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Accelerated Life Testing in Maritime Critical Systems.

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Climate change and the ice melting in the Arctic zone is a major environmental and geopolitical issue as well. Due to this phenomenon, cargo vessels are able to follow new maritime routes though the Arctic zone and also new energy resources fields are accessible. This change is a major challenge for maritime industry players, affecting maritime industry in many aspects. One aspect is that of the journey shortening from East Asia to Northern Europe, increasing transportation capacity and resulting finally to significant cost cuts for maritime industry stakeholders. A broad use of the new northern routes for the international trade leads to the use of ships that are not constructed according to extreme weather standards. Although Multi state systems and Markov chains are a reliable analysis tool for systems' availability assessment, the polar zone's extreme weather conditions affect the availability of the onboard systems, increasing its assessment's uncertainty. This paper is an attempt to model such changes on the expected availability of maritime critical systems. Combining the direct effect of polar weather conditions on the systems onboard with Markov chains and Multi State Systems modelling, Accelerated Life Testing theory is an additional research tool, contributing to the reduction of the uncertainty imposed by the new factors.

Keywords: Markov Chain, Multi State Systems, Accelerated Life Testing, Maritime Transportation, Maritime Routes

1. Introduction

Climate change is a global major issue affecting many sectors of the human activity. The ongoing climate change results to a reduction of the sea ice extent in polar zone implying further changes in nature and affects many human activity sectors. The greenhouse phenomenon as part of the climate change is closely related with the greenhouse gas sources, maritime industry and transportation vessels (Ntziachristos et al, 2016 and Erying et al, 2010). Concerning this major issue some questions arise about the way to deal with it, to reverse this process, or how to use it in order to reduce its effect. The process reversal seems quite difficult and presupposes a total approach of the problem. This major environmental challenge implies additional changes related with the operational sector of maritime industry. The emissions problem led the International Maritime Organization (IMO) to adopt a new environmental strategy imposing new requirements (MEPC 2018a, MEPC2018b, and MEPC 2021) on the use of maritime fuels. This policy change and the increased need for energy, forces the maritime industry stakeholders to seek for more energy efficient alternatives either in onboard systems or in operational strategy (Abadie et al. 2015). The additional problem of the climate change brings new challenges. The first one for the ship owners and managers is to adapt their assets to the new requirements and action strategy of the International Maritime Organization (MEPC 2018a, MEPC2018b, and MEPC 2021), considering the fuel quality challenges by using on their ships cleaner fuels such as Liquefied Natural Gas (LNG) (Herdzik, 2011), distilled Marine Gas Oil (MGO) or low sulphur variants (Very Low Sulphur Fuel Oil-VLSFO, Ultra Low Sulphur Fuel Oil - ULSFO) (Markopoulos and Platis, 2020). One "hybrid" alternative increasing the emission control using the existing heavy fuel oil (IFO 380) is the use of scrubbers (Fagerholt et. al 2015, Flagiello et. al. 2018, Markopoulos et al. 2021) in order to keep the ordinary diesel machinery as is, minimizing the adaption costs on the one hand and to filter the undesired emissions within the required levels on the other.

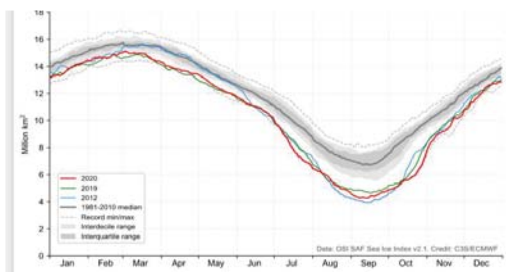

Figure 1: Arctic daily sea ice extent Source:climate.copernicus.eu

The ice melting (Figure 1) of the arctic zone (Fetterer et al 2020) is a recent process in progress and will impose significant changes in economic and geopolitical context (Drewniak et al, 2018).

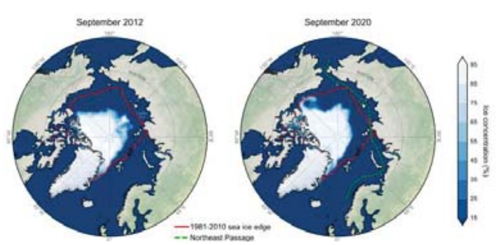

Figure 2: September Mean sea ice concentration in 2012 and 2020. Source: climate.copernicus.eu.

The ice extent reduction in the arctic zone provides new alternative maritime routes (Bayhiran and Gazioglu, 2021, Sheehan et al. 2021) to international trade and goods transportation from East Asia to Europe (Figure 2) implying additional geopolitical issues as well (Dalaklis and Vaxevani, 2016, Drewniak et al. 2018). A new route such as the Northeast Passage close to arctic Siberia results to a significant distance cut in the transportation process from Asia to Europe and North America. On the other hand this cut could lead to further emission reduction for each journey and an indirect reduction of the greenhouse gas issue. Another new route due to the ice melting that will be possible is the transpolar one which is close enough to the North Pole and the Northwest Passage close to North Canada (Figure 3).

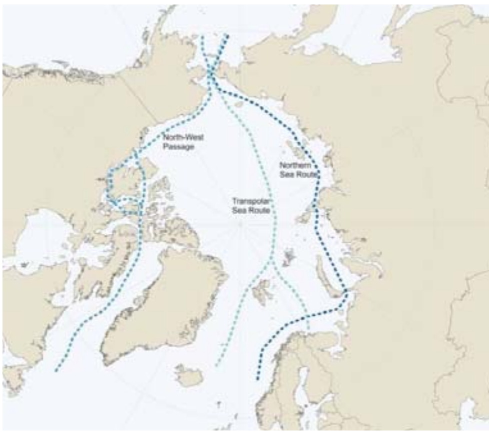

Figure 3: Northern Sea Route, Northwest Passage and Transpolar Sea Route. Source: Arctic Centre, University of Lapland

The common characteristic of these new routes is the prevailing extreme temperature conditions which can affect the technical equipment of vessels as well. The new context imposes new needs although studying and standardization of testing processes have old roots (Jollies and Mittleman 1980, MIL-HDBK-217F 1991, MIL-STD-202G 2002). Since the extreme temperature conditions affect the systems significantly increasing their performance and reliability uncertainty, challenges exist in reliability analysis (Martin et al. 2009). The effect of low external temperature during operation and its implying issues have been studied early in the past, in an attempt to identify the corrosion mechanisms in mechanical systems (Blackwood, 1935) since low temperatures (-50°C and -30°C) create significant problems to mechanical systems and elements (Yan et al. 2006, Tian Et al, 2014). In order to assure a minimum required performability level for specific time during journey in North Pole region, it is necessary to apply methods assuring the systems operation and their minimum performance level. One such approach used broadly, is the accelerated life testing (ALT) (Nelson 2004), except degradation (Yu et al. 2014) analysis of electrical – electronic technology (Thomas et al. 2008, Kang and Kim 2022, Kaymaz 2022, Ha et al. 2014) in food technology (Calligaris et al 2022). According to this method, it is possible to simulate the operation of a system in certain conditions whereas this simulation takes place in different conditions. Like all kinds of simulation, this method increases the systems efficiency and its main advantage is that the testing time is a fraction of the field operation time, reducing the cost and time of the analysis significantly. The simulation is a reduced time operation of the sensitive to the extreme weather conditions systems. In case of the arctic zone navigation, such preliminary short duration testing can be conducted anytime just before the entrance of the vessel in the interest area.

2. System Description

The type of the system under examination is a general pumping unit which is widely used as auxiliary system in the maritime industry. It consists of two major subsystems (components), an electric motor and a motor driven pump. Although it is considered an auxiliary system it is used in a broad range of different transferring applications on a ship such as fuel management, systems lubrication (Neale, 2001), liquid cargo management, gas transfer, ballast water transfer, fire extinguishing water, sea water transfer for exhaust gas scrubbers, etc (Dagkinis 2017). The variety of its applications proves also its critical contribution to the normal operation of major systems such as the main engine or the cargo and fuel management of a ship.

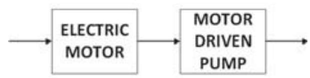

Figure 4: System Layout

The Electric motor drives the pump and both subsystems are serial connected as it is shown in Figure 4. Although the system is simple, the contribution of the two components is different. In case of an electric motor failure the system presents poor performance even if the pump operates normally. On the other hand, if the pump fails, especially in incipient failure mode there is a possibility of delay the crew to notice it. Due to the serial layout of the system once one of the subsystems fails, the whole system fails. Both subsystems include revolving elements and are subjected to mechanical strain due to extreme low temperatures (SKF 2000). Concerning the main failures modes according to the available information and the international standards (International Standardization Organization, 2016), there are three types of them for both components. They are *Incipient*, *Degraded* and *Critical*. The first one the incipient failure is *"an imperfection in the state or condition of an item so that a degraded or critical failure might (or might not) eventually be the expected result if corrective actions are not taken". Thus,* if an incipient failure occurs any registration or corrective action should be taken using specific criteria. The degraded failure is a situation *"that does not cease the fundamental function(s), but compromises one or several functions".* This failure is possible to be gradual and/or partial. The characteristic of this type of failure is that the system presents reduced performance and in case of a delay to repair the system additional development of its severity can be expected, leading to critical failures. Finally, the third type of failure is the critical one. According to the standards a critical failure is *"failure of an equipment unit that causes an immediate cessation of the ability to perform a required function"*. Once such a failure occurs an immediate corrective action is necessary, otherwise severe damages can be expected on the system requiring major unscheduled repairs. Once one of the components fails, then the whole system is in failure mode. Thus, if T_1, T_2,.. T_n is the time to failure for each failure mode, the time to failure of the whole system is:

$$T = min(T_1, T_2, .., T_n) \quad (1)$$

Concerning the state of the whole system it depends on the state combination of the individual subsystems. Depending on the structure of the system its availability is affected by the availability of each subsystem. In this study the authors assume that for the electric motor – pump system, the subsystem having the most severe failure characterizes the state of the whole system, i.e. the system is in a critical failure state if one of the subsystems is in a critical failure state. In the same manner the system is in incipient or a degraded state if one of the subsystems is in incipient or degraded failure state and the other one is in a less severe failure state respectively. The number of states is determined by the repair priority policy. Thus, once the electric motor fails, the repair process starts. If both systems present an incipient failure there is no specific repair priority. In case of a critical or degraded failure it is prioritized against the incipient one. Considering all above information the system can pass through twelve different states as they are shown in Table 1. For each state of the model the first letter depicts the state of electric motor (N-Normal operation, I-incipient, D-degraded, C-Critical failure) and the second one the state of the electric motor driven pump.

Table 1: States of the system

State#	Symbol	Motor	Pump	System
1	NN	Normal	Normal	Normal
2	NI	Normal	Incipient	Incipient
3	ND	Normal	Degrading	Degrading
4	NC	Normal	Critical	Critical
5	IN	Incipient	Normal	Incipient
6	II	Incipient	Incipient	Incipient
7	ID	Incipient	Degrading	Degrading
8	IC	Incipient	Critical	Critical
9	DN	Degrading	Normal	Degrading
10	DI	Degrading	Incipient	Degrading
11	CN	Critical	Normal	Critical
12	CI	Critical	Incipient	Critical

Due to operational scenario of navigation in the arctic zone, the weather conditions are considered "extreme". So, the authors assume that the repair process is possible not to start immediately for different reasons once a subsystem fails. For example, if the pump is in incipient failure state, then a repair delay due to extreme icing conditions is possible and the pump will jump to a degraded or critical failure state with a final result of system's shutdown. In the same manner, if a subsystem is in degraded failure state, then after the delay of the repair process, it jumps to critical failure state worsening the functional problem, leading to a total system shutdown. This assumption adds more complexity and possible uncertainty to the system model but on the other hand provides more accurate analysis and more ample results.

3. System Model Analysis

Given that the two subsystems of the system are in serial layout. When the system operates normally, it is in state N-N. Once a failure occurs in any of them the system is in failure mode and the system jumps to another state depending on the occurring failure.

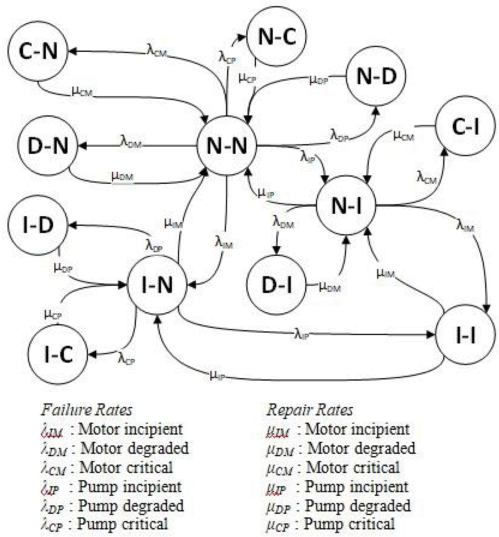

Figure 5: Transition state diagram

All states and the transition paths are shown in Figure 5. The main assumption is that once a failure occurs, then a repair process starts immediately. One question is what would happen with the repair process in case of extreme weather conditions. Concerning the repair process the possibility of a new failure to occur before the start or a delay of the repair process exists. So, there are certain paths in the model, leading from incipient to degraded or critical failure modes. These paths (failure rates) can be expressed as a fraction of the failure rates that lead to a specific state. For example, if one subsystem presents an incipient failure, then it is possible to start the repair immediately or for any reason the crew to delay the repair process. Thus, the incipient failure is expected to be transformed either to degraded or critical failure. This transformation is the transition from one state to another and can vary from zero to one depending on the probability of the failure transformation.

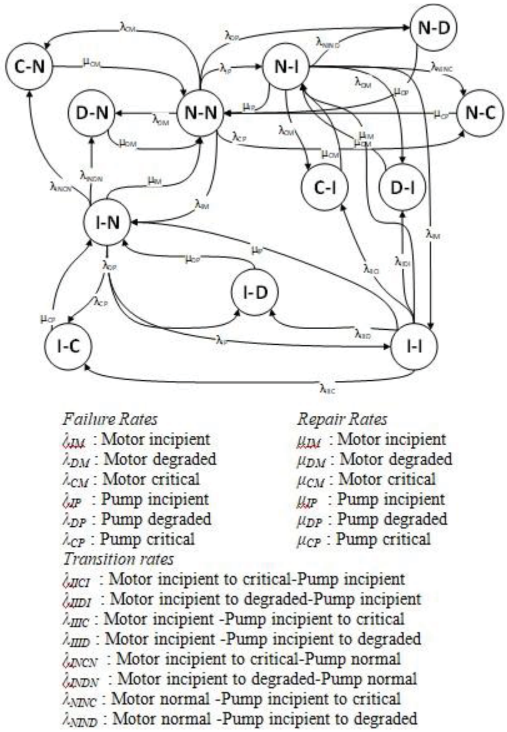

Figure 6: Transition state diagram of the system with modified failure paths.

Therefore the basic model of Figure 5 can be transformed to a modified model shown in Figure 6. Each one of these transitions is proportional to the incipient failure rate that leads to the respective failure as is shown in equations (1) to (8).

$$\lambda_{NIND} = \alpha \cdot \lambda_{IP} \quad (1)$$
$$\lambda_{NINC} = \beta \cdot \lambda_{IP} \quad (2)$$
$$\lambda_{INDN} = \gamma \cdot \lambda_{IM} \quad (3)$$
$$\lambda_{INCN} = \delta \cdot \lambda_{IM} \quad (4)$$
$$\lambda_{IIID} = \varepsilon \cdot \lambda_{IM} + \zeta \cdot \lambda_{IP} \quad (5)$$
$$\lambda_{IIIC} = \eta \cdot \lambda_{IM} + \theta \cdot \lambda_{IP} \quad (6)$$
$$\lambda_{IIDI} = \iota \cdot \lambda_{IM} + \kappa \cdot \lambda_{IP} \quad (7)$$
$$\lambda_{IICI} = \xi \cdot \lambda_{IM} + \psi \cdot \lambda_{IP} \quad (8)$$

where $0 \le \alpha, \beta, \gamma, \delta, \varepsilon, \zeta, \eta, \theta, \iota, \kappa, \xi, \psi \le 1$

This assumption exists only for the incipient failure according to the failure definitions because further action is not necessary. The data for failure rates and time to repair for each subsystem is shown in Table 2 (OREDA 2002). Since the system is an auxiliary one, it can be used occasionally; therefore it is not considered operating continuously. Additionally it is assumed that one crew member repairs the failure so, man-hours are equal to tie required time to repair in hours. In this study the availability analysis takes into account both calendar and operational time data and the respective failure rates given by the respective databases in order to consider all possible cases.

Table 2: Failure rates and time to repair for the subsystems

Failure	Electric Motor			
	Calendar Time		Operational Time	
	Failure Rate/10^6 hrs	Time to repair (Manhours)	Failure Rate/10^6 hrs	Time to repair (Manhours)
Incip(λ_{IM})	20.37	11.4	25.16	11.4
Degr(λ_{DM})	16.37	22.7	18.96	22.7
Crit(λ_{CM})	29.10	55.6	33.41	55.6
Failure	Electric Motor Driven Pump			
	Calendar Time		Operational Time	
	Failure Rate/10^6 hrs	Time to repair (Manhours)	Failure Rate/10^6 hrs	Time to repair (Manhours)
Incip(λ_{IP})	56.94	15.1	761.26	15.1
Degr(λ_{DP})	44.85	26.4	239.06	26.4
Crit (λ_{CP})	20.97	53.1	65.85	53.1

4. Accelerated Life Testing

Starting with the fundamentals on Accelerated Testing it is a set of methods facilitating the performance estimation under specific conditions that are not possible to exist during the study of the system development (Nelson 2004). These methods refer to a wide range of applications concerning temperature, corrosion, humidity, fatigue, vibration, load, voltage and pressure (Di Nisio et al, 2013). The actual problems that are possible to arise in electromechanical systems can be oxidation and galvanic corrosion of metals, degradation of hermetically sealed products, changes in electrical and thermal characteristics etc. The purpose of such life testing is to determine the material resistance capability to exposures in extreme temperatures either high or low (MIL-STD_202G, 2002). There are many cases where it is necessary to assess the reliability parameters of a system. The problem with this approach is that it is not possible due to the duration of the reliability tests. Concerning revolving systems such as electric motors and pumps and their components such as bearings using grease and lubricants, they are subjected to deterioration due to thermal (and cycling) stress. So, it is necessary to consider temperature possibly the most important life factor of the system or component (Tian 2006). Thus, it is necessary to apply estimating methods that shorten this duration. Such method is the accelerated life testing. Its main idea is the estimation of an acceleration factor showing the shortening of the test period against the estimated operating life of the system. Concerning the Accelerated Life Testing the basic form of Arrhenius equation for temperature is used. According to the theory, the accelerated factor estimation is possible through this model. More specifically, relating the reaction rates to temperature time of life is estimated by equation (9).

$$TL = Ae^{-E_a/(kT)} \quad (9)$$

Where A is a constant based on the specific test, e is the natural logarithm base; E_a is the activation energy depending on the kind of the reaction expressed in electron-Volts (eV). The term “activation energy” refers to the minimum energy that a molecule must have to participate in a reaction that produces the failure mechanism; k is the Boltzmans's constant 8.62E-05 eV/°K and T the temperature in degrees Kelvin (°K). If the life test aims to the simulation of the component performance in a different operational temperature an acceleration factor (AF) can be estimated through the following equation (Bayle and Mettas, 2010):

$$AF = e^{-\frac{E_{aa}}{k}\left(\frac{1}{T_{use}}-\frac{1}{T_{test}}\right)} \quad (10)$$

Where AF is the acceleration factor, E_{aa} is the apparent activation energy, T_{use} is the Use Temperature and T_{test} is the Test Temperature. The major difficulty to the above calculation is the estimation of activation energy since it depends on the experimental tests of each manufacturer. A rule of thumb approach is that the Acceleration Factor doubles with every 10°C according to the following equation (Tian 2006):

$$AF = 2^{\left(\frac{T_{test}-T_{use}}{10}\right)} \quad (11).$$

Assuming that the activation energy is $E_{aa} = 0.7eV$. Whereas the assumed temperatures for use in arctic zone are use temperature $T_1 = 223°\text{K}\ (-50°\text{C})$, and test temperature $T_2 = 273°\text{K}\ (0°\text{C})$. Depending on the manufacturer and the testing temperature, the power raised factor in equation (11) may vary below 2. Thus,, a factor of 1.5 can also be used (Tian 2006).

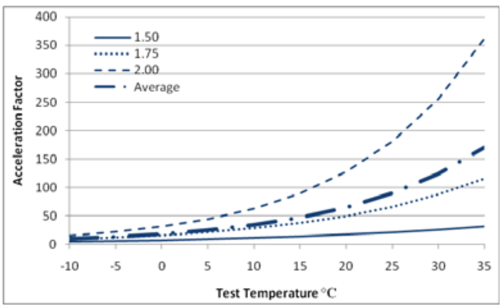

Figure 7: Acceleration Factors based on test temperatures (°C)

Due to the need for experimental data in this study the authors consider three different values for the factor of equation (11), 1.5, 1.75 and 2.0. Adapting previous equations to failure rate estimation it is possible to obtain the acceleration factor for each test temperature. One approach providing the big picture of the acceleration factors would be taking the average of three accelerating values for each testing temperature (Figure 7). The average power raised factor for equation (11) is estimated to be 1.83 and the estimated average AF value is 40.684. Using the information mentioned above, the use time period is the test time period, extended by the acceleration factor (*AF).*

$$Time_{use} = AF \cdot Time_{test} \quad (12)$$

Another method to evaluate the reliability of the system in the target conditions is to apply the Arrhenius HTOL model (Ellerman 2012). The first step is to divide the number of the failures (incipient, degraded, and critical) by the operational time of each component (OREDA 2002) calculating the failure rate per hour.

$$\lambda_{hour} = \frac{r}{D \cdot H \cdot AF} \quad (13)$$

where r is the number of failures occurred in the D is the number of devices (two devices – one electric motor, one pump), H is the test time in hours per device and AF is the acceleration factor derived by the Arrhenius equation (10). In order to obtain more accuracy in failure rate, we can replace the number of failures (r) with the probability function provided by the Chi squared distribution given that

$$r \sim \frac{X^2(a,v)}{2} \quad (14)$$

where a is the confidence level and v is the degrees of freedom of the distribution. Thus, the final form of equation (13) is

$$\lambda_{hour} = \frac{X^2(a,v)}{2 \cdot D \cdot H \cdot AF} \quad (15)$$

The term λ_{hour} refers to the sum of all kinds of failures for each subsystem (electric motor and pump).

$$\lambda_{hour} = \sum_{i=1}^{3} \lambda_i \quad (16)$$

where i refers to the type of failure (incipient, degraded or critical). The term λ_{hour} can be calculated easily (OREDA 2002) using data shown in Table 3.

Table 3: Number of Failures observed in operational time

	Electric Motor	Pump
Operational time 10^6 hrs	4.3894	8.6743
Failures		
Incipient	80	1124
Degraded	76	754
Critical	119	524

The necessary time to test the system can be calculated by the following equation:

$$H = \frac{X^2(a,v)}{2 \cdot D \cdot \lambda_{hour} \cdot AF} \quad (17)$$

Assuming the journey duration in the arctic zone and the desired reliability level, it is possible to determine the test duration before the entrance into the interest area. Analysis of the equation shows that the bigger the failures rate (λ_{hour}) the shorter the test duration. This observation is reasonable because a higher failure rate means a shorter mean time to failure and consequently, the test can be completed in a shorter time. Due to extreme weather conditions there is increased uncertainty on the repair capability and consequently, the mean time to failure (*MTTF*) is a decisive parameter to take into account in order to evaluate the system reliability until the first failure. Thus, MTTF for each component and consequently for the whole system in hours is

$$MTTF = \frac{1}{\lambda_{hour}} \quad (18)$$

Since the components are repairable, the mean time between failures (MTBF) is also useful. It is the sum of MTTF and mean time to repair (MTTR). Thus, the MTBF in hours is

$$MTBF = \frac{1}{\lambda_{hour}} + MTTR \quad (19)$$

5. Results

The first step to the system analysis is to evaluate its availability. The electric motor – pump system does not operate continuously.

Table 4 Steady State probabilities for Basic Model (Calendar and Operational time)

#	State		Steady State Probability	
			Calendar Time	Operational Time
1	NN	Normal	9.946E-01	9.766E-01
2	NI	Incipient	8.552E-04	1.123E-02
3	ND	Degraded	1.178E-03	6.164E-03
4	NC	Critical	1.108E-03	3.415E-03
5	IN	Incipient	2.310E-04	2.801E-04
6	II	Incipient	1.986E-07	3.219E-06
7	ID	Incipient	2.736E-07	1.768E-06
8	IC	Critical	2.573E-07	9.794E-07
9	DN	Degraded	3.697E-04	4.204E-04
10	DI	Degraded	3.178E-07	4.833E-06
11	CN	Critical	1.609E-03	1.814E-03
12	CI	Critical	1.384E-06	2.086E-05

Thus, availability assessment of the electric motor – pump system is conducted through the analysis for an operational time period.

Table 5: Steady State probabilities for Basic Model (Calendar and operational time)

#	State	Steady State Probability	
		Calendar Time	Operational Time
1	Normal	9.946469E-01	9.766480E-01
2	Incipient	1.086680E-03	1.151164E-02
3	Degraded	1.547697E-03	6.589047E-03
4	Critical	2.718727E-03	5.251272E-03

Assuming that the system is a continuous time Markov chain model and using data from Table 2, the solution of the respective system of equations is the steady state probabilities for each state which are shown in Table 4. It is important to remind that the probability of delay to repair has been taken into account and consequently, some incipient or degraded failures become critical ones. Given that each state of Table 4 refers to a specific failure mode, the final probabilities for each operational (or failure) mode are shown in Table 5. Considering that there is possibility the repair process not to start immediately upon the occurrence of an incipient failure and solving the modified model (Figure 6) for different values of the failure parameters (equations 1-8) the minimum and maximum availability of the system is shown in Table 6.

Table 6: Performance comparison for Modified system model (Calendar and Operational Time)

Parameter	Calendar		Operational	
	Min	Max	Min	Max
Availability	9.946443 E-01	9.946469 E-01	9.762459 E-01	9.766480 E-01
α	1.00	0.00	1.00	0.00
β	1.00	0.00	1.00	0.00
γ	0.02	0.00	1.00	0.00
δ	0.03	0.00	1.00	0.00
ε	0.02	0.00	1.00	0.00
ζ	0.02	0.00	1.00	0.00
η	1.00	0.00	1.00	0.00
θ	1.00	0.00	1.00	0.00
ι	0.00	0.00	0.00	0.00
κ	0.00	0.00	0.00	0.00
ξ	0.02	0.00	1.00	0.00
ψ	0.02	0.00	1.00	0.00

According to findings of Table 6, and the respective parameters for calendar and operational time, the steady state probabilities for minimum availability of the modified model are shown in Table 7.

Table 7 Steady State probabilities for minimum availability of Modified Model (Calendar and Operational time)

#	State		Steady State Probability	
			Calendar Time	Operational Time
1	NN	Normal	9.946E-01	9.762E-01
2	NI	Incipient	8.537E-04	1.097E-02
3	ND	Degraded	1.179E-03	6.382E-03
4	NC	Critical	1.110E-03	3.857E-03
5	IN	Incipient	2.309E-04	2.798E-04
6	II	Incipient	1.984E-07	3.112E-06
7	ID	Incipient	2.734E-07	1.830E-06
8	IC	Critical	2.572E-07	1.108E-06
9	DN	Degraded	3.698E-04	4.204E-04
10	DI	Degraded	3.173E-07	4.778E-06
11	CN	Critical	1.610E-03	1.814E-03
12	CI	Critical	1.381E-06	2.052E-05

Finally, the steady state probabilities for each failure mode are shown in Table 8. Assuming that the journey through the arctic zone lasts twenty days approximately, the expected time the system would probably operate in extreme weather is a period of 480 hours. According to Tables 4 and 5, the expected time of Normal Operation in Operational time is 20 Days · 24 · 9.7664E-01 =468 hours and 47 minutes. Similarly, the expected time of Normal Operation for calendar time is 20 Days · 24 · 9.9465E-01 =477 hours and 26 minutes.

Table 8 Steady State probabilities for minimum availability of Modified Model (Calendar and Operational time)

#	State	Steady State Probability	
		Calendar Time	Operational Time
1	Normal	9.946443E-01	9.762459E-01
2	Incipient	1.085102E-03	1.125451E-02
3	Degraded	1.549083E-03	6.806902E-03
4	Critical	2.721561E-03	5.692727E-03

The *MTTF* and *MTBF* for the whole system differs depending on which failure occur. Both *MTTF* and *MTBF* for each type of failure are shown in Table 9.

Table 9: Mean times to failure (MTTF) and between failure (MTBF) in hours for system components

Failure	MTTF	MTBF
Electric Motor		
Incipient	34,360.8	34,416.4
Degraded	61,074.7	61,097.4
Critical	49,078.2	49,089.6
Pump		
Incipient	47,683.8	47,736.9
Degraded	22,296.7	22,323.1
Critical	17,562.8	17,577.9

Similarly to the equation (1) the *MTTF* for the whole system is the minimum one of all *MTTF's* ant it is 17.562.81 hrs for the critical failure mode of the pump. In the same manner, the minimum *MTBF* is 17,577.9 hrs for critical failures of pump again. Finally, the required time to test the system before the entrance to the interest area according to equation (10) is shown in Table 10. The final duration of the test should be the longest one in order to assure that all failures are taken into account.

Table 10: Minimum test duration for each type of failure

Failure type	Test Duration (hrs)
Electric Motor	
Incipient	0.101936
Degraded	0.119220
Critical	0.094144
Pump	
Incipient	0.157904
Degraded	0.043496
Critical	0.013659

Considering duration for all failure modes, the test of the whole system should last the maximum duration in order to cover all possible modes. Thus, the test should last 0.157904 hours or 9 minutes and 29 seconds, ten minutes approximately.

6. Conclusions

The combination of an electric motor and a pump is an essential auxiliary system on board, facilitating the normal operation of other major systems. Due to significant environmental changes (climate change), and the changing conditions in maritime industry, new developments are expected on the vessels operational management through new challenging maritime routes. The industry stakeholders will need to adapt their decision making systems to the new conditions. The prevailing extreme weather conditions on the new maritime routes in the arctic region show that the industry should apply new methods in order to meet the safety and availability requirements of these conditions. Reliability tests before the entrance in the arctic zone of the new maritime routes should be applied on the onboard systems in order to assure that they will operate normally during all time the vessel travels in extreme weather and temperature conditions. Referring to the Acceleration Life Testing methodology, it can provide useful information concerning the reliability of the system for specific time periods especially when failure handling difficulties exist due to external causes such as extreme weather conditions. Concerning the operation duration, there are different auxiliary systems onboard. Some of them are used in continuous operation (calendar time) i.e. engine fuel-oil system transfer whereas others operate on demand such as cargo transfer systems, fire system etc (operational time). The proposed method includes an initial system availability assessment of a pumping the system for calendar and operational time. Additionally, it is assumed that due to extreme weather conditions and for different reasons in case of incipient failures the repair process possibly, does not start upon the occurrence of the failure and a part of them is transformed to degraded or critical failures. A comparison of the findings in Tables 5 and 8 shows the availability difference between the two models is relatively low, meaning that even if a part of incipient failures are developed in more severe failure modes due to extreme conditions, the system availability will remain relatively stable. An additional operation test is conducted before the entrance to the interest area. This test provides prediction on how the system will operate for an extended time period based on the accelerated life testing methodology. Additional parameters are necessary to take into account for this analysis. The first part is the Mean time to Failure (*MTTF*) and Mean time Between Failures (*MTBF*) that show whether the system is expected to fail during journey in the arctic zone. The second part is the required testing time depending on the acceleration factor (*AF*) and the failure rate (λ) the components present(s). It is inversely proportional with the failure rate, the number of tested devices and the accelerating factor. According to the findings and due to relatively low failure rate and high accelerating factor, the required time is relatively low, since only approximately ten minutes of testing is sufficient to provide the necessary information about the system reliability. On the other hand, since there are a number of similar systems this preparation process could be quite long.

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