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Application of Generator-Electric Motor System for Emergency Propulsion of a Vessel in the Event of Loss of the Full Serviceability of the Diesel Main Engine

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Abstract: Oil tanker disasters have been a cause of major environmental disasters, with multi-generational impacts. One of the greatest hazards is damage to the propulsion system that causes the ship to turn sideways to a wave and lose stability, which in storm conditions usually leads to capsizing and sinking Despite the perceived consequences of maritime disasters in the current solutions for the propulsion of oil tankers, there are no legal or real solutions for independent emergency main propulsion in this type of ship. Stressing that the reliability of the propulsion system has a significant impact on the ship's safety at sea, the authors presented a new solution in the form of a power take-off/power take-in (PTO/PTI) system. This is the emergency use of a shaft generator as the main electric motor, operating in parallel in a situation when the main engine (ME), (the main engine of the ship's direct high-power propulsion system that is slow-speed) loses the operational capability to propel the ship. Since one cause of wear, or failure, of the main engines is improper operational decisions, the paper shows the wear mechanism in relation to the accuracy of operational decisions. Using classical reliability theory, it also shows that the use of the proposed system results in an increase in the reliability of the propulsion system. The main topic of the paper was the use of an electrical system called PTO/PTI as an emergency propulsion system on the largest commercial vessels, such as bulk carriers and crude oil tankers, which has not been used before in maritime technical solutions. Semi-Markov processes, continuous in time, discrete in states, and which are used in technology, were also proposed as a tool describing the process of the operation of such a ship propulsion system, and they are useful to support operational decisions affecting the state of the technical condition of the engine. There are two ship operation strategies that can be adopted: the four-state model, for normal operation, and the three-state model, which operates with the occurrence of failure. For these types of models, their limiting distributions were defined in the form of probabilities. It was also demonstrated that faster than expected engine wear and the occurrence of inoperability of the main engine can be caused by wrong operational decisions made by the shipowner or crew. Using this type of main engine operating methodology, it is possible to support the decision of the engineer to stop the main engine and to subject it to the process of restoration to an acceptable state of technical condition (before the failure or during the failure in severe storm conditions), with the parallel use of the proposed electric propulsion (PTO/PTI) as an emergency propulsion, giving the crew a chance to maintain the steering necessary to maintain safe lateral stability.

Keywords: shaft generator–electric motor (PTO/PTI); reliability of the ship's main propulsion; model of exploitation process; technical states of the engine; semi-Markov process

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1. Introduction

Ships such as bulk carriers of the "Capesize" class, with a deadweight of more than 150,000 t, and tankers of the very large crude carrier (VLCC) and ultra large crude carrier (ULCC) classes are among the largest types of maritime transport. ULCC tankers are ships of up to about 360 m in length, and with a carrying capacity of up to 400,000 t. Their cargo tanks can hold up to 500,000 t of crude oil, and their fuel tanks up to 10,000 t of toxic heavy fuel oil (HFO).

Such large amounts of fuel are needed to drive large power propulsion units, such as steam turbines or compression ignition reciprocating internal combustion engines (e.g., marine low-speed, long/super long stroke two-stroke main engines, with power outputs of up to 80,080 kW [1]). These engines and equipment are necessary to ensure the movement of the ship, propelled by the main engine and the other main propulsion equipment of the ship, and to drive its auxiliary machinery, powered mainly by the diesel electric generators.

The safety of a ship performing transportation tasks in difficult, unpredictable sea conditions depends on many factors. One of the main requirements, apart from hull integrity and lateral stability [2–5], is to maintain the ship's maneuverability, which is possible only when the positive speed of the ship is relative to the water. This requires an adequate reliability of the main propulsion system [6], in particular the main engines (ME) [7,8]. A failure of the main propulsion system or steering device, or damage to the hull plating, often leads to shipwreck [3,9–12], resulting in environmental disasters. In the search for alternatives to propulsion powered by internal combustion engines fueled by hydrocarbon fuels, research is being conducted on internal combustion engines fueled by gaseous fuels, alcohol, and biofuel, in addition to investigations into propulsion powered by electricity. Due to the subject of this paper, research related to electric drives was analyzed.

In the paper [13], one of the largest marine engine manufacturers, MAN Energy Solutions, proposed the solution of using a generator/electric motor solution, i.e., a power take-off/power take-in (PTO/PTI) system. This solution concerns using the generator as a motor, but only as a support for the main combustion engine when fully operational and working at full load. Such a solution is aimed at increasing the efficiency or lowering the exhaust gas emission.

A thematically similar study on the cooperation of a shaft alternator and an internal combustion engine is presented in [14]. The results of the study on the use of the IHIMU-CRP hybrid electric fuel propulsion system in coastal, short-range ships are shown. A method for optimizing this propulsion, thereby reducing fuel consumption and exhaust emissions, is presented.

Authors of the paper [15] analyzed the probability of main engine failure during severe weather conditions at sea, and effective ways of dealing with such a situation by the shipboard crew. They pointed out that the described bulk carriers, carrying up to 400,000 t (dwt) and powered by engines of up to 80,000 kW, may fail during severe weather conditions. They also suggested that this work should be adopted as a guideline by seafarers to assist in ship risk management.

The work [16] presented a new decision-making process based on reducing multiple evaluation criteria (sometimes unquantifiable) to an evaluation against a single quantifiable criterion—financial values. This methodology was used to compare the performance of a ship with diesel-electric hybrid propulsion against a ship with conventional propulsion. The analysis is presented using the example of a selected vessel.

Wartsila, a manufacturer of marine engines and propulsion systems, proposed hybrid solutions [17,18], using medium-speed, medium-power engines as the main internal combustion engines driving the electric generators that power the electric motors of the ship's main propulsion.

In paper [19], the key application during the use of multiple electric generators was the use of high-power current rectifiers, and paper [20] presents assumptions for the design of electrical systems and overload protection.

In paper [21], technical solutions for environmental protection and alternative propulsion systems, including electric propulsion, were described. Their advantages and disadvantages were then described.

The application of electric drives on warships is presented in [22]. This refers to ships of special military application.

The literature on alternative solutions powered by electric energy also impact the solutions for inland waterway vessels.

In publication [23], the concept of using alternative configurations of propulsion systems for inland waterway vessels in order to reduce their carbon footprint was presented, as well as models for assessing emissions and related costs over the lifetime (life cycle assessments—LCAs) of a propulsion system using an internal combustion engine, and of electricity powered engines in various configurations (including batteries and photovoltaics). The economic viability of both solutions, according to the life cycle cost assessment (LCCA), was compared using the GREET 2020 program.

Due to the specificity of river navigation, the authors proposed the concept of diesel-hydraulic and hybrid propulsion system for inland waterway vessels. The solution of the hybrid design with a pumping system driven by a battery bank in regard to the aspect of energy efficiency was also presented. The results of experimental investigations carried out on a natural scale parallel hybrid and a diesel-electric drive controlled by a smart propulsion system are presented in [24].

Based on the measurements, the authors analyzed the fuel consumption and investment costs of four alternative propulsion systems. A simplified method of cost and savings analysis was presented. A solution of “green propulsion” on a passenger ship in the “green shipping” concept was presented in [25].

An analysis of the available literature shows that the use of battery electric propulsion is very limited to low-power, short-range craft, often used in inland passenger shipping. The biggest problem is the availability of battery charging stations, as well as the battery capacity. Analogies can be seen with the problems encountered in automotive transport [26,27]. In contrast, hybrid systems, in which the main engines are high-power electric motors, depend on the power of the internal combustion (emission) engines driving the electric current generators, which supply these electric motors.

So far, no research has been found on the issue of the electric main propulsion of very large merchant ships, especially during a failure of the internal combustion slow-speed, two-stroke main engine.

Ship constructors and engine manufacturers proposed the solution of using the shaft generator as the engine (PTI) only to support the main propulsion of the ship at full load e.g., in difficult sailing conditions with the excess energy coming from generator sets [28–30].

However, it should be noted main engine failure often occurs due to improper engine operation. Therefore, the safe operation of ships requires making proper, and rational operational decisions concerning the use and operation of the main engines (ME) in particular [7,31]. Damage in such large ships, especially sinking, can cause disasters, and difficult to estimate losses due to the contamination of the marine environment that is not only harmful to flora and fauna, but also to many generations of the population living on polluted coasts [32]. Therefore, in addition to equipping main engines (MEs) with appropriate diagnostic systems (SDGs) to warn of engine wear (deterioration) or failure, the use of diesel-electric propulsion (referred to as PTO/PTI)is proposed, using an electric motor supplied back from the ship’s mains.

The solution proposed by the authors is to use a shaft generator, working in PTI mode, as an emergency main propulsion engine. The configuration will be calculated by the constructor to ensure the ship’s minimum maneuvering speed in difficult sailing conditions, taking into account the adoption of the most safety-compliant emergency course.

However, apart from the use of PTI as an emergency solution, the biggest problem for mechanics is making the rational decision of at what point emergency propulsion needs to be used, as this requires significant changes in the structure of this type of propulsion system.

Many researchers have described operational uncertainty states using various sophisticated research methods, such as in publications [33,34].

The authors assumed that in order to rationally make such decisions (not allowing the complete destruction of the internal combustion engine or the possibility of explosion), it is necessary to assess the technical condition of the main engine on an ongoing basis, using methods presented in [7,8,31,35]. It has been shown that the wrong operational decisions lead to permanent degradation of the engine structure, causing faster wear of the engine than it was designed for, which was the basis for determining the operational time between scheduled overhauls.

The authors adopted a design solution that enabled a significant improvement of shipping safety, by confirming the correctness of such actions using the general theory of reliability of the ME presented in publications [36,37]. The design solution also considers the protection of the marine environment, and other forms of protection resulting from rational engine operation are presented in publications [38,39].

In Figure 1, an illustrative diagram of the ship's main propulsion is shown, using a low-speed, two-stroke piston engine as the main engine with a shaft generator, and a PTO/PTI system (generator (G)) driving the common propeller shaft of the ship.

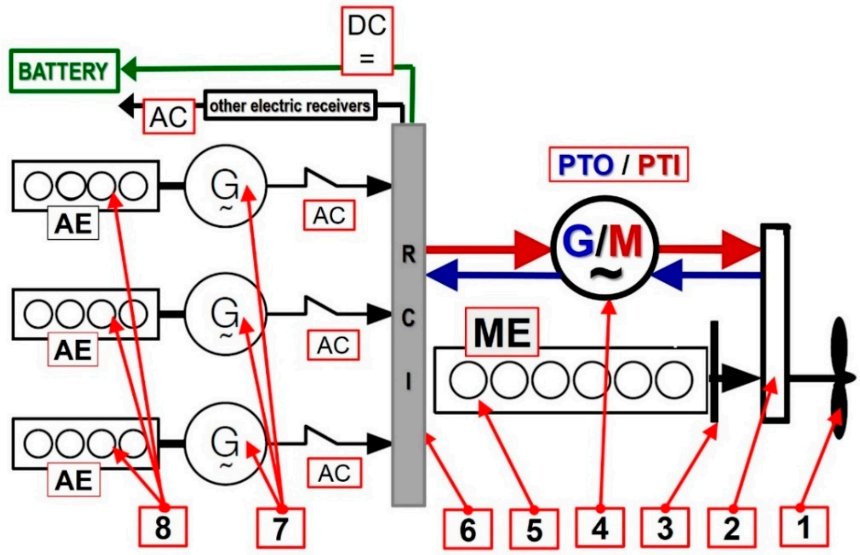

Figure 1. Example of the main propulsion system of the vessel: 1. Unregulated pitch drive screw propeller (fixed pitch propellers—FPP); 2. Electricity generator gearbox; 3. Clutch disconnector; 4. Shafted alternator (PTO/PTI); 5. Marine low-speed, two-stroke main engine (ME); 6. RCI main power unit (AC/DC rectifier, AC/AC converter, DC/AC inverter); 7. Auxiliary engine (AE)—driven generators (G); 8. Auxiliary engine (AE) driving generators of ship power plants.

Further consideration of the use of marine diesel-electric propulsion systems (Figure 1) ensured the safety of the ship in emergency operating situations (the scenarios studied and presented in publications [3,10,40]) in probabilistic terms. The bases of this method are developed in publications [41–43], and are made on the example of the propulsion system of an oil tanker adapted to transport crude oil. Particular attention was paid to the considerations of reliability, one of the most important features of such a system.

2. General Description of the Reliability of the Propulsion System of an Oil Tanker

An oil tanker adapted for the transport of crude oil is characterized by its very large size. It enables the use of ship propellers with a non-adjustable (fixed) pitch, which are driven by means of marine low-speed, two-stroke piston, internal combustion engines [1].

A drive system with such a screw and engine often consists of the following devices [30]:

- marine low-speed, two-stroke, internal combustion piston crosshead engine;
- disconnectable or inseparable coupling;
- intermediate shaft with bearings;
- screw shaft with stern tube;
- drive screw with non-adjustable stroke (unregulated).

Such a system is called a direct propeller system, where the engine speed is equal to the propeller speed. The devices of such a system are, in terms of reliability, elements connected in series, which makes its reliability structure a serial one. Since the failure of one of the elements of the serial structure causes the failure of the whole system, they require the correct exploitation decisions. The dependence of correct exploitation decisions on the exploitation conditions is presented in publications [7,44–46]. A schematic diagram of the structure of the aforementioned drive system is shown in Figure 2. From this diagram, it is clear that the reliability structure of such a drive train is a serial structure.

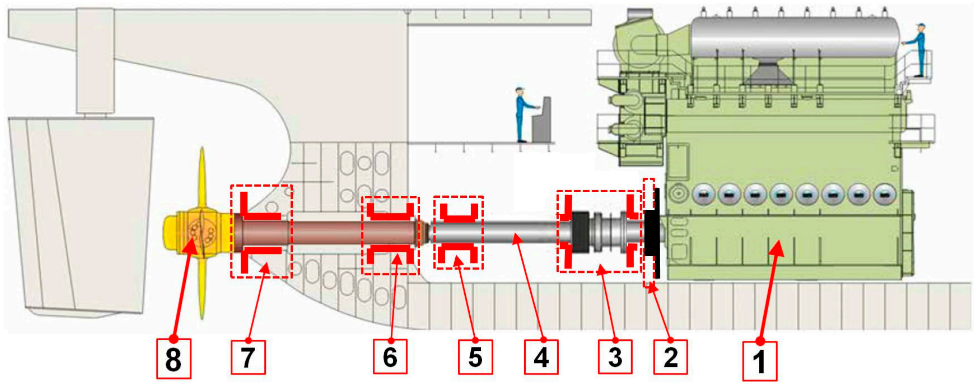

Figure 2. Sample diagram of the main propulsion system of the ship: 1—marine low-speed, two-stroke internal combustion main engine (ME), winged and slow-running; 2—non-disconnectable hydraulic coupling; 3—thrust bearing; 4—intermediate shaft; 5—bearing of intermediate shaft; 6—bearing of screw shaft; 7—scabbard of screw shaft; 8—fixed pitch propeller (own elaboration using MAN BW drive drawing [30]).

The reliability of any such drive system, as a system with a serial structure, is closely linked to the reliability of all its individual components [33,34,36,37,47]. This is because the inability of any of the elements of this system causes failure. The reliability of such a drive system is unambiguously characterized by the reliability function, which can be presented in the form of dependency (1):

$$R(t) = P\{T_1 > t,\ T_2 > t,\ \ldots\ T_8 > t\} = P\{T_1 > t\}P\{T_2\}\ldots P\{T_8 > t\} = \prod_{i=1}^{8} R_i(t) \quad (1)$$

From the diagram shown in Figure 2, it follows that the elements (in terms of reliability) are: 1. marine low-speed, two-stroke diesel engine—main engine (ME); 2. hydraulic separable coupling; 3. thrust bearing; 4. intermediate shaft; 5. bearing of intermediate shaft; 6. support bearing of screw shaft; 7. main bearing of screw shaft; 8. stern tube; and 9. fixed pitch drive screw. This diagram also shows that the reliability of the vessel's propulsion system can be increased if a shaft generator (4) driven by the main engine (1), through a gearbox (3), is used. A diagram of such an arrangement is shown in Figure 3.

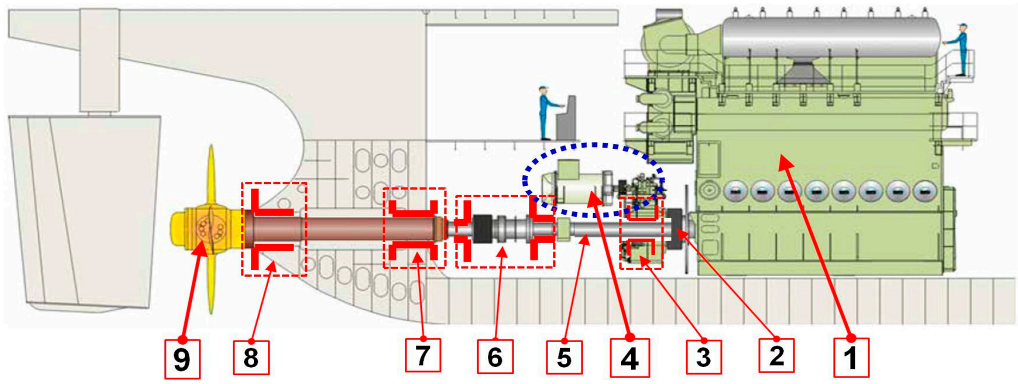

Figure 3. Example of ship's main propulsion with shaft generator and PTO/PTI system: 1—marine low-speed, two-stroke diesel engine—main engine (ME); 2—hydraulic separable coupling; 3—shaft generator gear; 4—shaft generator (PTO/PTI); 5—intermediate shaft; 6—thrust bearing of intermediate shaft; 7—bearing of screw shaft; 8—stern tube; 9—fixed pitch propeller (own elaboration using MAN drawing [30]).

The use of a shaft generator in the ship's propulsion system allows one to drive the ship's propeller, in case of damage to the main engine. In such a case, it operates as an electric engine, powered by electricity generated by the vessel's power plant generating sets. As a result, a parallel reliability structure of the system can be obtained, as shown in Figure 4. The reliability of such a system $R_s(t)$, consisting of shaft generator systems (*SGS*): generator set (4) into gearbox (3) with distribution $F_1(t)$; and main engine set (*MES*): main engine (1) into clutch (2) with distribution $F_2(t)$, capable of driving a common intermediate shaft (5), together or separately, may be described by Formula (2):

$$R_S(t) = 1 - F_1(t)F_2(t) \tag{2}$$

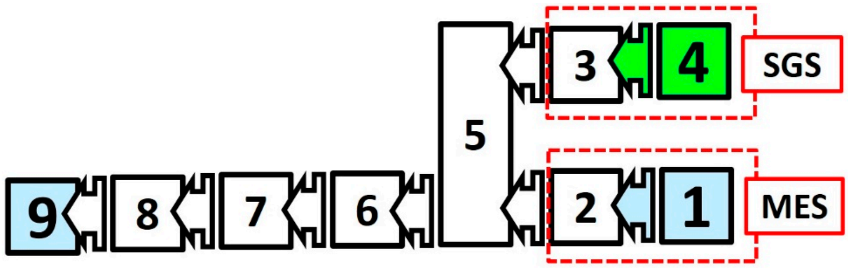

Figure 4. Scheme of main propulsion of the ship with shaft generator and PTO/PTI system: 1—two-stroke main motor; 2—hydraulic coupling; 3—shaft generator gear; 4—shaft generator (PTO/PTI); 5—intermediate shaft; 6—thrust bearing of intermediate shaft; 7—bearing of screw shaft; 8—stern tube; 9.—fixed pitch propeller; *SGS*—shaft generator systems; *MES*—main engine set (own elaboration).

The reliability function of the propulsion system with the reliability structure is presented in Figure 4, and including the PTO/PTI system, can be presented as Formula (3):

$$R_S(t) = \left(1 - \prod_{j=1}^{4} F_j(t)\right) \prod_{5}^{9} R_j(t) \tag{3}$$

where:

$$F_j(t) = (1 - R_1(t)R_2(t))$$

and:

$F_j(t)$—the distribution function (distributor), the probability of failure of the *j*th *MES* unit consisting of main engine (ME), and clutch or *SGS* consisting of a generator and gearbox (PTO/PTI);

j = 1, 2, 3, 4;

$R_i(t)$—the reliability of the ith component of the propulsion system, other than the component of MES and SGS units, and SGS, i = 4, 5, 6, 7, 8, 9;

T—time of correct operation of MES and SGS.

The approach presented to determine the reliability of the ship's propulsion system with the diagram shown in Figure 4 is the result of the adoption of an alternative classification of its reliability states of the type: fit/unfit. In the operational practice of sea-going vessels, other states of their propulsion equipment are also important, especially the main engines (ME), such as the fully effective and ecological condition [43,44], the fully effective condition, the partial condition, and the unfit condition. For this reason, there is a need for a clear interpretation of these states.

3. Change in Engine Condition Due to Engine Operation

The mechanical energy generated by the engine, under strictly defined conditions, is considered as a measure of its ability to perform We. For this purpose, the formulas developed in [6,7] determining the action of A_M are used. Action is a concept that has been defined differently. In this paper it is taken as represented in [6,7], as a physical quantity with a unit of measure called "*joulesecond*" (product joule times second). Thus, the action defined always results in energy consumption E, and requires time t, and the less efficient it is, the higher the energy consumption. Compression ignition internal combustion engines produce and transmit energy to consumers (e.g., the ship's propeller) in the entire load range for which they are designed and manufactured. The basic figure that clearly defines the motor load is the torque M_0. Torque is closely related to the average dose of fuel G_p, injected successively into each engine cylinder, and thus, to the average effective pressure p_e. The dependence of M_o on the dose G_p and pressure p_e can be presented as follows [7]:

$$M_o = C_1 G_p = C_2 p_e \tag{4}$$

Therefore, it was assumed that it is most convenient to measure the torque M_0 with a torsiometer. This allows the measurement the angle φ of the crankshaft torsion, or the tangential stresses τ created in the shaft due to its torsion, which depend on the engine's M_o torque, according to the dependence [7]:

$$M_0 = s\varphi \ lub \ M_0 = \tau W_0 \tag{5}$$

Therefore, engine action can be determined by Equation (6):

$$A_\varphi = \int_{t_0}^{t_n} s\varphi\omega t dt \tag{6}$$

or

$$A_\tau = \int_{t_0}^{t_n} \tau W_0 \omega t dt \tag{7}$$

where:

s—the torsional stiffness of the shaft;

W_0—the indicator of the torsional strength of the tested section of the shaft, where:

$$W_0 = \frac{\pi d^3}{16}, \qquad d - shaft\ diameter$$

Taking the pressure p_e of the Formula (8):

$$p_e = \frac{W_d p_0 \eta_i}{V_{A0} R T_0 \lambda} \eta_v \eta_m \tag{8}$$

where:
W_d—gas calorific value;
P_0—ambient pressure;
V_{A0}—amount of air theoretically necessary for combustion of 1 kg of fuel;
R—gas constant;
T_0—ambient temperature;
η_i—indicated efficiency;
η_v—filling efficiency;
η_m—mechanical efficiency;
λ—excess air ratio.

Therefore, Formula (6) can take the form:

$$A_M = \int_{t_0}^{t_n} C_2 \frac{W_d p_0 \eta_i}{V_{A0} R T_0 \lambda} \eta_v \eta_m \, \omega t dt \tag{9}$$

Instead of p_e, a momentary pressure $p_M = f(\omega t)$ was used to allow the engine to generate a momentary torque. Formula (6) can be presented as follows:

$$A_M = \int_{t_0}^{t_n} C_2 p_M \, \omega t dt \tag{10}$$

Using Poisson's process, it is possible to present a physical interpretation of the process of reducing W_e using a fixed value of e [7]. Assuming that from the moment the engine starts operating (assuming that this is the moment $t_0 = 0$) until the moment when the measuring device registers for the first time, event A consisting of reducing the operation of W_e by a value of $\Delta W_e = e$, any value of W_e's operation (including at the maximum load of the engine) can be performed in particular periods of the engine's operation. As time passes, further wear and tear of the engine causes further drops in W_e's operating value by another equal e value, recorded by the measuring device. Therefore, if the accumulated number of B_t of events A, described by a homogeneous Poisson process, is recorded up to t, a total reduction of W_e by ΔW_e up to t, can be presented with the following relation:

$$\Delta W_e = e B_t \tag{11}$$

The random variable B_t has a distribution [6]:

$$P(B_t = k) = \frac{(\lambda t)^k}{k} \exp(-\lambda t); k = 1,\ 2,\ \ldots,\ n \tag{12}$$

where:

λ—the constant quantity (λ + idem), interpreted as the intensity of the reduction of W_e by equal e values, recorded by the measuring device during tests, $\lambda > 0$.

The expected value of $E(B_t)$ and the variance of the process of the increase in the number of events A, i.e., the decrease in W_e's operation by successive values e recorded by the measuring device, can be presented as follows:

$$E(B_t) = \lambda t; \quad D^2(B_t) = \lambda t \tag{13}$$

Therefore, the expected value and the standard deviation of the reduction of W_e's work performed by the motor until t, can be expressed by formulas:

$$E[\Delta W_e(t)] = eE(B_t) = e\lambda t \qquad \sigma_l(t) = e\sqrt{D^2(B_t)} = e\sqrt{\lambda t} \tag{14}$$

Assuming that a new engine (when t = 0) performs the greatest work, i.e., that $W_e(0) = W_{emax}$, can be expressed by a mathematical relation describing the reduction of work with time t, with the formula:

$$W_e(t) = \begin{cases} W_{emax} & for\ dla \quad t = 0 \\ W_{emax} - e\left(\lambda t \pm e\sqrt{\lambda t}\right) & for\ dla \quad t > 0 \end{cases} \tag{15}$$

The graphical interpretation of the relationship recorded in Formula (15) is shown in Figure 5.

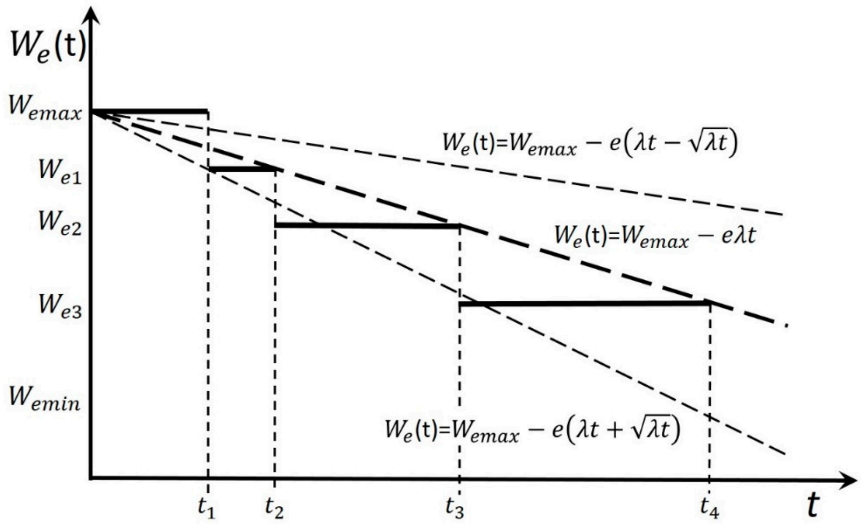

Figure 5. Graphic interpretation of the example realization of the reduction of the useful work of the engine: W_e—useful work, e—quantum by which the work of W_e is changed [6,7].

From Formula (12), it follows that for any moment t, the work We performed by the engine can be determined, and that it is possible to determine the probability of the appearance of such a reduction in the work We of the engine wear and tear that will make it impossible to perform a given task in the operation process. Thus, the probability $P(B_t = k$, k = 1, 2, . . . , n) as determined by the Formula (12) is considered as an indicator of engine reliability, or is taken as an indicator of engine operating safety in case it concerns such a reduction of We performance that it may lead, e.g., to a shipping accident.

The above presented relations between the action of a human being and the engine they are operating, in a certain period of time, causing the drop of the work done W_e as a result of the wear and tear of the device. This allows the introduction of the theory of the vector of the accuracy of decisions (decision accuracy vector) and the concept of the curve of the engine technical condition potential (C_{ETCP}) [6].

Introducing the curve of the engine technical condition potential (CETCP) is a necessary element in the analysis of the processes. It is presented as a set of vectors of decision accuracy $\overline{V_{DAi}}$ where i = [1, . . . , 6], with different values of the consequences of these decisions other than the value in point A. It was assumed that as a result of the exploiter's action, the use of the engine, being in a technical condition with a specific potential, causes adequate wear and tear of the engine, lowering the technical condition potential, which has an impact on lowering the level of ability to perform an exploitation task, and thus, lowering its life span. It was assumed on the basis of expert knowledge that the lower the potential of the engine's technical condition, the lower the quality of processes taking place in the engine (e.g., combustion, charging, and lubrication due to degradation of oil properties), and consequently, the quicker the process of engine wear [8,31].

In addition to the processes that are a natural consequence of using the engine with different potential, it is important to note, for example, that the desire of users to perform a transportation task even/or especially when the potential of the engine's technical condition is reduced, results in additional negative events that accelerate engine wear. An incorrect operating decision may cause the set of technical condition potential values of the engine, presented as the C_{ETCP} engine condition potential curve (wear and tear during operation), to decrease by an appropriate value ΔS_{ETC} (S_{ETC}—state of technical condition of the engine). This phenomenon has been shown as the curve of the state of the engine technical condition, with C_{SETCn}, C_{SETC2}, C_{SETC3}, C_{SETCP4}, and C_{SETC5} presented as consequences of adequate decisions, shown in Figure 6 as decision accuracy vector $\overline{V_{DAi}}$ where i = {1, . . . , 6}.

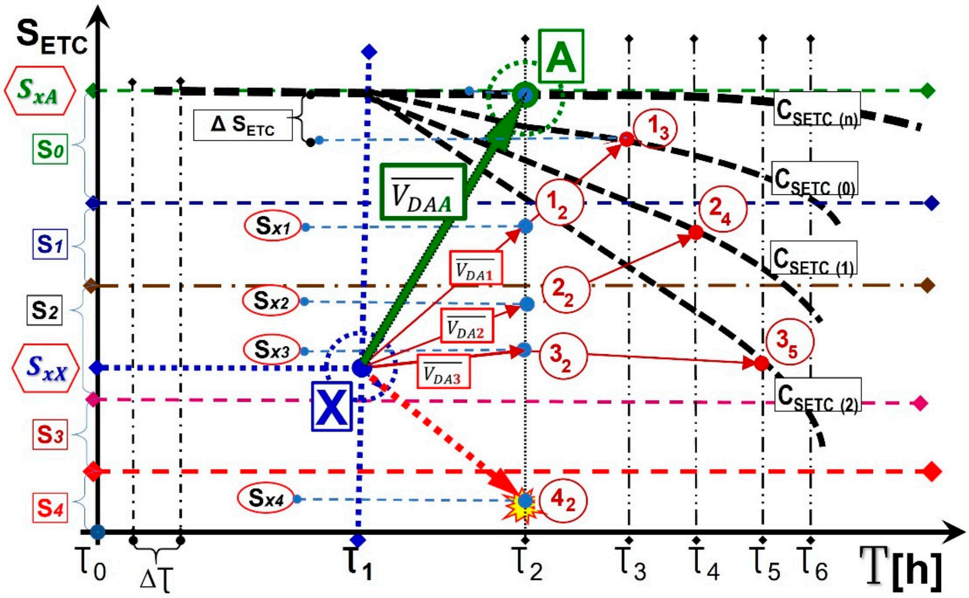

Figure 6. An overview drawing presenting graphically the vector concept of the decision accuracy vector $\overline{V_{DA}}$ where: S_{ETC} axis—the axis of the state of the engine's technical condition; T axis—the axis of the engine's lifetime; τ_W axis—the axis of the relative lifetime of the engine; "X"—the point where values of the state of the engine's technical condition have been assigned to the corresponding technical condition S_x in time τ_1; "A"—the point where values of the state of the engine's technical condition have been assigned to the corresponding technical condition S_{xA} in time τ_2; $\overline{V_{DAA}}$—the decision accuracy vector in the area "A"; C_{STCP}—curve of the state engine technical condition; C_{STCPn}—curve of the state of the engine's technical condition nominal (n), i.e., predicted during the design process (author's own elaboration).

4. Engine Technical Conditions

From operational experience, it is important to maintain a high level of reliability for an oil tanker when performing transportation tasks in difficult, unpredictable sea conditions, especially with regard to the main engine (ME). This means that it is necessary to rationally control both the use of the motor and its operation [46]. In order to act rationally in this respect, diagnostic tests should be carried out to determine the technical condition of the engine [41].

The technical condition of an engine is defined by the set of technical characteristics of its structure that enable it to operate reliably, and carry out its operational tasks in accordance with the intended use for which it was designed, manufactured, and assembled. As presented in works [6,7], this state, at any moment t of operation depends not only on this moment, but also on the technical condition of the engine at the initial moment to <t, any changes of the engine load in the time interval [t_0, t], and the course of control of the engine in this interval. This control has a major impact on the change in engine condition. The state of the engine at the end of the manufacturing process depends on many factors, which are of a random nature (these dependencies are presented in publications [7,31,37,41,42,44]). This means that the process of changing the condition of each engine is stochastic, continuous in states, and over time. Assuming that the criterion for creating a set of states for the engine's suitability to perform a transport task while maintaining ecological standards, the following classes of technical states are distinguished, called directly the states (determination of technical states of machines, including marine engines, has been presented in publications [7,31,37,41,42,44]):

- *The state of full effective and ecological operability of the engine* s_1, which allows the engine to be used in the whole load range for which it was designed;
- *The state of full effective operability of the engine* s_2, which allows the engine to be used in the whole load range for which it was designed, but with significantly lower overall efficiency, i.e., significantly higher fuel consumption and not meeting environmental protection standards;
- *The state of partial operability of the engine* s_3, which allows the engine to be used in a limited load range, smaller than that for which it was designed, does not meet environmental protection standards, and where the levels of wear and tear of the engine components, exceeding the alarm parameters of the media, indicate the need to perform maintenance allowing the engine to be renewed (at least) to s_2 in order to take the ship to a place of refuge;
- *Engine inoperability state* s_4, which prevents the engine from being used as intended (e.g., due to damage, prevention work, etc.).

The set elements $S = \{s_i; i = 1, 2, 3, 4\}$ are the process values of $\{W(t)\colon t \geq 0\}$, which are consecutive states of $s_i \in S$, known to be causal.

It is important to distinguish between states $s_i \in S$ ($i = 1, 2, 3, 4$) because it is crucial to use the motors when they are in state s_1, or possibly in state s_2. When engines are in state s_2, and s_3, they are used in the shortest possible time due to the occurrence of intense degradation processes.

Shipboard internal combustion piston engines in *full operability* s_1 can be used at any time under different loads and ecological standards. In the s_2 condition, they can be freely loaded, but they cannot meet ecological standards. Partially operability s_3 can be used or operated depending on the decision situation, i.e., when the operating conditions (high wave, strong wind, proximity to land, too low depth, saturation of the body of water with other objects, etc.) are not sufficient. This does not put the engine out of action and take up service, but this condition gives a chance to reach the place of shelter [3].

An engine in the *inoperability state* s_4 must always be operated, especially at sea (which gives a chance of survival to the vessel) or in port, if this is still economically justified. During states s_1, s_2, and s_3, the engines can operate and thus send out diagnostic signals, which makes it possible to recognize the elementary states classified into the listed state classes. The changes in these states are influenced by the operating conditions of the engines. Knowledge of these conditions enables rational engine control [45].

If diagnostic information (parameters, change trends) and information about expected engine operating conditions (e.g., expected weather conditions) are available, the operator (engine user) may risk undertaking the task when the engine is in state s_2, or even risk undertaking some tasks in state s_3.

However, the problem is that to analyze the data displayed on the screens of units processing engine parameters requires knowledge exceeding the knowledge and skills of about 70% of mechanics, especially those who do not have an academic education (IMO requires secondary education). Secondary education does not require knowledge of the so-called higher mathematics. However, knowledge of the basics of so-called higher mathematics is necessary to correctly read the graphs displayed on the screens of computers processing engine parameters. Diagrams appearing on the ship's computer screens are shown in Figure 7.

In state s_3, when the operating parameters of the engine indicate significant degradation of the engine structure and further operation can lead to serious damage, called failure, the only rational decision is to stop using the engine and start maintenance. This involves putting the engine out of service, dismantling its components, renewing those components that need to be renewed, or replacing them with new ones. Such a decision taken during the voyage involves stopping the ship, which may result in a loss of maneuverability and the ship's sideways alignment.

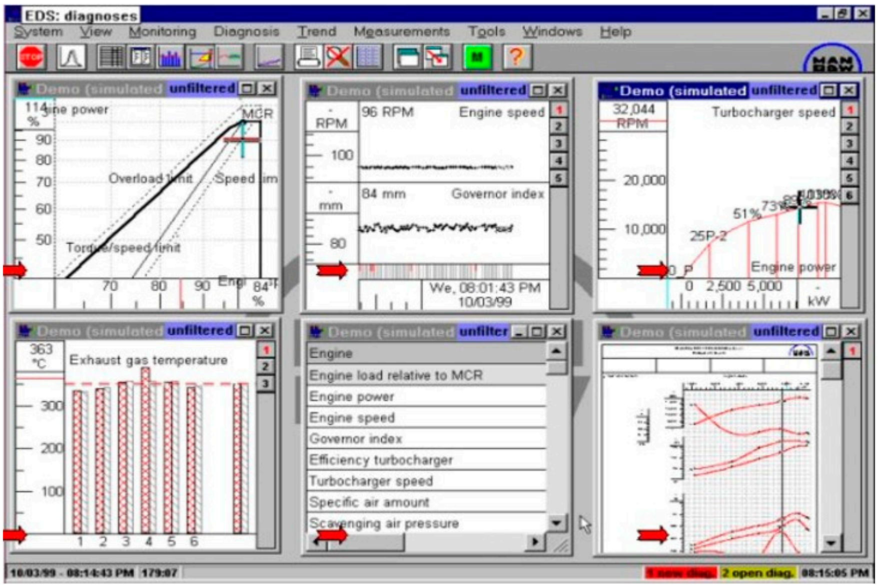

Figure 7. Complicated graphs of mathematical dependencies (at the level of higher mathematics, e.g., nonlinear functions) showing trends in changes of engine condition, on the basis of analysis of data provided by sensors placed on the engine, requiring [48].

On the other hand, if the weather conditions are good, the decision to start a service of the engine causes the voyage to be stopped and too long a stoppage means the possibility of suffering the economic consequences of not entering the port on time. In unfavorable weather conditions, or only unfavorable sea waves, during lateral heeling the ship may lose its lateral stability and drown. Therefore, during the voyage of each oil tanker, it is necessary that the propulsion system of that tanker is in the condition s1 to maintain the ship's maneuverability. This state of the ship's propulsion system is provided by the PTO/PTI electrical unit. This is a solution proposed by engine manufacturers. The selection of the shaft alternator (PTO) should be determined by the electricity demand necessary to maintain the safe movement of the vessel when operating the main propulsion system, which the shaft alternator (PTO/PTI) produces electricity according to the electrical power demand of the auxiliary equipment.

At the planned load of the ship's propulsion system, the transmitted output of the shaft generator (PTO/PTI) is about 10–15% of the power of this main engine [29].

Where it is not relevant in the operating strategy adopted for these engines to distinguish between states s_1 and s_2, a simpler process of $\{W^*(t)\!: t \geq 0\}$ changes in the technical states of the engines may be considered, namely a model with a set of states $S = \{s_1, s_2, s_3\}$ [42], with the following interpretation of these states:

- The *full operability state* s_1, which allows the engine to be used under all the conditions and load ranges for which it is designed and manufactured (including eco-sufficiency);
- The *partial operability state* s_2, which allows the engine to be used under restricted conditions and load ranges smaller than those for which it is designed and manufactured (e.g., "green" and "economic"), but with less favorable economic coefficients;
- The *engine inoperability state* s_3, the failure condition which prevents the engine from being used as intended (e.g., due to damage to components or subassemblies, preventive work on subassemblies, or an inability to provide adequate parameters for the operating media, etc.).

Thus, the process consists of three stages with continuous execution over time. The elements of the set $S = \{s_1, s_2, s_3\}$ are also considered as the values of the said process $\{W^*(t) : t \geq 0\}$ following one another during engine operation. This process is characterized by the fact that, if states s_2 or s_3 do not occur, the internal combustion engine is in state $s_{1,}$ and that the operating time of the internal combustion engines is not a good measure of the wear of their structural structure. This means that a change in the technical condition of this type of engine is poorly correlated with the wear and tear of the expected operating hours. This was justified in the works [7,31]. It follows from the above consideration that the commonly used strategy of carrying out preventive maintenance of internal combustion engines (including ship engines) after the expiry of the designated, fixed periods of their proper operation (time reservations) is ineffective, and therefore, unreasonable. Hence, the conclusion that preventive maintenance of engines should be carried out depending on the results of wear tests, which is possible if the appropriate technical diagnostics are used. The application of such diagnostics requires the development of a diagnostic model for a given type of internal combustion engine, and the application of an appropriate diagnostic system adapted to that model, which is adopted to identify the technical condition of those engines [8,38].

5. Change of Engine States Model

For each marine diesel engine, the change process in engine states is random. The scientific works [31,37] show that the models of this process can be a stochastic process $\{W(t)$: $t \geq 0\}$, with a discrete set of states and continuous during the distinguished technical states of these engines. The development of a model of the process of changing the technical states of diesel engines in the form of a stochastic process requires the establishment of a finite set of S states of these engines. Taking as a criterion for distinguishing such states of suitability of compression ignition engines for performing operational tasks, a set of technical states (significant in operational practice) can be defined in the form of relation:

$$S = \{s_i;\, i = 1, 2, 3, 4\}, \tag{16}$$

with the interpretation presented earlier applicable here, i.e., s_1—full effective and environmental *operability*; s_2—full effective *operability*; s_3—partial *operability*; s_4—*inoperability*.

The set elements $S = \{s_i;\, i = 1, 2, 3, 4\}$ are the values of the process $\{W(t) :\ t \geq 0\}$, which are consecutive states of $s_i \in S$, and causal to each other. The distinction between $s_i{\in}S$ (i = 1, 2, 3, 4) states for a ship's main engines is extremely important as it is vital to use these engines when they are in state s_1 or, if necessary, for the shortest possible time (after which they should be renewed) when they are in state s_2.

This process is fully specified if its functional matrix is known:

$$Q(t) = [Q_{ij}(t)], \tag{17}$$

the non-zero elements of which have the following interpretation:

$$Q_{ij}(t) = P\{W(\tau_{n+1}) = s_j,\, \tau_{n+1} - \tau_n < t \mid W(\tau_n) = s_i\};\, s_i, s_j \in \mathrm{S};\, i, j = 1, 2, 3, 4;\, i \neq j$$

When the initial distribution is given:

$$p_i = P\{W(0) = s_i\},\, s_i \in S;\, i = 1, 2, 3, 4 \tag{18}$$

It was assumed that the changes in state of the ship's main two-stroke, slow-speed main engine used for the propulsion of sea-going vessels, such as cargo and oil tankers, take place according to the transition graph, which is shown in Figure 8 [31].

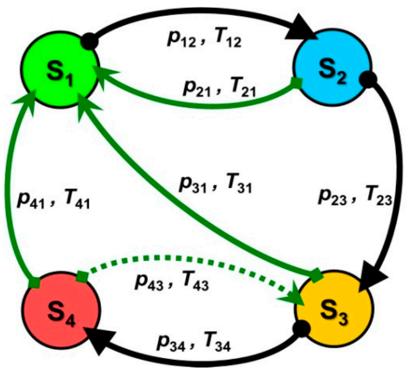

Figure 8. The graph of state changes $s_i \in S(i = 1, 2, 3, 4)$ of the process $\{W(t) : t \geq 0\}$ [4].

In Figure 8 a transition is marked, with an arc depicted by a dashed line, from the state s_4 to the state s_3, which in rational control can only take place in exceptional situations, and therefore, as it is unreasonable, is not included in the developed model under consideration of the process of changes in states of the ship's main engine. Therefore, the process limit distribution $\{W(t)$: $t \geq 0\}$ can be presented in the formulas [7]:

$$P_1 = E(T_1)M^{-1},\ P_2 = E(T_2)M^{-1},\ P_3 = p_{23}E(T_3)M^{-1},\ P_4 = p_{23}p_{34}E(T_4)M^{-1} \tag{19}$$

whereby:

$$M = E(T_1) + E(T_2) + p_{23}p_{34}E(T_4) \tag{20}$$

where:

$E(T_j)$—expected duration of the state $s_j \in S(j = 1, 2, 3, 4)$,

P_{ij}—probability of the process passing $\{W(t)$: $t \geq 0\}$ from state s_j to state s_j (s_i, $s_j \in S$; i, $j = 1, 2, 3, 4$; $i \neq j$).

The individual probabilities Pj ($j = 1, 2, 3, 4$), as defined by Formulae (19), are interpreted as follows:

$$P_1 = \lim_{t\to\infty} P\{W(t) = s_1\},\ P_2 = \lim_{t\to\infty} P\{W(t) = s_2\}, P_3 = \lim_{t\to\infty} P\{W(t) = s_3\}, P_4 = \lim_{t\to\infty} P\{W(t) = s_4\}$$

In the presented model of state changes s_i ($i = 1, 2, 3, 4$), there are situations when the operator may decide to use the PTO/PTI system: at state s_2 of the engine at time $\Delta\tau_{12}$; at state s_3 of the main engine at a time presented as $\Delta\tau_{45}$ or $\Delta\tau_{89}$, and in good weather conditions, the PTO/PTI system should be used and operated with ME; and at state s_4 at time $\Delta\tau_{56}$, the propulsion with PTO/PTI is necessary and gives a chance for the survival of the vessel (Figure 9).

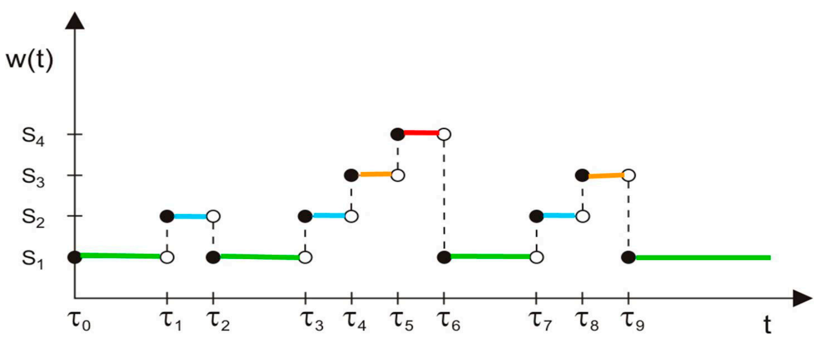

Figure 9. Example of the implementation of the $\{W(t)$: $t \in T\}$ process of a compression ignition engine: $\{W(t)$: $t \in T\}$—process of state changes; t—operating time; s_1—full serviceability; s_2—incomplete serviceability; s_3—partial serviceability; s_4—unsuitable state; periods of time during which the use of a PTO/PTI system is justified.

An important feature of the graph shown in Figure 9 is that the relationship between states reflecting the execution of full recovery to state s_1 is taken into account if the engine is in state s_2 or s_3. Therefore, this variant of $s_i \in S$ condition means changes should be taken into account in creating a simpler (tri-state) graph to show the technical condition changes of a ship's main engines and a related diagnostic model of this type of engine (Figure 10).

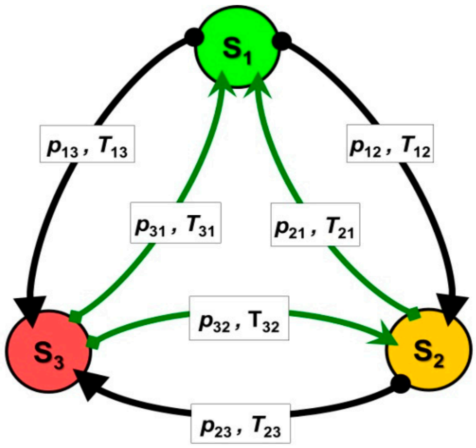

Figure 10. Ship's main engine state change graph: s_1—full effective operability, s_2—partial operability, s_3—inoperability. p_{ij}—probability of process transition from s_i to s_j, T_{ij}—duration of s_i provided that process transition to s_j, i, j = 1, 2, 3.

In the strategy adopted for the operation of marine diesel main engines, it is not relevant to distinguish between states s_1 and s_2, it can be considered a simpler process of $\{U(t) : t \in T\}$ changes in the technical states of these engines, namely a process with a set of states, can be considered:

$$S = \{s_1, s_2, s_3\} \tag{21}$$

for interpretation: s_1—full effective *operability*, s_2—partial *operability*, s_3—*inoperability*.

The graph of state changes s_i (i = 1, 2, 3) of the process $\{u(t) : t \in T\}$ of these engines is shown in Figure 7.

This process is also a three state process (like the process $\{W(t) : t \geq 0\}$) with continuous execution over time. It is assumed that if either of the states s_2 or s_3 do not occur, the internal combustion engine is in state s_1.

Therefore, the set of technical states $S = \{s_1, s_2, s_3\}$ can be considered as a set of stochastic process values $\{U(t) : t \in T\}$, with fixed compartments and right-hand continuous execution (Figure 11).

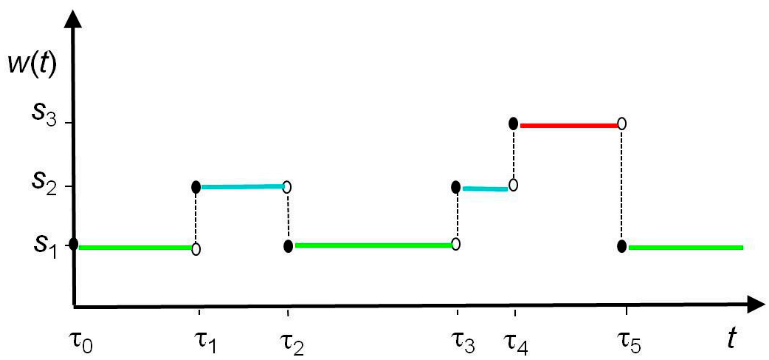

Figure 11. Example of the implementation of the process: $\{U(t) : t \in T\}$ of a marine diesel main engine; (ME): $\{U(t) : t \in T\}$—process of state of repair; t—service life; s_1—full effective *operability*; s_2—partial *operability*; s_3—*inoperability*. Periods of time during which the use of the PTO/PTI system is justified.

The initial distribution of the process under consideration (Figure 11) about the transition graph (Figure 10) is defined by a formula:

$$P_i = P\{W(0) = s_i\} = \begin{cases} 1\ for\ i = 1 \\ 0\ for\ i = 2, 3 \end{cases} \tag{22}$$

The function matrix, on the other hand, is as follows, when the function $Q_{32}(t)$ is non-zero, or $Q_{32}(t) \neq 0$:

$$\mathbf{Q(t)} = \begin{bmatrix} 0 & Q_{12}(t) & Q_{13}(t) \\ Q_{21}(t) & 0 & Q_{23}(t) \\ Q_{31}(t) & Q_{32}(t) & 0 \end{bmatrix} \tag{23}$$

When the function $Q_{32}(t)$ is zero, i.e., $Q_{32}(t) = 0$, the matrix (23) will take the form:

$$\mathbf{Q(t)} = \begin{bmatrix} 0 & Q_{12}(t) & Q_{13}(t) \\ Q_{21}(t) & 0 & Q_{23}(t) \\ Q_{31}(t) & 0 & 0 \end{bmatrix} \tag{24}$$

Therefore, for the presented process $\{U(t)$: $t \in T\}$ with the functional matrix defined by the Formula (24), the following limit distribution can be determined:

$$P_1 = \frac{\pi_1 E(T_1)}{H}, P_2 = \frac{\pi_2 E(T_2)}{H}, P_3 = \frac{\pi_3 E(T_3)}{H}, \tag{25}$$

whereby:

$$\pi_1 = \frac{1}{2 + p_{12}p_{23}}, \pi_2 = \frac{p_{12}}{2 + p_{12}p_{23}}, \pi_3 = \frac{1 - p_{12}p_{21}}{2 + p_{12}p_{23}},$$
$$H = \pi_1 E(T_1) + \pi_2 E(T_2) + \pi_3 E(T_3),$$

where:

P_1, P_2, P_3—the probability that the compression ignition engine is in the states s_1, s_2, s_3 respectively;

π_j—limit probability of the process $\{U(t) : t \in T\}$ of the Markov string describing the possibility of the state s_j appearing, j = 1, 2, 3;

p_{ij}—probability of the process passing $\{W(t) : t \in T\}$ from the state s_i to the state s_j;

$E(T_j)$—expected duration value of the state s_j.

The presented technical conditions of the marine diesel main engine are related to the respective operating conditions of these engines. These technical states and the associated operating states (states of use and operation) are mutually exclusive. Therefore, taking into account these types of conditions when making operational decisions, it is reasonable to control the operation of the ship's propulsion system by taking into account the application of the PTO/PTI system, in operational situations where it is reasonable to exclude the ME from service in case of malfunction, or when the ME is in an unsuitable state.

A properly designed computer program based on the proposed models could work out unambiguous conclusions from the analysis of trends in changes of engine states, and unambiguously suggest to the mechanic-operator to change the type of drive to the emergency one, i.e., to use the PTI system. However, this requires the involvement of the engine manufacturer, who avoid such unambiguous solutions and leave such decisions to the mechanics. This is related to complicated post-accident procedures conducted by insurance companies in order to determine responsibility for failures.

6. Conclusions

The paper presented the concept of a technical solution of a ship propulsion system, consisting of a two-stroke, low-speed main diesel engine (ME) and a shaft generator that can be used as an emergency electric motor when it is necessary to put the ME out of service.

This is an innovative solution, because it is not currently used on very large ships where there is such a large disproportion between the main and the emergency power.

The main problems to be solved in the research process identified by the research team can be divided into direct and indirect problems.

Indirect issues are that with this type of main engine propulsion system, and the use of a fixed pitch propeller, the shaft generator cannot be used to power the ship's power plant while the ship is stationary at the loading terminal, or used as a power source for the cargo pumps. Therefore, the power of the shaft generator is designed adequately for the energy demand for powering the equipment ensuring the movement of the ship at sea. At the same time, when controlling the power of such an engine by changing the revolutions, shaft generators are used only when the hydrometeorological conditions make operation possible. This means a limited range of revolutions and use only during a sea voyage.

The direct problems consist of the fact that in order to achieve the minimum maneuvering speed, generators with a power corresponding to at least about 30–40% of the nominal power of the two-stroke diesel engine (depending on the state of loading of the ship) are needed, with standard generators of about 6–10% of the nominal power of the ME.

Therefore, engine manufacturers will not use over-powered generators, associated with an increase in investment and operating costs, and with a decrease in the efficiency of the generator when only partially loaded during the voyage.

Based on operational experience, it was suggested to change the thinking from "economic" to "safe", which requires additional costs, but a similar cost increase occurs with "safe" to "ecological" thinking.

Therefore, in justifying the proposed solution, the paper shows that it is possible to increase the reliability of the main propulsion system of crude oil tankers, and bulk cargo ships adapted to carry bulk cargo, by using a shaft generator as an emergency engine (PTO/PTI) when the main engine loses its fully operational condition.

Since one of the biggest exploitation problems leading to failure is rational decision making, it was shown that depending on the adopted exploitation strategy, one of the two exploitation process models of marine main engines can be applied using the semi-Markov process, i.e., four-state, when making decisions in order to protect the environment [16], or three-state, when the main engine must be stopped before it reaches the state of inoperability. For both of these models, their limiting distributions were determined, which formed the probabilities of the engine staying in their respective states.

It was shown that such a model was useful in the operational practice of the ships under consideration, especially in the process of diagnosing the engine technical condition and facilitating the operational decision at the right moment.

In conclusion, on the basis of the above-mentioned research, it seems reasonable that in order to avoid both serious breakdown and a loss of maneuverability of the ship, the PTO/PTI system should be applied at the appearance of the main engine partial operational state (s_2 in the three-state model). This is a prerequisite for maintaining the ship's maneuverability and safely performing engine maintenance. It was also found that when a ship's propulsion engine is in an unserviceable condition (s_3 in three-state model), it is absolutely necessary to use the shaft generator (PTO/PTI) as an electric motor of emergency main propulsion.

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