Journal of POLISH CIMAC
Faculty of Ocean Engineering & Ship Technology
GDAŃSK UNIVERSITY OF TECHNOLOGY

ON MAKING OPERATIONAL DECISIONS WITH TAKING INTO ACCOUNT VALUE OF OPERATION APPLIED TO SHIP MAIN PROPULSION ENGINE AS AN EXAMPLE

Jacek Rudnicki

Gdansk University of Technology
Faculty of Ocean Engineering & Ship Technology
Department of Ship Power Plants
tel. (+48 58) 347-29-73
e-mail: jacekrud@pg.gda.pl

Abstract

Objectivity and rationality in making decision, assumed optimal in given conditions, forces to apply an evaluating (quantitative) approach to the problem, hence to search for such their parameters (indices) which, in a given decision situation, can be deemed most adequate.

And, to precisely determine the task it is necessary to specify also its duration time, apart from conditions in which it will be realized.. When considering propulsion engine, i.e. the main element of ship propulsion system, especially important becomes not only the problem which amount of energy could be at one's disposal but also within which time interval it could be delivered. Therefore apart from applying the commonly used reliability indices, it seems sensible to consider the operation in such evaluating approach as it could be determined by energy and time simultaneously. The presented method may be deemed a valuable supplement to the ways have been applied so far of description of reliability features of the driving system, considered crucial for ship power plant and ship itself.

Keywords*: operation, ship power plant, Poisson process, Markov process*

1. Introduction

As described elsewhere [4, 5], in operational practice of ship devices (like in the case of other complex functional systems of mechanical devices) working life of the same elements installed in different power plants is not an adequate criterion for unambiguous determination of an operation strategy because it is not an unambiguous measure of their wear and tear.

In decision making situation, reality of operation can be better represented by introduction of at least one random variable as a model parameter though it leads solely to more or less probable conclusions , that results from the fact that to particular values of decision variables not only one value of criterion function but many values occurring with different probabilities, are attributed. To the most often applied probabilistic decision models belong those in which the expected value of consequence of taking the decision is selected to aid in choosing optimum value of decision variable [10]. Hence in choosing an optimum value of a decision variable one should be aided by the expected value of criterion function [4].

In such situation it is easier - from formal point of view - to present decision-making procedure in one of the structural forms most commonly met, namely : decision tree or decision table. In general case the decision tree takes the form shown in Fig.1.

For the below presented tree, the criterion function is constituted by maximization of the expected value of the consequence $c(d_j, s_i)$, which , for particular decision tree nodes which symbolize the fact of taking a given decision d_j , can be determined as follows [8, 9]:

$$E(c/d_j) = \sum_{i=1}^{k} \left[p(s_i)/d_j \cdot c(d_j, s_i) \right] \qquad i = 1,2,\ldots,k \qquad j = 1,2,\ldots,n \tag{1}$$

And, it should be observed that the decision situation is deterministic as it consists in choosing only one decision out of n possible ones, in spite of that occurrence probabilities of the state s_i (i = 1,2, …, k) under assumption of taking the decision d_j (i = 1,2, …, n) appear.

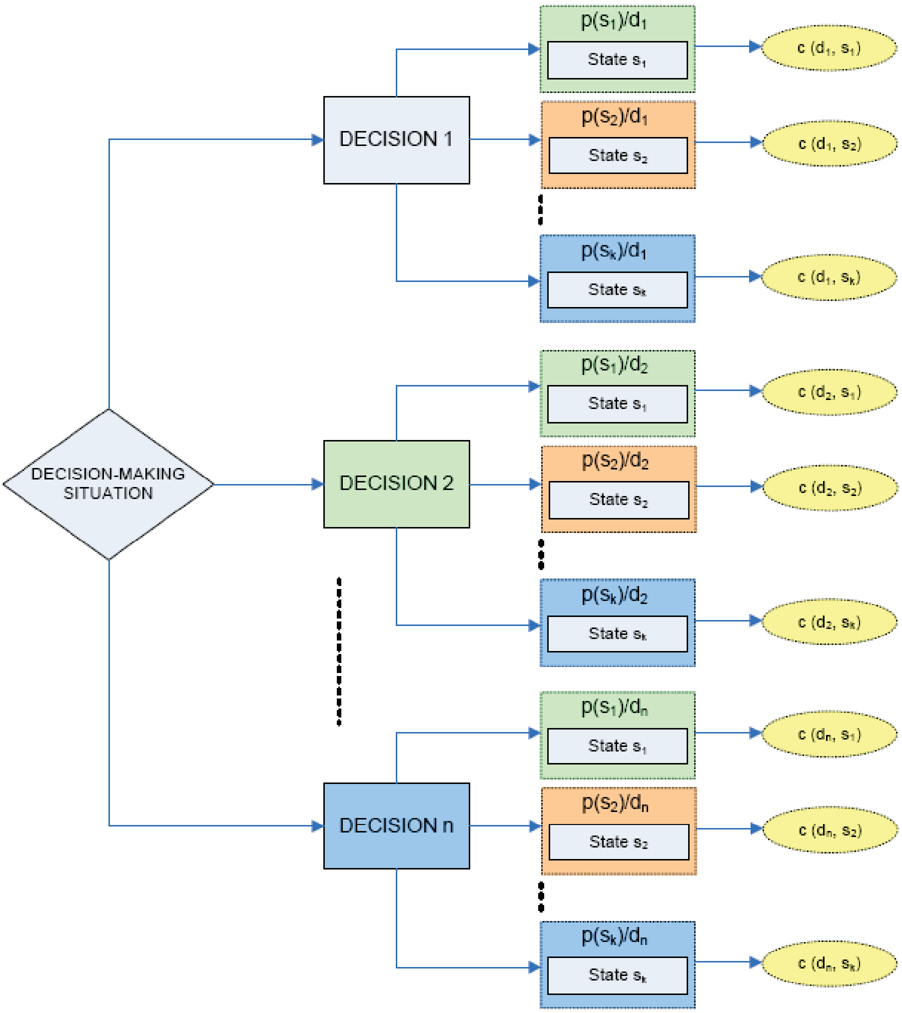

Fig.1. General case of decision tree. n – number of considered decisions; $p(s_i)/d_j$ – conditional probability of occurrence of the state s_i in the case of taking the decision d_j,; $c(d_j, s_i)$ – consequence of occurrence of the state s_i in the case of taking the decision d_j

Application of the decision procedure shown in Fig. 1. requires, apart from determination of a repertoire of possible decisions, to know how to determine values of the conditional probabilities $p(s_i)/d_j$.

In practice, predictions concerning tasks to be realized are usually based on the wide-understood notion of service reliability of an object or system. And, when considering the notion of service reliability of power devices (e.g. ship diesel engines) attention should be paid to that from the user's point of view the most important problem is quality of execution of a given task (in extreme case – its not fulfillment). This way the notion of reliability is inseparably associated with unambiguous determination of the task in question.

Moreover to precisely determine a task , apart from assuming conditions in which it will be performed, it is necessary to specify is duration time. The problem is especially important in such domains as sea shipping where specificity of tasks is as a rule associated with necessity of the functioning of crucial mechanisms and devices (e.g. installed on ships) for long periods.

Therefore it is especially important not only which quantity of energy would be available during operation of a given power device but also for which duration time it could be delivered.

The presented approach is made realizable by considering engine's operation (further referred only to ship main propulsion engine) in such evaluating way as to make simultaneous determining it by energy and time possible.

In this case the operation (D) within the time interval [0, t] can be interpreted as a physical quantity determined by the product of the time-variable energy E = f(t) and time t , which can be generally expressed by the following relation [7]:

$$D = \int_0^t E(\tau)d\tau = 2\pi\int_0^t M_0\, n\, t dt \qquad (2)$$

2. Estimation of occurrence probability values of ship motion limitations resulting from the lowering of total efficiency of ship main propulsion engine

One of the possible ways of estimation of occurrence probability values of limitations in ship motion with a given speed is the above mentioned quantitative evaluation of operation. The way is as much versatile that it is possible to apply it in the case when results of operational investigations are lacking, and adopted assumptions and model parameters are determined exclusively on the basis of engine's technical and operational documentation and determined task realization conditions.

In the case of ship main engine, with a view of taking into account the so-called design sea margin as well as service power margin [10] for the engine operating under partial loads , the process of the decreasing of available power output (hence also of the possible operation D_M) will be realized in two phases:

- In the first phase only an increase of hourly fuel oil consumption will take place (at a relatively constant value of developed engine torque), hence operational cost will also increase;
- in the second phase a limitation of effective power developed by the engine will appear due to design limitations and lack of possible increasing fuel charge.

If partial engine load is assumed constant the phenomenon can be interpreted as follows:

- In the first phase the time-variable drop of total engine efficiency results first of all in increasing its hourly fuel oil consumption (increase of specific fuel oil consumption). It can be described as a series of the recordable events F consisting in increasing the fuel charge $g_p^{i\%}$ by the increment Δg_p at a relatively constant value of the torque M_o (appropriate to a given engine load state) . This way an increase of engine's operational cost is generated, however without any limitations imposed on ship motion parameters, in principle;
- Gradual degradation processes during further engine operation result in that the recordable events U which consist in decreasing the engine torque M_o at the constant fuel consumption g_p (i.e. $g_p = G_{p\ max}$), to occur. Further long-lasting operation of the engine results in significant worsening its characteristics which impose serious limitations on ship motion with a given speed or course. In heavy weather conditions such situation will obviously lead to producing a hazard to ship safety.

In the context of the above mentioned quality of task realization to know the following data becomes important in making decisions with the use of a probabilistic decision process :

a) expected value of increased cost of task realization, resulting from increased fuel oil consumption,
b) value of occurrence probability of such number of F events which cause the fuel oil charge $g_p^{i\%}$ to increase up to the value $G_{p\,max}$, and ship motion limitations to occur subsequently.

In the considered case of ship main diesel engine the problem defined in a) can be solved by making use of the assumption that the number of repetitions $N_{\Delta gp}$ of the event F within the time interval (0, t) is a random variable of non-negative integer values.

The dependence of the random variable on time constitutes the stochastic process $\{N(t): t \geq 0\}$.

3. An example of application of stochastic process theory to estimation of value of the probabilities $p(s_i)/d_j$

Under assumptions on stationarity [3, 11], lack of consequences and flow singularity, the Poisson's homogeneous process can be applied to the process of increasing the fuel charge $g_p^{i\%}$ as a result of decreasing the engine's total efficiency η_e (in steady load conditions of the engine), and the random variable $N_{\Delta gp}$ is characterized by the distribution [1]:

$$P(N_{\Delta gp} = k) = \frac{(\lambda_f \cdot t)^k}{k!} \exp(-\lambda_f t); \quad k = 1,2,...,n \tag{3}$$

where:

λ_f - a constant interpreted as occurrence intensity of the event F (increasing $g_p^{i\%}$ by the value Δg_p).

Main particulars of the engine, on which the carried out calculations are based, deal with 9RT-flex60C-B Wartsila engine (according to [12]); hence for the selected contract parameters : the contract power output N_x = 80% N_{R1} = 17370 kW, engine speed n_x = 90% n_{R1} = 102,6 rpm it can be assumed that the state of engine operation under 85% load is typical one as in this point of engine's working area specific fuel oil consumption value reaches its minimum. Hence the parameters of the typical state of operation are determined as follows:

- n = 97,2 rpm,
- N_e = 14 764,5 kW,
- $g_e = 169{,}4 \frac{g}{kWh}$.

Taking into account the above mentioned , one can determine value of the fuel charge $g_p^{85\%}$ as follows:

$$g_p^{85\%} = \frac{N_e \cdot g_e}{n \cdot i} = \frac{14764{,}5 kW \cdot \frac{168{,}2}{3600} \frac{g}{kW \cdot s}}{\frac{97{,}2}{60} \frac{1}{s} \cdot 9} = 47{,}3 g \tag{4}$$

$G_{pmax} = g_p^{110\%}$ can be simultaneously assumed as precise data concerning parameters of injection apparatuses are lacking, and:

$$g_p^{110\%} = \frac{19107 kW \cdot \frac{170{,}8}{3600} \frac{g}{kW \cdot s}}{\frac{105{,}9}{60} \frac{1}{s} \cdot 9} = 57{,}1 g \tag{5}$$

therefore:

$$\Delta G_{pmax} = g_p^{110\%} - g_p^{85\%} = 9{,}8g \approx 10g \tag{6}$$

Next, value of T_{Gpmax} at which value of G_{pmax} resulting from degradation processes is reached, should be estimated. In the case of lacking appropriate results of operational investigations the only one, practically useful way of its determination is to analyze engine's technical and maintenance documentation on the basis of which the most unreliable engine's elements and systems can be selected in line with indications of engine's manufacturer.

In the considered example such analysis revealed that the most unreliable functional subsystem of the engine is its fuel system (which complies with many results of other independent research [6]) . Therefore when analyzing the service time-scale of the above mentioned system as well as other maintenance operations, to assume T_{Gpmax} = 1000 h has been deemed justified.

If accuracy class of the applied flowmeters is assumed equal to 0,5 and value of recorded fuel flow rates is also assumed, then in the considered case the value of Δ_{gp} can be determined on the level of Δ_{gp} = 0,004 kg/s. Therefore on the basis of the above mentioned assumptions it can be stated that during the time T_{Gpmax} the following number of F events which would result in imposing limitations in realizing the assumed ship sailing speeds:

$$N'_{\Delta g_p} = k' = \frac{G_{p\max} - g_p^{x\%}}{\Delta g_p} = \frac{10}{4} = 2{,}5 \approx 3 \tag{7}$$

Hence the determined value of λ_f amounts to:

$$\lambda_f = \frac{N'_{\Delta g_p}}{T_{\Delta G_{p\max}}} = \frac{3}{1000} \cdot \frac{1}{h} \tag{8}$$

Finally, for the considered example the occurrence probability of k' number of F events amounts to:

$$P(N_{\Delta gp} = k') = \frac{(\lambda_f \cdot t)^k}{k!} \exp(-\lambda_f t) = \frac{(3 \cdot 10^{-3} \cdot t)^3}{3!} \cdot \exp(-3 \cdot 10^{-3} \cdot t) \tag{9}$$

and, the function $P(N_{\Delta gp} = k') = f(t)$ is presented in Fig.2.

Moreover , to make the figure more clear, the occurrence probability of a lower number (k = 2) as well as higher ones (k = 4 and 5) of F events is also shown in it. Interpretation of the probabilities presented in function of time confirms expectations as it can be observed that occurrence probability of a lower number k of F events decreases along with time in favour of their greater values. In decision-making process such analysis of the probabilities in question makes it possible to estimate expected consequence values and to select a task realization variant. The assumptions concerning T_{Gpmax} as well as Δg_p may be deemed somewhat doubtful , however in any instant their determined values can be replaced by different, more realistic ones, but the procedure itself does not undergo any modifications.

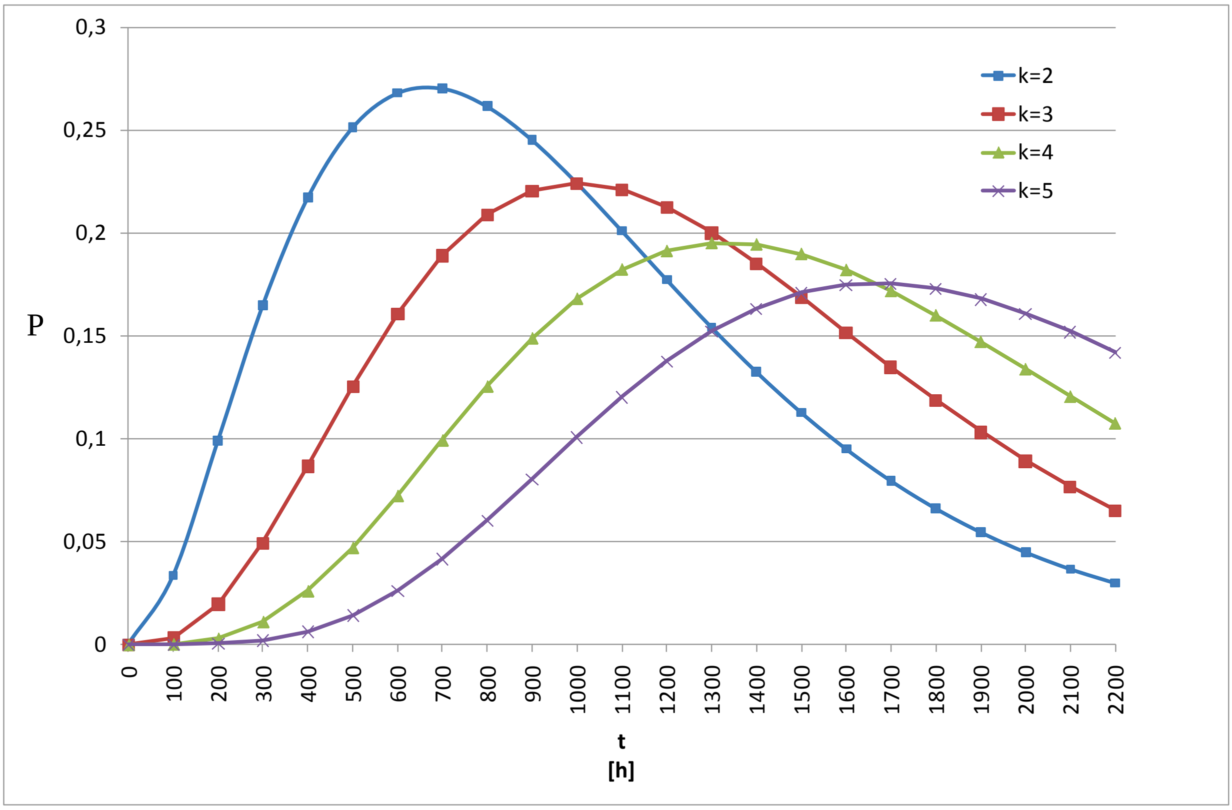

Fig. 2. $P(N_{\Delta gp} = k) = f(t)$

In the next phase the above presented problem was solved by using a model in the form of the Markov process $\{X'(t) ; t \geq 0\}$. The state transition graph of the considered process with taking into account the values obtained from the relation (8) is presented in Fig. (3)

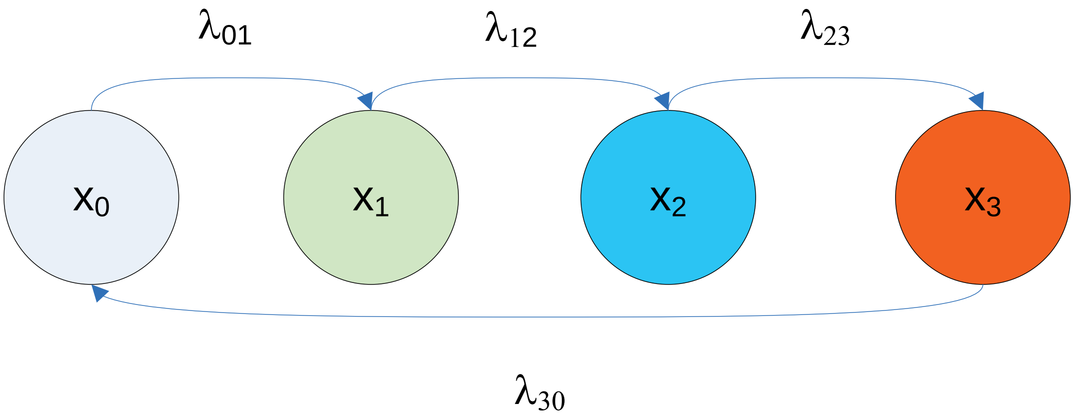

Fig. 3. State transition graph of the process $\{X'(t) ; t \geq 0\}$

and the initial distribution of the proces:

$$p_0 = P\{X(0) = x_0\} = 1,$$

$$p_i = P\{X(0) = x_i\} = 0 \text{ dla } i = 1,2,3. \qquad (10)$$

Therefore the set of Kolmogorov – Smirnov equations takes the form:

$$\left.\begin{aligned}
&\frac{dP_0(t)}{dt} = -\lambda_{01} \cdot P_0(t) + \lambda_{30} \cdot P_3(t) \\
&\frac{dP_1(t)}{dt} = -\lambda_{12} \cdot P_1(t) + \lambda_{01} \cdot P_0(t) \\
&\frac{dP_2(t)}{dt} = -\lambda_{23} \cdot P_2(t) + \lambda_{12} \cdot P_1(t) \\
&\frac{dP_3(t)}{dt} = -\lambda_{30} \cdot P_3(t) + \lambda_{23} \cdot P_2(t) \\
&P_0(t) + P_1(t) + P_2(t) + P_3(t) = 1
\end{aligned}\right\} \tag{11}$$

The set can be transformed by applying Laplace transform [2] as well as the assumed initial distribution of the process to the set of linear equations in the domain of transforms having the following form:

$$\left.\begin{aligned}
&s \cdot P_0^*(s) - 1 = -\lambda_{01} \cdot P_0^*(s) + \lambda_{30} \cdot P_3^*(s) \\
&s \cdot P_1^*(s) = -\lambda_{12} \cdot P_1^*(s) + \lambda_{01} \cdot P_0^*(s) \\
&s \cdot P_2^*(s) = -\lambda_{23} \cdot P_2^*(s) + \lambda_{12} \cdot P_1^*(s) \\
&s \cdot P_3^*(s) = -\lambda_{30} \cdot P_3^*(t) + \lambda_{23} \cdot P_2^*(s) \\
&P_0(t) + P_1(t) + P_2(t) + P_3(t) = 1
\end{aligned}\right\} \tag{12}$$

Attempting to solving the above mentioned set one should determine the transition intensity λ_{ij}. To estimate values of the parameters is possible provided expected values of the random variables T_{ij} are known. In practice the mean time of remaining the process in the state x_i provided the next will be the state x_j , can be considered to be the estimator $E(T_{ij})$. In such case the searched for value λ is expressed as follows:

$$\lambda_{ij} = \frac{1}{E(T_{ij})} \cong \frac{1}{\bar{x}_{ij}} \lambda_{ij} = \frac{1}{\mathrm{E}(\mathrm{T}_{ij})} \tag{13}$$

In the case in question, as 3 transitions of the process, which result from the lowering of total engine efficiency by the same value, are considered, it is justified to assume the following assumptions associated with determining λ_{ij} values :

- in the most common case of lacking results of operational investigations it is possible to assume that in a rational system of operation to distinguish duration time of any of the states except the state x_k , i.e. in this case - x_3 , is unjustified (as there is no reason to claim that any of the states should last for a longer or shorter time),
- it can be therefore assumed that $E(T_{01}) \approx E(T_{12}) \approx E(T_{23})$, hence $\lambda_{01} \approx \lambda_{12} \approx \lambda_{23} = \lambda$,
- the mean duration times of the distinguished states x_0, x_1 and x_2 should be then assumed the same, it is therefore justified to assume its value equal to:

$$\bar{x} = \frac{T_{G_{p\max}}}{k'} \tag{14}$$

On substitution of the data for the considered case the value : $\lambda \approx 0{,}003$ was obtained. By taking into account the above specified assumptions and the notation : $\lambda_{30} = \mu$, the set of equations (12) can be presented in the following form:

$$\left.\begin{aligned}
&s\cdot P_0^*(s)-1=-\lambda\cdot P_0^*(s)+\mu\cdot P_3^*(s)\\
&s\cdot P_1^*(s)=-\lambda\cdot P_1^*(s)+\lambda\cdot P_0^*(s)\\
&s\cdot P_2^*(s)=-\lambda\cdot P_2^*(s)+\lambda\cdot P_1^*(s)\\
&s\cdot P_3^*(s)=-\lambda\cdot P_3^*(t)+\lambda\cdot P_2^*(s)\\
&P_0(t)+P_1(t)+P_2(t)+P_3(t)=1
\end{aligned}\right\} \tag{15}$$

The solving of the above mentioned set of equations in the domain of transforms and the subsequent executing of inverse Laplace transform makes it possible to find the searched for distribution $P_3(t)$ graphically presented in Fig. 4.

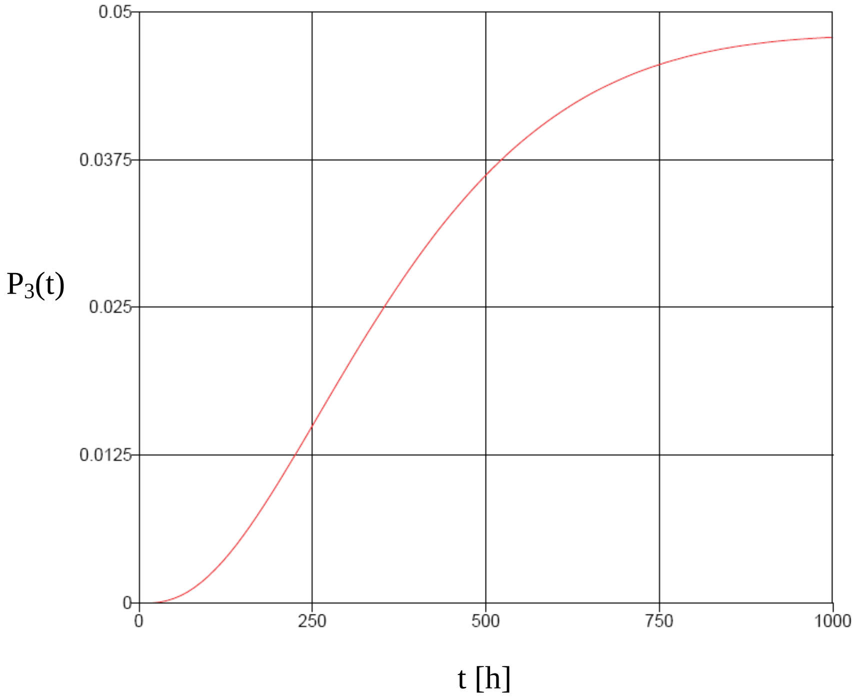

Fig.4. The probability distribution $P_3(t)$

4. Summary

The presented method may be deemed a valuable supplement to the ways have been applied so far of description of reliability features of the driving system, considered crucial for ship power plant and ship itself . Its basic advantage consists in connecting energy assessment with duration of time in which a task is realized. The time is very important in the case of sea shipping tasks usually long lasting.

Making use of it one is able to determine, for a given instant , useful work (useful energy) which can be produced by the whole driving system, as well as to determine value of occurrence probability of such number of F events which would cause additional limitations to form during realization of a task (due to not possible propelling the ship with a given speed) or to make its realization impossible at all. Value of the probability can be hence taken as that of reliability index and implemented in making operational decisions. Its additional advantage is versatility which makes it possible to apply it to reliability analysis of every ship power device or subsystem including those not being machines, e.g. heat exchangers.

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