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Contributions on the use of probability laws and statistical tests in the analysis of ship maintenance work in a shipyard

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Abstract. Probability theory studies random experiences, which reproduced several times, unfold each time differently, and the outcome cannot be predicted. Statistics studies phenomena and processes that occur in many units, vary in level from one unit to another, are different in time, space and organizational structure. The period during which a ship is detained in the shipyard for the execution of maintenance works (dock and/or quayside) can easily be included in the category of stochastic phenomena, influenced by many factors with deterministic or random, essential, or non-essential action. Probability laws and statistical tests could be used to solve this topic, the authors believing it is possible to develop original contributions in solving aspects of the complex process of ship maintenance in shipyards for repair. This paper aims to illustrate, by means of justifying examples, the opportunity to use probability theory in solving complex problems from the maritime vessels shipyard maintenance and repairing activity, conditioned by uncertainty, risk and variability.

1. Introduction

The period for carrying out maintenance work on ships in dock or at the quay of a shipyard shall be part of the maintenance programme required by classification societies at predetermined intervals to confirm that hull structure, machinery, installations, systems and equipment conform to the applicable requirements and are considered in satisfactory technical condition, respecting the norms and norms in force [1] [4]. In assessing the total period of time and docking period required to carry out the work referred to in the Technical Specification drawn up by the Technical Owner/Manager of the ship, account shall be taken of: identification of variables with significant influence and their interrelation as a result of estimates made in bidding and programming-planning activities carried out in shipyards for execution of ship maintenance works; elaboration of a mathematical model suitable for solving the proposed problem [5] [9].

2. Theoretical aspects

Probability theory operates with a series of specific notions which, succinctly, present themselves as follows [2]:

- *the experiment* (it is defined as the practical realization of a well-defined set of conditions, according to a research criterion);
- *the event* (it is defined as any result of an experiment, which can be said to have been or has not been carried out, after the experiment under consideration has been performed).

The probability of an event is the ratio of the number of cases favourable to the event to the number of possible cases.

The random variable, where only one measurement is made, is that quantity which, in an experiment, can take an unknown value a priori, and if a sequence of measurements is made, it is a notion that gives information on the numerical value of the measured quantity, and how often a numeric value occurs in a string. If the numerical values of a data string belong to the set of integers or rational, then a *discrete random variable is defined*, and if values belong to the set of real numbers, a *continuous random variable is defined* [3] [6].

Discrete random variables refer to experiments or phenomena that are governed by statistical laws (when there is a certain degree of uncertainty as to the occurrence or recurrence of a result) and not by deterministic laws (when it is known for sure what result will or will not occur). For such experiments or phenomena to be known and therefore studied, the possible results of the experiment are important and necessary and the statistical law or probabilities with which the results of the experiment under consideration are likely to emerge [3] [7] [8].

If repeated measurements give results that are significantly different from most of results, it is to be assumed that aberrant errors have been recorded and it is necessary to consider whether they should be eliminated at the statistical processing stage of the results.

This operation is possible based on tests that require the choice of a probability according to which the decision is made to preserve or eliminate them.

The tests for removing data affected by aberrant error are [6] [8]:

- Chauvenet test (3σ test);
- Romanovski test;
- Irwin test (λ test);
- Grubbs test;
- Dean-Dixon test (Q test).

Tests to verify the concordance between a theoretical distribution and an empirical one (experimentally determined) are [6] [8]:

- normality test (χ^2 test);
- high number test (Kolmogorov-Smirnov test);
- Massey-Junior test;
- Shapiro-Wilk test.

3. Results

This chapter of the paper presents some suggestive results obtained by the authors in the research carried out for the subject mentioned in the title.

3.1. Examples of the use of probability theory

Example 1:

Three sections of a shipyard, S_1, S_2, S_3 exceed the daily schedule of maintenance work performed on a ship, with the probabilities of 0,.7; 0.8 respectively 0.6. It is required to calculate the probabilities of events:

A - at least one section to carry out the works ahead of schedule

B - all sections to carry out the works ahead of schedule

Solution:

Let $\mathrm{A_i}$ to be the event as Section $\mathrm{S_i}$ to carry out the works ahead of schedule. It is known that $\mathrm{A} = \mathrm{A_1} \cup \mathrm{A_2} \cup \mathrm{A_3}$, so $\mathrm{P(A)} = \mathrm{P(A_1 \cup A_2 \cup A_3)} = 1 - \mathrm{P}(\overline{\mathrm{A}}_1 \cap \overline{\mathrm{A}}_2 \cap \overline{\mathrm{A}}_3) = 1 - \mathrm{P}(\overline{\mathrm{A}}_1) \cdot \mathrm{P}(\overline{\mathrm{A}}_2) \cdot \mathrm{P}(\overline{\mathrm{A}}_3) = 1 - (1 - 0.7)(1 - 0.8)(1 - 0.6) = 1 - 0.3 \cdot 0.2 \cdot 0.4 = 0.976$

$\mathrm{B} = \mathrm{A_1} \cap \mathrm{A_2} \cap \mathrm{A_3}$ and, considering the independence of events, it can be write:

$\mathrm{P(B)} = \mathrm{P(A_1 \cap A_2 \cap A_3)} = \mathrm{P}(\overline{\mathrm{A}}_1) \cdot \mathrm{P}(\overline{\mathrm{A}}_2) \cdot \mathrm{P}(\overline{\mathrm{A}}_3) = 0.7 \cdot 0.8 \cdot 0.6 = 0.336$

Example 2:

When performing maintenance work on a 4-cylinder inline diesel engine It is necessary to replace the segments on the 4 pistons using parts from the spare stock which consists of a total of 26 segments. It is required the probability that by randomly extracting a segment 5 times and placing them in the order of extraction, to obtain the order of mounting the segments on a piston (compression-I, scraper-I, lubrication, compression -II, segment-II).

Solution:

Let note X the event that we are looking for, so to obtain by successive extractions the order of mounting the segments on a piston. It is also noted:

A_1= the event to obtain compression-I segment at the first selection;

A_2 = the event to obtain scraper-I segment at the second selection;

A_3 = the event that at the third selection to obtain lubrication segment;

A_4 = the event that on the fourth selection a compression-II segment is obtained;

A_5 = the event that at the fifth selection a shaving-II segment is obtained.

Then the event X if $X = A_1 \cap A_2 \cap A_3 \cap A_4 \cap A_5$.

Results:

$$P(X) = P(A_1)P(A_2|A_1)P(A_3|A_1 \cap A_2)P(A_4|A_1 \cap A_2 \cap A_3)P(A_5|A_1 \cap A_2 \cap A_3 \cap A_4)$$
$$= \frac{1}{26}\frac{1}{25}\frac{1}{24}\frac{1}{23}\frac{1}{22}$$

Example 3:

When drawing up a technical specification for maintenance work required to be carried out on a ship, those n independent work $A_1, A_2, \ldots A_n$ have the probabilities of realization $P(A_k = p_k, k = \overline{1,n})$. Of interest is the average value and dispersion of the number of independent works that are carried out when the ship enters a shipyard to carry out work according to the technical specification.

Solution:

It is denoted by X random variable having as values the number of maintenance works carried out on the ship in the shipyard according to the technical specification. Probability that X take the value k $(k = 0,1,2, \ldots, n)$ is, according to the generalized binomial-Poisson law, the coefficient x^k from the polynomial

$$Q(x) = (p_1x + q_1)(p_2x + q_2) \ldots (p_nx + q_n)$$

where $q_i = 1 - p_i, i = 1,2, \ldots, n$

If it is written developed, $Q(x) = a_0 + a_1x + a_2x^2 + \cdots + a_nx^n$, then the distribution table for variable X is

$$X: \begin{pmatrix} 0 & 1 & 2 & \ldots & n \\ a_0 & a_1 & a_2 & \ldots & a_n \end{pmatrix}$$

The sum of all elements on the second line of the distribution table is 1 because

$$a_0 + a_1 + \cdots + a_n = Q(1) = (p_1 + q_1)(p_2 + q_2) \ldots (p_n + q_n) = 1$$

Mean value of variable X is $E(X) = \sum_{i=0}^{n} ka_k$.

By deriving the expression of the polynomial $Q(x)$ it is obtained

$$\dot{Q}(x) = a_1 + 2a_2x + 3a_3x^2 + \cdots + na_nx^{n-1}$$

and, finally

$$\dot{Q}(1) = a_1 + 2a_2 + 3a_3 + \cdots + na_n = \sum_{i=0}^{n} ka_k = M(X)$$

On the other hand,

$$\dot{Q}(x) = p_1 \prod_{k=1} (p_kx + q_k) + p_2 \prod_{k=1} (p_kx + q_k) + \cdots + p_n \prod_{k=1} (p_kx + q_k)$$

and for $x = 1$ becomes $\dot{Q}(1) = p_1 + p_2 + \cdots + p_n$.

Hence, $E(X) = \sum_{k=1}^{n} p_k$.
For the calculation of dispersion, it is calculated initially $E(X^2) = \sum_{k=0}^{n} k^2 a_k$
It is obtained

$$x\dot{Q}(x) = a_1 x + 2a_2 x^2 + 3a_3 x^3 + \cdots + n a_n x^n$$

and by derivation is obtained

$$\dot{Q}(x)+x\ddot{Q}(x)=a_1 + 2^2 a_2 x + 3^2 a_3 x^2 + \cdots + n^2 a_n x^{n-1}$$

For $x = 1$ becomes $\dot{Q}(1)+x\ddot{Q}(1) = \sum_{k=1}^{n} k^2 a_k$, so

$$E(X^2) = \dot{Q}(1) + \ddot{Q}(1) = \sum_{k=1}^{n} p_k + \ddot{Q}(1)$$

It is derived to calculate $\ddot{Q}(1)$ and it is obtained

$$\ddot{Q}(x) = p_1 \left[p_2 \prod_{j=1,2} (p_j x + q_j) + p_3 \prod_{j=1,3} (p_j x + q_j) \ldots + p_n \prod_{j=1,n} (p_j x + q_j) \right] + \cdots$$

$$\ldots + p_n \left[p_1 \prod_{j=1,n} (p_j x + q_j) + p_2 \prod_{j=1,n} (p_j x + q_j) \ldots + p_{n-1} \prod_{j=1,n-1} (p_j x + q_j) \right]$$

For $x = 1$ becomes

$$\ddot{Q}(x) = p_1 \sum_{k=1} p_k + p_2 \sum_{k=2} p_k + \cdots + p_n \sum_{k=n} p_k =$$

$$= p_1[E(X) - p_1] + p_2[E(X) - p_2] + \cdots + p_n[E(X) - p_n] =$$

$$= E(X)(p_1 + p_2 + \cdots + p_n) - (p_1^2 + p_2^2 + \cdots + p_n^2) = [E(X)]^2 - \sum_{k=1}^{n} p_k^2$$

It is obtained

$$E(X^2) = \sum_{k=1}^{n} p_k + [E(X)]^2 - \sum_{k=1}^{n} p_k^2$$

The dispersion for $E(X)$ is

$$Var(X) = E(X^2) - [E(X)]^2 = \sum_{k=1}^{n} p_k + [E(X)]^2 - \sum_{k=1}^{n} p_k^2 - [E(X)]^2 == \sum_{k=1}^{n} p_k - \sum_{k=1}^{n} p_k^2$$

$$= \sum_{k=1}^{n} p_k (1 - p_k) = \sum_{k=1}^{n} p_k q_k$$

Example 4:

When inspecting the bottom of a ship in the dock for repairs, measurements of sheet metal thicknesses are made at 256 points. What is the probability that the number of occurrences of sheet thicknesses below the permissible limit is between 112 and 144?

Solution:

It is denoted by X, the random variable which has as values the number of occurrences of sheet thicknesses below the permissible limit when executing measurements on the tabs of the sheet metal at the 256 points.

The variable X has binomial distribution with parameters $n = 256$ and $p = 1/2$ (the probability that a measurement executed on the sheet tabs will record a thickness below the permissible limit).

It is necessary to calculate $P(112 < X < 144)$.

Because $E(X) = np = 128$ and $\sigma_x = \sqrt{npq} = 8$, the relationship takes place

$$P(112 < X < 144) = P\left(-2 < \frac{X - 128}{8} < 2\right)$$

Using the Moivre–Laplace theorem and approximating the distribution $\frac{X-128}{8}$ with the standard normal distribution Y, will lead to

$$P\left(-2 < \frac{X-128}{8} < 2\right) \cong P(-2 < Y < 2) = \phi(2) - \phi(-2) = 2\phi(2) \cong 0{,}95$$

3.2. Examples of applicability of tests for removing data affected by aberrant error

3.2.1. Romanovski Test

For the application of the Romanovski test to eliminate a disparate value x_d, shall be calculate the average value

$$\bar{x} = \frac{x_1 + x_2 + \cdots x_n}{n} \quad (1)$$

and standard deviation

$$s = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-2}} \quad (2)$$

The ratio shall be determined

$$R_{calc} = \frac{|x_d - \bar{x}|}{s \cdot \sqrt{\frac{n}{n-1}}}, \quad (3)$$

and compare with breakpoints established for a proposed risk, and if the value exceeds the critical value, $R_{calc} \geq R_{critic}$, then the result x_d can be removed with a certainty of conclusion at least the one proposed. Otherwise, it must be concluded that there are insufficient reasons to eliminate the value x_d.

3.2.2. Irwin test

The data string, n, shall be ordered upwards or downwards, the disparate value, x_d, likely to be aberrant one, being located at the ends of the string.

To apply the Irwin test to eliminate an aberrant value x_d, shall be calculate the average value

$$\bar{x} = \frac{x_1 + x_2 + \cdots x_n}{n} \quad (4)$$

and standard deviation

$$s = \sqrt{\frac{\sum_{i=1}^{n} x_i^2 - \bar{x}}{n-1}} \quad (5)$$

The ratio shall be determined

$$\lambda_{calc} = \left|\frac{x_d - x_a}{s}\right| \quad (6)$$

where x_a is the value closest to the disparate value x_d.

Compare the calculated value with critical ones set for a proposed risk, and if the value exceeds the critical value, $\lambda_{calc} \geq \lambda_{critic}$, then the result x_d can be removed with a certainty of conclusion at least the one proposed.

Otherwise, it must be concluded that there are insufficient reasons to eliminate the value, x_d.

3.2.3. Grubbs test

To apply the Grubbs test to eliminate a disparate value x_d, shall be calculate the average value

$$\bar{x} = \frac{x_1 + x_2 + \cdots x_n}{n} \quad (7)$$

and standard deviation

$$s = \sqrt{\frac{\sum_{i=1}^{n} x_i^2 - \frac{\left(\sum_{i=1}^{n} x_i\right)^2}{n}}{n-1}} \quad (8)$$

The ratio shall be determined

$$G_{calc} = \frac{|x_d - \bar{x}|}{s} \quad (9)$$

and compare the calculated value with critical ones set for a proposed risk, and if the value exceeds the critical value, $G_{calc} \geq G_{critic}$, then the result x_d can be removed with a certainty of conclusion at least the one proposed.

Otherwise, it must be concluded that there are insufficient reasons to eliminate the value, x_d.

Example 5:

For the execution of the same maintenance work on a series of 19 ships, relatively similar in construction type and carrying capacity, in a shipyard there was a labor consumption, expressed in working hours, according to the table below.

It is required to determine whether the disparate value $x_d = 149$ hours, is wrong with respect to the value string and whether it should be removed from calculations.

Solution:

Order the string in ascending order and solve the problem using, in turn, the tests to eliminate aberrant errors (EXCEL software was used to resolve).

n	x_i	x_i orderly ascending	x_i^2	$x_i - \bar{x}$	$(x_i - \bar{x})^2$
Ship no. 1	164	149 likely to be aberrant	22201	-23.842	568.446
Ship no. 2	169	164	26896	-8.842	78.183
Ship no. 3	176	167	27889	-5.842	34.130
Ship no. 4	172	167	27889	-5.842	34.130
Ship no. 5	167	169	28561	-3.842	14.762
Ship no. 6	167	169	28561	-3.842	14.762
Ship no. 7	179	172	29584	-0.842	0.709
Ship no. 8	176	172	29584	-0,842	0.709
Ship no. 9	189	172	29584	-0,842	0.709
Ship no. 10	149	174	30276	1.158	1.341
Ship no. 11	181	174	30276	1.158	1.341
Ship no. 12	184	174	30276	1.158	1.3412
Ship no. 13	172	176	30976	3.158	9.972
Ship no. 14	172	176	30976	3.158	9.972
Ship no. 15	174	176	30976	3.158	9.972
Ship no. 16	169	179	32041	6.158	37.920
Ship no. 17	174	181	32761	8.158	66.551
Ship no. 18	176	184	33856	11.158	124.499
Ship no. 19	174	189	35721	16.158	261.078

Critical values for the most used applications, set for a proposed confidence / risk level, are tabulated in the literature (Table 1).

Table 1. Critical values for proposed confidence levels [8]

Name of test	IRWIN	GRUBBS	ROMANOVSKI

Analytic expression	$\lambda_{calc} = \left\|\frac{x_d - x_a}{s}\right\|$			$G_{calc} = \frac{\|x_d - \bar{x}\|}{s}$			$R_{calc} = \frac{\|x_d - \bar{x}\|}{s \cdot \sqrt{\frac{n}{n-1}}}$		
Number of elements in the string	TRUST LEVEL								
	95%	98%	99%	95%	98%	99%	95%	98%	99%
6	1.39	1.81	2.45	2.78	3.64	4.36	2.07	2.13	2.16
7	1.31	1.69	2.30	2.62	3.36	3.96	2.18	2.27	2.31
8	1.24	1.57	2.16	2.51	3.18	3.71	2.27	2.37	2.43
9	1.20	1.51	2.09	2.43	3.05	3.54	2.35	2.46	2.53
10	1.18	1.46	2.03	2.37	2.96	3.41	2.41	2.54	2.62
11	1.14	1.43	2.00	2.33	2.89	3.31	2.47	2.61	2.69
12	1.11	1.41	1.97	2.29	2.83	3.23	2.52	2.66	2.75
13	1.09	1.39	1.94	2.26	2.78	3.17	2.56	2.71	2.81
14	1.07	1.37	1.91	2.24	2.74	3.12	2.60	2.76	2.86
15	1.06	1.35	1.88	2.71	2.27	3.08	2.64	2.80	2.91
16	1.05	1.33	1.86	2.68	2.68	3.04	2.67	2.84	2.95
17	1.04	1.31	1.84	2.66	2.66	3.01	2.70	2.87	2.98
18	1.03	1.29	1.82	2.64	2.64	3.00	2.73	2.90	3.02
19	1.03	1.28	1.81	2.62	2.62	2.95	2.75	2.93	3.05
20	1.03	1.27	1.80	2.00	2.60	2.93	2.78	2.96	3.08

TEST IRWIN	TEST GRUBBS	TEST ROMANOVSKI
$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n} = \frac{\sum_{i=1}^{19} x_i}{19} = \frac{3284}{19} = 172.842$	$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n} = \frac{\sum_{i=1}^{19} x_i}{19} = \frac{3284}{19} = 172.842$	$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n} = \frac{\sum_{i=1}^{19} x_i}{19} = \frac{3284}{19} = 172.842$
$s = \sqrt{\frac{\sum_{i=1}^{n} x_i^2 - \bar{x}}{n-1}}$ $s = 177.75$	$s = \sqrt{\frac{\sum_{i=1}^{n} x_i^2 - \frac{\left(\sum_{i=1}^{n} x_i\right)^2}{n}}{n-1}}$ $s = 173.035$	$s = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \bar{x})^2}{n-2}}$ $s = 8.645$
$\lambda_{calc} = \left\|\frac{x_d - x_a}{s}\right\|$ $\lambda_{149} = 0.084$ For a confidence level of 95% $\lambda_{critic} = 1.03$ For a confidence level of 98% $\lambda_{critic} = 1.28$ For a confidence level of 99% $\lambda_{critic} = 1.81$ $\lambda_{149} < \lambda_{critic}$ **149 shall NOT be deleted**	$G_{calc} = \frac{\|x_d - \bar{x}\|}{s}$ $G_{149} = 0.138$ For a confidence level of 95% $G_{critic} = 2.62$ For a confidence level of 98% $Gu_{critic} = 2.62$ For a confidence level of 99% $Gu_{critic} = 2.65$ $G_{149} < \lambda_{critic}$ **149 shall NOT be deleted**	$R_{calc} = \frac{\|x_d - \bar{x}\|}{s \cdot \sqrt{\frac{n}{n-1}}}$, $R_{149} = 2.684$ For a confidence level of 95% $R_{critic} = 2.75$ For a confidence level of 98% $R_{critic} = 2.93$ For a confidence level of 99% $R_{critic} = 3.05$ $t_{149} < \lambda_{critic}$ **149 shall NOT be deleted**

4. Discussions

The information necessary to develop analyses or predictions of the very complex processes carried out in the shipyards for repairs work must be *of a quantitative nature,* to allow the expression in numerical form of the specific characteristics of the analysed phenomena.

This condition implicitly supposes the need for appropriate instruments for measuring the characteristics of phenomena and units of numerical expression (with or without physical equivalent). However, both the instruments used for expressing themselves in a quantitative form and the units of measurement are characterized by some inaccuracy and instability, and their use generates a multitude of errors.

5. Conclusions

Studies and researches carried out – supported by examples suggestive of the various processes and activities carried out in a shipyard for the repair of seagoing ships – have led to the conclusion of the need to develop a relevant mathematical model that allows a more accurate estimation of the time the ship is detained in the repair dock and/or quayside, to carry out the works included in the Technical Specification drawn up by the owner/Technical Manager of the vessel. It was concluded that the use of probability theory and probability tests could satisfactorily answer the subject of interest.

Future research will aim to develop examples of the use of modelling and simulation methods in shipyard maintenance projects, with contributions to: *systematization* of data collection and processing methods; *correlation* of information in the management of repair operations; *analysis of possible risks* during the evolution of ship maintenance projects in maritime repair yards, through the Critical Path Method – CPM; *elaboration of examples of planning* of ship maintenance projects in maritime repair yards, from a probabilistic point of view, through the PERT Method (Programme Evaluation and Review Technique); *analysis of the resources* required for a project according to the available method, using the diagram method, which provides a comparative view of the daily requirement profile for a certain resource associated with the project compared to the daily available profile.

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