	0,548	0,452	0,30	0,70	0,741	0,259	0,741	0,259
32.000	0,0899	0,91	0,448	0,552	0,201	0,799	0,67	0,33	0,67	0,33
40.000	0,0492	0,951	0,366	0,634	0,134	0,866	0,607	0,393	0,607	0,393
48.000	0,0269	0,973	0,30	0,70	0,0899	0,91	0,549	0,451	0,549	0,451
56.000	0,0147	0,985	0,245	0,755	0,0601	0,94	0,497	0,503	0,497	0,503
64.000	0,00807	0,992	0,201	0,799	0,0402	0,96	0,449	0,551	0,449	0,551
72.000	0,00442	0,996	0,164	0,836	0,0269	0,973	0,407	0,593	0,407	0,593
80.000	0,00242	0,998	0,134	0,866	0,018	0,982	0,368	0,632	0,368	0,632
88.000	0,00133	0,999	0,11	0,89	0,0121	0,988	0,333	0,667	0,333	0,667
96.000	0,000726	0,999	0,0899	0,91	0,0081	0,992	0,301	0,699	0,301	0,699
104.000	0,000397	1,00	0,0735	0,926	0,0054	0,995	0,273	0,727	0,273	0,727
112.000	0,000217	1,00	0,0601	0,94	0,0036	0,996	0,247	0,753	0,247	0,753
120.000	0,000119	1,00	0,0492	0,951	0,0024	0,998	0,223	0,777	0,223	0,777

(**a**) (**b**)

Figure 8. (**a**) Calculated values using the program; (**b**) numerical values for reliability.

Numerical results under Figure 8b show values for reliability R_1, R_2, R_3, R_4, and R_5 and unreliability F1, F2, F3, F4, and F5 of ship cranes over a time period of 120,000 working hours, obtained from the simulation.

The frequency of failures follows the bathtub curve, which is a base curve for the frequency of failures from which the length of initial failures can be determined, i.e., failures due to the system running in. To confirm that the reliability follows an exponential distribution, the frequency of failure must be constant, as shown in Figure 9.

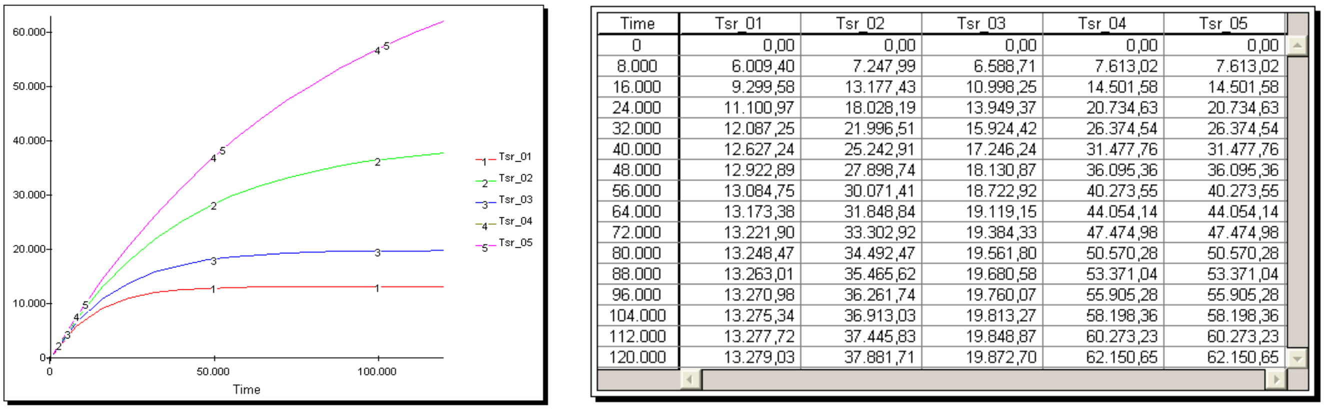


Time	Lam1	Lam2	Lam3	Lam4	Lam5
0	0,0000753	0,0000251	0,0000502	0,0000125	0,0000125
8.000	0,0000518	0,0000212	0,0000377	0,0000114	0,0000114
16.000	0,0000443	0,0000189	0,0000323	0,0000106	0,0000106
24.000	0,000041	0,0000173	0,0000295	0,00000993	0,00000993
32.000	0,0000394	0,0000162	0,0000279	0,0000094	0,0000094
40.000	0,0000386	0,0000154	0,0000269	0,00000897	0,00000897
48.000	0,0000382	0,0000148	0,0000263	0,00000861	0,00000861
56.000	0,0000379	0,0000143	0,0000259	0,00000831	0,00000831
64.000	0,0000378	0,0000139	0,0000256	0,00000806	0,00000806
72.000	0,0000377	0,0000137	0,0000254	0,00000784	0,00000784
80.000	0,0000377	0,0000135	0,0000253	0,00000766	0,00000766
88.000	0,0000377	0,0000133	0,0000253	0,0000075	0,0000075
96.000	0,0000377	0,0000131	0,0000252	0,00000736	0,00000736
104.000	0,0000377	0,000013	0,0000252	0,00000724	0,00000724
112.000	0,0000377	0,0000129	0,0000251	0,00000713	0,00000713
120.000	0,0000377	0,0000129	0,0000251	0,00000703	0,00000703

(**a**) (**b**)

Figure 9. (**a**) Failure intensity functions over a time period of 120.000 working hours; (**b**) numerical values for failure intensity.

The curve in Figure 9a shows failure intensity obtained empirically (calculated) and by simulation of the ship crane state over a time period of 120.000 working hours, from which it can be observed that in the first period of operation, i.e., 0–50.000 working hours, the failure intensity drops, and in the period from 50.000 to 120.000 working hours, it remains constant. Therefore, it can be concluded that fault intensities tend to be constant, are random, and cannot be avoided. They also appear with a certain probability, as can be seen from the simulation results and monitoring realities (failure history from the maintenance program package GALIOT software package database). The conclusion is that reliability follows an exponential distribution, as shown in Figure 9a. Failure frequency is directly related to the mean time of operation in individual states, as shown in Figure 10a,b.



Time	Tsr_01	Tsr_02	Tsr_03	Tsr_04	Tsr_05
0	0,00	0,00	0,00	0,00	0,00
8.000	6.009,40	7.247,99	6.588,71	7.613,02	7.613,02
16.000	9.299,58	13.177,43	10.998,25	14.501,58	14.501,58
24.000	11.100,97	18.028,19	13.949,37	20.734,63	20.734,63
32.000	12.087,25	21.996,51	15.924,42	26.374,54	26.374,54
40.000	12.627,24	25.242,91	17.246,24	31.477,76	31.477,76
48.000	12.922,89	27.898,74	18.130,87	36.095,36	36.095,36
56.000	13.084,75	30.071,41	18.722,92	40.273,55	40.273,55
64.000	13.173,38	31.848,84	19.119,15	44.054,14	44.054,14
72.000	13.221,90	33.302,92	19.384,33	47.474,98	47.474,98
80.000	13.248,47	34.492,47	19.561,80	50.570,28	50.570,28
88.000	13.263,01	35.465,62	19.680,58	53.371,04	53.371,04
96.000	13.270,98	36.261,74	19.760,07	55.905,28	55.905,28
104.000	13.275,34	36.913,03	19.813,27	58.198,36	58.198,36
112.000	13.277,72	37.445,83	19.848,87	60.273,23	60.273,23
120.000	13.279,03	37.881,71	19.872,70	62.150,65	62.150,65

(**a**) (**b**)

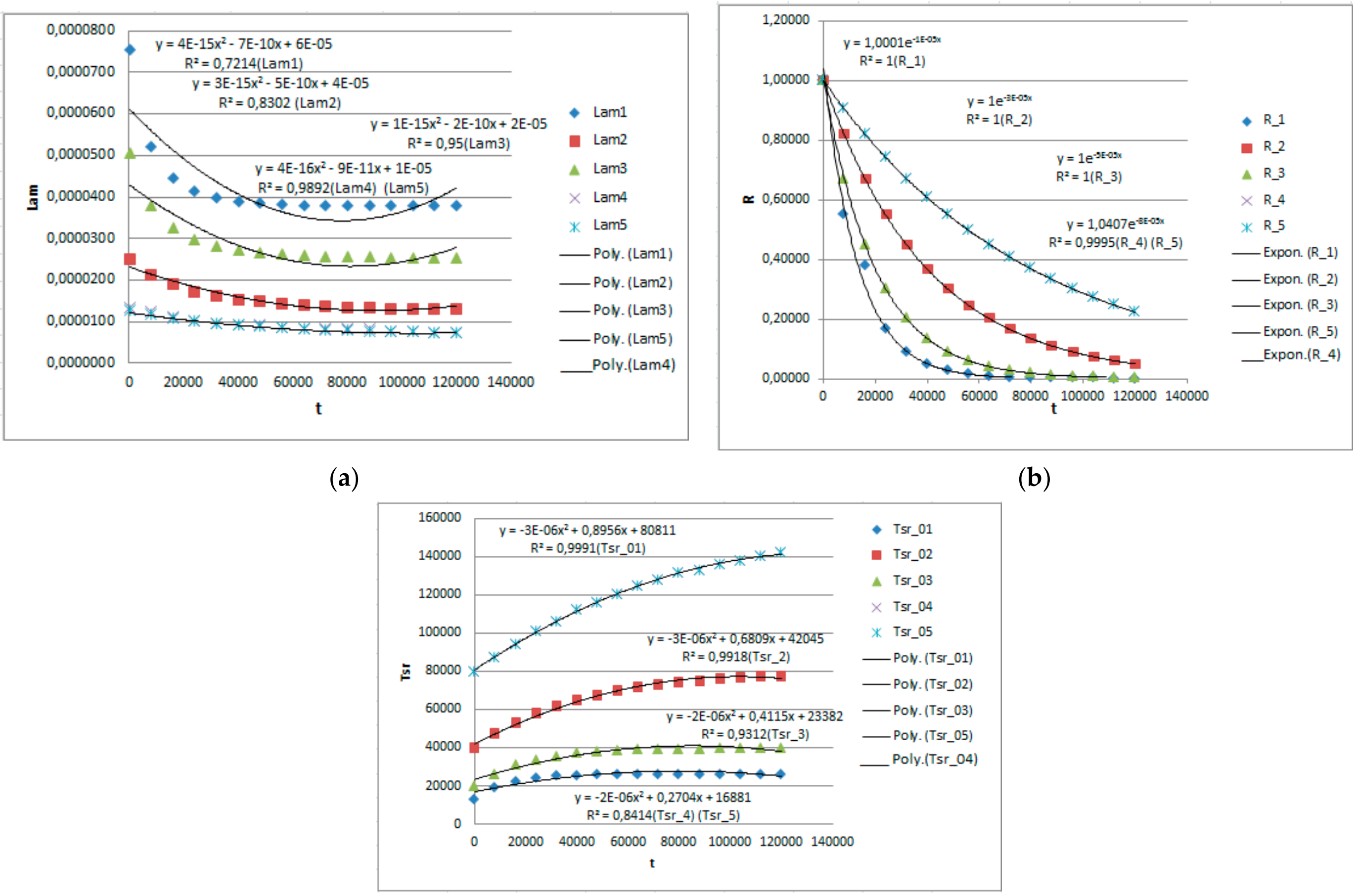
Figure 10. (**a**) The mean time in operation functions until reaching state 1, 2, 3, 4, and 5; (**b**) numerical values for mean time in operation.

From Figure 10a,b and numerical values obtained by simulation, where curves Tsr_4, Tsr_5, and Tsr_2 indicate that the system transitions into failure in states 4, 5, and 2 least frequently, i.e., state 4 "damage to hydraulic motor housing", state 5 "damage to hydraulic pump gear" and state 2 "broken vanes on hydro motor" rarely occur. Tsr_1 and Tsr_3 show the frequency of transition to state 1 "control valve blocked" and state 3 "safety valve blocked".

An increase in failure intensity (Figure 9) and mean time in operation (Figure 10) are affected by the tear and wear of components, aggressive environment—corrosion, fatigue, and the lifespan of materials.

3.5. Regression Analysis of Results Obtained from Simulation of a Given Scenario

To verify (confirm) the validity of the simulated mathematical model of ship crane states on board the *m*/*v* "O", this paper used regression analysis as one of the most common statistical methods [4,17–22]. Values obtained from the simulation for reliability R_*n*, failure frequency Lam_*n*, and mean time Tsr_*n* depending on the given period of time (120.000 working hours) were statistically analyzed using regression analysis to confirm whether a strong correlation between the monitored parameters and times exists (see Figure 11a–c).



(**a**) (**b**)

(**c**)

Figure 11. Regression analysis of reliability and failure frequency on ship cranes on board the *m/v* "O", obtained by simulation; (**a**) change of system reliability R_*n* (*n* = 1, 2, 3, 4, 5) as a function of time *t*; (**b**) change of transition frequency Lam_*n* (*n* = 1, 2, 3, 4, 5) as a function of time *t*; (**c**) mean time in operation for "n" states Tsr_*n* (*n* = 1, 2, 3, 4, 5) as a function of time *t*.

Besides the dependence of reliability, the mean time in operation, and failure frequency on time, it is necessary to show the dependence of the same reliabilities and mean times in operation with respect t to failure frequency for the parameters obtained by simulation (see Figure 12).

Figure 12 shows the dependence of two variables (mean time in operation Tsr_*n* in relation to failure frequency Lam_*n*), which is best described using an exponential dependence in the form of a curve, while the two other dependent variables (reliability of system R_*n* in relation to failure frequency Lam_*n*) are best shown using linear dependence. As failure frequency Lam_*n* increases, mean time in operation Tsr_*n* and system reliability R_*n* decrease, as shown in Figure 12. It indicates a strong correlation between the data obtained by simulation and shown by the determination coefficient R2, ranging from 0.966 to 0.99, and also indicates a 96–99% deviation described and interpreted by this regression model. It further indicates a large percentage of the representation. The conclusion is that the simulation model corresponds to real situations, and any state can be simulated with great accuracy.

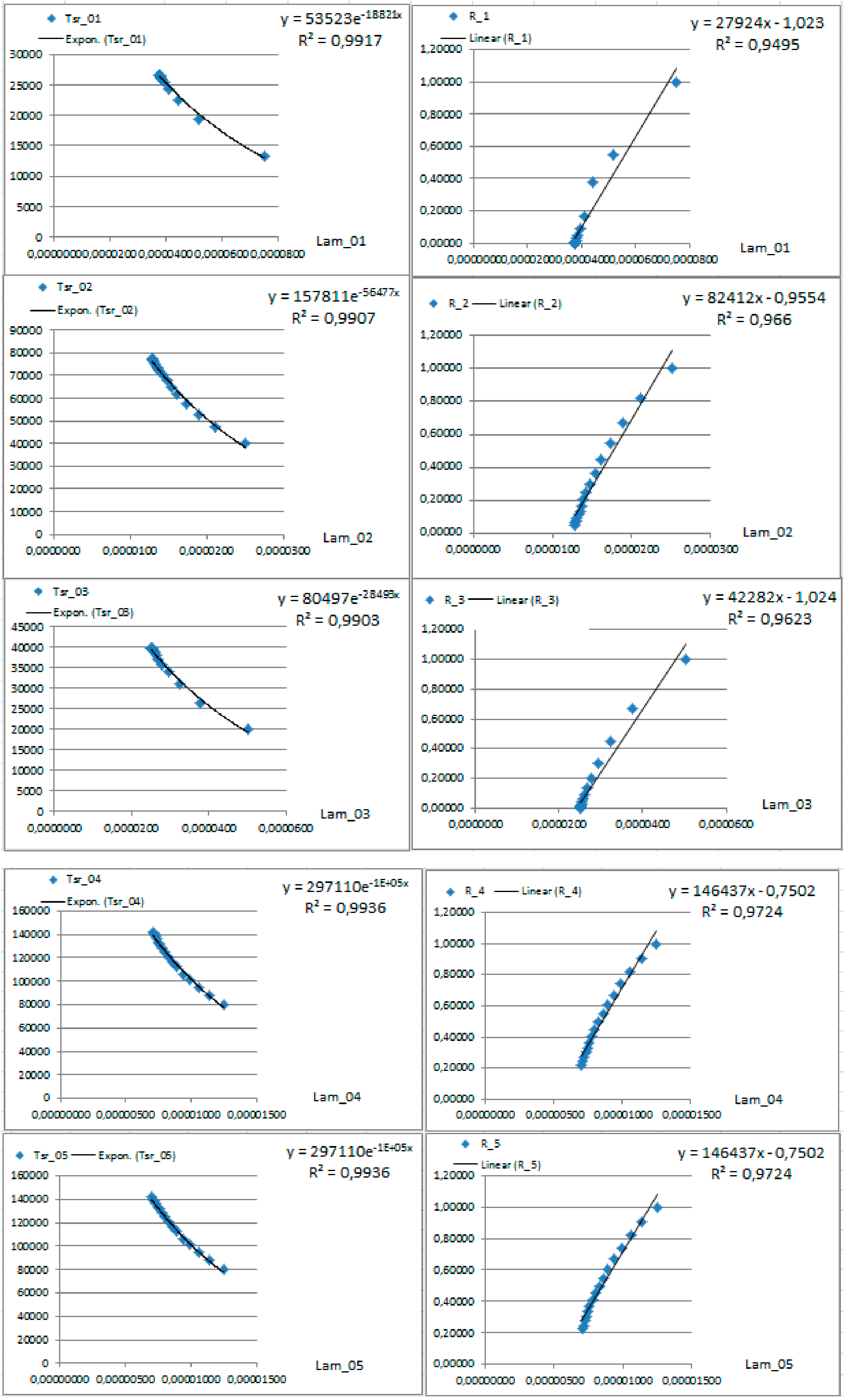


Figure 12. Correlation between reliability R_*n* and the mean time in operation Tsr_*n* (*n* = 1, 2, 3, 4, 5) shown on the *y*-axis in relation to the failure frequency shown on the *x*-axis.

4. Conclusions

The main objective of this research has been to develop a continuous simulation model for predicting ship crane failures in order to increase their reliability and reduce unplanned downtime during cargo loading and unloading operations. The key findings indicate that a model has been developed to predict failures in hydraulic motors and pumps of ship cranes. The Markov model achieves a precise estimation of the frequency of transitions between states, and the simulation model shows high reliability of cranes and a constant frequency of failures over a period of 120.000 operating hours. Regression analysis confirms the validity of the model and shows a strong correlation between the analyzed variables. These findings are significant as they provide insight into the possible development of a simulation model that can effectively predict ship crane failures. The results of the simulation and regression analysis show that the model can accurately estimate the transitions between failure and maintenance states, which supports the initial hypothesis. The practical implications are that the model can be used to plan the maintenance of ship cranes, reduce unplanned downtime, and promptly detect failures. The theoretical implications confirm the validity of the combined approach using FTA, the Markov model, system dynamics, and regression analysis to predict the reliability of complex technical systems. The research had some limitations, including the use of data specific to only a particular type of ship crane and a time period of 120.000 operating hours, which can generalize the results. The recommendation is to research other types of cranes under different operating conditions and environmental factors to determine when the frequency of failures transitions from exponential to a normal distribution, which would deepen our understanding and prediction of ship crane failures.

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