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The analysis of class survey methods and their impact on the reliability of marine power plants

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Abstract

This article examines the selection methodology of class surveys of a shipborne engine room and its impact on the reliability and operation indicators of a marine power plant. We describe the characteristics of four available class survey methods and then carry out a reliability analysis on the basis of four months of activity on six different ships operating on international voyages, taking into account the two most common supervision methods: renewal and continuous survey. Based on this analyses, we conclude that the reliability indices of a marine power plant, classified according to the continuous method, were slightly lower than for the renewal method. However, we identified potential benefits in terms of overall ship maintenance costs, due to a faster and more economical 5-yearly shipyard survey.

Introduction

Every watercraft under a qualifying association's regulation, should implement a system of supervision and repair of the ship's equipment (ABS, 2017; PRS, 2017; DNV-GL, 2017, 2018). Such a system adopts continuous supervision and maintenance of equipment within a defined survey interval (Chybowski, 2009a, 2009b; Chybowski & Gawdzińska, 2017a, 2017b). The survey is typically a set of activities dealing with the ship, its mechanisms, devices, equipment, etc., and is carried out by checking the technical documentation and conducting appropriate visual inspections, measurements, and tests (PRS, 2017). This supervision enables the reporting of any failures or deviations from the norm, which may occur in the operation and should also include the mechanism for repair. The ship's maintenance system is based on a "service life" maintenance model (Czajgucki, 1984; Macha, 2001; Adamkiewicz & Zeńczak, 2017). In accordance with this model, the rules for class surveys are developed. For the case of a vessel to be classified for the first time, the class is assigned to it by conducting a baseline survey, the scope of which is set in each case by the classifying body (DNV-GL, 2017, 2018).

Currently, as the operation of ships becomes more dynamic and is constantly adjusted to market conditions, it is possible, depending on the needs and conditions of use of the vessel, to apply one of four types of class survey methods, these are illustrated in Figure 1. In addition to the well-known renewal and continuous surveys, there is also a survey based on the ship maintenance management software and a survey to examine the condition and parameters of the relevant elements (Gawdzińska, Grabian & Przetakiewicz, 2008; Bejger, Chybowski & Gawdzińska, 2018).

Amongst periodic surveys, we can distinguish between surveys for class renewal and surveys for class confirmation. The class renewal survey is intended to state that the technical condition of the vessel complies with the provisions of the classification body and outline any additional requirements.

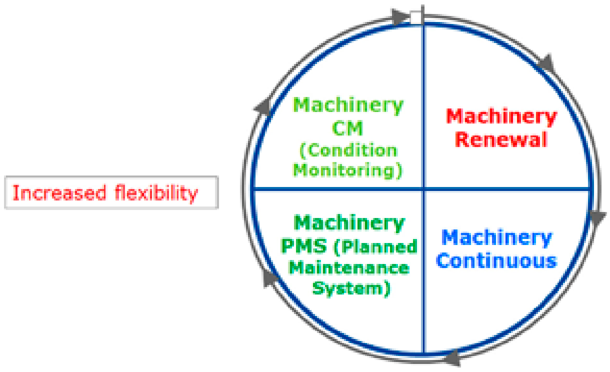

Figure 1. The types of class survey methods (DNV-GL, 2017)

The survey confirming the class is to state that the vessel has sufficiently complied with the conditions to remain in said class by checking the functioning of the individual mechanisms, equipment, and installations, these are subject to the requirements of the classification body.

Methods of carrying out class surveys

The 5-yearly class renewal survey (machinery renewal) is a classic type of supervision carried out by the classification bodies, such as DNV-GL. Every five years, with a possible deviation of up to 15 months, the ship and all its equipment are surveyed in the class shipyard. All equipment is verified for reliability and seaworthiness for the next 5 years. All inspections should be held in the presence of the qualification association's representative. Survey reports are usually drawn up and processed using dedicated software, such as myDNVGL, an example of the online version is presented in Figure 2 (myDNV, 2018).

The second type of supervision is the continuous class survey (machinery continuous) carried out during the permanent operation of the ship. The purpose of such supervision is to reduce, as much as possible, the time and funds needed for a five-yearly shipyard stay. This is done by inspecting every possible component of the system during the survey, considering the service life of the equipment in operation. In this method, it is assumed that an average of 20% of equipment surveys will be supervised and conducted during each year of operation, and only components that cannot be inspected during the normal operation of the vessel will be inspected at the five-yearly shipyard survey. For this method, a maximum deviation of up to 6 months is allowed. All entries confirming inspections should be based on the best possible documentation created during repairs, containing as many photos and measurements of the inspected elements as possible.

A summary of the work carried out, with a possible time deviation, is available through online systems, an example of which is shown in Figure 3. It is assumed that half of the equipment, when there is more than one item, may be surveyed by a chief engineer officer within a minimum period of two years' service at sea and the other half by a representative of the classification body. The rule does not apply to the main propulsion steam turbines, the propulsion of generators, or the reduction gears used

Name of vessel
TROMS FJORD
IMO 9348211

DNV·GL

DNV GL ID no.
26364

Code	**Description**	**Last survey**	**Next survey**	**Status**
MDEMAB	Propulsion engine P > Main bearing 3	2015-10-02	2020-10-02	
MDEMAB	Propulsion engine P > Main bearing 4	2015-10-02	2020-10-02	
MDEMAB	Propulsion engine P > Main bearing 5	2015-10-02	2020-10-02	
MDEMAB	Propulsion engine P > Main bearing 6	2015-10-02	2020-10-02	
MDEMAB	Propulsion engine P > Main bearing 7	2015-10-02	2020-10-02	
MDEMAB	Propulsion engine P > Main bearing 8	2015-10-02	2020-10-02	
MDEMAB	Propulsion engine P > Main bearing 9	2015-10-02	2020-10-02	
MDEVID	Propulsion engine P > Vibration dampers P	2015-10-02	2020-10-02	
MDECAM	Propulsion engine P > Camshaft arrangement P	2015-10-02	2020-09-24	
MDEFUO	Propulsion engine P > Fuel system P	2015-10-02	2020-10-02	
MDETUR	Propulsion engine P > Turbocharger P	2015-10-02	2020-09-24	
MDESTA	Propulsion engine P > Starting system, pneumatic P	2015-10-02	2020-12-18	
MDETST	Propulsion engine S	2015-10-02	2020-09-24	
MDEFIX	Propulsion engine S > Fixation arrangement S	2015-10-02	2020-09-24	
MDECAS	Propulsion engine S > Engine casing arrangement S	2015-10-02	2020-09-24	
MDECYA	Propulsion engine S > Cylinder head 1	2015-10-02	2020-10-02	
MDECYA	Propulsion engine S > Cylinder head 2	2015-10-02	2020-10-02	
MDECYA	Propulsion engine S > Cylinder head 3	2015-10-02	2020-10-02	

Figure 2. An example of an extract from a class status report, based on information from the myDNVGL software (myDNV, 2018)

✓ *Machinery items (185)*	ⓘ	2012-09-10	2017-03-10	2017-09-10
Propulsion diesel engine test	ⓘ	2012-09-10	2017-03-10	2017-09-10
Propulsion diesel engine > Fixation arrangement	ⓘ	2012-09-10	2017-03-10	2017-09-10
Propulsion diesel engine > Engine casing arrangement	ⓘ	2012-09-10	2017-03-10	2017-09-10
Propulsion diesel engine > Tie rods	ⓘ	2012-09-10	2017-03-10	2017-09-10
Propulsion diesel engine > Cylinder head 1C(F)	ⓘ	2012-09-10	2017-03-10	2017-09-10
Propulsion diesel engine > Cylinder head 2C	ⓘ	2015-08-31	2020-02-29	2020-08-31
Propulsion diesel engine > Cylinder head 3C	ⓘ	2012-09-10	2017-03-10	2017-09-10
Propulsion diesel engine > Cylinder head 4C	ⓘ	2015-08-31	2020-02-29	2020-08-31
Propulsion diesel engine > Cylinder head 5C	ⓘ	2015-08-31	2020-02-29	2020-08-31
Propulsion diesel engine > Cylinder head 6C	ⓘ	2012-09-10	2017-03-10	2017-09-10
Propulsion diesel engine > Cylinder head 7C(A)	ⓘ	2012-09-10	2017-03-10	2017-09-10
Propulsion diesel engine > Cylinder liner 1C(F)	ⓘ	2012-09-10	2017-03-10	2017-09-10
Propulsion diesel engine > Cylinder liner 2C	ⓘ	2015-08-31	2020-02-29	2020-08-31
Propulsion diesel engine > Cylinder liner 3C	ⓘ	2012-09-10	2017-03-10	2017-09-10
Propulsion diesel engine > Cylinder liner 4C	ⓘ	2015-08-31	2020-02-29	2020-08-31
Propulsion diesel engine > Cylinder liner 5C	ⓘ	2015-08-31	2020-02-29	2020-08-31
Propulsion diesel engine > Cylinder liner 6C	ⓘ	2012-09-10	2017-03-10	2017-09-10
Propulsion diesel engine > Cylinder liner 7C(A)	ⓘ	2012-09-10	2017-03-10	2017-09-10

Figure 3. An example of a summary of the continuous inspection periods based on the myDNVGL report (myDNV, 2018)

in such propulsion systems. Such surveys must be carried out on an alternating basis, every 10 years. Over a single period, it may be a chief engineer officer and, during the next inspection, it must be a representative of the classification body.

Another, relatively new, method of supervision of the vessel's machinery, as well as over the entire ship, is based on the records given in software programs such as Amos, NS5 or Premaster (Machinery PMS), these supervise the condition and progress of work towards maintaining components of the ship's system. Figure 4 shows an example of a work plan generated by the Premaster system (Premaster, 2018). The classification body does not inspect the condition of the equipment during annual audits but relies on the work records drawn up in the monitoring programs. The hourly service life for individual devices, specified by the manufacturer, is set in

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Maintenance Schedule

Page 2 of 3

Site: 61 Troms Fjord for Period: 01/09/2015 to 22/04/2018
Department: EL, EN
Job Definition: CE, CL, CO, CR, DD, ET, HP, IN, ME, PA, QM, SO, SP
Job Responsible: 2E, CA, CE, CO, EL
Condition: 1, 2, 3, 4, 5 Criticality: 5

Due Job(s) : 26

Job No	Short WO Description	Critical	Risk Assessment	Dept.	Job res.	Run Hours Interval	Due Hour	Estimated due	Period Interval	Due
601.26.08 ME 1 HP FUEL PUMP NO. 8 (FWD) (Run hours = 74294)										
1	INJECTION PUMP. INSPECTION/DISASSEMBLY			EN	CE	15000	74181	17/04/2018		*
601.53.01 ME 1 ENGINE TURBOCHARGER (Run hours = 74294)										
4	PERIODICAL MAINTENANCE PROCEDURES 12 000 H			EN	CE	12000	73000	15/02/2018		01/03/2018*
601.74.12 ME 1, FUEL OIL BOOSTER PUMP ATTACHED (Run hours = 74294)										
2	FUEL FEED PUMP. MAINTENANCE DISASSEMBLY			EN	CE	15000	74181	17/04/2018		*
601.76.11 ME 1 FW HT COOLING PUMP, ATTACHED (Run hours = 74294)										
2	COOLING WATER PUMP. MAINTENANCE/DISASSSEMBLY			EN	CE	15000	74181	17/04/2018		*
601.77.11 ME 1 FW LT COOLING PUMP, ATTACHED (Run hours = 74294)										
2	COOLING WATER PUMP. MAINTENANCE/DISASSSEMBLY			EN	CE	15000	74181	17/04/2018		*
602.01.01 ME 2 (MAIN ENGINE NO. 2 STBD) (Run hours = 74331)										
3	COMPRESSED AIR STRAINER.			EN	CE	7500	74318	22/04/2018		*
4	PERIODICAL MAINTENANCE PROCEDURES 150H			EN	CE	150	74335	22/04/2018		
602.22.01 ME 2 CAMSHAFT ARRANGEMENT (Run hours = 74331)										
1	VIBRATION DAMPER ON CAMSHAFT			EN	CE	15000	74282	20/04/2018		*
602.44.02 ME 2, LO COOLER/ATTACHED (Run hours = 74331)										
1	WATER ANALYSIS IS REGULARY CARRIED OUT.			EN	CE	250	74330	22/04/2018		*
602.53.01 ME 2 ENGINE TURBOCHARGER (Run hours = 74331)										
1	MAINTENANCE/CLEANING			EN	CE	48	74321	22/04/2018		*

Figure 4. An example of a summary of work scheduled in the Premaster supervision software (Premaster, 2018)

the software and its accuracy is checked during the initial inspection. The software itself must also be accredited by a supervisory authority before it can be installed on board the vessel. Equal importance is attached to the extensive documentation drawn up by the surveyor and properly added to the work report produced by the software. As part of the annual audit, the ship managements familiarity with the service is verified.

The final supervision method is based on the state of the equipment determined during a component inspection which considers the condition and parameters of individual elements of the system (Machinery Condition Monitoring). The classification body allows some machines (such as the stern tube, the measurement of which is shown in Figure 5) to be certified based on operating parameters, such as the temperature of the oil and the bearings or the oil content in the water which is recorded continuously. If all the standards are met, and there are no contraindications due to, e.g., water leaks into the oil or significant losses of a lubricant, the classification body may decide not to open the equipment for inspection and to allow it to continue to be used.

The methods described above in this section are intended to maximize the reliability of the vessel and of the equipment operating in it. The management


DET NORSKE VERITAS
TAILSHAFT MONITORING

STERN TUBE BEARING TEMPERATURE
AND LUB. OIL QUALITY

Name of Ship: Troms Fjord — TROMS FJORD — DNV Id. No. 26364

SB STERN TUBE — YEAR 2017

Stern tube bearing temperature	H	L	H	L	H	L	H	L	H	L	H
MONTH	1		2		3		4		5		6
Sensor: INNER	39	36	33	34	39	36	40	37	41	37	43
" : OUTER	29	27	29	27	30	27	31	30	32	27	34
" :											
" :											
" :											
SEA WATER											
MONTH	7		8		9		10		11		12
Sensor: INNER	48	42	46	43	45	43	45	40	41	39	41
" : OUTER	36	33	36	35	36	34	35	32	33	31	32
" :											
" :											
" :											
SEA WATER											

Lub. oil cheo

MONTH	1	2	3	4	5	6
% water	0,0 %	0,0%	0,05 %	0,05%	0,05%	0,05[illegible]
Oil refilled	25	11	9	0	3	4
MONTH	7	8	9	10	11	12
% water	0,05%	0,05%	0.05%	0.05%	0.05 %	0.0[illegible]
Oil refilled	12	4	4	12	8	0

Figure 5. The measurement of the temperature and water content in the stern tube oil

body of a ship, having consulted with the supervisory association, faces the choice of which classification method that makes the operation of the seagoing vessel as safe and reliable as possible, whilst also considering the shipowner's finances.

Comparative analysis of class survey methods

In order to compare the different methods of class surveys, a comparative analysis was made using data from scheduled and emergency maintenance work performed on six ships operating on international voyages, of which the author of the article conducted this study for a total of 4 months, spread over 3 years. During the study, he collected data on the time and reasons for exclusion of the generators from the overall standby time due to the above-mentioned maintenance work. The author's idea was to observe the correlation between the chosen method of supervision and the deviation from the standard value of 0.98 of the readiness factors that are characteristic of the monitored generators. The monitoring was conducted by the same classification association using two methods: renewal for the case of bulk carriers and continuous for the case of container ships. This article, reporting the comparison of these power plants is intended to demonstrate which system of monitoring has a greater impact on the reliability of marine power plant equipment.

As shown in Table 1, ships and marine power plants differ significantly in their age, power, type of fuel consumed, and degree of complexity. According to their characteristics, bulk carriers are equipped with smaller generators, which deliver sufficient power for the needs of the engine room, whereas on larger container ships, the power plant must have sufficient power to supply a large number of cooled containers and there is much larger equipment in the engine room. The list of failures applies only to systems directly affecting the operation of the generating set, such as the fuel system, the cooling system, oil, the compressed air system, the crankshaft, and the piston system, as well as the changes to the operating medium.

The running hours in Table 2 are calculated from the machine logbooks. The mean time between failures, which was lowest for the "San Vincente", can be calculated by comparing the data collected from repairs carried out. The MTBF has 153 running hours for the generators, the largest being for the ship "Butterfly", namely 662 hours.

Table 1. List of vessels involved in the comparison

Name of the vessel	Type	Year of building	Engine manufacturer	Engine power [kW]	Power plant rating [kW]	Fuel	Load: port/sea/manoeuvring/ number of generators
Theoforos I	bulk carrier	1986	Yanmar	500	1500	blend	1/1/3/3
Martha	bulk carrier	1995	Yanmar	800	2400	heavy	2/1/3/3
San Vincente	container ship	1993	Yanmar	700	2900	light	1/0/2/2
Santa Giuliana	container ship	1995	Yanmar	700	3400	light	1/0/2/2
MSC Charleston	container ship	2005	MAN	2600	10400	heavy	1/2/3/4
Butterfly	container ship	2008	MAN	2200, 2800	12200	heavy	1/2-3/3-4/5

Table 2. Summary of running hours of generators

Ship	AE No.	RHs at the end of the contract	RHs at the beginning of the contract	Number of faults per engine	Number of faults per power plant	RHs of an engine per contract	RHs of a power plant per contract	RHs of an engine/number of faults	RHs of a power plant/number of faults
Theoforos I	1	80442	79231	3	6	1211	3395	404	566
	2	54222	53092	1		1130		1130	
	3	65441	64387	2		1054		527	
Martha	1	38344	35962	4	12	2382	6278	596	523
	2	54412	51728	2		2684		1342	
	3	1212	0	6		1212		202	
San Vincente	1	12233	11922	3	7	311	1072	104	153
	2	17994	17233	4		761		190	
Santa Giuliana	1	22739	22344	2	3	395	826	198	275
	2	19452	19021	1		431		431	
MSC Charleston	1	11989	11788	0	12	201	6680	0	557
	2	8782	6722	2		2060		1030	
	3	12878	10293	2		2585		1293	
	4	17622	15788	8		1834		229	
Butterfly	1	14338	11738	1	12	2600	7944	2600	662
	2	11733	11629	1		104		104	
	3	8212	7890	2		322		161	
	4	13882	11423	5		2459		492	
	5	15212	12753	3		2459		820	

Table 2 shows that the component requiring the least intervention by the user was generator No. 3 of MSC Charleston, while the engine most frequently affected by failures was generator No. 4 of the same vessel. By comparing the mean running time between failures in power plant to the information about ships, we obtain the mean time between failures for the required number of generators running during "sea travel".

Engine manufacturers provide special maintenance and inspection schedules to facilitate maintenance planning and thus prevent damage. According to the designers, work on the engine should enable failure-free operation until the next survey specified in the manual (YANMAR, 1985, 1992, 1993; MAN, 2004, 2007). The list presented in the Table 3 shows all the failures that occurred during the study and the time until failure, as a percentage of the time recommended before the next survey.

Table 4 lists all the scheduled work carried out on the generators. The work is based on the manufacturer's recommendations for a given engine, which have been additionally uploaded in the ships computer program, supervising the correct schedule for inspections and surveys. In addition to routine tasks, such as cleaning turbines or oil testing, additional work was carried out at appropriate running hours for the individual elements, such as injector replacements and engine cylinder head repairs.

Most of the planned daily-routine work during the performed contracts was carried out on engine No. 1 in the Martha's engine room. Together with engine number 1 of Theoforos I, the two ships reached the largest number of running hours for maintenance.

Table 3. A list of failures with hourly data

Ship/Engine	RHs since the last overhaul	RHs in the period of overhauling	%
Theoforos I Yanmar 220	8233	16000	51
	239	2000	12
	544	2000	27
	1454	2000	73
	1822	2000	91
	1454	3000	48
Martha Yanmar 240	2001	6000	33
	3	6000	0
	5000	5000	100
	1	2000	0
	8	2000	0
	2466	6000	41
	1822	6000	30
	15443	16000	97
	12	6000	0
San Vincente Yanmar 200	7010	16000	44
	4034	8000	50
	12020	16000	75
	300	500	60
	1944	2500	78
	184	300	61
	407	500	81
Santa Giuliana Yanmar 200	2388	2500	96
	14545	16000	91
	8600	8000	108
	14344	16000	90

Ship/Engine	RHs since the last overhaul	RHs in the period of overhauling	%
MSC Charleston Man 27/38	2103	3000	70
	8237	16000	51
	11178	16000	70
	15889	16000	99
	4590	6000	77
	1750	2000	88
	12766	16000	80
	14766	16000	92
	12689	16000	79
	13676	16000	85
Butterfly Man 27/38	13423	16000	84
	4929	16000	31
	2934	16000	18
	13522	16000	85
	14247	16000	89
	15490	16000	97
	140	500	28
	12111	16000	76
	12433	16000	78
	13193	16000	82
	8322	16000	52
	8498	16000	53

Table 4. The summary of scheduled works carried out on the power plant engines

Ship	AE No.	T/C cleaning	Filter cleaning	Performance	Valve clearance check	Alarms check	HP FP baffle screw check	Additional maintenance	Total
		(time/quantity)							
Theoforos I	1	6/6	14/7	8/4	4/4	4/2	16/2	8/6	60/31
	2	5/5	14/7	8/4	4/4	4/2	16/2		51/24
	3	5/5	14/7	8/4	4/4	4/2	16/2		51/24
Martha	1	10/10	10/5	8/4	4/4	4/2	16/2	8/6	60/33
	2	12/12	10/5	8/4	4/4	4/2	16/2		54/24
	3	5/5	10/5	8/4	4/4	4/2	16/2	12/6	59/28
San Vincente	1	2/2	2/1	8/4	4/4	4/2	8/1		28/14
	2	5/5	2/1	8/4	4/4	4/2	8/1		31/17
Santa Giuliana	1	2/2	2/1	8/4	4/4	4/2	0/0		20/13
	2	2/2	2/1	8/4	4/4	4/2	8/1		28/14
MSC Charleston	1	1/1	0/0	8/4	4/4	4/2	16/2	2/1	35/14
	2	10/10	2/1	8/4	4/4	4/2	16/2	2/1	46/24
	3	13/13	2/1	8/4	4/4	4/2	16/2	2/1	49/27
	4	6/6	2/1	8/4	4/4	4/2	16/2		40/19
Butterfly	1	13/13	2/1	8/4	4/4	4/2	16/2		47/26
	2	1/1	0/0	8/4	4/4	4/2	0/0		17/11
	3	3/3	0/0	8/4	4/4	4/2	0/0		19/13
	4	12/12	4/2	8/4	4/4	4/2	16/2		48/26
	5	5/5	4/2	8/4	4/4	4/2	16/2		47/25
		every 200 h	Yanmar: 200 h MAN: 2000 h	once a month	once a month	once every two months	every 500 h	according to the manual	

The engine that needed the least routine work, which is related to its low unit load, was the engine room in the Butterfly, and engines No. 2 and 3. In addition, because of the use of shaft generators on the open sea voyage, the generators installed on San Vincente and Santa Giuliana had lower maintenance hours than average.

Quantitative comparison indicators

In order to determine the best possible assessment of the machineries readiness and reliability, indicators are used to determine the degree of machine use, prevention, and readiness. Reliability is defined as the objects property that provides information on its ability to perform specific functions, under specific conditions, and at specific times (Piaseczny, 1992). This analysis is based on the failures observed during operation and maintenance and is compared with the time usage of the machinery. This list includes 19 generating sets located in the engine rooms of the 6 ships described. All the variables, together with the indicators calculated by the formulae (1)–(5), are given in Table 5.

- The mean time out of operation, $\bar{\tau}_p$ defined as the mean time attributable to breakdowns or servicing operations, during which the equipment cannot perform its function due to the maintenance operations being carried out,

$$\bar{\tau}_p = \frac{1}{m}\sum_{i=1}^{m}\tau_{pi} \quad \text{[h]} \tag{1}$$

where:
m – the number of items,
τ_{pi} – total time out of operation of the i-th item over the period of survey;

- utilization rate, q_w, is the probability of an event in which the object is seaworthy at any time and performs the task for which it is intended:

$$q_w = \frac{\bar{\tau}}{\bar{\tau} + \bar{\tau}_r + \bar{\tau}_{pr}} \quad [–] \tag{2}$$

where:
$\bar{\tau}$ – average lifespan,

Table 5. A list of engines surveyed with the calculated reliability indicators

Vessel	Generator No.	Hours of unplanned work t_r	Amount of unplanned works n_t	Duration of planned servicing operations t_{pr}	Amount of planned servicing operations n_{pr}	Duration of all works τ_0	Amount of all works n_0	The total operating time t_{exp}	The total engine's running time τ_ε	Readiness time t_{ready}	Idle time $t_{st\text{-}by}$	Average time out of operation $\bar{\tau}_p$	Average time of planned servicing operations $\bar{\tau}_{pr}$	Average time of unplanned works $\bar{\tau}_r$	Utilisation rate q_w	Prevention rate q_z	Prevention rate q_c	Readiness indicator k_g
Theoforos I	1	6	3	60	31	66	34	2880	1211	2814	1603	1.94	1.94	2.00	0.33	2.03	0.92	0.95
	2	2	1	51	24	53	25	2880	1130	2827	1697	2.12	2.13	2.00	0.34	1.95	0.71	0.96
	3	3	2	51	24	54	26	2880	1054	2826	1772	2.08	2.13	1.50	0.36	1.75	0.78	0.95
Martha	1	12	4	60	33	72	37	2880	2382	2808	426	1.95	1.82	3.00	0.29	2.48	0.84	0.97
	2	4	2	54	29	58	31	2880	2684	2822	138	1.87	1.86	2.00	0.33	2.06	0.90	0.98
	3	16	6	59	28	75	34	2880	1212	2805	1593	2.21	2.11	2.67	0.32	2.16	0.72	0.94
San Vincente	1	17	3	28	14	45	17	2880	311	2835	2524	2.65	2.00	5.67	0.26	2.90	0.29	0.87
	2	14	4	31	17	45	21	2880	761	2835	2074	2.14	1.82	3.50	0.29	2.48	0.46	0.94
Santa Giuliana	1	4	2	20	13	24	15	2880	395	2856	2461	1.60	1.54	2.00	0.31	2.21	0.56	0.94
	2	6	1	28	14	34	15	2880	431	2846	2415	2.27	2.00	6.00	0.22	3.53	0.29	0.93
MSC Charleston	1	0	0	35	14	35	14	2880	201	2845	2644	2.50	2.50	0.00	0.50	1.00	0.60	0.85
	2	10	2	46	24	56	26	2880	2060	2824	764	2.15	1.92	5.00	0.24	3.21	0.49	0.97
	3	14	2	49	27	63	29	2880	2585	2817	232	2.17	1.81	7.00	0.20	4.06	0.44	0.98
	4	46	8	40	19	86	27	2880	1834	2794	960	3.19	2.11	5.75	0.29	2.47	0.34	0.96
Butterfly	1	4	1	47	26	51	27	2880	2600	2829	229	1.89	1.81	4.00	0.25	3.07	0.61	0.98
	2	4	1	17	11	21	12	2880	104	2859	2755	1.75	1.55	4.00	0.24	3.17	0.35	0.83
	3	18	2	19	13	37	15	2880	322	2843	2521	2.47	1.46	9.00	0.19	4.24	0.22	0.90
	4	24	5	48	26	72	31	2880	2459	2808	349	2.32	1.85	4.80	0.26	2.86	0.53	0.97
	5	12	3	47	25	59	28	2880	2459	2821	362	2.11	1.88	4.00	0.26	2.79	0.57	0.98

$\overline{\tau}_r$ – average time of unplanned works,
$\overline{\tau}_{pr}$ – average time of planned servicing operations over the period of the survey;

- the prevention rate, q_z, is the ratio of the time the device underwent maintenance over the period of the survey to the period itself,

$$q_z = \frac{\overline{\tau}_r + \overline{\tau}_{pr}}{\overline{\tau}} \quad [–] \tag{3}$$

where:
$\overline{\tau}$ – average lifespan,
$\overline{\tau}_r$ – average time of unplanned work over the period of survey,
$\overline{\tau}_{pr}$ – average time of planned servicing operations over the period of survey;

- prevention rate, q_c gives the ratio of the number of service operations to the survey time

$$q_c = \frac{\overline{n}_{pr} + \overline{n}_r}{\overline{\tau} + \overline{\tau}_r + \overline{\tau}_{pr}} \ [1/\text{h}] \tag{4}$$

where:
$\overline{n}_{pr}$ – average number of planned servicing over the period of survey,
$\overline{n}_r$ – average number of works not planned over the period of survey,
$\overline{\tau}$ – average lifespan,
$\overline{\tau}_r$ – average duration of works not planned over the period of survey,
$\overline{\tau}_{pr}$ – average time of planned servicing over the period of survey;

- readiness indicator, k_g the ratio of time when the machine is ready to perform the task immediately in a random place and at a random time to the total duration of the survey

$$k_g = \frac{\tau_\varepsilon}{\tau_\varepsilon + \tau_0} \quad [–] \tag{5}$$

where:
τ_ε – the total running time of the auxiliary engine,
τ_0 – the time of all work carried out during the operation of the auxiliary engine.

On the basis of calculations carried out for auxiliary engines installed within the engine rooms of ships inspected, the value of the readiness indicator ranged from 0.83 to 0.98. The lowest value was observed on engine number 2 of the Butterfly's engine room and on MSC Charleston's engine number 1. The engines with the highest readiness were those with a readiness ratio of 0.98, considered equal to the standard values, installed on the Martha, MSC Charleston and Butterfly ships.

Discussion

The power plant with the highest failure rate, as shown in Table 3, is the container ship San Vincente's power plant. It should be noted that the shaft generator operation was not taken into account, which means that 153 operating hours of the power plant are sufficient for one month of normal operation. Calculations show that the power plant of the Theoforos I had the longest mean time between failures, while the components in the power plant of the Butterfly broke down most often. The generators were made by two manufacturers: Yanmar, Japan, with their engines installed directly in Japan, and MAN, Germany. The installation of the German manufacturers engines is licensed by Korean factories: STX for MSC Charleston and Hyundai for Butterfly. A summary of the data shows that Yanmar is the manufacturer which is most susceptible to failures. Their generators failed 28 times, on average 2.8 times per generator, and the mean time between failures was 406 hours. German engines were more reliable by over 200 hours. The type of ship on which they run is of great importance to the ship operators. It is widely believed that bulk carriers are more comfortable to operate than container ships. According to the data collected in Table 3, this is not true when we consider this study, as there were more frequent repairs on the bulk ships than on container ships.

Table 3 shows that 4 out of 45 failures, a 9% share of all defects, occurred shortly after the survey or previous overhauls. This may be due to incorrect installation or poor quality of the spare parts. Particular attention should be given to the fact that a failure occurs when the engines exceed a period of 12,000 running hours. As a result of the crisis in the carriage market, the company's policy was to extend the period between surveys by 4,000 hours. Table 3 shows that 14 failures (31%), mainly in the fuel system, occurred during the added time between surveys. This calls into question the advisability of extending the survey period for the systems, other than the crankshaft and piston system which operated correctly throughout their useful life. A special case is a failure when 100% of the expected failure-free operation period has been exceeded. This confirms the immediate need to conduct surveys at a prescribed time.

The graph presented in Figure 6 shows the trend lines of reliability indicators as a function of the year the ship was built (marine power plant). These indicators and the characteristics of the trend line are affected by all the data presented in the previous

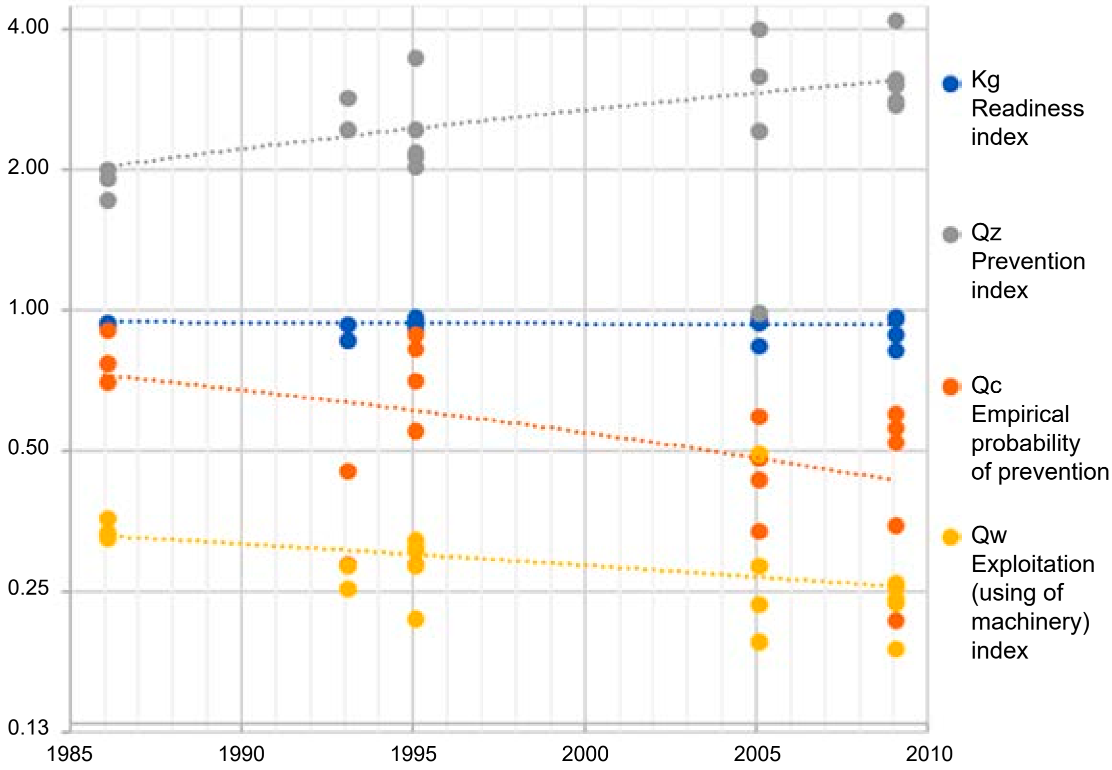

Figure 6. Reliability indicators as a function of the age of power plants/engines

calculations. Based on the calculations, a trend line is obtained and marked in blue, indicating a slight increase in the readiness indicator as the power plants age increases. The trend shown in the figure is opposite to the generally accepted trend of readiness (Czajgucki, 1984, Chybowski, 2009a, 2009b). The main reason for this is the Butterfly's engine No. 2, which lowers the readiness indicator of newer engines. The trend indicates values between 0.93 and 0.95, which is a good result if one compares it with the reference value of 0.98.

The highest utilization rate is found in the generator of the MSC Charleston's engine No. 1. This was due to a great reserve of hours available until the upcoming overhaul, which was to utilize the operating time available between surveys, foreseen by the manufacturer, to the greatest possible extent. The lowest value was found on generating set No. 3 of the same vessel. This was because the engine exceeded the permissible running hours between main surveys and the engine was started only when other engines failed.

Conclusions

From the analysis carried out, it follows that the readiness rate of ships classified by continuous surveys has decreased, as illustrated by the blue trend line. This is due to the work that is carried out on generating sets during the normal operation of the vessel, which reduces the rates of utilization of the equipment. In addition, an inspection/survey is likely to be carried out incorrectly, which may increase the unused time even further. This is one of the disadvantages that a shipowner must take into account if he decides to classify in this mode. Studies have also shown that, despite the more advanced age of power plants operating in the mode of a class renewal survey, their utilization rate in day-to-day operation remains higher. This is understandable because some work is postponed or planned to take place during a 5-year classification period in the shipyard. Failures caused by material defects (Bryll et al., 2017; Gawdzińska et al., 2016, 2017), construction defects (Migdalski, 1982; Piotrowski & Witkowski, 2003), and the exceedance of load limits permissible during operation (Włodarski, 1982; Pajor, Marchelek & Powałka, 1999; Żółkiewski, 2008; Zapłata & Pajor, 2016; Chybowski, Grządziel & Gawdzińska, 2018) are additional problems, however, they are largely independent of ship's engine room operators.

In addition, the results obtained were influenced by significantly varied technical conditions in the power plants, found by the author at the beginning of the study. Bulk ships had been transferred from one owner to another many times, which caused frequent changes of crews and thus reduced the quality of service and had a potential impact on the unused time in the future. Since their launch, four of the container ships being surveyed were operated and managed by a single shipowner, whose objective was to operate the ships for many years, and therefore to take care of the condition of the marine engine room system. In conclusion, it should be noted that the continuous survey is a very good alternative to the renewal survey, slightly reducing the readiness rates of the marine power plant, but able to significantly reduce the cost and the time spent in the classification shipyard.

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