Predictability and the modern maritime environment

Diesel engine failure prediction and monitoring techniques- A case study

Mikael Kannelhovi

Master's thesis

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Author: Mikael Kannelhovi

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Supervisor(s): Thomas Finne, Johannes Lauterbach, Pasi Väänänen

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Abstract

With the continuously increasing competition in the shipping industry, it is of utmost importance that each part of the vessel performs safely and efficiently. This thesis targets the main engines as delivered by MAN Energy Solutions – former MAN B&W on a specific RoRo vessel.

As everything from spare parts to fuel is constantly becoming more and more expensive, this author finds it relevant to involve the term *prediction*. In this thesis there will be a map presenting possible failures on component level and an investigation on how to predict these failures by looking at expected symptoms. Furthermore, an investigation of historical events ranging from the year 2015-2022 was made to understand if there are certain patterns of activities and events related to the operation of the main engines. This material acts as the largest informational input per extent for the research and according to the findings the author selected some interesting additions of techniques that mainly target improved monitoring to understand long time equipment behavior. Improved monitoring in this context aims to improve on-board situation awareness as well as adding a remote monitoring solution – the MAN PrimeServ Assist to benefit from the knowledge of the genuine engine manufacturer.

This complete thesis, as well as the research relies on the vessel acting as case study and the technique as it was delivered in 2001. It is therefore important to understand that the suggested updates mean retrofitting an existing installation with additional automation to improve operational safety and efficiency and that certain limitations are present.
In this context safety targets failure avoidance while efficiency aims to maintain operation in accordance with design parameters.

Therefore, this study does not focus on major changes to the existing setup to drastically improve efficiency (reduce fuel consumption) but instead the target is set on maintaining the engine performance and reliability in accordance with the initial design parameters set by the manufacturer at delivery. This is what the author finds to be the most cost-effective solution on this particular vessel.

Language: English Key words: Diesel engine failure prediction, MAN

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Definition of terms

ACC	Active Combustion Control
CUS	MAN Customer Information Letters
DF	Dual Fuel
IAS	Integrated automation system
MAN ES	Man Energy Solutions
MMS	MAN Multi brand engine safety management system
NDA	Non-disclosure agreement
OEM	Original equipment manufacturer
OPEX	Operational Expenses
PLC	Programmable Logic Control
PMS	Planning and maintenance system
rpm	revolutions per minute
SaCoS	MAN Safety and Control System
SFOC	Specific Fuel Oil Consumption
SOLAS	Safety of Life At Sea
TLS	Transport Layer Security

1 Introduction

This thesis is the result of a cooperation between MAN Energy Solutions and this author. Finnlines Plc acts as contributor in this case study. The main questions are further described in Chapter 1.1 and includes suggestions on technique of how to maintain and possibly improve operational reliability and efficiency of the main engines on-board the RoRo vessel M/V Finnmill, owned and operated by Finnlines. The engines in question are the MAN 48/60 inline nine-cylinder four stroke diesel engines installed at the building of M/V Finnmill in year 2001. The term *prediction* has a heavy impact on this thesis and the aim is to investigate monitoring techniques to improve understanding of the actual engine condition and longtime behavior on a component level as input for a predictive maintenance concept. The actual research relies on historical data in the engine event log ranging from year 2015-2022. This material was analyzed to identify problem areas of these engines and in accordance with the findings, some suggestions are made to improve monitoring.

1.1 Research questions

The main question targets how to improve reliability and efficiency in the case study. This author does realize that this is a very broad question, and the reason was simply to not create unnecessary borders when the initial plan was made, if the process did not develop as planned. Unfortunately, this turned out to be the case, as the initial plan was to rely mostly on recent data in digital format by the MAN PrimeServ Assist remote monitoring service. As this was not implemented on-board, this author selected available historical data. This arrangement created a significant increase in workload as the historical data was available only in paper format. The main idea was to put most of the effort on investigating different methods or concepts to improve monitoring, but instead the largest workload became the manual analyzing of historical events. As this option was still interesting to MAN ES, it did provide motivation to proceed. With the different monitoring techniques suggested in later chapters, additional perspective was gained regarding how to maintain and how to possibly improve reliability and efficiency of the engine operations in terms of input for both on-board operators and for the PrimeServ Assist experts.

1.2 Problem formulation

To maintain and improve safe and efficient operations considering this generation of vessel(s) does involve challenges but also makes room for retrofitting new techniques into existing configurations. This is because the technique has developed considerably since the construction of this particular vessel. The author wants to highlight some important aspects supporting the importance of this specific research by the list below. These few aspects also aim to present a high-level understanding of the problems encountered due to the relatively high age of the machinery on the vessel acting as a case study:

- new and stricter regulations already in force regarding control of ship´s emissions
- considerable increase of costs related to services and spare parts
- fuel costs considerably higher than at the time of building this generation of techniques
- remote *monitoring* considered to be an initial step towards remote *operations* and, possibly fewer on-board crew members

The above aspects create challenges on many levels but as one can understand it is certainly important to maintain reliability and design efficiency of the equipment on-board in order to maintain the ability of competitiveness for the vessel in question. It is simple to understand that an engine suffering from unplanned downtime due to failures of any kind is not an efficient engine.

1.3 Purpose

The main purpose was to find and identify certain patterns of activities related to the main engines and, with these patterns be able to pinpoint areas where additional automation can benefit operational safety and overall efficiency to avoid unplanned engine stops and keep the engine running in accordance with *design parameters*. This author would like to point out that the research relates strictly to this generation of the MAN 48/60 engine and that neither the research nor any other content of this thesis aims to highlight *reasons and actual root causes behind the example cases used*. Instead, the target is to find technical solutions

to predict such unwanted scenarios resulting in considerable expenses and danger to human life.

1.4 Research limitations

The possibilities of making this type of research are basically unlimited. Even if the focus of this research is in on the specific main engines on-board the M/V Finnmill this approach does allow the research to be quantified in many ways. Each component forming the complete engine is designed according to certain criteria and parameters making opportunities in terms of research close to immeasurable. This in turn explains very well why this research must be limited in a concrete manner. To summarize this statement, the author decided to focus on different measures to maintain, and possibly improve the efficiency and reliability of the engine on a somehow basic level. These measures are connected to real scenarios and events found in the event log, which in turn forms the basis of this thesis.

1.5 The Non-Disclosure Agreement (NDA)

During the initial stage of this thesis, a non-disclosure agreement or confidentiality agreement was made upon the commissioner’s initiative. This is a formal agreement that demands the thesis writer to follow certain guidelines and requirements in terms of confidentiality to ensure that any information considered as sensitive does not end up in the hands of competitors. For this specific thesis, the information below is considered sensitive and will therefore not be shown in the public version.

- limitations and specifications related to the MAN 48/60 engine design
- quotation on upgrading the existing engine safety and control system to a later version named SaCoS RETRONE on the vessel Finnmill
- quotation on installation of MAN PrimeServ Assist remote monitoring on the vessel Finnmill
- full list of events related to the main engines as in the IAS event log on Finnmill

1.6 Research methods

Due to the very specific research approach of this thesis, one can clearly see that the methods used in this research as described by (Thattamparambil, 2020) in the Figure below clearly indicate a connection to the right column, Qualitative research methods.

Table 1. Quantitative and qualitative research methods. (Thattamparambil, 2020)

Quantitative research methods	Qualitative research methods
Focus on testing theories and hypotheses	Focus on exploring ideas and formulating a theory
Is analyzed through math and statistical analyzing	Is analyzed by summarizing, categorizing and interpretting
Mainly expressed in numbers, graphs, and tables	Mainly expressed in words
Require many respondents	Require few respondents
Multiple choise questions	Open-type questions
Key terms: testing, measurement, objectivity,	Key terms: Understanding, context, complexity,
replicability	subjectivity

It is obvious when reading the content in Table 1, that the methods described above uses different approach to the research. Depending on actual subjects within the research, each of these methods will provide a path to assist the author in finding answers. (Thattamparambil, 2020)

For this thesis, the method selection was made according to the key terms below:

- case study to explore theories
- equipment specific literature
- technique targets highly specific components and aim to explore ideas
- a questionnaire and in-depth interviews with open questions was used to target specialists on different levels

If the author had selected a quantitative approach to the research instead, as described in Table 1, the majority of the content would have been quite different as quantitative research methods tend to target the various subjects with a significant contrast. This approach means that collection and analyze of data is through utilizing statistics in graphs and tables to find patterns rather than focusing on specific cases and parameters as in this thesis. Quantitative methods generally mean a more objective approach and are mainly expressed through numbers and mathematical relationship´s to target quantification.

Additionally, questionnaires are made in a structured manner containing close-ended questions. According to the author of this paper, the use of quantitative methods would have limited this actual research and was therefore not used.

1.7 Scientific approach

Maintaining a scientific approach in this type of research was considered challenging. This is due to the nature of this thesis as a very equipment specific research, and the collected data targeting a designated area or component of the vessel. In spite of that, the author has followed instructions agreed upon with the commissioners. The research is limited to MAN ES and focuses on further development of the ”B” generation of the popular MAN in-line 48/60 diesel engine. Any type of direct comparison to competitors and their solutions will not be considered in this thesis.

2 Thesis structure and theory

This thesis aims to investigate possibilities to maintain and possibly improve operational safety and efficiency on an existing installation through the addition of certain technical equipment. In other words, it can be described as a theoretical and simulated case study of retrofitting. Due to the nature of this thesis, a major part of the sources used are limited to those available by the original equipment manufacturer, MAN ES, and all suggestions on solutions target the specific “B” generation of the MAN 48/60 diesel engine. To provide understanding and perspective this author will summarize this by the essential points below:

- the thesis and research are limited to a specific installation
- the research targets a specific equipment on the installation
- research is based on technique “as-is”
- possibilities regarding advancement are based on technical solutions considering the specific engine type
- practical limitations are set by the manufacturer

Furthermore, the thesis and actual research was made according to a certain structure initiated by the author. A brief introduction is presented below.

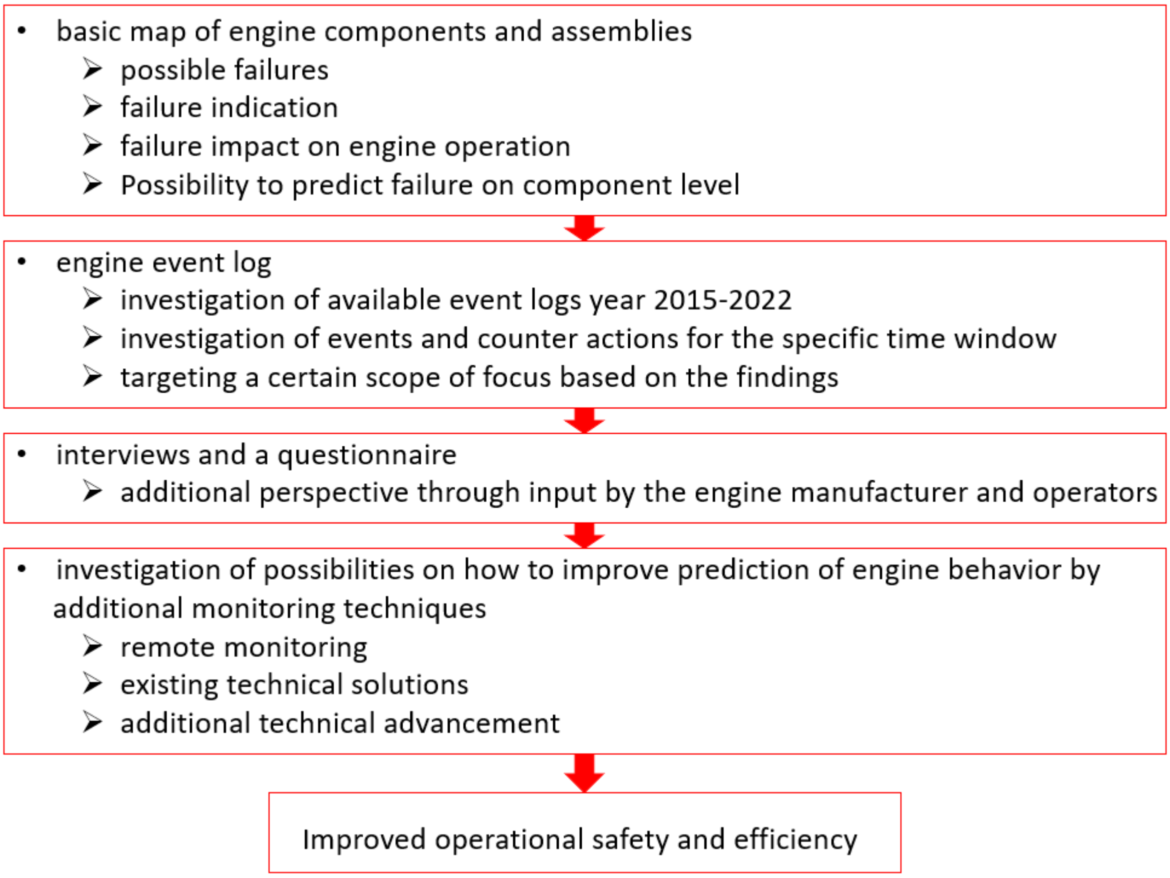


Figure 1. Thesis structure.

The intention is to have a logical structure where each part or module rely on the other and additionally a set-up that is easy to follow and understand. A more in-depth description of the research and its structure is included in Chapter 3. The working principle and basic operation of a four-stroke medium speed diesel engine as well as basic terms will not be described in this thesis. The reader can find this information in other sources such as the book *Diesel Engines 1* and *Diesel Engines ll* by Kees Kuiken. These two books include explanations on component level and description of the complete diesel engine plant. (Kuiken, 2008).

3 The research

Upon agreement of thesis subject and layout with the main commissioner, MAN ES, a preliminary research setup was adopted. The final layout is made in accordance with the author´s initiative in a logical order and incorporates the following parts:

- making of a basic map including engine main components and assemblies that are mapped against related maintenance activities and the operational impact expected if the specific component would fail

- investigation of engine event log including all events printed during years 2015-2022

- investigation of other supporting historical records such as engine workbooks, event logbooks and the planned maintenance system used on-board, AMOS

- compilation of all events related to the main engines within the time window selected and mapping of actions taken for each event

- interviews with dedicated experts at MAN ES

- questionnaire to collect additional ideas and experiences on personal level of first engineers and chief engineers within the Finnlines fleet

- after completing above parts, a summary of technical measures targeting monitoring was done to suggest techniques that can improve operational reliability and efficiency

- as final step of the research, a custom-made remote monitoring setup was *planned* by MAN ES for implementation

3.1 Case study

This thesis, and the research within, targets a specific vessel with technique as it was delivered in 2001. The vessel selected, RoRo vessel M/V Finnmill is owned and operated by Finnlines Plc.

Figure 2. M/V Finnmill. (Author´s collection).

The main reason why this vessel was selected was because during the writing of this thesis, this author was employed on this specific vessel. Also, the author´s genuine interest of MAN technique over the past 20 years contributed to vessel selection. To introduce a high-level presentation of this vessel this author will present some essential particulars below:

- built by: Jinling Shipyard, Nanjing, China
- ice class: 1A
- IMO Number: 9212656

- country of registry: Helsinki/ Finland
- gross tonnage (t): 25732
- dead weight (t): 11744
- net tonnage (t): 7720
- length over all (m): 187,1
- breadth over all (m): 26,5
- draught, summer (m): 7,1
- total lane length (m): 3259
- service speed (kt): 20

Finnmill is a traditional RoRo vessel and has two main engines supplied by MAN ES, former named MAN B&W type 9L 48/60, B-generation with 9450kW each. Each of these engines is connected to a mechanical gear box through a pneumatic controlled clutch, that transfers power to CPP type propellers through propeller shafts. Below Figure present the general arrangement on-board Finnmill.

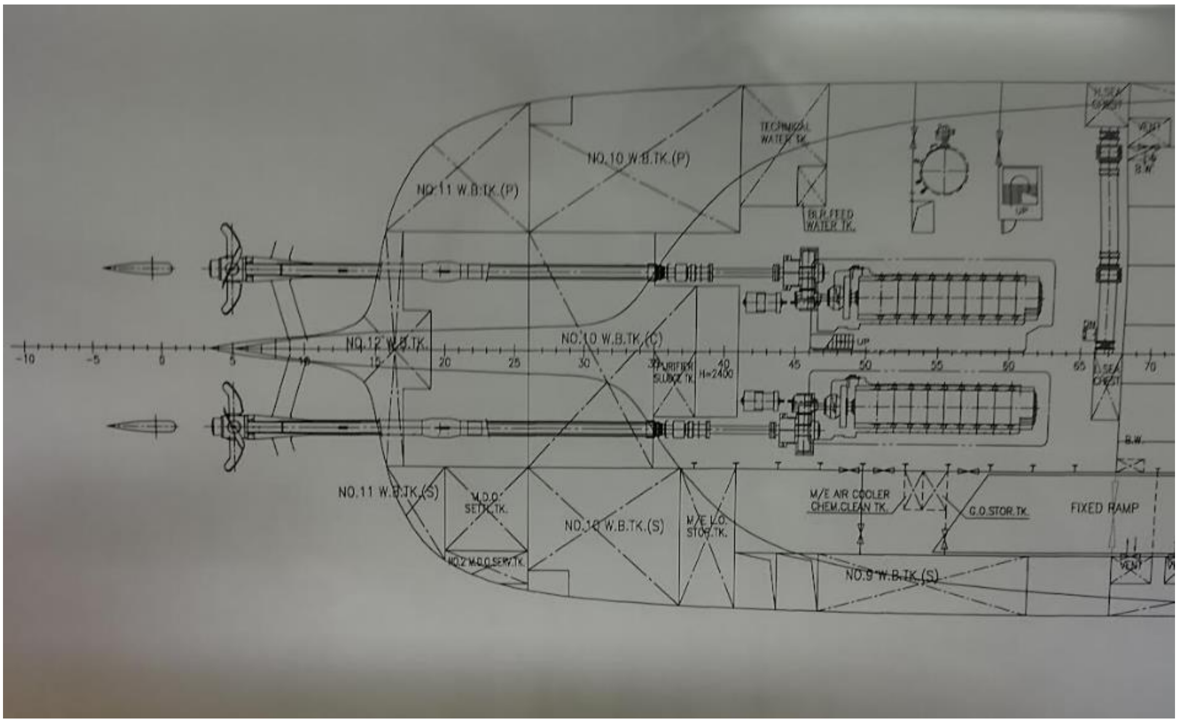


Figure 3. Finnmill general arrangement plan. (Author´s collection).

3.2 The MAN 9L48/60 B engine

The 48/60 B-generation engine is a 4-stroke large bore diesel engine within the MAN ES four-stroke engine family. As on October 31, 2022 the engines on-board Finnmill have accumulated approximately 115000 hours of operation since delivery.

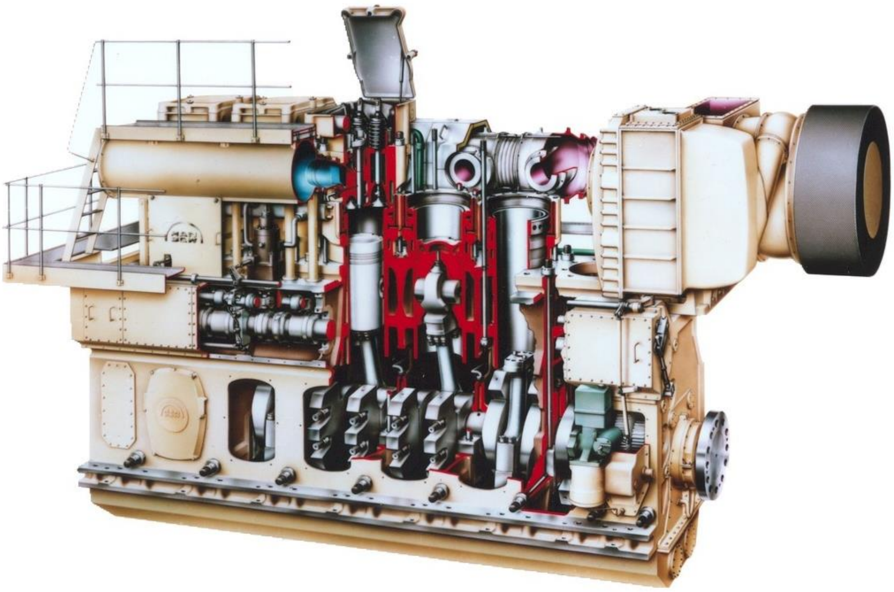


Figure 4. MAN Large bore four-stroke Diesel Engine. (Author´s collection).

This engine has a traditional mechanical injection system meaning each cylinder has its own fuel injection pump controlled by the governor via a mechanical fuel rack, and driven by the camshaft. The fuel used on-board Finnmill is HFO, RMG-380 High Sulphur.

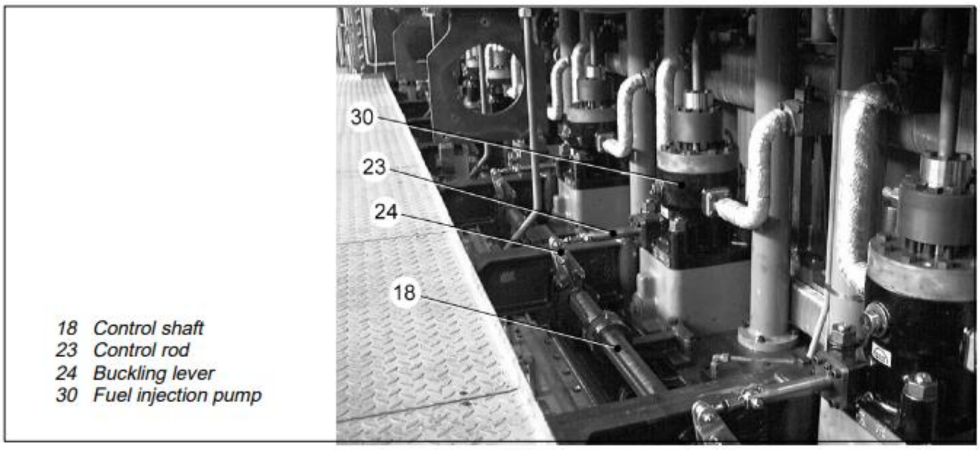


Figure 5. Control shaft with buckling lever for injection pumps Each pump has own isolation valves. (MAN Energy Solutions, 1999b, p. 07/08)

This engine generation utilizes the SaCos99 safety and control system that was introduced in late the 90s. Engine is electronically controlled by the “Woodward 723” through the Woodward PGG-EG200. This is a mechanical-hydraulic pressure compensated governor, combining a speed setting motor for remote control with manual speed control. (MAN Energy Solutions, 1995, p. 36). Refer to Figure 6 below.

Figure 6. Engine speed governor and actuator. (Author´s collection).

This engine utilizes electric-mechanical injection timing control. This is a part of the engine capability in operating at various fuel qualities to ensure post combustion after T.D.C is avoided. With the injection timing set in “late” position, a significant drop in firing pressure is achieved, thus a reduction in nitrogen oxide emissions at part load conditions. (MAN Energy Solutions, 1999a, pp. 01/03-03/03)

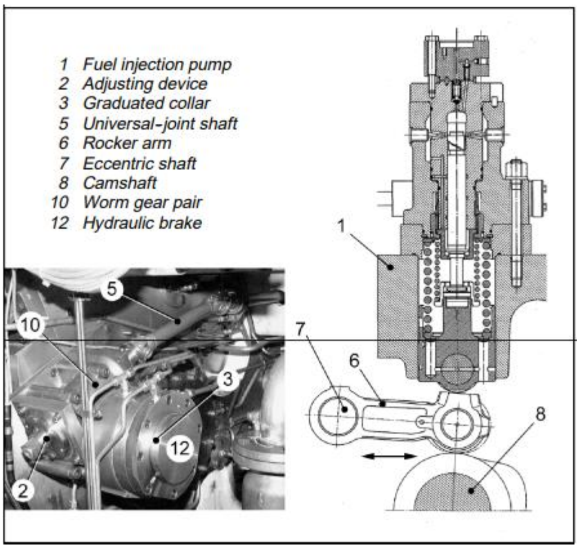


Figure 7. Injection timing adjustment. (MAN Energy Solutions, 1999b, p. 01/03)

Turbocharger used on the 9L48/60 engine is the MAN NA48/S, a conventional "single-stage" type. To improve engine response on part load conditions MAN ES has installed a system called Jet-Assist. This system connects starting air of up to 30 bars through a reduction valve to the compressor housing of the turbocharger to improve turbo acceleration.

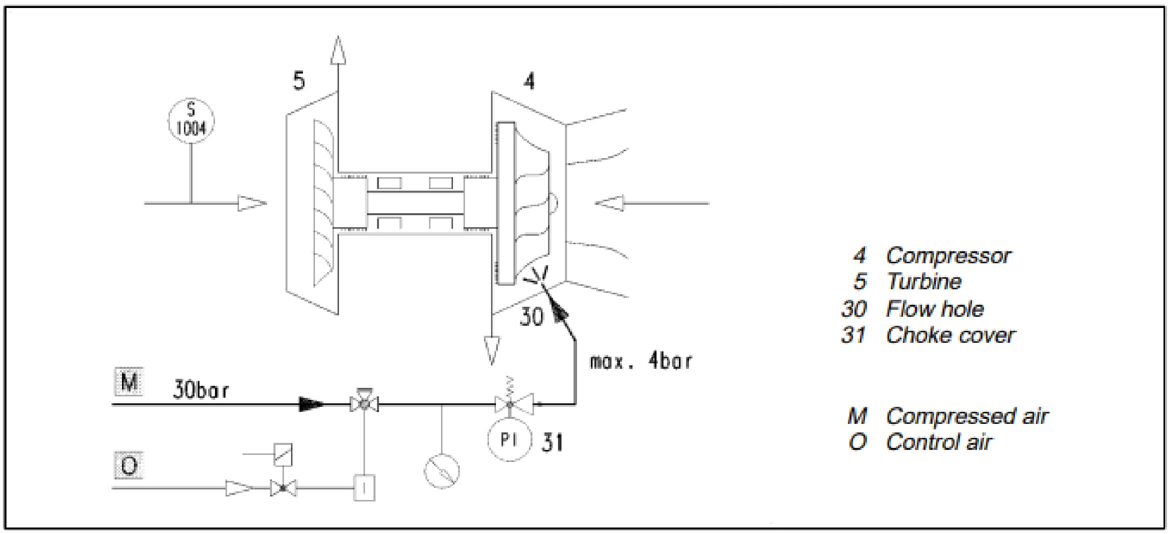


Figure 8. Jet-Assist turbocharger acceleration device NA48. (MAN Energy Solutions, 1999a, p. 03/04).

Below some general figures of the engine(s) as installed on the M/V Finnmill by different views. Refer to the attached appendix 1 for engine specifications.

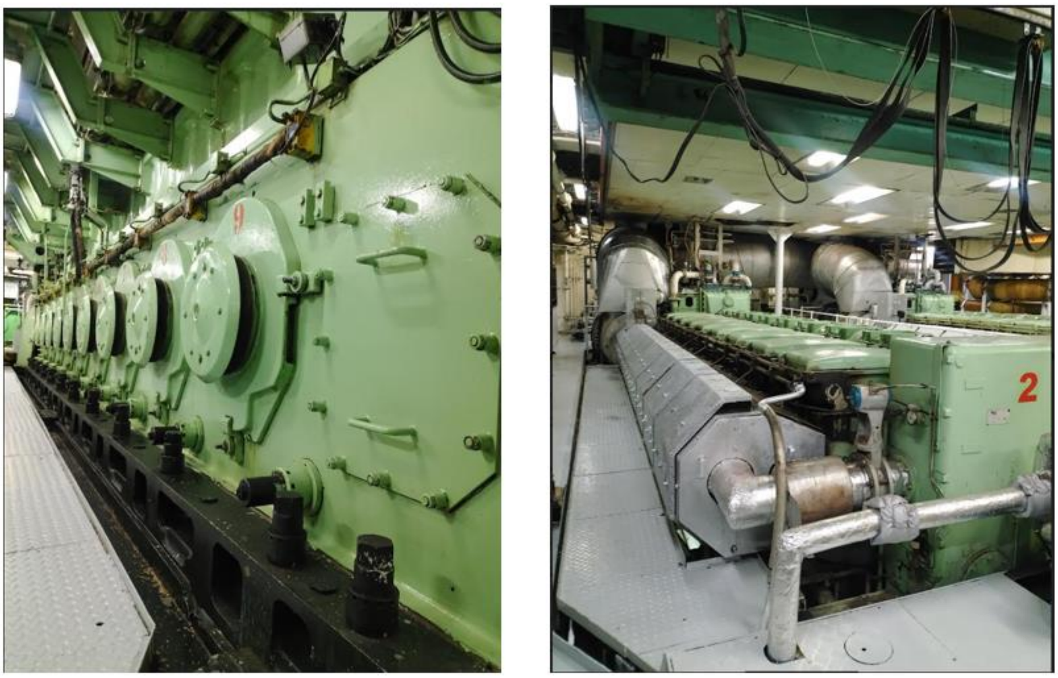


Figure 9. Main engine two views from engine free end, lower and upper floor. (Author´s collection).

3.3 Research structural aspects

The initial step of the research project was to create a basic map that includes engine components and assemblies as well as the preventive maintenance of these, and to connect the components to a worst-case scenario if the specific component fails. Furthermore, a predictive approach was adopted to specify whether it is possible to predict a failure of the component. For this primary research, the approach relies on historical operational and maintenance events. Because of the relatively high age of the ship, a large amount of historical data is available. The main source is the printed event (alarm) log that consist of approximately 24000 individual A4 matrix pages as of this day, November 18, 2022. This material was carefully investigated and due to certain aspects, such as lacking quality and missing related documentation to back up and prove counteractions of each event, a certain time window of the event log was selected. This takes place between the year 2015 and 2022 and consists of roughly 3500 individual pages.

3.4 Component failures and failure prediction

To get an understanding of the different components forming the MAN 48/60 B engine, this author created a simple map where each main component is included. This document is an excel file, which is available separately. The components were assessed against the possibility of predicting whether a failure on component level is possible. Furthermore, this was compared to the impact (consequences) on engine operation where any failure resulting in engine shutdown was considered as “major” or as a “disturbance” if a failure resulted in a forced power reduction. Minor impacts are such failures that have limited impact on operation, meaning that operation can continue as normal until repair is possible. The perhaps most interesting column is the one describing indications and predictability. The information here within relies on MAN ES engine manuals and this author´s experience. It is fairly easy in most cases to assess what happens if a certain component fails as these mostly have a related monitoring device such as a pressure or temperature sensor connected that can provide an indication. Also included in this map there is the preventive maintenance perspective for each component and additional customer information letters that highlight component lifetime limitations as informed by MAN ES. The preventive maintenance is in accordance with the recommendations provided by the OEM, and this is carefully estimated during the design and testing stage of the engine. The customer information letters (CUS)

refer to experience gained during the life cycle of the engine and pinpoint certain components that has shown to fail after a specific time in operation, usually under certain circumstances. It can also provide information of recommendation on available component upgrades that have shown to improve reliability and performance or, add on solutions and products developed at a later time. The engine specific manuals below was used for this part of the research.

- Technical documentation Engine system (A1)
- Technical documentation Engine operating instructions (B1)
- Technical documentation Engine working instructions (B2)
- Technical documentation Engine spare parts catalogue (B3)
- Technical documentation Turbocharger (C1, C2, C3)
- Technical documentation measuring, control and regulating systems (D1)
- Technical documentation Engine and systems accessories (E1)

3.5 The planning and maintenance system, AMOS

These systems are to be considered as powerful tools on-board in regards of many activities. With the planning and maintenance system (PMS), maintenance tasks are controlled, planned, and reported on a component level. Additionally, extensive systems such as AMOS can also manage stock keeping, project management, budgeting, and act as an interacting system for purchasing. (SpecTec Group Holdings Ltd., 2018, pp. 1, 151, 201, 337). According to the experience of this author, the PMS system is as effective as the users make it - the more carefully reporting and planning are conducted, the more effective the tool will be. For this research the author searched AMOS for historical events and reports separately for each event found in the event log in accordance with AMOS specific component codes. These codes are customer specific and, in this case, made according to the example work order below.

602.06.07 where one can see that 602 is the root directory of main engine number two and 06 refers to the fuel injection pumps. The last number, 07, tells the user actual cylinder number.

History Date: 13/05/2017 **Last Updated:** 01/01/1800 00:00:00

Work Order No.: FMIL/17/01361
Component No.: 602.06.07
Component Name: FUEL INJECTION PUMP N.7 M/E2
Component Type: 9L48/60
Serial No.:
Counter:
History Comments: E/ME2 C7 fuel pump element overhaul
Written by: FLERKSA

Full Description:

Changed fuel injection pump complete with ovehauled ready spare,
new pump element plunger and barrel. new seals and gasket in it.
Changed/new baffle screw were installed as well
Removed pump for overhauling for next overdue maintenance,
done in accordance of manual job description
done date may 13,2017
RH-83325

N° Piano Rina:: N.d.P.: 601b.26g
Job Code/Rev:
Job Title:
Unexpected Work: No
Maint. Class:
Maint. Type:
Maint. Cause:
Date Done: 13/05/2017
Due Date: 15/04/2017
Created By: FLNEERA
Planned By: FLNEERA

Figure 10. Historical workorder example as reported in AMOS.

Detailed reporting in the PMS system adds value to these systems if a component is prone to failures, the user can easily follow up history details regarding the component to estimate further actions and create understanding. AMOS has a function that enables the user to select if there is an "unexpected work" related to any component included in the system. Unfortunately, this function has not been extensively used but it is a useful tool to find patterns related to component failures and breakdowns. Finally, the author found that the input from AMOS did explain some of the events in the log, but the details of available records were limited.

3.6 Engine logbooks

Without exceptions, all motor ship´s keep engine logbooks. It is the responsibility of the Chief Engineer on-board to ensure the logbook is filled in according to given guidelines. The intention is to maintain records of all essential events connected to ship operations. The logbook includes the following information on a daily basis:

- port of departure and arrival
- departure and arrival related events such as start and stop of main propulsion machinery and auxiliary engines including time stamps
- fuel and lubricating oil consumption
- bunkering operations
- sludge and bilgewater discharge
- selected engine operating data
- running hours of machinery
- completed work tasks

Following up on the engine logbooks for the selected time frame of the event log provided a useful way of explaining the reasons behind each event. Most of the content of the logbooks was of such quality that it gave the author necessary details in regard to time stamps and more specific circumstances as well. To understand a specific event, it is important to know aspects such as the ship´s route and schedule as well as essential parameters such as load pattern, fuel in use, and possible known factors affecting the engine behavior at a specific time stamp.

Figure 11. Engine logbooks Finnmill. Author´s collection.

3.7 Interviews

To gain perspective throughout this research, this author reached out to dedicated MAN ES experts in different segments to understand the technical development and history of the 48/60 diesel engine. Interviews through open discussions were held to achieve an overview as wide as possible and to open up a path for new theories and ideas while maintaining a connection to the example cases included in the research of this thesis. The discussions involved topics including previous technical inventions and advancements of a majority of the main components forming the 48/60 engine. In short why certain solutions and innovations have been adapted based on actual research by MAN ES. Below is a brief description of the MAN ES experts involved in the interviews that were accomplished during the year 2022:

- Turbocharger Experts: discussion targeting different options and views of monitoring as well as general aspects connected to turbocharger performance and reliability.

- Engine Experts: discussion of the 48/60 engine in general and existing monitoring. The experts view on various technical advancements as in the content of this thesis were also discussed.

- MAN ES Digitalization management: multiple contacts throughout the research. Discussed subjects targeting the MAN PrimeServ Assist remote monitoring service and MAN CEON.

3.8 Engineer’s records: workbooks

The engineer´s records refers to the daily filed logs of completed job tasks. On-board M/V Finnmill, these are simple excel sheets where all daily actions are recorded. Even though this is a very basic approach on recording, it is in digital format providing possibilities to search and filter by date and equipment. For the time frame of the research, this documentation was not completely available anymore and could therefore not provide any useful information in other ways than comparing data from the event log against actions taken in similar cases at different time stamps.

The Figure below present an example of the daily recorded workbook.

Work Book 2022

Date	Run. Hrs.		System	Carried-out by:
		Replaced halogen bulb in aft mooring station	Lightings	eto
19.09.2022		Replaced motor of ME FO Supply pump #2	ME FO	2e/eto
		Replaced suction manometers of ME FO Supply pumps	ME FO	2e
		Prepared and brought down the spares for ME Piston Overhaul and ME2 Camshaft bearings replacement	ME2 Camshaft	1e/fitter/wiper
		Repaired the toilet of bridge	Sewage	fitter
		LTH-Baas 4 technicians took out from ME1 Unit #3 the cylinder head, top land ring, piston, and liner from 20:00 to 23:30		LTH-Baas
		Replaced buls in main deck exit area	lightings	eto
		Replaced the plug of deck pressure washer	deck	eto
20.09.2022		Cleaned low sea chest strainer (1 big pail of shells were collected)	SW	2e/wiper
		Received 500 MT of HFO	HFO	2e/wiper
		Received reconditioned piston from LTH-Baas		
		Received FMIL/22/0197, FMIL/22/0290, and FMIL/22/0222		1e
	ME1-112775	Continuation of ME1 Unit 3 overhaul; they took out connecting rod then prepared every part for assembling.		
		They used the following parts and assembled accordingly; new connecting rod with new big end bearing but the con-rod big end was from ME1 Cyl 3 ;		
		reconditioned liner; new piston with new rings; reconditioned top land ring; and reconditioned cylinder head; (backing ring was not replaced)		
		fuel injector was calibrated only but with new spring; installed with reconditioned starting air valve		
		Old top land ring and piston (with 1 new o-ring and 1 small end bearing) were taken by LTH-Baas for reconditioning;		
		Exhaust gas sensor's cable of ME1 Cyl 3 was broken during assembly; eto replaced it with new one		eto
		To fabricate special cleaning tool for lashing points in cargo holds		fitter
		Replaced stern navigation light	Bridge	eto
		Changed bearing in ME FO supply motor	M/E	eto
		Hand-over to new electrician		eto
21.09.2022	AE1-66956	To change oil AE1		2e
		To continue cleaning the candle filters from ME LO Duplex filter		wiper

Figure 12. Workbook extract 2022.

3.9 Historical events – The event log

Obviously, the largest contributor in terms of historical events is the event log. Every piece of equipment on-board that has a measuring device (sensor) is monitored by the ship´s monitoring, alarm and control system, hereafter referred to as IAS. The system used on-board this ship is MEMAC, an obsolete system incorporated in YORK refrigeration systems corporation. Anytime there is an anomaly in the equipment, an alarm will be triggered in MEMAC in accordance with preset thresholds. When there is an anomaly in a main engine, the MAN ES supplied safety and control system (SaCoS99), including an alarm pre-processing unit will process the sensor signal and trigger an alarm through the IAS. The pre-processing unit provides a link between the engine automation system and the IAS. Figure 13 on next page provides a schematic illustration of the MAN Safety and Control System interface.

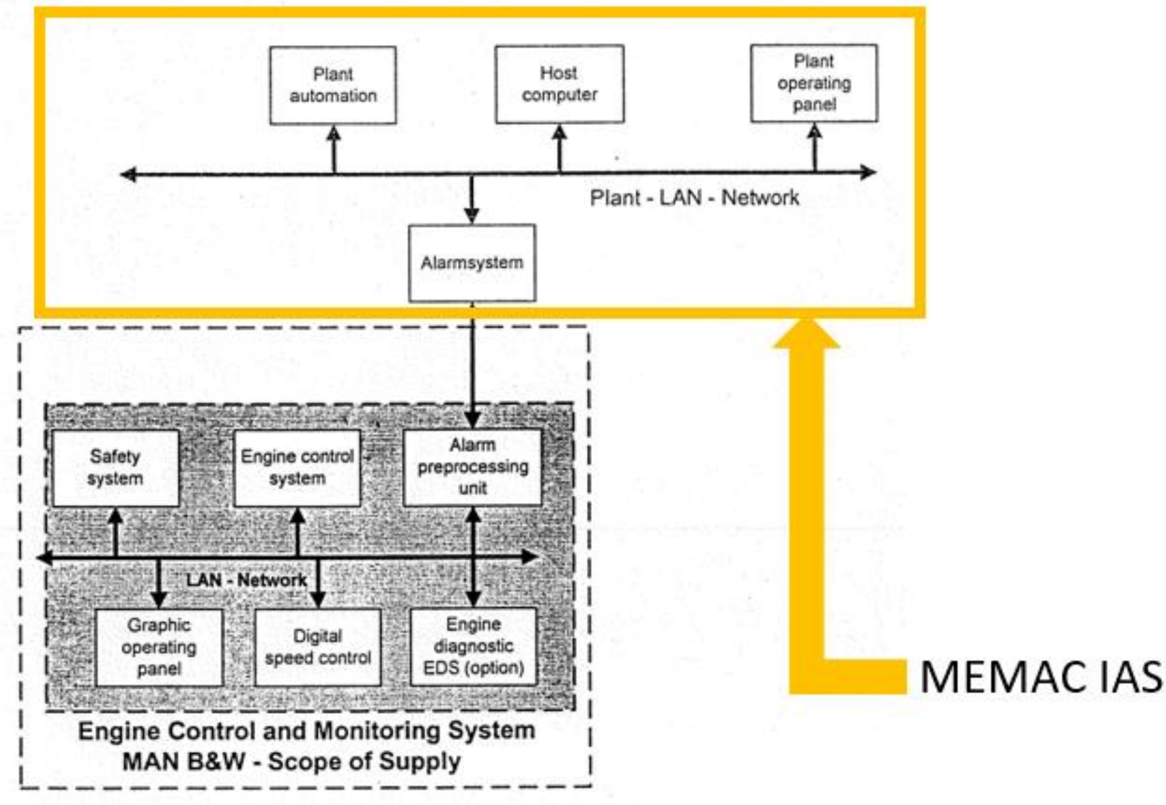


Figure 13. MAN safety and control system interface. (MAN Energy Solutions, Technical Documentation D1, 2001a, p. 391)

So, to summarize the interaction between the MAN ES supplied automation and the IAS refer to below dots.

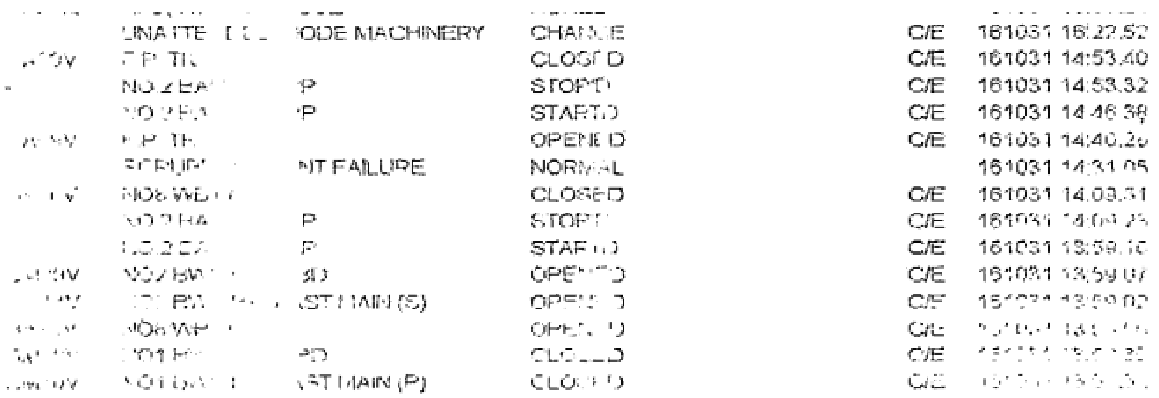
- Collect engine binary and analog sensor data. Convert to digital format.
- Data interface to external IAS system

(MAN Energy Solutions, Technical Documentation D1, 2001a, p. 391)

In this thesis only events somehow related to the main engines are of interest. However, to select events that are of interest the full content of approximately 24000 pages had to be investigated.

Figure 14. Event log archive. Author´s collection.

As mentioned earlier, a specific time window was found to provide the best quality. This window had the least errors related to print quality and did have other important records supporting the information. In total, this author sent about 3500 pages for scanning to the premises of MAN ES in Augsburg. These pages of the event log are range from the year 2016 to 2018. This content is considered as confidential and is therefore only shared with the commissioners. There were considerable parts of the log that the mass scanner could not recognize due to poor quality of the original printout such as the example in figure 15.



	[illegible]	[illegible] MACHINERY	[illegible]	C/E	161031 16:22.52
	[illegible]		CLOSED	C/E	161031 14:53.40
	[illegible]	P	STOP[illegible]	C/E	161031 14:53.32
	[illegible]	P	START[illegible]	C/E	161031 14:46.38
	[illegible]		OPENED	C/E	161031 14:40.2[illegible]
	[illegible]	[illegible]NT FAILURE	NORMAL		161031 14:31.05
	[illegible]		CLOSED	C/E	161031 14:03.[illegible]
	[illegible]	P	STOP[illegible]	C/E	[illegible]
	[illegible]	P	STA[illegible]	C/E	161031 13:59.[illegible]
	[illegible]	[illegible]	OPEN[illegible]	C/E	161031 13:59.0[illegible]
	[illegible]	[illegible]ST MAIN (S)	OPE[illegible]	C/E	[illegible]
	[illegible]		OPE[illegible]	C/E	[illegible]
	[illegible]	[illegible]	CL[illegible]	C/E	[illegible]
	[illegible]	[illegible]ST MAIN (P)	CLO[illegible]	C/E	[illegible]

Figure 15. Event log screen print page 2106.

The following example presented in Figure 16 is a screen print randomly selected that is obviously good quality.

** EVENTS **

'n this page: 1448147-1448205 Page 23701

vent-ID	Tag No.	Description	Status	Value	Unit	Ini.	LMT Date & Time
448205	822	F.O PRESS LOW	NORMAL				171001 14:42.41
448204	824	F.O SUPPLY STBY P/P RUNNING	NORMAL				171001 14:42.39
448203	APL-01	APL, ENGINE CTRL ROOM	ACKED				171001 14:42.32
448202	822	F.O PRESS LOW	ALARM				171001 14:42.30
448201	60201	INTERFACE ALARM, LOAD COMPUTEF	NORMAL				171001 14:42.13
448200	60201	INTERFACE ALARM, LOAD COMPUTEF	ACKED			C/E	171001 14:42.05
448199	APL-01	APL, ENGINE CTRL ROOM	ACKED				171001 14:41.55
448198	APL-01	APL, ENGINE CTRL ROOM	ACKED				171001 14:41.54
448197	60201	INTERFACE ALARM, LOAD COMPUTEF	ALARM				171001 14:41.50
448196	816	EMERGENCY FUEL CONTROL ACTIVE	ACKED			C/E	171001 14:39.17
448195	APL-01	APL, ENGINE CTRL ROOM	ACKED				171001 14:39.10
448194	APL-01	APL, ENGINE CTRL ROOM	ACKED				171001 14:39.09
448193	816	EMERGENCY FUEL CONTROL ACTIVE	NORMAL				171001 14:38.54
448192	822	F.O PRESS LOW	NORMAL				171001 14:38.54
448191	-	ME2 F.O PRESS	NORMAL				171001 14:38.54
448190	-	ME1 F.O PRESS	NORMAL				171001 14:38.54
448189	816	EMERGENCY FUEL CONTROL ACTIVE	ALARM				171001 14:38.39
448188	824	F.O SUPPLY STBY P/P RUNNING	ACKED			C/E	171001 14:38.16
448187	APL-01	APL, ENGINE CTRL ROOM	ACKED				171001 14:38.10
448186	824	F.O SUPPLY STBY P/P RUNNING	ALARM				171001 14:38.07
448185	-	NO2 PREH UNIT CIR PMP	STARTD			C/E	171001 14:38.06
448184	-	NO1 PREH UNIT CIR PMP	STARTD			C/E	171001 14:38.00
448183	824	F.O SUPPLY STBY P/P RUNNING	NORMAL				171001 14:37.30
448182	824	F.O SUPPLY STBY P/P RUNNING	ACKED			C/E	171001 14:35.41

Figure 16. Event log screen print page 1052.

While considering the total content of the event log, and the overall quality the estimated 6,5% representing such result that is not readable the scanning was a success.

At this point this author would like to make a brief summary of the findings in the investigated parts of the event log. Even as the selected time window of the event log can be considered as limited in terms of extent, this author likes to highlight his perspective with the following statement. This statement relates to the fact that if the *scheduled maintenance is carried out on correct criteria and assumptions, and if the engine maintenance is in accordance with this maintenance schedule, then there should not be any larger failures present in the event log at any selected time interval.* During the investigation of the event log, there were no larger failures within the investigated period; therefor the author´s statement is proven as correct. The content within the event log instead presents disturbances, where many findings relate to auxiliary systems of the engine instead of the engine itself. Also, there are a considerable number of disturbances related to the automation system. According to the author, these cannot be pointed out as even while some trigger the

same alarms, the actual root cause is not the same. For instance, in some cases there are failures related to the electronically controlled speed governor. There can be similar alarms triggered involving governor control error, missing speed reference or governor wire break. The root cause can be earth fault in cabling, sensor fault or error in I/O modules, thus this does not create any pattern. In most cases these errors could be confirmed by external documentation such as the Engine logbooks. Where confirmation was not possible, the author commented that no additional information was available making it impossible to assess the event. However, finding events that are directly critical and related to safe and efficient engine operations was possible and the author chose to target the rotating assembly of the engine to investigate possibilities to improve monitoring. Currently the monitoring of these essential components is in no way part of any predictive maintenance concept but instead the engine is equipped with protective measures to prevent catastrophic consequences instead of providing early indication of anomalous. The example cases confirm the effectiveness of these protective measures. One additional contributing factor behind the initiative of targeting the rotating assembly is that there are recent events related to this particular area that involve information from multiple sources providing more detailed data than the historical events in the event log. This setup is suitable since with more information and therefore accuracy, improvements can be suggested in a more sophisticated way. Briefly, there are cases in the historical event log indicating space to improve monitoring of the rotating assembly and therefore, later events are connected to provide better perspective.

3.9.1 Historical events – Summary

As mentioned earlier, a specific time window of the event log was selected for this research. Even as there were findings related to the engine operation during this period, it is clear that the MAN 9L48/60 diesel engine is a well proven and reliable design. On this author´s initiative, the findings were distributed in a certain manner and on specific conditions. Initially, findings are split to separate different categories of errors that directly relate to the engine itself as well as those that could be connected to the auxiliary systems. The full list of findings is considered confidential and is only available to the commissioners. Figures 17 and 18 on page 23 present the distribution of findings.

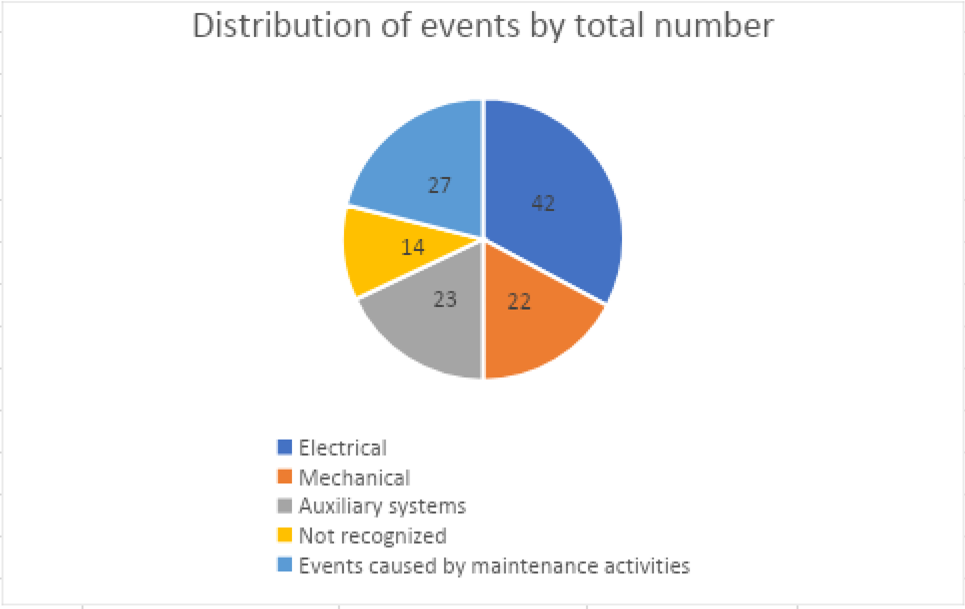


Figure 17. Distribution of events by categories.

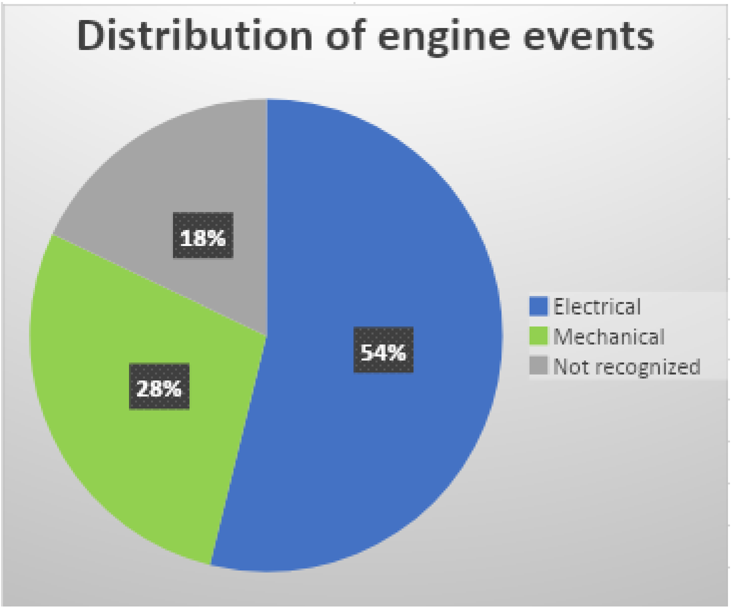


Figure 18. Distribution of events related to the engine itself.

It is essential to separate different events into categories to clarify what areas need to be targeted. The list below describes the background and idea behind the different categories:

- mechanical errors refer to errors on mechanical components or assemblies of the engine

- electrical errors refer to the engine monitoring and control system (automation), and involves sensors, cables, controllers and the SaCos99 software as installed on the engine

- not recognized errors and events are those that are found to be connected to the engine where the outcome is known but the root cause could not be established due to lacking documentation

- auxiliary systems refer to all necessary systems that are connected to the engine and required to operate the engine. This includes control and starting air systems, cooling water systems, fuel and lubricating oil systems, electrical power sources and exhaust systems. It is commonly recognized, when a malfunction or error appears on the engine, the root cause can be found in either one of the auxiliary systems

- errors that are classified as major disturbances during engine operation are the ones that will cause either an automatically triggered shutdown or a shutdown manually triggered by the operators to avoid major failures. Refer to page 27

- events triggered because of maintenance activities are classified as not interesting in this context but are included as a part of the total number of event findings related to the main engines

The items in the list above are quite easy to recognize and understand. However, regarding events that relate to electrical errors, the situation is more complex. The reason behind this is that the individual components of the electrical installation are not part of the preventive maintenance. Therefore, approaching this area by a predictive concept by other means than the manufacturer´s knowledge is considered as highly complicated. The electrical components that are subjected to monthly testing and are checked on a routine basis according to the ship´s planned maintenance or PMS. However, to predict life lifetime of electrical components is not considered possible by this author. Simultaneously, this is considered to be the reason behind the relatively high failure rate amongst electrical components in this content. Contributing factors making life cycle estimations difficult are environmental aspects such as heavy vibration, heat stress and moisture as these can be a result of external sources not recognized by the manufacturer upon delivery. For the reasons described above, the author is not able to provide proof on concrete facts behind the estimated lifetime of electrical components, nor the reason of failure and due to this the research will not involve this subject any further. With regard to this, MAN ES has sent out

customer information that target the complete electrical installation of the engine. As in the customer information letter number 208 below, MAN ES recommended periodical inspection to ensure reliability.

MAN

Diesel Customer Information

Cus 208 • 01/05

Enclosure: Scope of the ELECTRONIC CHECK-UP-Services

Hardware inspection

Consisting of visual inspection and function test of the following components:

- Plugs/plug and socket connections
- Cable routes
- Installation
- Switch cubicle inspection
- Sensors

Software inspection

Consisting of function test, checking and setting of the switch, resp. alarm points, if required:

Engine control

- Start/Stop
- Cylinder lubrication
- Charge-air bypassing
- Charge-air blow off
- Exhaust-gas blow off
- Charge-air preheating
- Injection timing
- Valve control timing
- Speed setting
- Slow turn
- Jet Assist
- Charge-air dependent admission limitation
- Coupling control for propeller
- Coupling control for PTO
- Pump controls

Speed control

- Governor/engine-mounted setting device
- Governor electronics
- Alarm points and shutdown points

Temperature controls

- HT cooling water temperature
- LT cooling water temperature
- Charge air temperature
- Lube oil temperature

Figure 19. MAN Customer information letter No. 208, p 1.

Diesel Customer Information

Cus 208 • 01/05

Software inspection

Safety system

- Safety system release via speed or admission signal
- Overspeed 1
- Overspeed 2
- Lube oil pressure before engine
- Lube oil temperature before engine
- Lube oil pressure before turbocharger
- Lube oil discharge temperature, turbocharger
- Cylinder cooling water pressure before engine
- Cylinder cooling water temperature after engine
- Monitoring of the exhaust gas temperature average value after cylinder
- Exhaust gas temperature before/after turbocharger
- Splash oil temperature
- Main bearing temperature
- Oil mist detector
- Override

Alarm system

- Alarm system release via speed and admission signal
- Overspeed relay 1
- Overspeed relay 2
- Lube oil pressure before engine
- Lube oil temperature before engine
- Lube oil pressure before turbocharger
- Lube oil discharge temperature, turbocharger
- Cylinder lubrication
- Nozzle cooling water pressure
- Nozzle cooling water temperature
- Charge air cooling water pressure
- Charge air cooling water temperature
- Fuel pressure
- Fuel temperature
- Monitoring of the exhaust gas temperature average value after cylinder
- Exhaust gas temperature before/after turbocharger
- Control air pressure
- Emergency stop air pressure
- Starting air pressure

CoCoS – EDS

- Preparation of a back-up data file
- Parameter checking
- Checking of the measuring values

Figure 20. Customer information letter No. 208, p 2.

Lastly, and most interesting in context of this thesis, the percentage of critical events in relation to total number of events is shown in Figure 21 on next page. This Figure refers to events that has resulted in an engine shut down, either automatically by the engine automation system or manually by the operators.

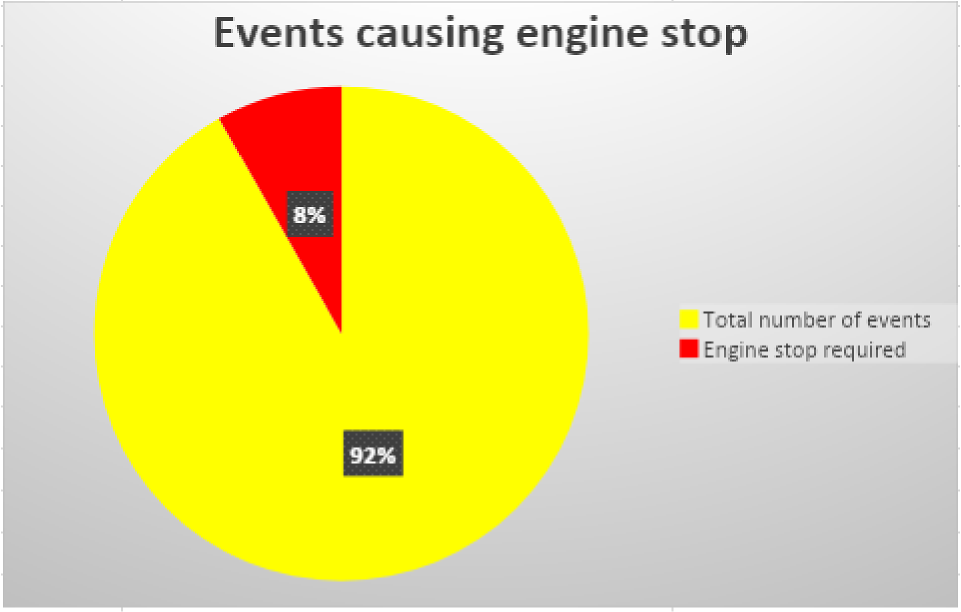


Figure 21. Shutdowns in relation to total amount of events.

In numerical figures there were nine events out of 128 that resulted in shutdown during the investigated time frame. It turned out that five of these were triggered by the oil mist detector. Two events are represented by major cooling water leakages causing shortages in the engine automation system that were not connected to the engine itself. The last two were due to a mechanical failure of a cracked exhaust valve seat and an error in the speed control system. By the relatively high occurrence of events triggered by the oil mist detector, the author finds this area most interesting and will target such events that contribute to circumstances that are connected to a high level of oil mist in the crankcase. Several of the events that triggered oil mist shutdown were because of high water contamination of the lubricating oil. Unfortunately, not all cases could be defined by the available information which led to the decision in using recent but highly relevant events from the year 2022 that resulted in a piston seizure and crankcase explosion. These cases will be described as example cases in the following chapters. To maintain a direct connection to the historical events, there will be monitoring techniques included to detect water contamination of the lubricating oil. The intention is to present techniques that enable an improved awareness of the engine condition and to implement measures for predicting such events.

3.9.2 Example case I – Piston seizure and crankcase explosion

The ship´s engine crew was notified of an error in the main engine, in this case already several days before the actual breakdown occurred, but due to certain circumstances it was possible to circumvent the actual problem. What the author would like to point out is how to prevent similar situations by providing additional parameters to monitor.

First, a brief description of what the term crankcase explosion means. The term relies on certain circumstances in the engine crankcase related to atmosphere. Most cases involve so-called hotspots when there is metal to metal contact between any of the moving elements. When clearances decrease due to heat, lubricating oil starvation occurs leading to a fast increase in temperature of the elements now in contact. In normal circumstances there is always a mixture of air and lubricating oil in the crankcase – a mixture named oil mist that consists of relatively large particles that are not prone to ignite. In circumstances when there are hot spots, the lubricating oil will begin to condensate, typically in cooler areas of the crankcase creating smaller oil particles that are more prone to ignite. When there is a correct balance of air, lubricating oil mist and heat, the mixture will self-ignite, and the result is a crankcase explosion. Additionally, lubricating oil polluted by fuel and combustion residues will contribute to optimal circumstances for a crankcase explosion. (Knapp, 2000)

The oil mist detector unit on main engine one triggered failure alarm that is common when there is an error in the unit itself. The crew investigated the matter and found that the oil mist detector was not correctly adjusted. This was approximately seven days before the piston seizure and the crankcase explosion that followed. After readjustment and cleaning, there still were some failure alarms from the oil mist detector unit in the following days until a high oil mist concentration in crankcase alarm was triggered. This alarm automatically stops the engine without delay. As this is a very critical situation the crew opened up the inspection covers (crankcase doors) and used a digital temperature measuring device to spot check temperatures of the engine internal parts, especially the rotating assembly. Oil sample test was also taken and showed a TBN value of 32 and water content in % of 0,02. The lubricating oil purifier MT value (water transducer) usually provide reliable indication if there is *high water content* in the engine lubricating oil showed “81”, a value considered as normal on-board. A cylinder leak test was performed but no larger deviations were observed between individual cylinder units. The event log was checked, especially the automatic print out including essential temperatures and pressures for the most recent time window and there were no alarming values found.

Two days later, the same event occurred, and the same counter measures and actions were taken without finding any useful information. It was decided that the oil mist detector unit itself was not functioning properly and another new unit to be ordered.

Below bearing temperature print from 02:00 the May 02, 2022. This is the most recent available as seen from the event time stamp.

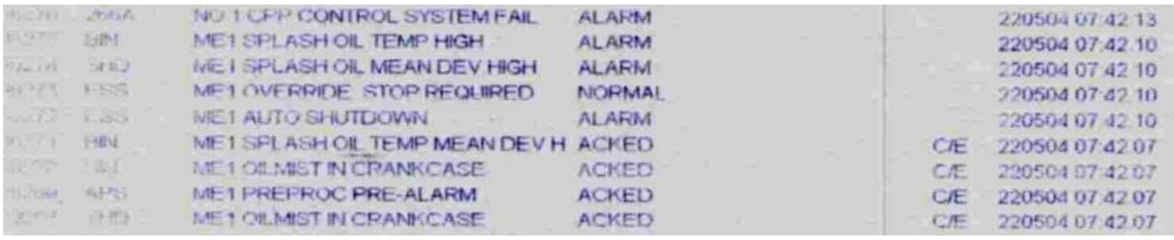
** Group 25. ME'S BEARING TEMPERATURE (By Descr.) **

Lines: 67 On this page: 1-59 Page 1 of 2

NI/MIC	Description	Value	LoLim	HiLim	Unit	Gr
30/06/02	ME1 FUEL ADMISSION	67.0			%	4
30/04/06	ME1 LO PRESS ENGINE(<400RPM)	4.39	2.50		Bar	4
30/05/01	ME1 LO TEMP BEFORE ENGINE	49.24	39.00	60.00	°C	4
30/02/01	ME1 MAIN BEARING TEMP 0I	64.57		90.00	°C	4
30/02/02	ME1 MAIN BEARING TEMP I	73.75		90.00	°C	4
30/02/03	ME1 MAIN BEARING TEMP II	77.76		90.00	°C	4
30/02/04	ME1 MAIN BEARING TEMP III	81.86		90.00	°C	4
30/02/05	ME1 MAIN BEARING TEMP IV	79.13		90.00	°C	4
30/02/10	ME1 MAIN BEARING TEMP IX	75.71		90.00	°C	4
30/02/06	ME1 MAIN BEARING TEMP V	76.98		90.00	°C	4
30/02/07	ME1 MAIN BEARING TEMP VI	78.74		90.00	°C	4
30/02/08	ME1 MAIN BEARING TEMP VII	76.68		90.00	°C	4
30/02/09	ME1 MAIN BEARING TEMP VIII	78.54		90.00	°C	4
30/02/11	ME1 MAIN BEARING TEMP X	74.63		90.00	°C	4
30/03/01	ME1 SPLASH OIL TEMP A/B 1	66.2		81.0	°C	4
30/03/02	ME1 SPLASH OIL TEMP A/B 2	66.0		81.0	°C	4
30/03/03	ME1 SPLASH OIL TEMP A/B 3	65.6		81.0	°C	4
30/03/04	ME1 SPLASH OIL TEMP A/B 4	65.6		81.0	°C	4
30/03/05	ME1 SPLASH OIL TEMP A/B 5	65.4		81.0	°C	4
30/03/06	ME1 SPLASH OIL TEMP A/B 6	65.3		81.0	°C	4
30/03/07	ME1 SPLASH OIL TEMP A/B 7	66.3		81.0	°C	4
30/03/08	ME1 SPLASH OIL TEMP A/B 8	66.5		81.0	°C	4
30/03/09	ME1 SPLASH OIL TEMP A/B 9	66.1		81.0	°C	4
30/04/07	ME1 T/C LO PRESS	1.70	1.37		Bar	4
30/05/02	ME1 T/C LO TEMP	72.68		90.00	°C	4

Figure 22. IAS ME´S Bearing temperatures print.

On the morning of May 04, 2022 when most of the crew were resting after a very late departure from Finland, the duty engineer got the high oil mist in crankcase alarm and the engine shut down automatically before he could attend the engine control room. After a short investigation, he decided to restart the engine and activate the oil mist override function as well as locally monitor the running engine. Once he reached the engine, he observed smoke coming from the oil mist detector drainpipe and decided to return to the engine control room to stop the engine immediately. Upon his return to the control room there was a crankcase explosion and at the same time the splash oil monitoring system stopped the engine automatically before a further breakdown occurred. Figure 23 illustrates the time stamp of the event with reference to the event log.



[illegible]	[illegible]	NO 1 CPP CONTROL SYSTEM FAIL	ALARM		220504 07:42:13
[illegible]	[illegible]	ME1 SPLASH OIL TEMP HIGH	ALARM		220504 07:42:10
[illegible]	[illegible]	ME1 SPLASH OIL MEAN DEV HIGH	ALARM		220504 07:42:10
[illegible]	[illegible]	ME1 OVERRIDE STOP REQUIRED	NORMAL		220504 07:42:10
[illegible]	[illegible]	ME1 AUTO SHUTDOWN	ALARM		220504 07:42:10
[illegible]	[illegible]	ME1 SPLASH OIL TEMP MEAN DEV H	ACKED	C/E	220504 07:42:07
[illegible]	[illegible]	ME1 OILMIST IN CRANKCASE	ACKED	C/E	220504 07:42:07
[illegible]	[illegible]	ME1 PREPROC PRE-ALARM	ACKED	C/E	220504 07:42:07
[illegible]	[illegible]	ME1 OILMIST IN CRANKCASE	ACKED	C/E	220504 07:42:07

Figure 23. Event log extract from IAS.

The following pictures were taken after this event and aim to illustrate the consequences of the crankcase explosion and the associated damages.

Figure 24. Crankcase safety valves have released pressure to the atmosphere. (Author´s collection).

Figure 25. Operating side of engine. Fasteners keeping crankcase covers in position broken off between cylinder four and five. (Author´s collection).

Figure 26. Crankcase venting before fault tracing commence. Photo taken approximately 30 minutes after the explosion. (Author´s collection)

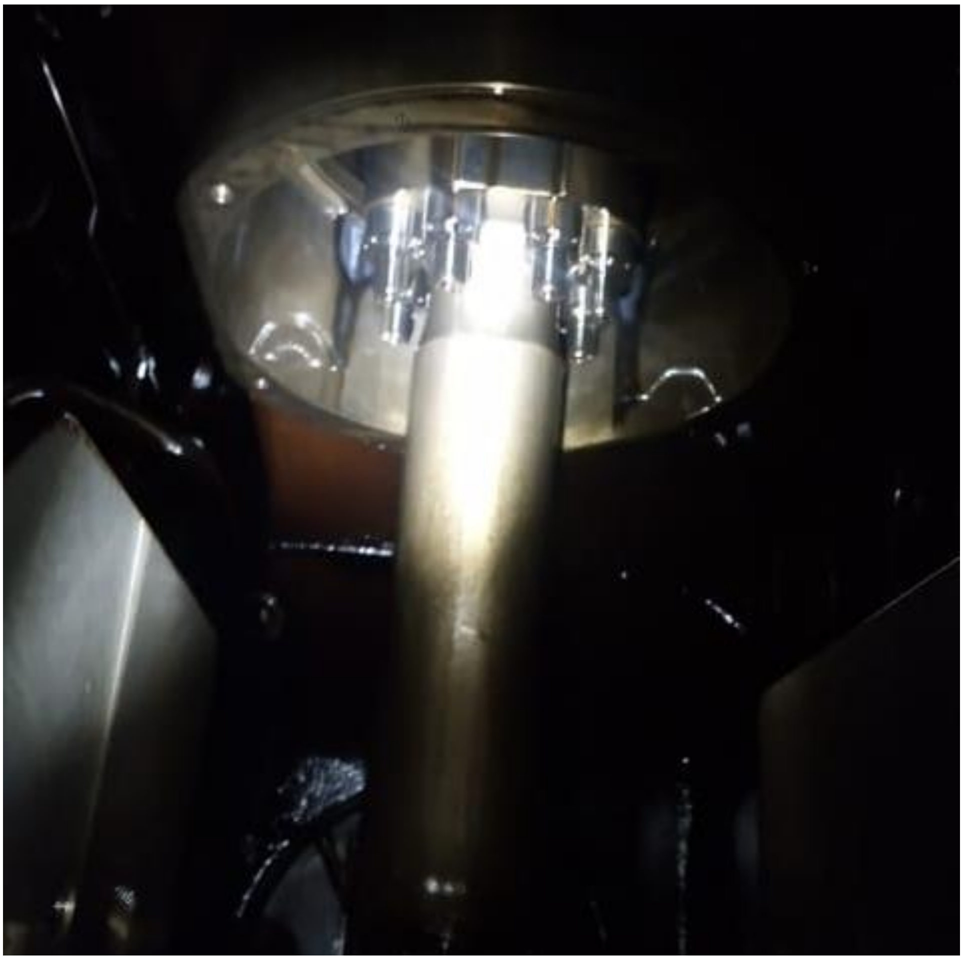


Figure 27. After crankcase venting the piston and liner of cylinder 7 was found to have deep scoring marks typical after a piston seizure. Measured liner temperature showed 110˚C compared to other cylinders where temperature was measured to approximately 70˚C. (Author´s collection).

So, in other words, after reading through this chapter one can understand that the engine does have a working protection system to prevent fatal errors and total breakdowns. However, the author finds it important to avoid failures leading to considerable expenses and equipment downtime, as in this case, and would like to target certain additional measuring and monitoring to minimize the risks of such failures. Different alternatives and possibilities were discussed with MAN ES to find out what could be done to conventional installations without significant changes to the affected engine components.

Figure 28. Damage on piston of cylinder 7. Deep scoring and severe overheating. (Author´s collection).

There are clear indicators that the event had started from excessive piston blow-by causing a lack of lubrication in the liner running surface leading to the piston seizure that finally occurred.

In this case, the component damage were limited to the piston (034), liner (050), and due to severe liner overheating the backing ring, also called water jacket (part of assembly 050) could not be separated from the liner without causing additional damage to these parts. Refer to Figure 29 on page 34.

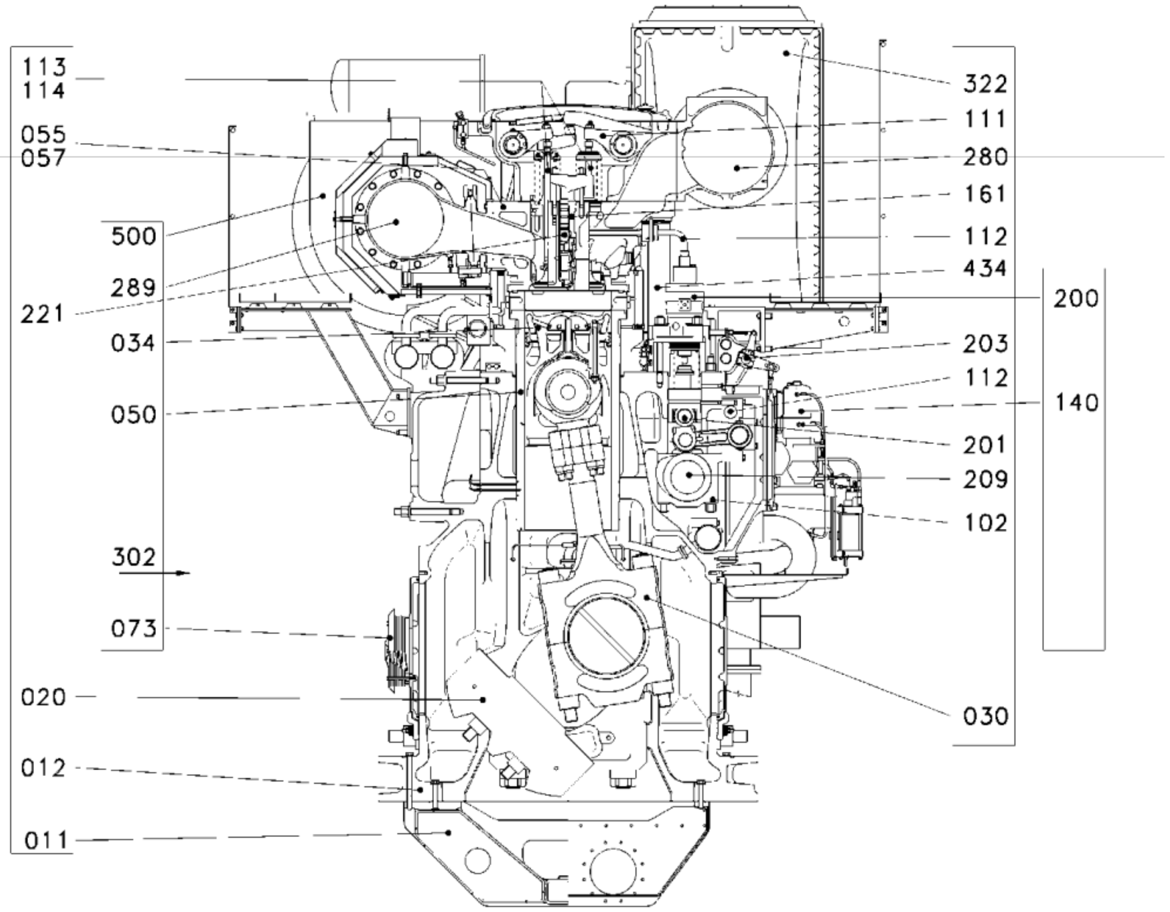
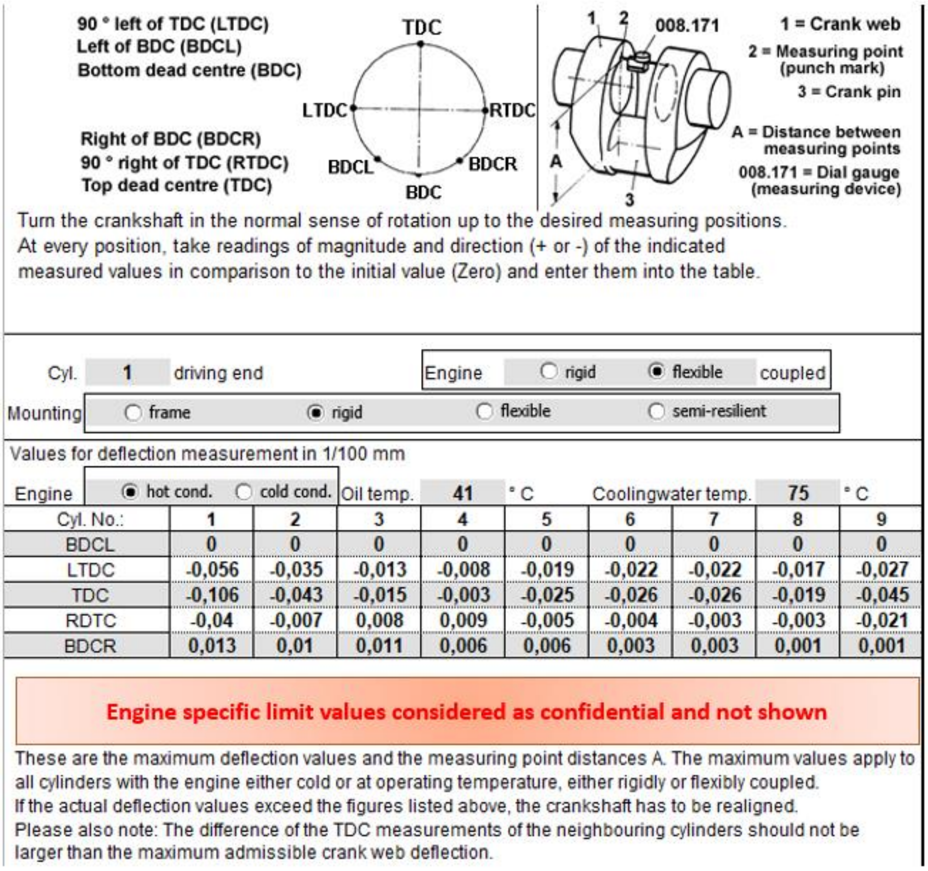


Figure 29. Engine cross section view. (MAN Energy Solutions, Engine spare parts catalogue B3, 1999b, p. 01/05)

The repair included full removal of the running gear of cylinder 7 including cylinder head, piston, connecting rod and liner with backing ring. See Appendix 2 for the attached service report. Removed parts were inspected for damage and cylinder unit 7 was re-assembled using new or reconditioned MAN ES supplied spare parts. These include piston with rings (pos 34), reconditioned liner and backing ring (pos 50), cylinder head (pos 55), and connecting rod with new bearings (pos 30) along with one crankcase cover (pos 73). Additionally, cylinder head cover (pos 111) had to be replaced due to damage. (MAN Energy Solutions, Engine spare parts catalogue B3, 1999b, pp. 20-24) A crankshaft deflection measurement was done and found to be in accordance with the limits set by the manufacturer as in Figure 30 on the following page.



Turn the crankshaft in the normal sense of rotation up to the desired measuring positions. At every position, take readings of magnitude and direction (+ or -) of the indicated measured values in comparison to the initial value (Zero) and enter them into the table.

Cyl. 1 driving end — Engine ○ rigid ◉ flexible coupled

Mounting ○ frame ◉ rigid ○ flexible ○ semi-resilient

Values for deflection measurement in 1/100 mm

Engine ◉ hot cond. ○ cold cond. Oil temp. 41 °C Coolingwater temp. 75 °C

Cyl. No.:	1	2	3	4	5	6	7	8	9
BDCL	0	0	0	0	0	0	0	0	0
LTDC	-0,056	-0,035	-0,013	-0,008	-0,019	-0,022	-0,022	-0,017	-0,027
TDC	-0,106	-0,043	-0,015	-0,003	-0,025	-0,026	-0,026	-0,019	-0,045
RDTC	-0,04	-0,007	0,008	0,009	-0,005	-0,004	-0,003	-0,003	-0,021
BDCR	0,013	0,01	0,011	0,006	0,006	0,003	0,003	0,001	0,001

Engine specific limit values considered as confidential and not shown

These are the maximum deflection values and the measuring point distances A. The maximum values apply to all cylinders with the engine either cold or at operating temperature, either rigidly or flexibly coupled. If the actual deflection values exceed the figures listed above, the crankshaft has to be realigned. Please also note: The difference of the TDC measurements of the neighbouring cylinders should not be larger than the maximum admissible crank web deflection.

Figure 30. Crankshaft deflection check after the event. Measurements within limits.

3.9.3 Example case ll – Piston seizure

On June 30, 2022 another similar event occurred as presented in Chapter 3.4.2. In this case there was a piston seizure, but the engine automation shut down the engine before any further damage occurred. This event did not generate a crankcase explosion. In the same way as in the previous event, the crew was warned about an abnormality several days before the failure occurred. In a similar manner, the crankcase covers were removed and spot checking of temperatures of the running gear was done without any obvious findings. Figure 31 below illustrates the time stamp of the event with reference to the IAS event log.

20015	BIN	ME1 OILMIST IN CRANKCASE	NORMAL		220630 08:44.57
20014	APS	ME1 PREPROC PRE-ALARM	NORMAL		220630 08:44.57
20013	BIN	ME1 SPLASH OIL TEMP MEAN DEV H	NORMAL		220630 08:44.50
20012	266A	NO.1 CPP CONTROL SYSTEM FAIL	ACKED	C/E	220630 08:44.19
20011	266A	NO.1 CPP CONTROL SYSTEM FAIL	ALARM		220630 08:44.18
20010	ESS	ME1 AUTO SHUTDOWN	ACKED	C/E	220630 08:44.17
20009	BIN	ME1 SPLASH OIL TEMP MEAN DEV H	ACKED	C/E	220630 08:44.17

Figure 31. Event log extract from IAS on June 30, 2022.

The following Figure 32, present splash oil temperatures in the engine, that are the closest available to the time stamp of the failure. The figure show records from 02:00 on the 29.06.2022. Unfortunately, the engines were stopped during the time of the automatic print out on the 30.06.2022 so in neither case this did not provide useful information.

30/03/01	ME1 SPLASH OIL TEMP A/B 1	64.5	81.0	°C	4
30/03/02	ME1 SPLASH OIL TEMP A/B 2	64.5	81.0	°C	4
30/03/03	ME1 SPLASH OIL TEMP A/B 3	64.2	81.0	°C	4
30/03/04	ME1 SPLASH OIL TEMP A/B 4	64.0	81.0	°C	4
30/03/05	ME1 SPLASH OIL TEMP A/B 5	63.6	81.0	°C	4
30/03/06	ME1 SPLASH OIL TEMP A/B 6	63.7	81.0	°C	4
30/03/07	ME1 SPLASH OIL TEMP A/B 7	65.0	81.0	°C	4
30/03/08	ME1 SPLASH OIL TEMP A/B 8	65.0	81.0	°C	4
30/03/09	ME1 SPLASH OIL TEMP A/B 9	64.7	81.0	°C	4

Figure 32. Event log extract from IAS June 29, 2022.

As in the previous chapter, the engine had to be taken out of service for a considerable time window due to repairs, approximately 36 hours in total meaning that the vessel was out of schedule and delayed. Cylinder unit 5 had to be fully disassembled for inspection and installation of new or reconditioned parts. With reference to Figure 29 on page 34, these included piston with rings (pos 34), reconditioned liner and backing ring (pos 50), cylinder head (pos 55), and connecting rod with new bearings (pos 30). See attached service report in Appendix 3.

3.9.4 Example case lll – Engine shutdown due to oil mist alarm

On June 30, 2022 there was another automatic engine shut down due to high oil mist concentration in the crank case of main engine number two. This time the electrical power supply was through shaft generator starboard connected to main engine two and because of this reason, a black-out occurred when the engine shut down. The port side shaft generator was not in service at the time, meaning that there was a lack of stand-by when starboard generator stopped. Auxiliary engines received automatic stand-by start command.

In the following Figure 33 the reader find an extract of the event log to summarize the event.

27055	SHD	ME2 OILMIST IN CRANKCASE	ACKED	C/E	220730 17:56.14
27054	ESS	ME2 AUTO SHUTDOWN	ACKED	C/E	220730 17:56.14
27053	1820	NO.1 AIR COMPRESSOR ABNORMAL	ACKED	C/E	220730 17:56.07
27052	GCS	ME1 GOV WIRE BREAK SPEED REF	ACKED	C/E	220730 17:56.07
27051	911	NOZZLE MODULE FAIL/ST-BY START	ACKED	C/E	220730 17:55.50
27050	1822	NO.2 AIR COMPRESSOR ABNORMAL	ACKED	C/E	220730 17:55.50
27049	ECS	ME2 CTRL SYS COMMON ALARM	ACKED	C/E	220730 17:55.43
27048	2472	C/H ELECTRIC LOUVERS POWER FAIL	ACKED	C/E	220730 17:55.43
27047	1825	NO 3 AIR COMPRESSOR ABNORMAL	ACKED	C/E	220730 17:55.43
27046	SG228	SG2, MODE CANCEL	NORMAL		220730 17:55.42
27045	SG224	SG2, BUS BAR FREQUENCY TOO LOW	NORMAL		220730 17:55.42
27044	47995	SEA1201 DG-2 PMS SYSTEM ALARM	NORMAL		220730 17:55.41
27043	GCS	ME1 GOV WIRE BREAK ACTUATOR	NORMAL		220730 17:55.39
27042	GCS	ME1 GOV WIRE BREAK SPEED REF	NORMAL		220730 17:55.39
27041	ECS	ME1 CYLINDER LUBRICATOR	NORMAL		220730 17:55.37
27040	APL-01	APL, ENGINE CTRL ROOM	ACKED		220730 17:55.19
27039	GCS	ME2 GOVENOR MINOR ALARM	ACKED	C/E	220730 17:54.26
27038	GCS	ME2 GOVENOR CTRL COMMON ERRO	ACKED	C/E	220730 17:54.26
27037	ECS	ME2 COMMON SYSTEM ALARM	ACKED	C/E	220730 17:54.26

Figure 33. Event log extract from IAS on July 30, 2022.

Within minutes prior to the event, the lubricating oil purifier trigged alarm on high water content in the lubricating oil. The water transducer value indicated 87 which is significantly higher than the normally seen value of 81. Below Figure 34 illustrate the triggered alarm. Specific reason for the alarm must be confirmed locally at the purifier control panel.

27014	1808	NO.2 LO PURIFIER ABNORMAL	ACKED	C/E	220730 17:54.21

Figure 34. Event log extract from IAS the 30.07.2022.

As mentioned, this alarm was the first to be triggered, but as the engine room was un-manned at the time of the event, the engine automatically shut down before the duty engineer managed to reach the engine control room. According to the engine log books, the departure was about 1,5 hours before the event occurred. Crank case covers were opened to investigate the reason for high water content in the lubricating oil which was confirmed by a quick test. The water in lubricating oil indicated 1,0% water content which equals to approximately 80 liter of water contamination considering the total lubricating oil volume. Any visual indication of water leak was not seen in the crank case, neither was there any other observations that could explain the cause. On the actual engine, there are bores in the backing rings (water jackets) of each cylinder that is made to provide indication if there is a water leakage allowing cooling water to leak by the sealings holding the cooling water volume of each cylinder. As the engine had been drained of cooling water and allowed to fully cool down due to a major maintenance event during previous port call, it was decided that the water had entered (leaked) into the crank case when the engine was filled after completion of the maintenance work when the engine was still cold. This has been observed during

similar circumstances by the author and is due to aged and worn out sealings. When the engine is pre-heated the leak stops at a certain temperature which seemed to be the situation as no additional indications were found after the event. With the MAN fluid monitoring solution described in Chapter 8.3, this event could have been fully prevented as it would have alerted the operators on-board already at the start preparation stage, when the pre-lubricating pump is started and lubricating oil start circulating in the engine.

3.9.5 Example case IV - Turbocharger failure

This chapter does not directly relate to the findings in the event log but was instead decided to include on this author´s initiative upon discussions with the vessel responsible technical super intendent. According to the technical super intendent both this ship as well as a sister ship with identical technique has suffered from sudden turbocharger break downs during the 20 years in operation. Due to the fact that a mechanical turbocharger break down is very expensive, the author finds it relevant to include investigations on possibilities to develop monitoring of the turbo as this component is critical in terms of engine operation. Malfunction will result in considerable down time for repairs – not to mention the hazard of risking lives of the operators. The author has on other vessels experienced total turbocharger break down where the rotating assembly has exploded. The most critical parameter of a turbocharger is the internal balance, obviously because the rotor assembly spins at very high speeds. The MAN NA48S turbocharger on-board Finnmill is operated at speeds of 16000 rpm. An illustration of the NA/S turbocharger is shown in the following Figure 35.

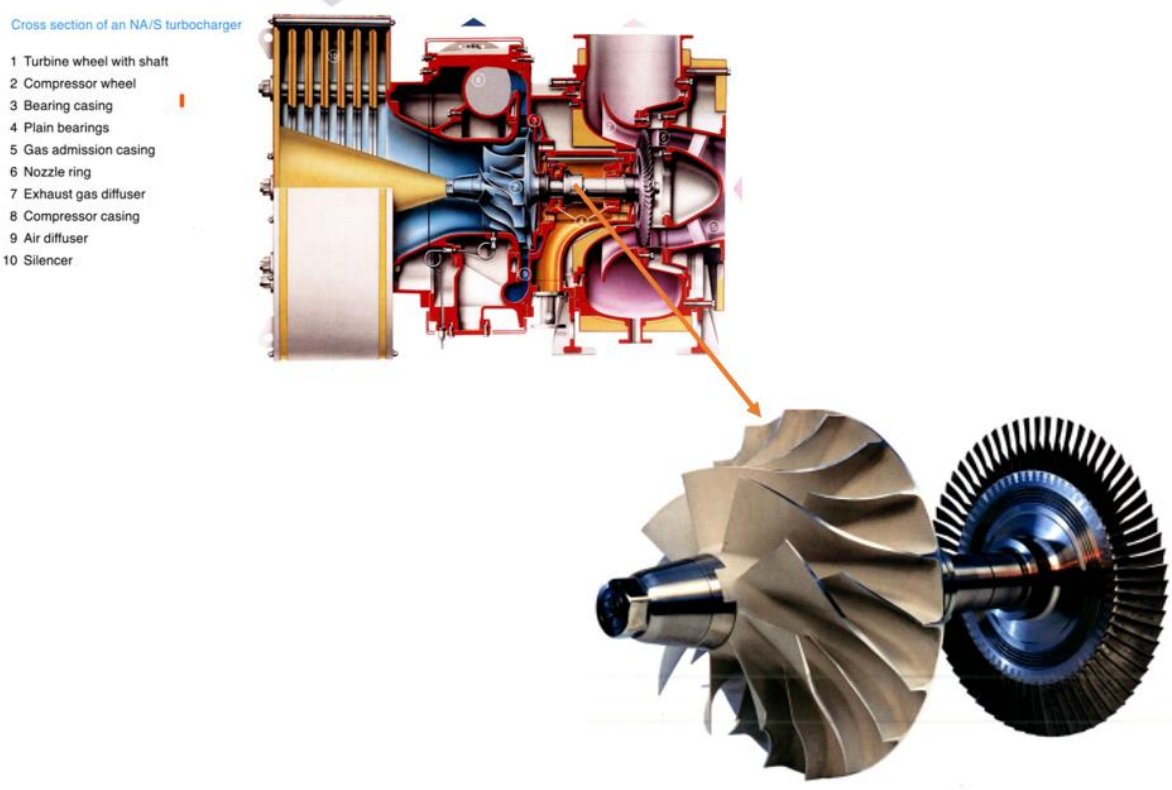


Figure 35. Turbocharger cross section view. (MAN Energy Solutions, 1997a, p. 7)

If the turbocharger suffers from unbalance in the rotating assembly, one can easily understand the forces acting on the rotor assembly as well as on the bearings. On the MAN 48/60 B engine, the turbocharger bearings (plain type) are lubricated by the engine lubricating oil and the pressure is carefully adjusted by a throttle or pressure reducing valve to maintain the correct lubricating oil pressure and flow to the turbocharger bearings. (MAN Energy Solutions;, 2001b, pp. 01/03-02/03). The following Figure 36 explains the lubricating oil flow in the turbocharger assembly.

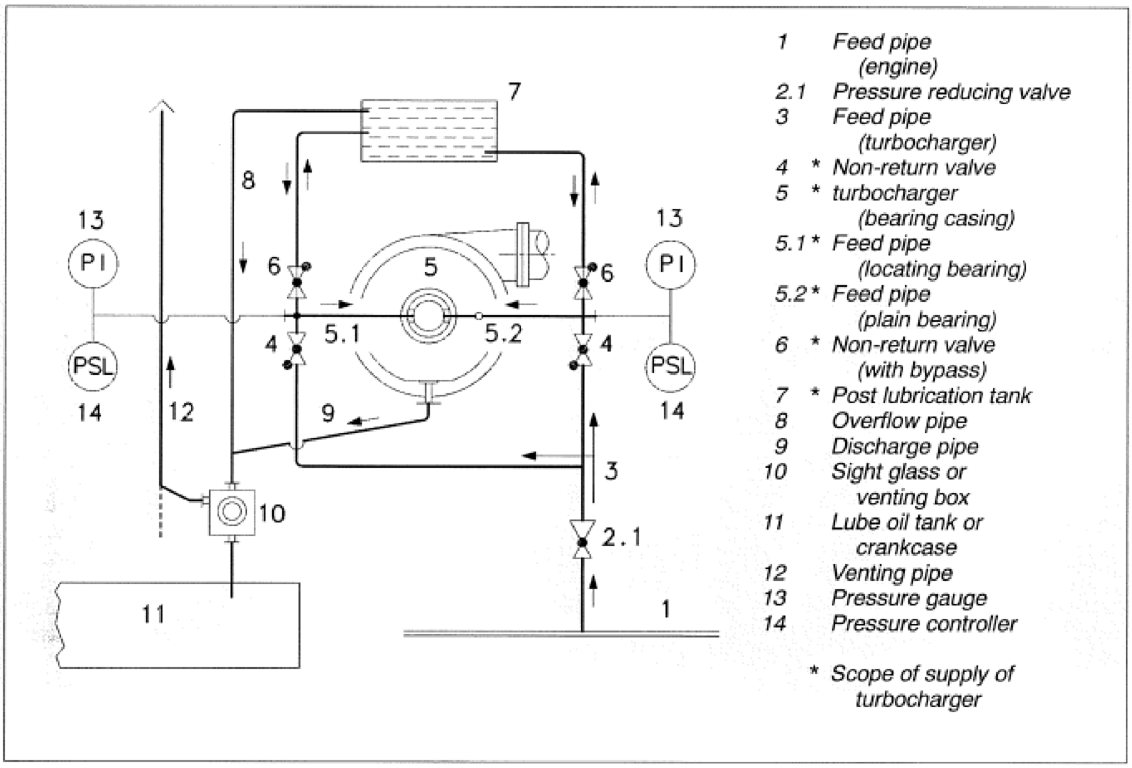


Figure 1. Lube oil system NA48/S on four-stroke engine

Figure 36. Schematic view of lubricating arrangement on NA48/S turbocharger. (MAN Energy Solutions;, 2001b, p. 03/03)

Because of the fact that the author does not have inputs on *how* the turbochargers have failed in the past as the reasons can be many, such as lacking routines on maintenance and turbocharger cleaning, poor lubricating oil quality, manufacturing or material related issues just to mention some, it was decided to focus on developing monitoring instead. (Personal communication with MAN ES Turbo Experts, 2022). Currently the monitoring of the turbocharger is limited to speed, lubricating oil pressure and temperature as well as exhaust inlet and out temperature. Figure 36 on page 41 illustrate the available measuring points.

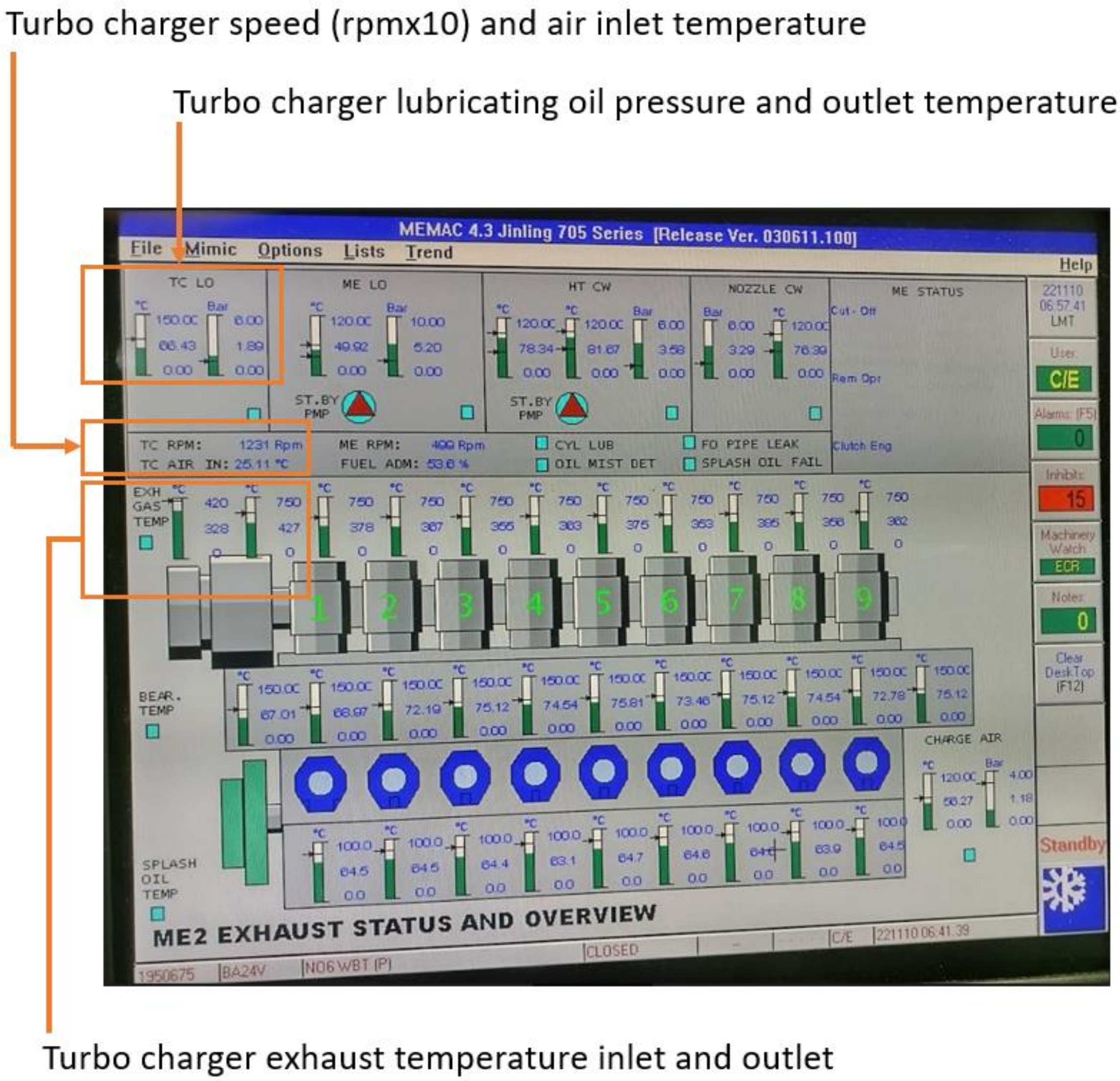


Figure 36. Turbocharger monitoring in IAS (Author´s collection).

During interviews with MAN PrimeServ turbocharger expert’s different options were discussed on how to develop monitoring by additional sensors such as vibration monitoring. However, this particular technique in terms of sensor signal reliability in combination with a highly challenging environment create potential for providing misleading information and is therefore not used. It was also mentioned that the turbocharger performance and reliability is highly dependent on the engine itself. This refers to the importance of a well-balanced injection system and naturally the condition of the charge air cooler to avoid circumstances that create additional thermal load and buildup of combustion residues on the internal parts of the turbocharger. To ensure that the injection system is balanced, it could provide valuable input to install continuous monitoring of firing pressures as this method effectively acknowledges bad fuel injection pumps and injection valves as an addition to exhaust

temperature monitoring. Exhaust backpressure must also be carefully monitored as this will obviously create high stress on the turbocharger rotor. According to this author´s impression, adding vibration and ultrasonic monitoring to the picture, balance issues as well as bearing degradation could possibly be detected before a break down. Anyway, as such technique is highly sensitive it might not be reliable in long term due to the challenging environment at the turbocharger. The biggest problem is the high rotating speed of the turbo, making long term prediction highly challenging. According to this author´s experience, break downs usually occur fast leaving the operators more or less without pre-warnings. Anyhow, by adding artificial intelligence and sensor fusion to the monitoring of turbocharger speed, exhaust back-pressure, lubricating oil pressure and outlet temperature in addition to vibration monitoring techniques, the author do find it possible on some level to improve situational awareness.

3.10 The questionnaire

To gain perspective, a questionnaire was made as an addition to the research. For the purpose the application found through Google documents was used. The questionnaire is of structured type consisting of six questions. Refer to Appendix 4 showing the complete questionnaire. The questions aim to assist this author to find additional ways on improving operational safety and efficiency from different perspectives based on experiences and expertise of other engineers within the Finnlines fleet. To benefit the most from the inputs, the author chose to include all available engine brands. Due to the uncertainty on how many replies would be available to analyze, the questions were made prioritizing an open perspective more than targeting statistics or trends. By this approach, the individual answers provide a wider overview of the subject which was considered important in this context. The questionnaire was sent out to approximately 20 recipients within the Finnlines fleet, and the receiver was provided the opportunity to remain anonymous.

Received replies represent engines from three different manufacturers, MAN, Wärtsilä and MaK which all have been common in similar marine applications. The following Figure 37 aims to summarize distribution of replies by brand in percentage. All represent large-bore four stroke engine type.

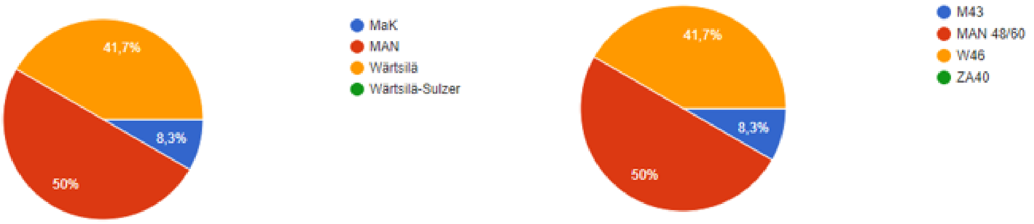


Figure 37. Engines by brand and type

The generation of each engine is presented by a code letter (B……F) where a higher letter generally means later generation. Referring to the Finnlines fleet, engine generation by age, as in the replies of this questionnaire ranges from year 1998 up to 2014. This means that there are more technically advanced engines, particularly with a more sophisticated automation and control system within the received replies. Anyhow, as this thesis target the MAN 48/60 B-generation engine there will not be any deeper investigation into the technique of competitors as all vessels within the Finnlines fleet equipped with MAN engines represent the B-generation. Nevertheless, it is important to identify generation to understand the replies and be able to relate to the content of this thesis.

Below subsections aim to summarize inputs received for questions 4-6.

4.) Possibilities to improve operational safety of the engine.

- Importance to use high quality spare parts supplied by genuine manufacturer.
- Maintenance to be followed as per manufacturers recommendations.
- Lessons learned over time: Customer information letters by the manufacturer to be taken seriously.
- Lower equipment stress by respecting ramping and load limitations at current circumstances.
- Improved monitoring of lubricating oil and fuel.
- Situational awareness of the operators.

5.) Means of emergency operation.

- Mechanical engine operation if control system fails.
- Override of safety system in emergency situations.
- Situational awareness of the operators.
- Masking (disconnection) of individual sensors to prevent unnecessary automatic shutdown during sensor failure.

6.) Engine efficiency and performance.

- Engine operation according to design parameters.
- Improved materials to prolong maintenance intervals.
- Lower fuel consumption by adapting better to environmental circumstances.

Clearly, there are both inputs regarding mechanical improvements as well as on monitoring and automation level. However, inputs regarding mechanical improvements are relatively few. In general, the replies present a picture that independent of brand, the engines are considered as reliable when planned maintenance schedule is followed and used spare parts are supplied by the genuine manufacturer. Regarding efficiency the general input is that operators shall follow design parameters as provided by the manufacturer at engine delivery. The importance of adapting to environmental circumstances is also mentioned. This relates to aspects such as avoid stressing the engine by exceeding load limitations and harmful vibrations due to ambient conditions. Emergency operating the engine deserves an own chapter and will not be further described at this point. Refer to Chapter 8.11.

4 Challenges related to the research

There are many aspects creating challenges during the making of this thesis. The vessel has operated in many areas globally during the time perspective of the research contributing to some level of changes in certain operational parameters due to variations in environmental circumstances. These circumstances refer to ambient conditions as well as operational patterns such as engine load. Besides the above mentioned circumstances there were found longtime equipment malfunctions not connected to the engine itself but that does affect engine operational parameters and provide misleading information, meaning the malfunction triggers alarms that are not normally present. Following chapters will describe in detail the different challenges and obstacles that have been present during the thesis writing in terms of data and other materials used.

4.1 Vessel traffic routes and schedule

During the selected time window for the research, the vessel had a high frequency of route changes. This, in combination with the limited parameters available made the planned mapping of operating patterns very challenging. Also, if the event log was available in digital format, it would simply have contributed to a more manageable data. Additional information about the digital advantage is presented in next chapter. A concrete follow-up of inputs regarding operational patterns and how these effect on parameter level would have been possible on a high level even with the available material if the vessel was on an ordinary route with a constant schedule and a limited number of ports.

During the selected time frame of the event log, the vessel sailed between the locations below and the schedule was changing frequently according to the engine logbooks:

- Kiel, Germany
- Rostock, Germany
- Travemunde, Germany
- Lubeck, Germany
- Aarhus, Denmark

- Hanko, Finland
- Helsinki, Finland
- Uusikaupunki, Finland
- Turku, Finland
- Bronka, Russia
- UST-Luga, Russia
- St. Petersburg, Russia
- Gdynia, Poland
- Zeebrugge, Belgium
- Bilbao, Spain

The previously mentioned reasons contributed to the conclusion that the author was not able to make a reliable and correct mapping of the operating parameters at different load conditions simply because they were not found stable enough to provide evidence. Recorded load from the IAS automatic print out in the event log show load conditions ranging from 33% to 88% and in addition to this the ambient conditions that have lacking documentation.

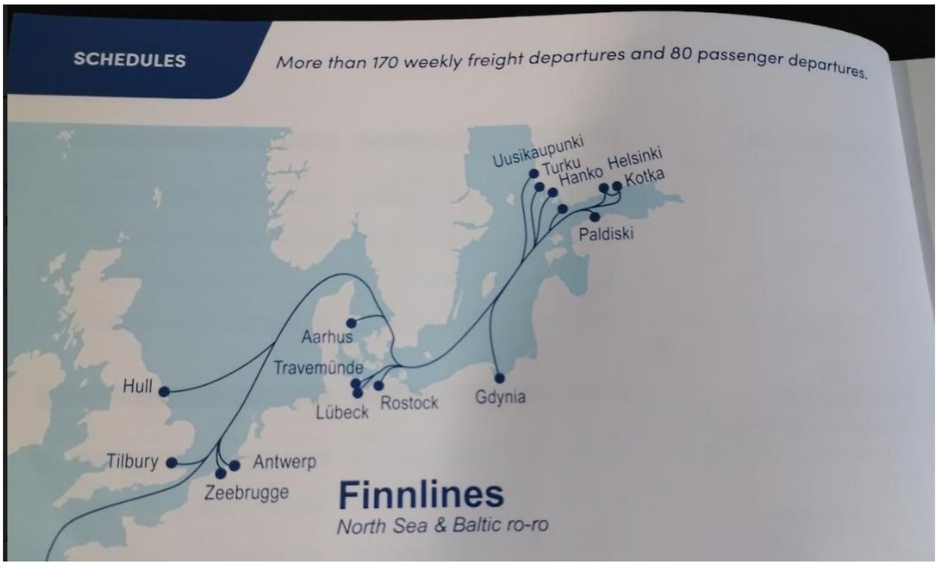


Figure 38. Finnlines Customer letter 01/2022 – Fleet destinations.

4.2 Digital advantage

This chapter target various digital tools and the aim is to clarify a basic perspective of material availability during the thesis process. During the writing of this thesis, it was observed multiple times that additional digital tools for data storage would have made the process a lot easier and more efficient. The largest contributor in terms of background material for the research process of this thesis was the alarm and event log. As of today, it is only available in A4 matrix paper format making any precise search very challenging. Every single page of the event log was analyzed and checked manually and due to lacking availability as well as quality the selected time window of the log was rather limited. Total availability was close to 24000 pages from which the adapted time window incorporates roughly 3500 pages. Below Figure 39 presents the event log printer.

Figure 39. Event log printer. (Author´s collection).

By using a digital storage system for the data, it would definitely contribute to adding quality and availability perspectives of any historical events. MAN ES provide this possibility currently as a part of the MAN PrimeServ Assist remote monitoring solution but this service

target the engines and does not include the majority of auxiliary systems for instance. An option that could fulfill the needs of storing event and alarm logs on-board could be the Norweigian Hoglund Marine Solutions Prilog, alarm and event logger. This system records all received events and data, has extensive filtering functions and additionally perform automatic back-ups. It also provides the possibility to add a remote connection via network/satellite. (Hoglund Marine Solutions, 2022). A digital storage device such as the prilog is highly recommended as it includes all events and alarms triggered by the IAS. When analyzing a certain event, it is necessary to include all available parameters as in many cases observed during this research the cause of events are commonly recognized and explained by processes in the auxiliary systems. Additionally, by implementing a digital storage system for alarm and event recording, it certainly would make all event follow-up more accurate due to availability of raw data or actual sensor values.

A key contributor that would explain relationship´s between the historical events and counter measures is the digitally recorded workbook. This is described later on, but it refers to a summarizing basic word document or excel file that involve all completed work tasks on a daily basis. This feature is used on-board but due to certain reasons the documents for the selected time window of the research was no longer available. Again, the author had to dive into the handwritten engine logbooks and therefor the process was slow and not effective as filtering of the information was not possible but instead analyzing had to be done page by page.

4.3 Budget related challenges and limitations

The initial plan was to develop the remote monitoring solution for this type of older four stroke medium speed diesel engines. MAN ES showed good will towards this research and were willing to invest a considerable amount of time and money in developing a custom solution specifically for this case study. This solution demanded that the customer, Finnlines, would sign an agreement based on a monthly fee per engine for the service provided. As of today, the service has not been agreed and this contributed to why this thesis made a relatively large change in direction by using existing data or in other words historical data by the event log and planned maintenance system inputs.

5 Maintenance concepts

With the advancing industry, many companies have leaned towards offering various types of condition-based maintenance techniques as a more cost-effective solution. As the name suggests, such technique aims to assist in determining actual equipment condition to predict when maintenance shall be done instead of following a specific pre-planned schedule. Below Figure 40 illustrate the main types of maintenance concepts.

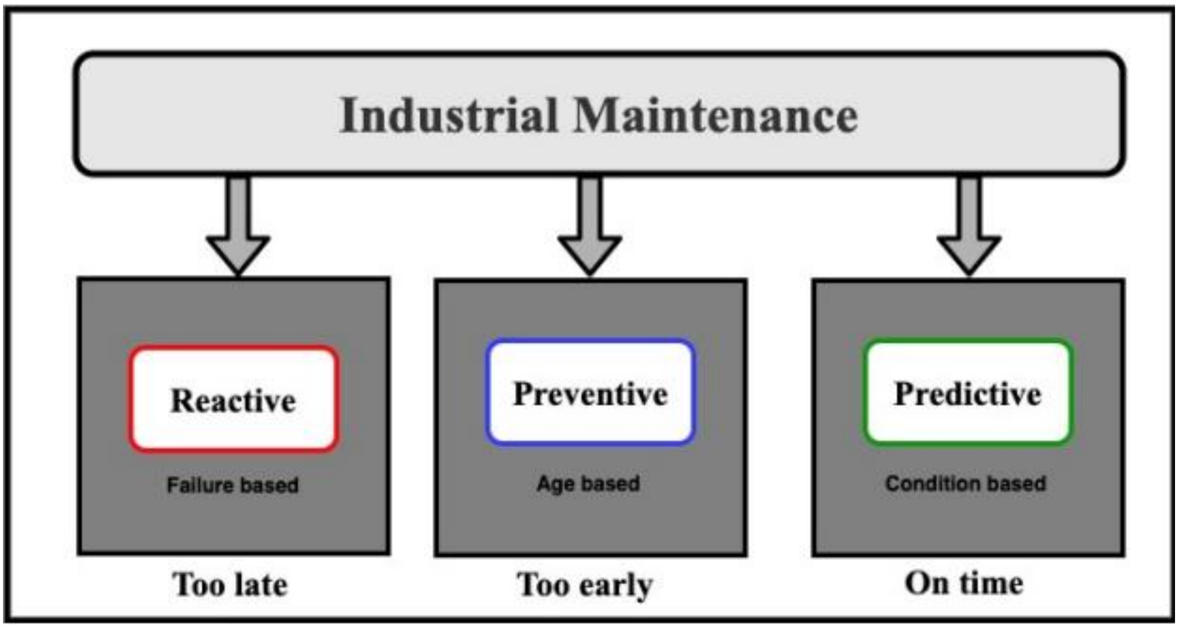


Figure 40. Industrial maintenance concepts. (Abbasi, 2021, p. 9)

The first option will not further be described in this thesis due to clear reasons. Reactive maintenance means according to this author in this context that either the engine manufacturer would have provided faulty instructions regarding maintenance interval, or the operator would not have followed or implemented the instructions provided by the engine manufacturer. This type of maintenance concept is due to obvious reasons a not wanted solution as it mean that engine operations are lacking both total reliability and efficiency.

The other two options are relevant in this thesis and will be explained in following chapters. This author also wants to highlight the fact that the intention of this thesis and related research is to provide suggestions on how to move towards predictive maintenance from the actual concept of preventive maintenance by different means.

5.1 Preventive maintenance

As mentioned previously, this is the current concept used on-board this installation. It has been a well proven concept relying on instructions provided by the engine manufacturer since delivery of the engines in year 2001. As described in the manual, certain circumstances will affect the maintenance schedule such as fuel in use and load patterns, and the below Figure 41 illustrate an example of scheduled maintenance for some of the engine components.

Wartungsplan (Motor · Schwerölbetrieb)
Maintenance Schedule (Engine · Heavy Fuel Oil Operation) 4.7.2 MAN B&W

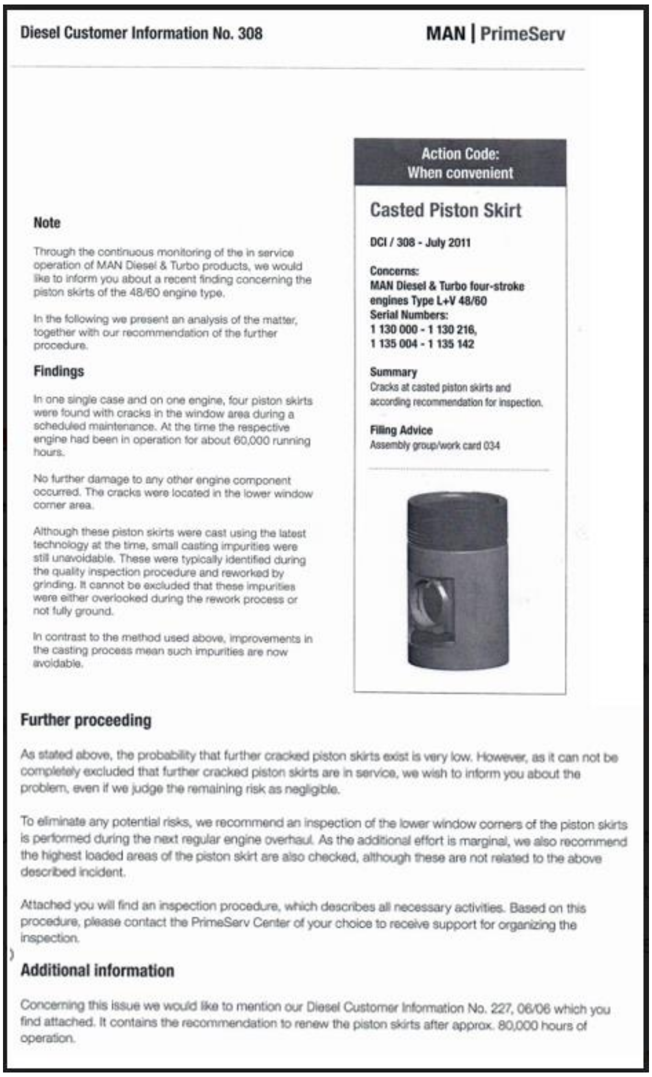
1, 2, 3				x ↔ y			per	24	150	250	500	1500	3000	6000	12000	24000	30000	36000
Drehzahlregler • Speed governor															***140***			
262	Mechanischer Regler: Ölstand kontrollieren	*Mechanical governor: Check oil level*	140.01	011 012	1	0.1	Motor *Engine*	4										
263	Mechanischer Regler und Booster-Servomotor: Öl und Ölfilter wechseln	*Mechanical governor and booster servo-motor: Replace oil and oil filter*	140.01 140.02		1	1	Motor *Engine*						4					
264	Mechanischer Regler: Reglerantrieb, d.h. Antriebswelle und Zahnräder kontrollieren.	*Mechanical governor: Check governor drive, i.e. drive shaft and gearwheels.*	140.01 140.03	202	1	1	Einheit *Unit*				2			4				
265	Mechanischer Regler: Regler durch Spezialwerkstatt überholen lassen	*Mechanical governor: Take the governor to be overhauled by a special workshop*	C		1	2	Motor *Engine*	3	3	3	3	3	3	3	3	3	3	3
266	Elektronischer Regler: Impulsgeber auf Verschmutzung und korrekten Abstand kontrollieren	*Electronic governor: Check pulse pickup for dirt and verify that space is correct*	A		1	0.2	Einheit *Unit*						4					
Anlaßsteuerschieber/Anlaßventil/Hauptanlaßventil • Starting air pilot valve/Starting valve/Main starting valve															***160/161/162***			
272	Alle Anlaßsteuerschieber ausbauen und überholen	*Remove and overhaul all starting air pilot valves*	160.01		1	1	Ventil *Valve*								X			
273	Anlaßventile auf Dichtheit kontrollieren	*Check starting valves for tightness*	161.01		1	0.2	Ventil *Valve*						X					
274	Alle Anlaßventile ausbauen und überholen	*Remove and overhaul all starting valves*	161.01 161.02		1	2	Ventil *Valve*								X			

X Wartungsarbeit fällig — *X Maintenance work is necessary*
1 Nach Bedarf/Zustand — *1 As required/depending on condition*
2 Kontrolle neuer oder überholter Teile erforderlich (einmal nach der angegebenen Zeit) — *2 Check new or overhauled parts once after the time given in the column*
3 Nach Vorschrift des Herstellers — *3 According to specifications of manufacturer*
4 Falls Bauteil/System vorhanden — *4 If component/system is installed*

10076 4.7.2-01 E 03.01 L 48/60 07/09

Figure 41. Example of component maintenance schedule. (MAN Energy Solutions, 1999b, p. 272)

Additionally, if the manufacturer reveals failure patterns during the equipment lifetime, they will send out additional information letters to inform the customer. These letters are named Customer Information letters or "CUS" and aims to urge the customer either to increase inspection frequency or replace specific components at a certain interval. The CUS can also include new options and offerings in terms of technical advancements. It is of outmost importance to react to these instructions as they are to be considered as an essential part of the preventive maintenance setup. The following Figure 42 presents an example of a customer information letter regarding findings related to piston skirts of the 48/60 engine.



Diesel Customer Information No. 308 MAN | PrimeServ

Action Code: When convenient

Casted Piston Skirt

DCI / 308 - July 2011

Concerns:
MAN Diesel & Turbo four-stroke engines Type L+V 48/60
Serial Numbers:
1 130 000 - 1 130 216,
1 135 004 - 1 135 142

Summary
Cracks at casted piston skirts and according recommendation for inspection.

Filing Advice
Assembly group/work card 034

Note

Through the continuous monitoring of the in service operation of MAN Diesel & Turbo products, we would like to inform you about a recent finding concerning the piston skirts of the 48/60 engine type.

In the following we present an analysis of the matter, together with our recommendation of the further procedure.

Findings

In one single case and on one engine, four piston skirts were found with cracks in the window area during a scheduled maintenance. At the time the respective engine had been in operation for about 60,000 running hours.

No further damage to any other engine component occurred. The cracks were located in the lower window corner area.

Although these piston skirts were cast using the latest technology at the time, small casting impurities were still unavoidable. These were typically identified during the quality inspection procedure and reworked by grinding. It cannot be excluded that these impurities were either overlooked during the rework process or not fully ground.

In contrast to the method used above, improvements in the casting process mean such impurities are now avoidable.

Further proceeding

As stated above, the probability that further cracked piston skirts exist is very low. However, as it can not be completely excluded that further cracked piston skirts are in service, we wish to inform you about the problem, even if we judge the remaining risk as negligible.

To eliminate any potential risks, we recommend an inspection of the lower window corners of the piston skirts is performed during the next regular engine overhaul. As the additional effort is marginal, we also recommend the highest loaded areas of the piston skirt are also checked, although these are not related to the above described incident.

Attached you will find an inspection procedure, which describes all necessary activities. Based on this procedure, please contact the PrimeServ Center of your choice to receive support for organizing the inspection.

Additional information

Concerning this issue we would like to mention our Diesel Customer Information No. 227, 06/06 which you find attached. It contains the recommendation to renew the piston skirts after approx. 80,000 hours of operation.

Figure 42. MAN customer information letter No. 308 page 1.

As a maintenance concept, preventive maintenance has been used extensively by all engine manufacturers during the years. It is well known and a well proven concept but with the technology available today it is not considered the most cost-effective solution, not in all cases. (Gonfalonieri, Towards Data Science, 2019). According to this author´s experience, it is highly dependent on the actual operating circumstances and the plant condition as a whole if the scheduled - or preventive maintenance is the most effective choice for safe and efficient operations. Anyhow, by mowing further into a modern type of maintenance concept such as predictive maintenance, it is necessary to involve the scheduled maintenance plan as a basic approach as this is based on comprehensive component lifetime simulations and testing by the genuine manufacturer. This author finds the best solution in terms of efficiency and reliability to implement predictive maintenance as an addition to the existing setup,

simply meaning that all maintenance activities should on some level relate to the preventive maintenance schedule. If found relevant for the specific installation to adjust maintenance intervals by inputs from a predictive approach it should only be done in close cooperation with the manufacturer, by for instance implementing remote monitoring.

5.2 Predictive maintenance

This approach to maintenance is also called condition-based maintenance as it relies on actual component or equipment condition. The intention is to provide a more cost effective and pro-active approach to maintenance and overall equipment lifetime. In today's industry it is popular to involve artificial intelligence and machine learning in predictive maintenance concepts. As mentioned in the article *how to implement machine learning for predictive maintenance* by implementing machine learning algorithms into the concept, you are able avoid "guess work" and maximize equipment lifetime. (Gonfalonieri, Towards Data Science, 2019). Simply, this means that algorithms are used to manage the large amount of sensor data generated by the asset to highlight the operators of any anomalies found in the data flow before a failure occur. This process is usually automated when artificial intelligence is used. According to this author´s experience, the most common type of utilizing machine learning in this context is to use data models and advanced algorithms to monitor normal equipment behavior over time to train a model on recognizing what is normal behavior and what is considered as not normal. Due to confidentiality aspects, this author cannot provide any additional facts concerning the principles behind MAN PrimeServ Assist that stands for the software developed and offered by MAN ES as an essential part of the predictive maintenance concept. Instead, this author will include some example cases from the PrimeServ Assist in chapter 10.2. It is important to remember that this thesis rely on the described case study, with technique as-is. Therefore many suggestions on improving reliability and efficiency are made by taking into account the generation of technology found on the site as this contribute with challenges related to design. According to this author, a predictive maintenance approach would benefit from additional measuring points simply to achieve a more precise picture of the actual engine health. Even as some of the suggested additions of sensors are considered as very basic, there are limitations present as the different sub-assemblies that would require modifications on component level. This in turn might require dimensional changes to ensure that component specifications remain the same. These

questions are highly equipment specific and was discussed with MAN ES engine experts. (Personal communication with MAN ES Engine experts, 2022)

In chapter 8, the author will present some techniques that support a predictive approach to maintenance, and that could be implemented on the actual site to support reliable and efficient engine operation.

6 Existing monitoring on-board

This chapter will describe the most essential sensors of the existing monitoring system installed and, the most relevant means to protect the engine against the failures described in chapters 3.8. According to regulations the engine must be equipped with certain protection devices to prevent fatal failures that can cause risk of human life, environmental pollution and loss of investment. These means of protection include a varying setup of sensors to measure temperature, pressure, and speed as visible in the IAS main engine mimic in below Figure.

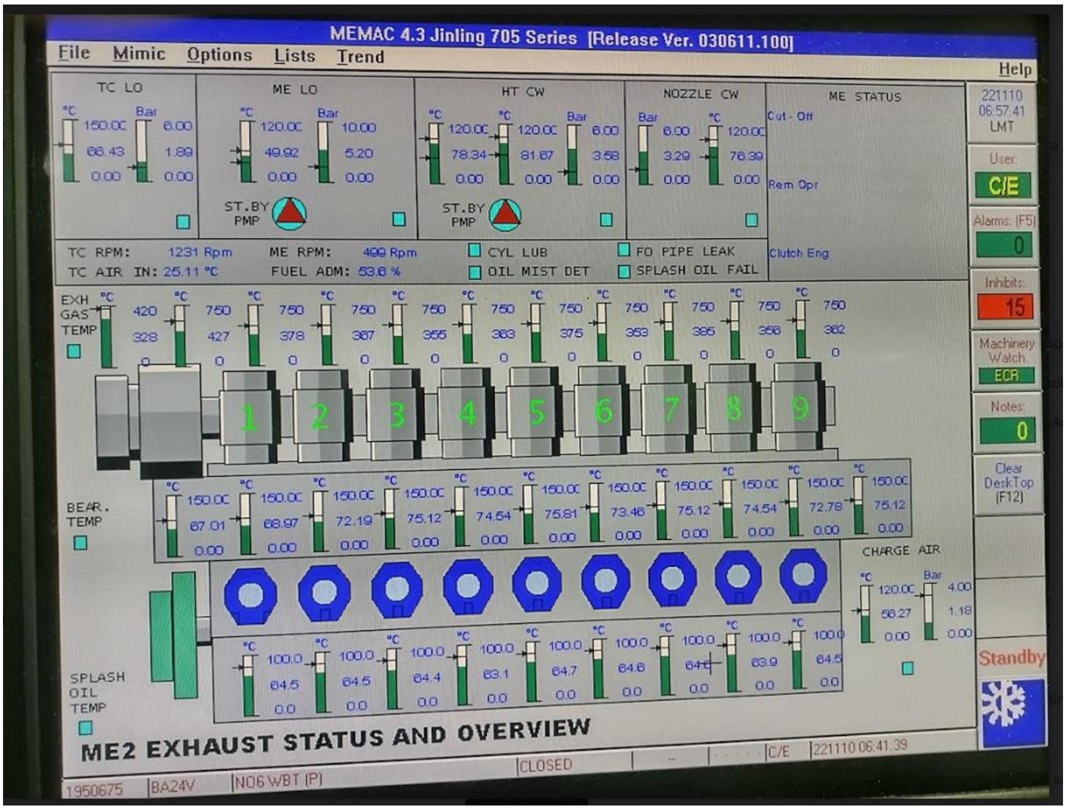


Figure 43. ME 2 Status. (Author´s collection).

The sensors are connected to both the IAS and the MAN ES supplied safety and control system (SaCoS99) that will trigger a warning by giving an alarm whenever there is a value that is out of normal range for the measured parameter. At a distinct and pre-set level depending on the parameter in question the safety and control system of the engine itself will trigger a load reduction or shutdown. The parameters in Figure 44 are considered as critical and refer to specific limit values set in accordance with instructions by the engine manufacturer. Whenever the engine is operated outside these parameters, the automation system will trigger an automatic load reduction (slowdown) or depending on the reading, a shutdown.

	Parameter		Limit value and unit
SHUT DOWN			
	Engine lubricating oil pressure		2.5 bar
	Turbo charger lubricating oil pressure		0.9 bar
	Turbo charger lubricating oil temperature		105˚C
	HT-Cooling water temperature		98˚C
	Main bearing temperature		95˚C
	Splash oil temperature		85˚C
	Splash oil mean temperature deviation		7˚C
	Engine overspeed		575 RPM
SLOW DOWN	Engine lubricating oil temperature		65˚C
	HT Cooling water pressure		1.5 bar
	HT Cooling water temperature		95˚C
	Exhaust gas temperature after cylinder		510˚C
	Exhaust gas temperature before turbo charger		580˚C
	Exhaust gas mean value deviation		80˚C
	Turbo charger overspeed		18100 RPM
	Engine under speed, clutch out		150 RPM

Figure 44. Main Engine limit values.

As the limit values are distinct values meaning that an alarm will only be triggered when any value exceeds the set limit, it will not alert the operator of an anomality before the alarm is activated. This is the reason why the existing IAS is more of a *preventive measure* rather than a *predictive concept*. A more predictive approach could be except additional sensors, to involve artificial intelligence that can highlight the operators on smaller parameter changes over time instead of only providing a warning when there already is an error present.

In the following chapters, this author will present some important engine protecting features that have proven to prevent total engine break down, that possibly could have been the result in example cases I and II.

6.1 The splash oil monitoring system

The splash oil monitoring system relies on the lubricating oil splash in engine crankcase during engine operation. It measures the temperature by catching a certain amount of the splash oil into a type of chute installed in each crank case cover on the operating side of the engine. The chute has a small reservoir with a temperature sensor installed. The oil catch in the reservoir is slowly and in a controlled manner drained out and returned to the crank case through an orifice in the bottom of the reservoir. Refer to the following figures.

Figure 45. Splash oil temperature sensor PT100. (Author´s collection).

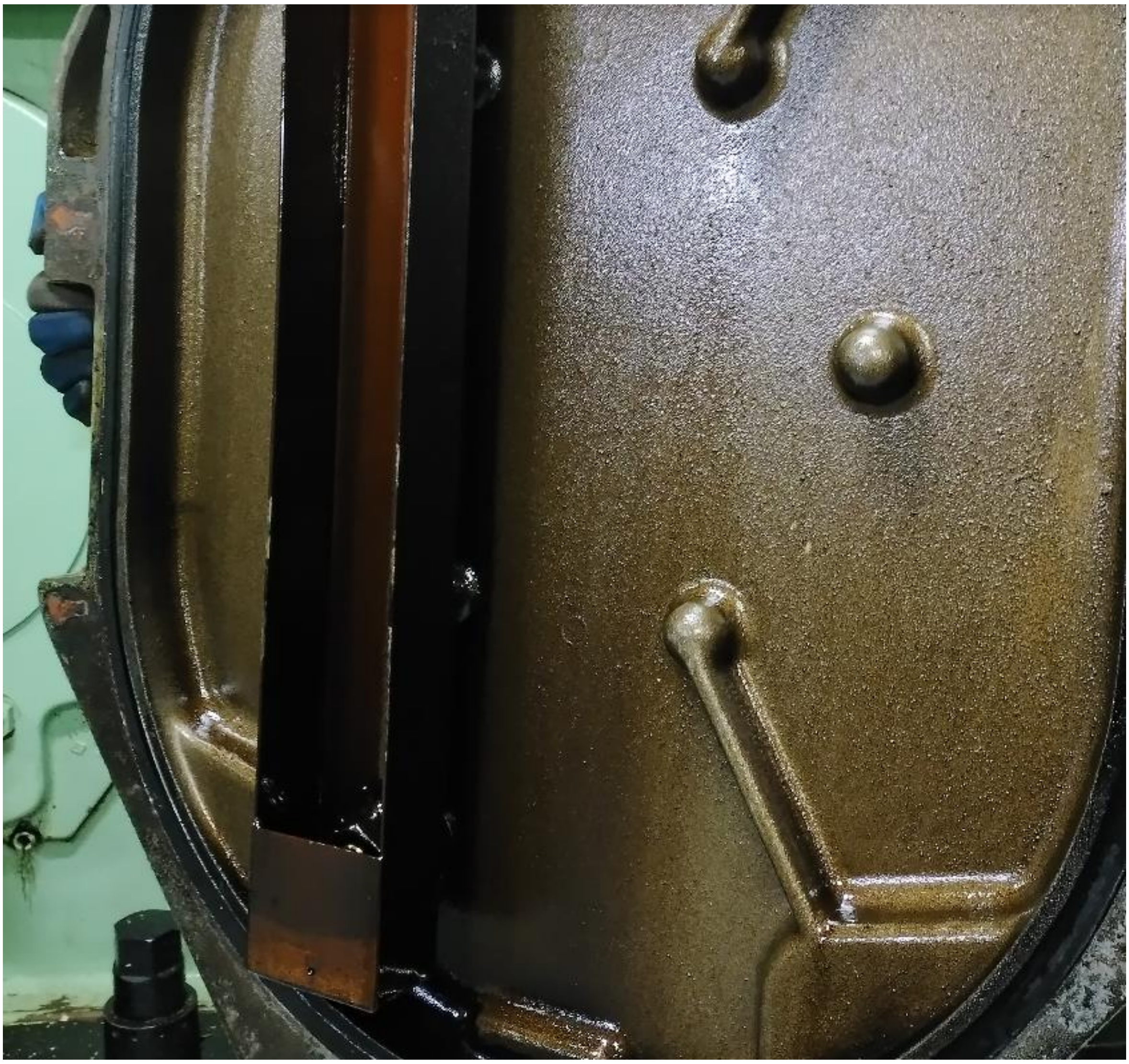


Figure 46. Splash oil monitoring arrangement on crank case cover. (Author´s collection).

According to MAN ES, this system has been able to prevent catastrophic failures of the engine rotating assembly by reacting to even small changes in the oil temperature measured. Below quote is referring to the attached Appendix 6, MAN diesel customer information letter No 224 approximately six years after the system had been released.

The special advantage of the splash-oil system is that any disturbance in normal operation, which causes an oil temperature increase, is recognized reliably and promptly. The splash-oil system is unable to prevent disturbances in normal operation, it is, however, able to minimize the extent of possibly severe damage.

By studying the example cases it is clear that the system does respond to critical failures and triggers an automatic engine shut down. However, this author has in these examples also

found that the splash oil monitoring system is efficient to prevent total break downs but does not address the actual error. The author does in no circumstances want to replace this system by suggesting improvements, but the intention is to add such monitoring functions that would effectively guide the operator in addressing the actual error behind the splash oil temperature alarm.

6.2 The oil mist detector

The VISATRON oil mist detector unit acts as a protective device that is built to monitor and react on oil mist concentration in the crankcase. This unit is mandatory on all marine engines with power above 2250kW, with periodically unattended machinery spaces. (Knapp, 2000) The operating principle of the unit is that it draws a specific amount of the atmosphere inside the engine through channels from each crankcase compartment and measure the oil mist concentration using optical absorption. The oil mist passing through these diodes where one acts as a transmitter and the other as receiver will absorb a certain amount infrared light which will reduce amount of light reaching the receiver. (Engine Protection Partner AS, 2005, p. 6).

The practical arrangement as well as a description of the oil mist detector is illustrated by following Figure 47.

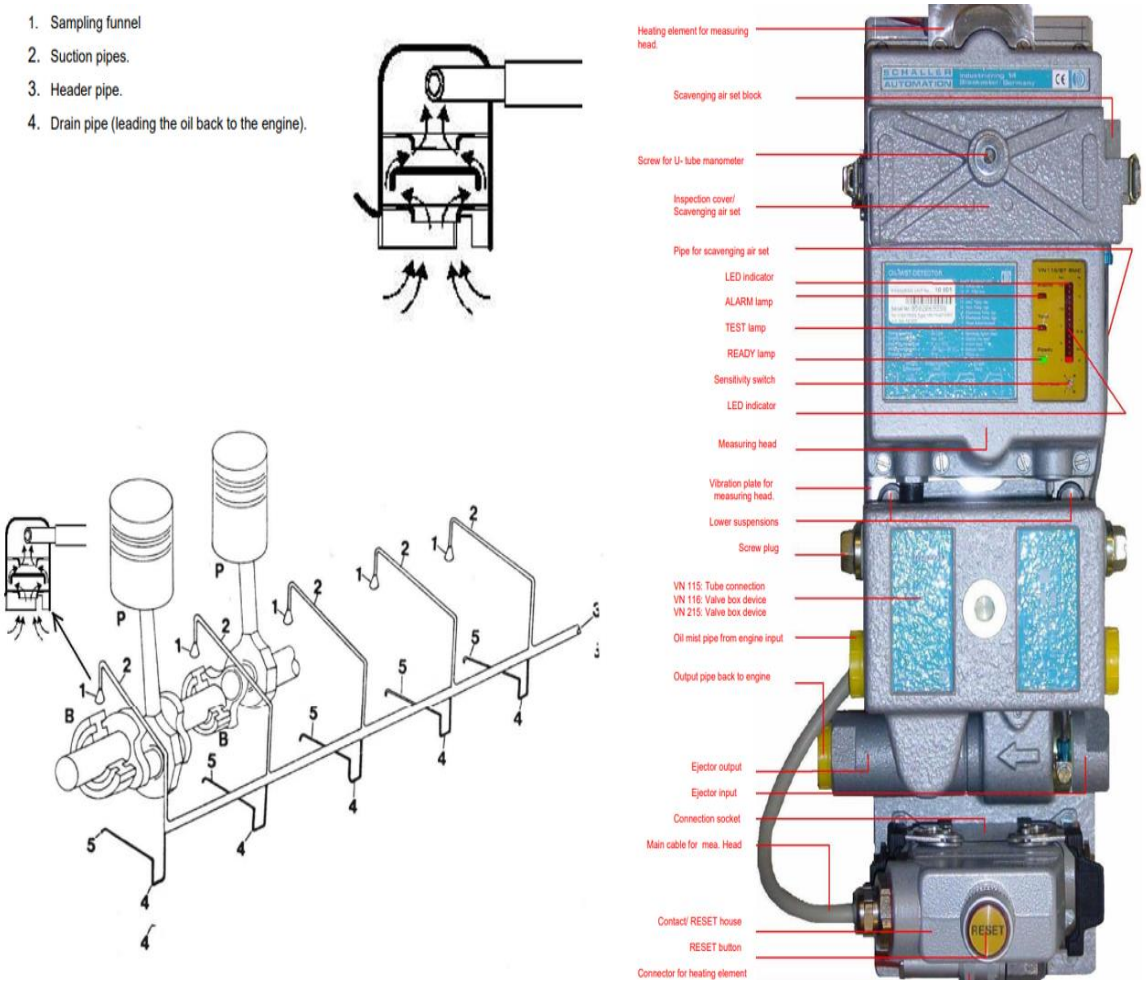


Figure 47. Oil mist detector arrangement. (Engine Protection Partner AS, 2005, pp. 9, 23)

The oil mist detector reacts to high oil mist concentration in crankcase caused by an overheating in any of the rotating components in the engine. The manufacturer *EPP.no* mention the following components as the main target of the oil mist detector on their website:

- pistons in cylinder liners
- crankshaft main bearings
- connecting rod big end bearings
- camshaft bearings and cams
- gears

(Engine Protection Partner AS, 2022)

According to EPP, there are an average of one to two crankcase explosions weekly on ship´s globally and the oil mist detector unit is a device to minimize the risk of these unwanted events. Although the oil mist detector does provide a good protection of the engine, it does not address the actual reason but instead it will trigger an alarm, and depending on the circumstances an automatic shutdown, as seen in the example cases presented in this thesis.

7 Condition prediction by additional monitoring technique

In this chapter different options and techniques will be presented that could be utilized to increase awareness of engine efficiency and reliability. With the technical advancement of today, major improvements are possible and in this chapter the author would like to point out some possibilities. Some of these are used by competitors, but this research targets the B-generation of the MAN 48/60 engine and any relevant technique that can be adopted to install as an add-on for this particular engine.

The intention of implementing certain equipment to the engine means in this context additional monitoring and automation to build safe barriers against failure and performance degradation. There is included additional sensors for improved monitoring locally on-board, as well as remote monitoring which is an additional option offered by MAN ES. Remote monitoring as offered by MAN ES, the PrimeServ Assist is presented in Chapter 10.

An efficient and reliable engine operates according to the design parameters. These parameters are the result of comprehensive testing before the engine is released to the industry. Whenever there is a deviation from these parameters, the engine is most likely not operating in the safest and most efficient way, therefore any anomaly should be addressed immediately to avoid such circumstances. For instance, if there is fouling in a heat exchanger the result with time will be that the heat balance suffers meaning that the design parameters are not fulfilled and therefore optimal output and fuel consumption will not be reached. If we consider the charge air cooler as an example, once it is contaminated it will affect the whole engine operation as charge air is not at the set temperature at a certain load. Furthermore, this will affect the exhaust temperature and combustion pressure in a negative manner resulting in lacking performance. Predicting such circumstances is the key to safe and efficient engine operations. (MAN Energy Solutions, 2022b)

According to the author, different additions to the existing monitoring could be installed to not only maintain safe engine operation but also in case of an anomaly effectively address the operator on where the problem is located to avoid unnecessary down-time.

We will be looking into certain techniques where some can provide information on what engine parts to investigate in case of anomalies. The MAN fluid monitor is one of the essentials in this perspective as this system can address what kind of error is causing the different alarms. A well proven protective system is also the splash oil system that will react in any case there is an overheating in the rotating assembly of the engine. The oil mist detector is also a well proven engine protection unit that do serve a purpose of shutting down the engine whenever there are circumstances contributing to extensive oil mist build up inside the engine. However, all the above lack on providing the exact root cause of the event. These systems do work each in their own way but to find the root cause triggering these protection systems, additional monitoring should be installed. Also, by providing the remote monitoring center as much parameter readings as possible it will be easier and more efficient to react to certain anomalies. This way of thinking refers to the term sensor fusion presented in Chapter 7.9 where multiple inputs reacting to certain deviations in a process. Naturally, combining different sensors will assist in predicting parameter trends more promptly as more information is available, through different perspectives. In the following chapters this author has selected some individual sensors as well as more sophisticated methods to improve monitoring on-board. The selection is highly based on this author´s experience on how and by what means the goals could be reached.

7.1 Individual sensors

This chapter will introduce some basic additions to the existing monitoring: important inputs for a predictive approach. In example cases I and II, where piston blow-by occurred it is easy to understand, that the anomaly in cylinder liner wall temperature that these failures resulted in would have provided indication by having temperature sensors installed in the walls of the cylinder liners. Other valuable inputs are the temperature of the connecting rod big-end, and crankcase pressure. The sensors suggested in this chapter are not in any perspective new technique, but on the actual engines they would provide important inputs for the operator when there are errors related to the rotating assembly that causes increased friction. The

following Figure 48 presents liner temperature monitoring that in the example case(s) would have contributed to providing highly essential inputs on cause of the event.

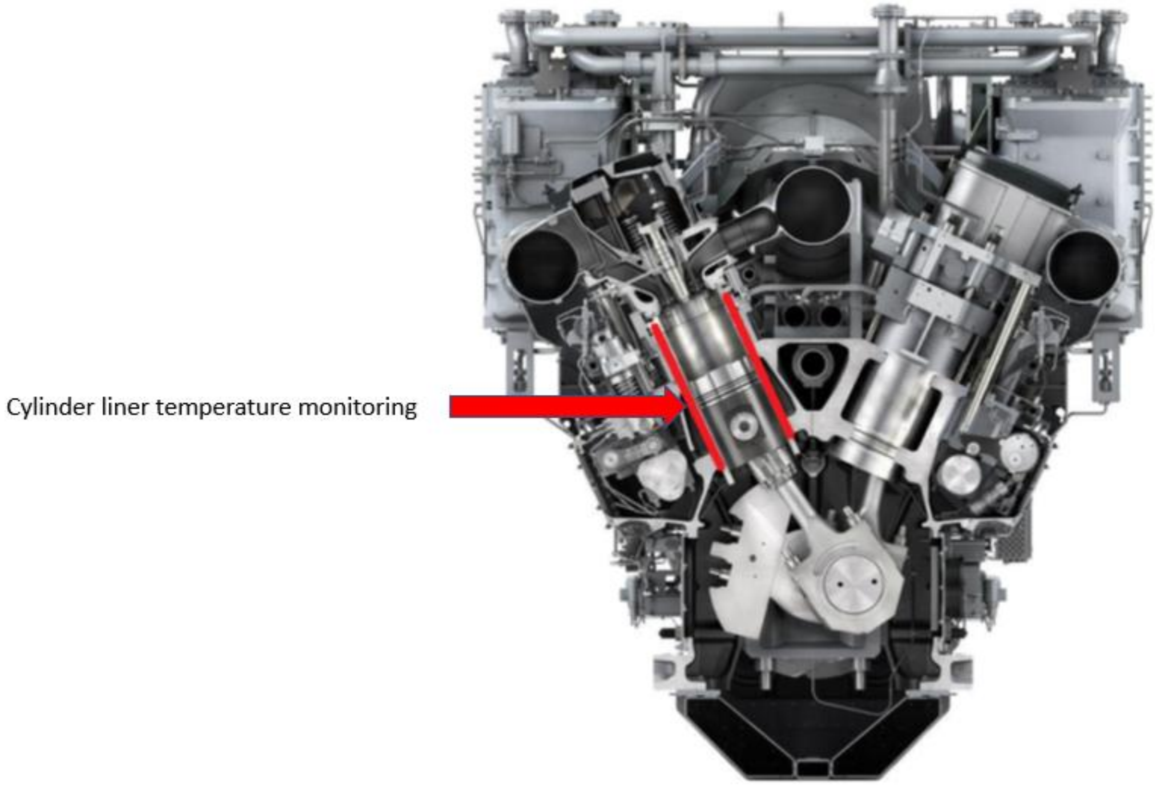


Figure 48. Principle of cylinder liner temperature monitoring on 48/60 shown in V-configuration.

As mentioned in the example cases where piston blowby occurred, there will be additional thermal load on the liner due to metal-metal contact between piston and liner as a result of lacking lubrication. This will naturally increase the liner wall temperature and provide indication to the operators that something is wrong in the specific cylinder unit. The option to include cylinder liner wall temperature monitoring was discussed with MAN ES engine experts. According to them, it is possible but would require severe modifications to the affected parts. Depending on circumstances, this measurement might not be fast enough to react in time in case of sudden break downs. The sensor location is highly critical and to benefit from this input, the sensor(s) must be installed in the upper area of the liner which creates additional challenges in the manufacturing process. (Personal communication with MAN ES Engine Experts, 2022).

While the following suggestion to improve monitoring of the rotating assembly does not directly relate to the example cases it would assist the operator to rule out possible errors. This targets monitoring of connecting rod big ends and may be presented through below Figure 49.

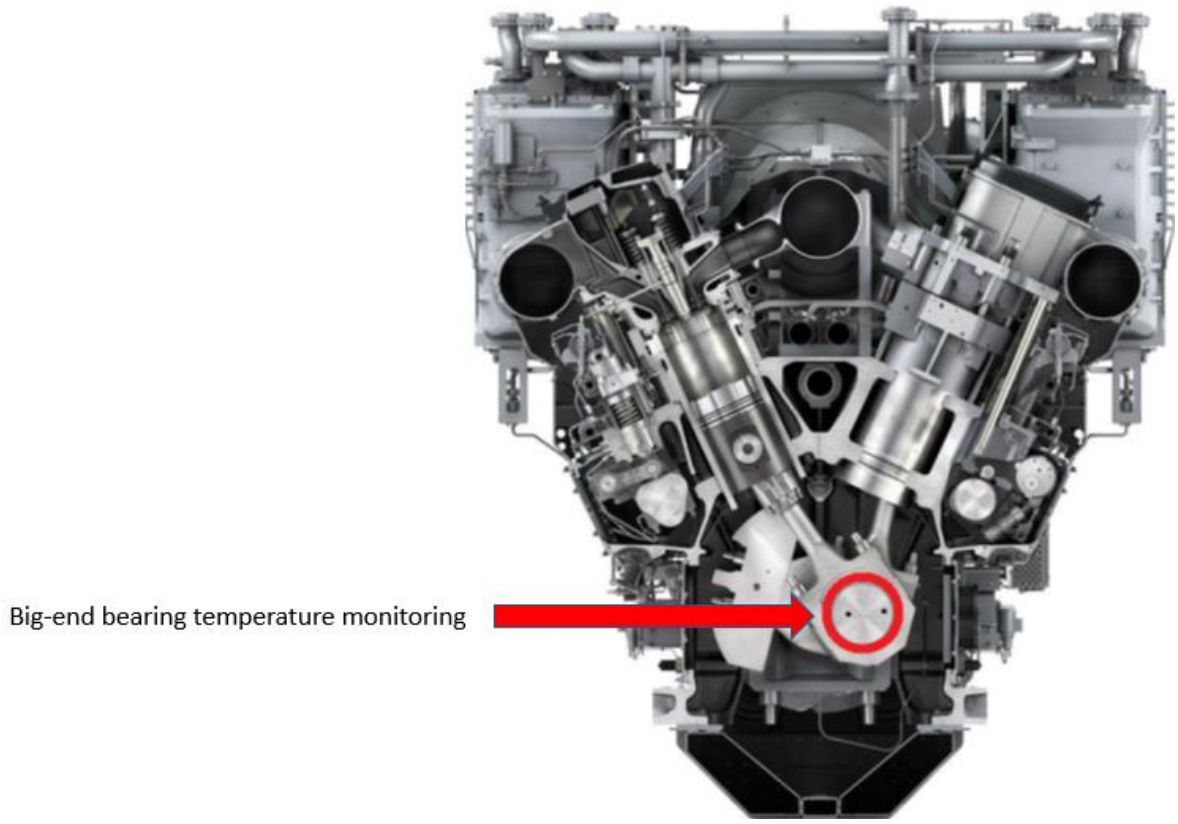


Figure 49. Arrangement of big end temperature monitoring on 48/60 engine shown in V configuration.

As a final option in terms of single sensor addition, the crankcase pressure sensor shown in Figure 50 is suggested. MAN ES has this option as a possible retrofit through the MAN Multi brand engine safety management system (MMS).

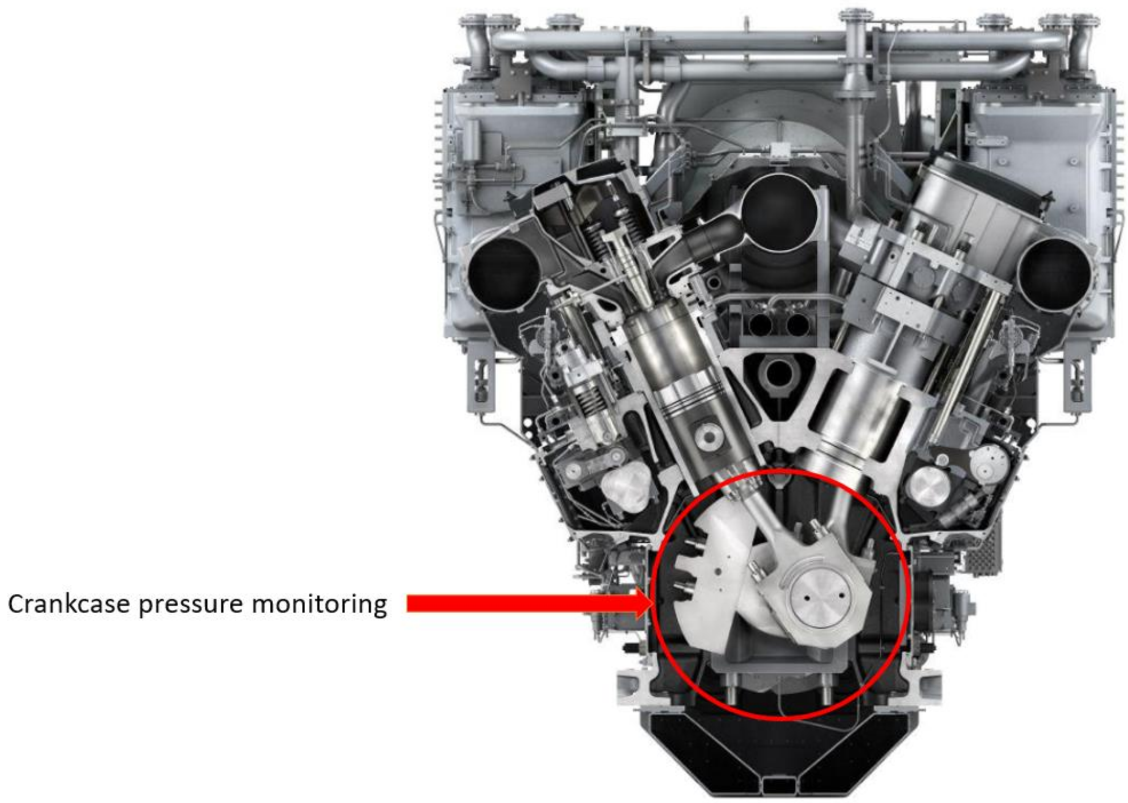


Figure 50. Crankcase pressure monitoring.

This system utilizes real time monitoring as a stand-alone setup and is made to suit all manufacturers 4-stroke engines. The MMS consist of three modules, as below. (MAN Energy Solutions, 2020a, pp. 1-3).

- Module A – Monitoring of crankpins (Connecting rod big-ends)
- Module B – Monitoring of main bearings
- Module C – Monitoring of crankcase pressure

According to MAN ES Engine Experts, the crankcase pressure monitoring could have reacted during the circumstances described in the example cases I and II. If this sensor would have alerted the operators earlier than the splash monitoring system is anyway difficult to proof afterwards. According to this author this is the easiest and therefore most obvious addition to the monitoring system.

7.2 Traditional performance testing

This topic relates to monitoring of engine condition by measuring firing pressures of each cylinder and can be described as a method to measure engine performance in relation to output (load). (Icon Research Ltd, 2018, p. 4) Currently, this type of performance testing is in use according to the scheduled maintenance program. It is performed once per month preferably at high load conditions to follow up engine balance and condition of injection equipment to understand the operational parameters of the engine. To see possible changes over time, the monthly test is performed at identical circumstances at each test. The instrument commonly in use on-board is the DK-20 by Icon Research. Below Figure 51 present the principal of this instrument.

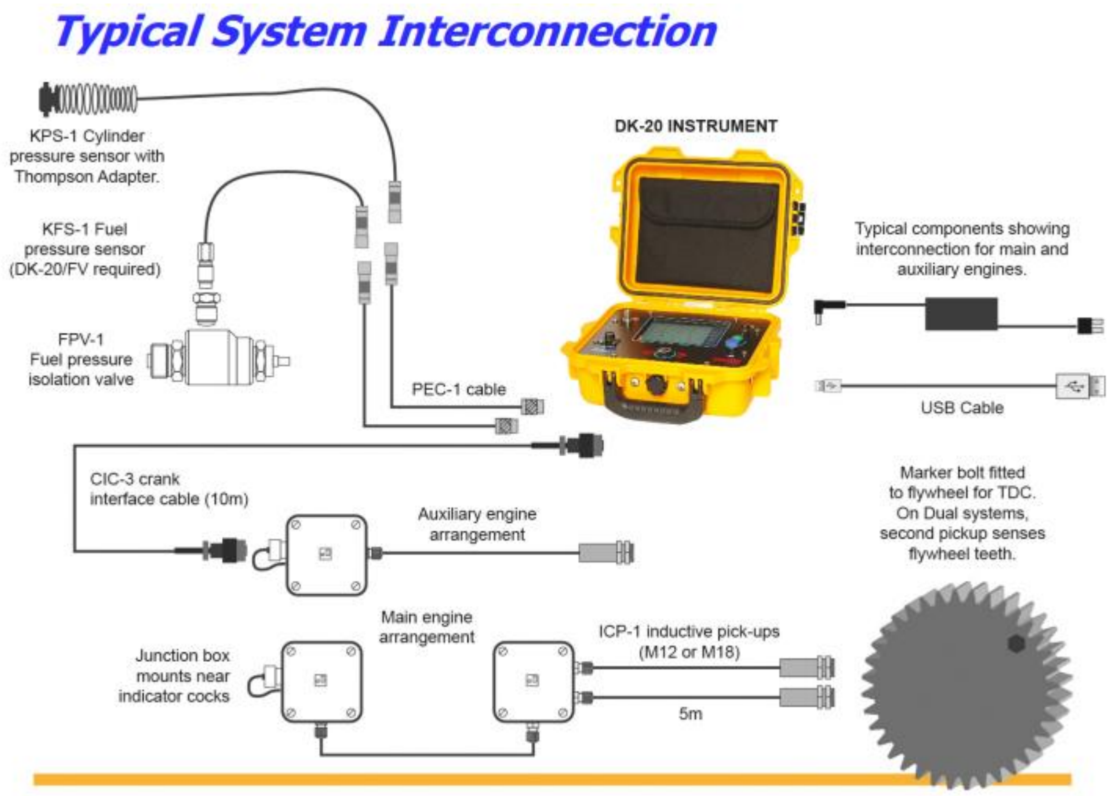


Figure 51. Icon Research DK-20 setup. (Icon Research Ltd, 2018, p. 4)

On later engines, typically high-performance engines it is common that constant (live) measuring of firing pressures is installed, and this method could according to this author´s experience provide essential inputs on a totally different level. This is simply because measurements are taken constantly, providing inputs even at varying loads. Also, by utilizing machine learning in combination with this method, the operators could be alerted on

performance degradations in a more predictive manner. During discussions with MAN ES Engine Experts, this subject was discussed. It is not currently offered for traditional diesel engines but is used on the 49/60DF engine under the name “Adaptive Combustion Control” or ACC version 2.0. Here the system is not mainly for monitoring purpose but instead used as feedback for the control system to optimize combustion automatically. (MAN Energy Solutions, 2022d).

However, to provide proof on what level constant monitoring of firing pressures could have revealed the occurring piston blowby in the example cases would require severe testing to provide evidence. According to this author´s experience, this method is not sensitive enough to recognize piston blow by but is instead to be considered as a performance measure.

7.3 MAN Fluid Monitor for lubricating oil

As the topic address, MAN fluid monitor targets the engine lubricating oil and is an existing monitoring option. It is a live (real time) feature for monitoring quality of the lubricating oil and acts as a part of the MAN condition monitoring solution. Additionally to temperature and pressure deviation, the system detects pollution and contamination of the lubricating oil caused by combustion residues, fuel, solid ferrous material (metal), non-ferrous material and water. According to MAN ES, 70% of major damages reveal a pollution of the engine lubricating oil. The system is already considered well proven after 50 000 hours in operation. (MAN Energy Solutions, 2022c).

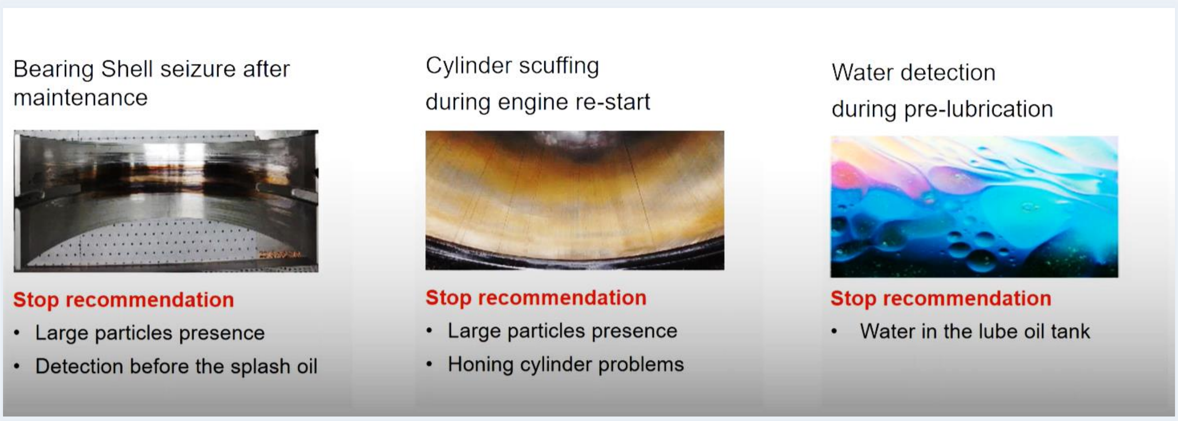


Figure 52. Example of anomalies detection feedback. (MAN Energy Solutions, 2020b).

The fluid monitor system is a stand-alone solution that can easily be included in the existing monitoring system on-board to effectively alert the operators whenever there is an anomaly found in the lubricating oil. Due to the design, the user has a good overview of the status – it is not only a simple alarm switch. Instead, this system highlights the reason for triggering an alarm and guiding the operator towards the root cause. Below Figure 53 show the basic display view on-board.

Inage 53. MAN fluid monitor. On-board display view. (MAN Energy Solutions, 2020b).

The system alerts the user about the anomaly and provides useful information regarding the source of the anomaly as in this case fuel contamination. This information is essential and provides clear direction on maintenance and repair actions before a possible major breakdown occurs. To provide an example, below Figure 54 demonstrate an anomaly timeline.

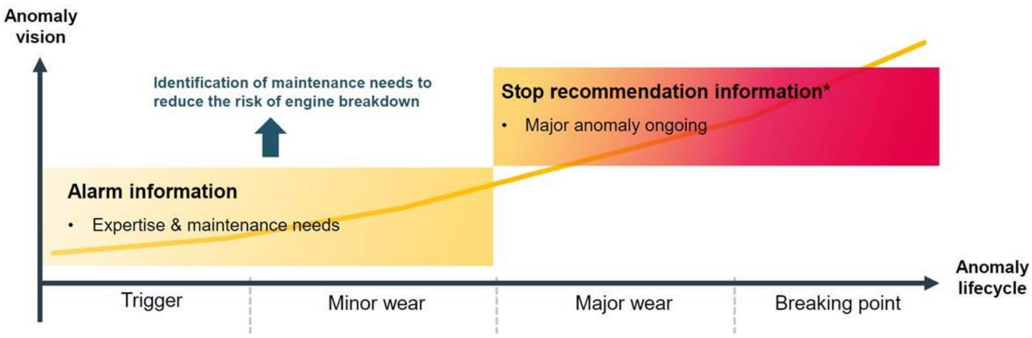


Figure 54. Anomaly timeline. (MAN Energy Solutions, 2020b).

According to MAN, the system reacts promptly to any deviation found in the lubricating oil. Below example illustrate a case where severe deviation is detected in the total base number (TBN) and high-water content is present. This address water mixture in the lubricating oil.

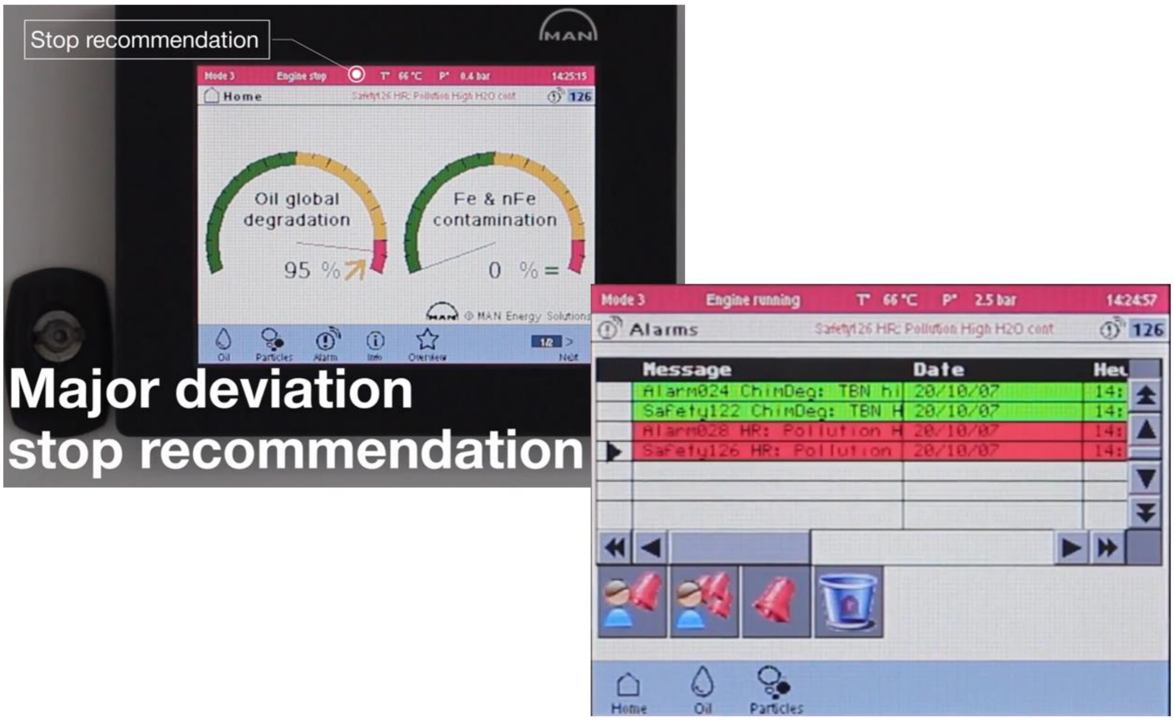


Figure 55. Alarm display view. (MAN Energy Solutions, 2020b).

The fluid monitor concept is perhaps the most obvious method that could have provided early (enough) indication on what the reason was behind the alarms triggered by the oil mist detector. The fluid monitor can detect combustion residues that does end up in the lubricating oil when there is a considerable piston blow-by. Even as this technique does not point out exactly from what cylinder the residues originate, it does provide clear indication of what the actual problem is. By adding some additional temperature sensors to the monitoring system, the author believe that the damage could have been limited in a considerable manner. In the case where the crew experienced a sudden automatic shutdown triggered by the oil mist detector, the fluid monitor system would have effectively alerted the operators of high-water content in the lubricating oil already when the engine was prepared for startup at departure. This would have avoided the following black-out that was the result of the shutdown as the crew would have been able to take counter measures before the ship departed from harbor.

7.4 Monitoring by Ultrasound

This technique is used for many purposes. It can be used to detect air leaks, but tests have also been done to monitor cylinder lubrication in smaller combustion engines. Both of these options can be utilized to contribute to safer and more efficient operations, especially the cylinder lubrication as a lack in lubrication will increase the risk of piston seizure or if over lubricating is present the result is un-efficient operation. The principle of this technique is as the name imply related to sound waves and ultrasonic pulses, and while measuring the layer of cylinder wall lubrication there are sensors outside the cylinder wall that transmit the ultrasonic pulses. This technique has been proven effective even at varying speed and load states. (Dwyer-Joyce, 2012). If considering the example cases (I and II) where piston blow-by was present, this technique could according to the author have reacted in an early stage and possibly assisted to prevent, or at least minimize damage. This is because whenever there is blow by occurring it allows the hot combustion gases under pressure to pass the piston rings and therefor eliminate the oil film that shall control friction between piston and cylinder liner.

If looking into another example on how to benefit from this technique it is also possible to monitor air and steam leaks. As mentioned, this technique relies on sound waves and it is effective to find leaks through this method as both air and steam leaks have specific frequencies and are directional meaning that locating such leaks are considered as easy even in high noise environments. (Hallum, 2019). When considering efficiency, it is important to eliminate unwanted leaks as if there is for instance steam or air leak present on the engine it means waste of energy. The engines on-board Finnmill use air for many purposes such as starting, and parts of the control system also utilize pressurized air. In terms of steam, it is used for preheating purpose while steam tracing is used for heating fuel piping. Implementing fixed ultrasound sensors to measure air and steam leaks is considered as quite challenging due to the extent of air piping on the engines. The author finds this technique more effective to use during regular inspections or whenever there is a suspected leakage as during these circumstances a traditional handheld measuring device is more useful.

An option on installing permanent sensors with target to monitor cylinder lubrication, it is a common challenge amongst the other suggestions to implement considering the existing engine. Installing sensors on permanent basis requires changes to existing components and severe testing in the manufacturer premises to be able to provide proof on how effective this method is on the actual engine, and for this purpose.

7.5 Vibration monitoring

During operation of a diesel engine there are many aspects contributing to vibrations. To explain this statement, the following quote is found useful.

During the process of energy conversion in diesel engines, several parameters cause the engine to vibrate which significantly deteriorate the efficiency and service life of the engine. Vibration in a diesel engine occurs due to unidirectional combustion forces caused by the changes in gas pressure inside the cylinder, structural resonance and alternating inertia forces concentrated on different engine parts. (K.LP, Shuyong, Shuai, & Yuan, 2020, pp. 1-2)

In the book Diesel Engines 1, there is a full chapter available about this phenomenon and description of the main causes of vibration in the context of diesel engines. The categories or orders to which each type belong relate to the wavelength in relation to acceleration or speed, and frequency.

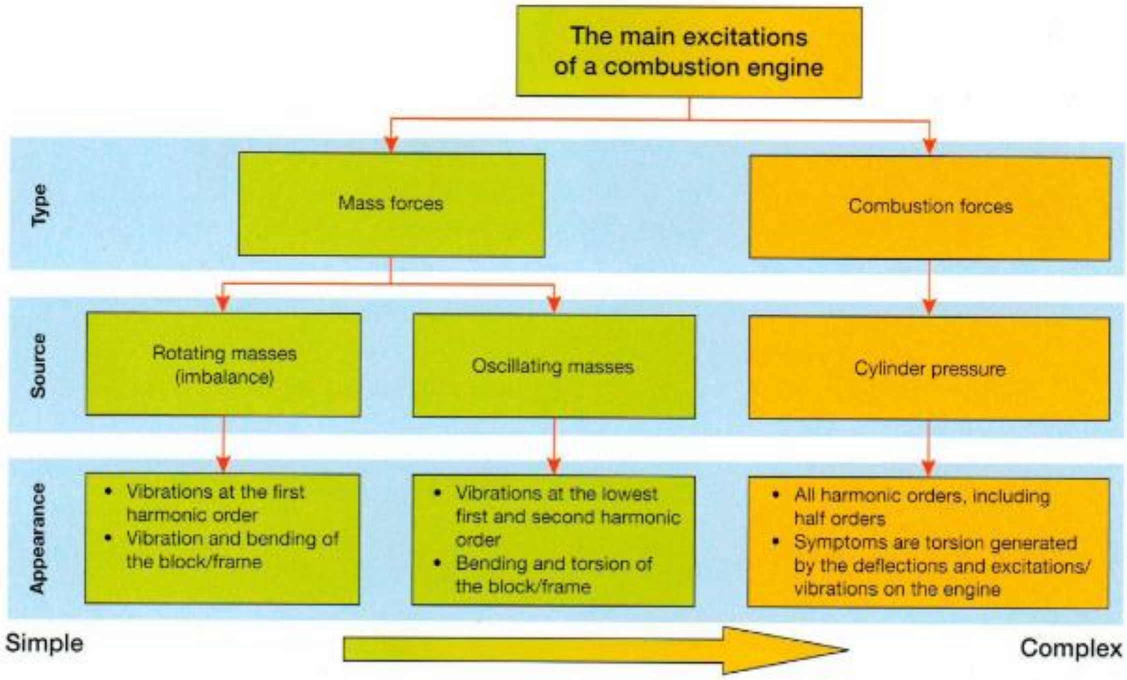


Figure 56. Main causes of vibrations in the diesel engine. (Kuiken, 2008, p. 444)

The two common units to measure vibration as a state of a repetitively mowing object are frequency in Hz and acceleration in mm/s^2. When looking at more sophisticated instruments for measuring vibration it is common to include amplitude and speed (velocity). (IMV Corporation Japan, 2022). The vibration monitoring as a contribution to a diesel engine

monitoring system can definitively provide interesting information. However, this author finds it necessary to implement a large number of sensors in multiple locations to achieve a meaningful picture of the engine status. This is simply due to the complex design of the engine where, for instance, the performance of each individual cylinder is highly dependent on its own pair in the injection system. To summarize some of the areas where vibration monitoring could provide additional insight in understanding actual condition of selected assemblies are the fuel injection system, individual cylinders, and turbochargers. All of these are sensitive to imbalance which could be detected by means such as vibration monitoring. When there is fouling in a turbocharger it will logically affect the balance and create unwanted vibrations that increase wear as well as affect long term performance. There can be various reasons when the turbocharger suffers from excessive fouling or deposit build-up according to this author´s experience, but one reason is poor combustion that generate residues like soot particles or unburnt fuel. This provides reason to also monitor the balance within the fuel injection system as leaking fuel injectors or weak injection pumps will affect the engine overall efficiency in an unwanted direction and cause unnecessary emissions.

The author made some small real time tests with a pen type vibration measuring instrument only to provide perspective of this method of measuring. Below Figure 57 illustrate the instrument used.

Figure 57. Vibration tester instrument PCE-VT 2700. Author´s collection.

The accuracy of the measurement is lacking and therefor the results are *not* valid, but to provide an understanding of how this type of measuring technique work the author included

the following sample, taken at the fuel injection supply pipe of cylinder five on main engine number two. It might be difficult to actually see on the figures 58 and 59 below, but only change between the measurements was that the sensor was mowed approximately 10 mm. This fact tells some of the difficulties related to vibration monitoring. Not only to understand what the result mean but also how sensitive the method is in relation to sensor location. This author finds the method valid and interesting but do realize that in order to find some concrete and accurate results (patterns) it will require severe testing and investigations already at the manufacturing premises.

Figure 58. Measured vibration in mm/s^2 at 65% engine load. Author´s collection.

Figure 59. Measured vibration in mm/s^2 at 65% engine load. Author´s collection.

To connect this technique to the example cases, inputs from vibration monitoring could have provided early indication of the piston blow-by that lead to severe overheating of the piston and liner running surfaces and resulted in piston seizure. According to some available research, vibration measuring can be used to detect changes in cylinder lubrication caused by for instance piston blow-by. When blow-by occur and combustion gasses passes the piston rings, it will cause a lack of cylinder lubrication and result in metal-metal contact. This phenomenon is connected to the term piston slap. The term can be defined as one of the main sources of transversal vibration in this type of engine and will be affected if there is metal-to-metal contact in the cylinder. (K.LP, Shuyong, Shuai, & Yuan, 2020, pp. 5-6).

As one can understand when involving large number of vibration sensors, this technique generates large amounts of data over time. To benefit fully from this technique artificial intelligence and machine learning should be utilized to provide essential information whenever there is an anomality in the sensor values to effectively alert operators of possible errors.

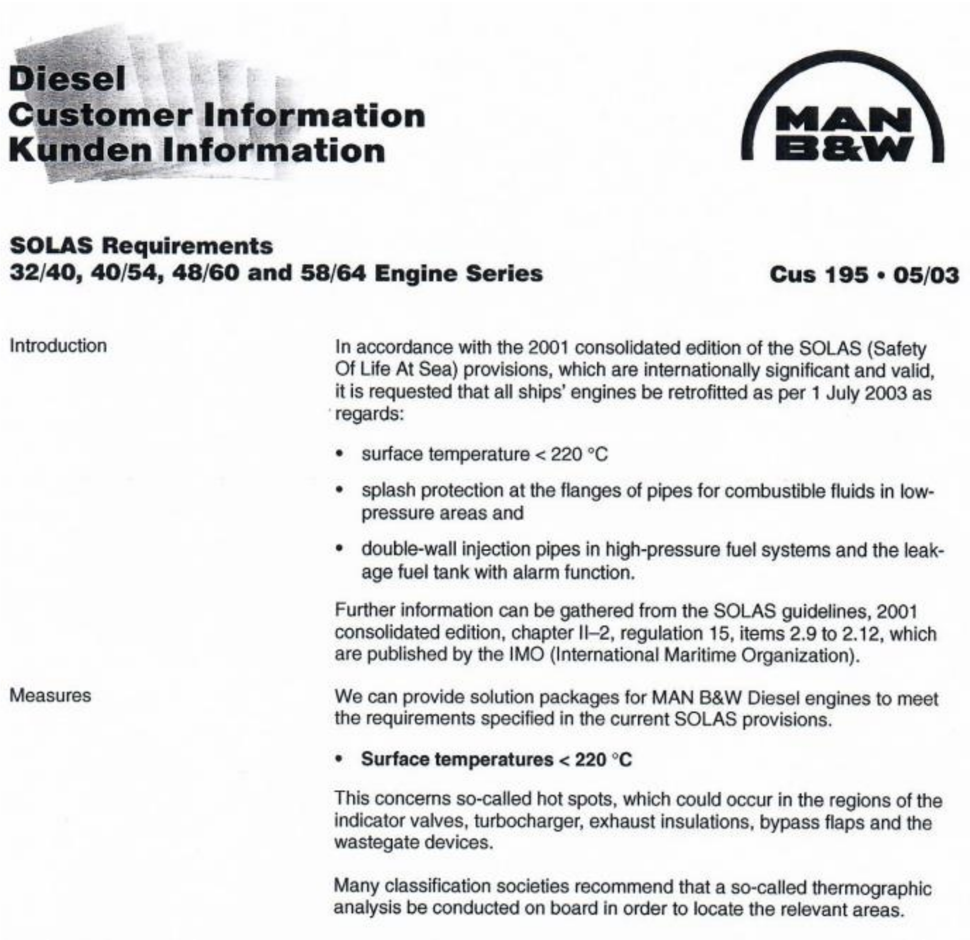
Understanding the input from vibration sensors at various locations on the engine does require deep knowledge of this technique as otherwise it is only numbers that are affected by many aspects – such as the specific engine installation, sensor location and operating

circumstances. (Personal communication with MAN ES Engine Experts, 2022). From the very simple test that this author made to illustrate this technique, it was found that the measuring point or sensor locations are highly critical. During the test the sensor was mowed with approximately one centimeter to see how the measurement is affected and the result was found to be scale wise totally different. So, to gain any benefit from the measurements, exact location of sensors must be determined as otherwise it is clearly not possible to compare measurements from identical components on the engine. When the engines are in operation, they generate vibrations due to the design. This must be carefully assessed when vibration monitoring on component level is considered and, require finding out not only what is considered as normal vibrations at different locations but also, how the engine as a unit behave in relation to total measured vibrations.

In addition to traditional vibration monitoring, there is a method called shock pulse monitoring or SPM that is commonly used today for condition monitoring purposes. Unfortunately, this author was not able to find proof on how this method would work in applications where plain type bearings are used, as in most components of the diesel engine and the connected turbocharger. The method seems well proven in applications where roller type bearings are used but no research has been found whether this technique is reliable in the context of plain bearings. (SPM Instrument, 2022).

7.6 Thermal monitoring

Today there are many options to benefit from thermal monitoring. It can be used to detect circumstances that create risk of fire or for instance to monitor leakage directly related to engine efficiency. It can also be used as a mean to improve situation awareness. As described in the MAN ES supplied customer information letter regarding SOLAS regulations where so-called hot spots must be limited so that any surface temperature of the engine must be lower than 220˚C. Refer to the following Figure 60.



Diesel
Customer Information
Kunden Information

MAN B&W

SOLAS Requirements
32/40, 40/54, 48/60 and 58/64 Engine Series **Cus 195 • 05/03**

Introduction

In accordance with the 2001 consolidated edition of the SOLAS (Safety Of Life At Sea) provisions, which are internationally significant and valid, it is requested that all ships' engines be retrofitted as per 1 July 2003 as regards:

- surface temperature < 220 °C
- splash protection at the flanges of pipes for combustible fluids in low-pressure areas and
- double-wall injection pipes in high-pressure fuel systems and the leakage fuel tank with alarm function.

Further information can be gathered from the SOLAS guidelines, 2001 consolidated edition, chapter II–2, regulation 15, items 2.9 to 2.12, which are published by the IMO (International Maritime Organization).

Measures

We can provide solution packages for MAN B&W Diesel engines to meet the requirements specified in the current SOLAS provisions.

- **Surface temperatures < 220 °C**

This concerns so-called hot spots, which could occur in the regions of the indicator valves, turbocharger, exhaust insulations, bypass flaps and the wastegate devices.

Many classification societies recommend that a so-called thermographic analysis be conducted on board in order to locate the relevant areas.

Figure 60. SOLAS requirements (MAN CUS No. 195)

This sets a definite upper limit of surface temperatures to decrease fire risks. In this context the thermal monitoring can be utilized to detect hot spots, but also directly be used to provide indication of other valuable information. For instance, using a thermal radar can detect exhaust leaks on the engine that contribute to lower turbocharger performance and therefor engine efficiency, not to mention the direct impact on the surrounding environment. A thermal radar is one option that can provide the necessary information. This refers to a continuously rotating thermal camera that provide 360-degree field of view. (Thermal Radar, 2022).

Today there are more advanced versions of thermal monitoring including LIDAR that utilize laser and hence can be considered as more accurate instrument but due to the simplicity of the thermal radar the author finds this option as sufficient for the purpose.

Below the reader can find some examples of how the view of the engine looks by thermal imaging. Settings related to color illustration and measuring points can be freely adjusted.

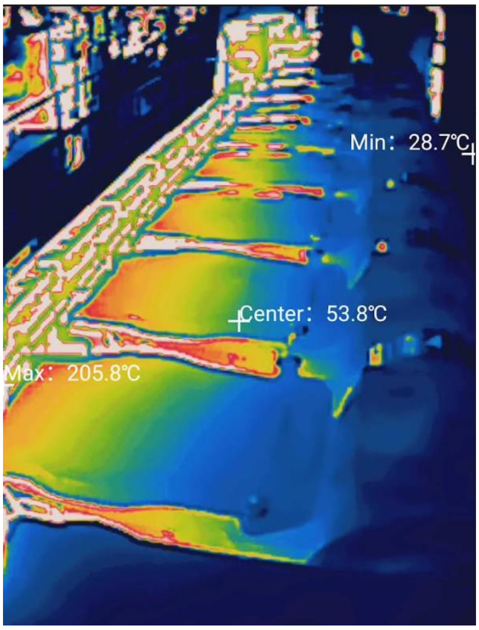


Figure 61. Engine top view from free end. Author´s collection.

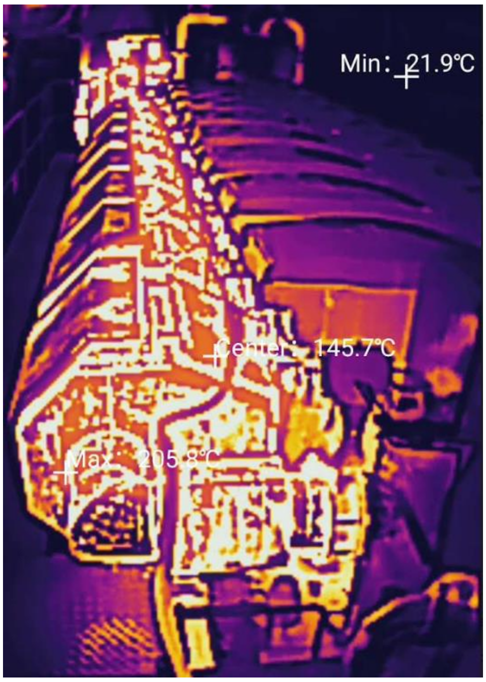


Figure 62. Engine exhaust piping view from free end. Author´s collection.

By combining this technique with some level of artificial intelligence and machine learning, it can effectively provide important information regarding hot spots for instance and automatically alert if there is a surface temperature that increase risk of fire. If we look at

this option from the perspective of the example cases, the benefits are obvious. When a crankcase explosion occurs, it will create a pressure inside the crankcase causing the relief valves on crankcase covers to open releasing highly concentrated oil mist to the atmosphere. If this oil mist is allowed to enter hot surfaces, a fire will most likely be the result. It is therefore easy to understand the importance of avoiding hot spots by means of insulation. The author finds it hard to point out this technique as a predictive approach and instead like to highlight this kind of monitoring as a preventive concept, nevertheless the importance is obvious.

7.7 Augmented reality

MAN CEON TechGuide was preliminary made to offer a new generation of instruction material that is based on augmented reality. MAN ES describe this feature as an augmented reality maintenance platform. It is based on 3D-models, animation, and video, and is intended to optimize safe and fast execution of both troubleshooting and maintenance activities. (MAN Energy Solutions, 2019a, p. 1). The following Figure 63 provide a brief understanding of what this concept is all about.

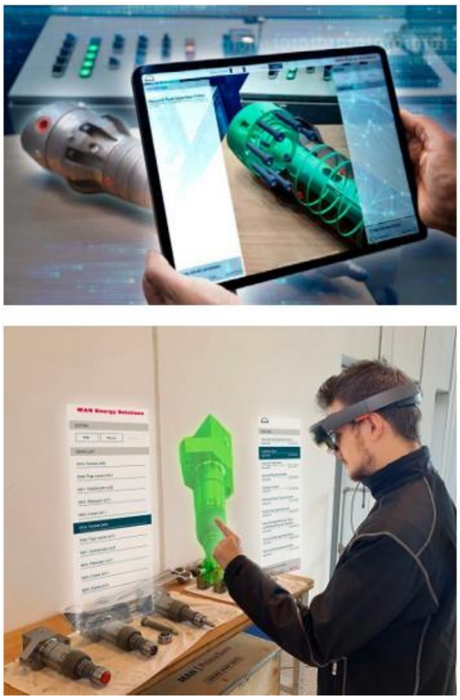


Figure 63. Augment content illustration. (MAN Energy Solutions, 2019a, p. 3)

As mentioned in the product description, a future “real time” technical support that enable shore-based MAN ES facilities to offer expert guidance to the crew on-board, would contribute to that the feature could be used as part of a condition-based maintenance system that does suit well in the sector of predictive maintenance. Component condition after certain time in operation is monitored through periodical inspections whereas understanding of component wear at a specific time stamp at the actual installation is achieved, thus making it possible to understand estimated remaining lifetime. The MAN CEON TechGuide concept can be summarized by the below lines:

- augmented reality view by “X-ray” layering information onto the engine components to enable automatic recognition of each component
- animations include multi-angle view as well as exploded views of each component assembly
- a multimedia platform incorporating audio in, - and output
- in-situ as well as workshop study modes for pre-planning of tasks and effective work conduction

(MAN Energy Solutions, 2019a, p. 2)

Relating this concept to the example cases, this technique as a live-based feature does provide input for a predictive approach as inputs and recordings could be analyzed in cooperation between local operators and experts at the MAN PrimeServ premises. Especially during component inspections, it is useful to provide information to determine remaining component lifetime for instance. Also, when there are circumstances like trouble shooting when assistance is required from the manufacturer the augmented reality could provide important feedback and additional perspectives for the engine expert at MAN to effectively assist.

Augmented reality should not be mixed up with digital twins which is a more modern concept that rely on the actual circumstances rather than being limited to pure models. Digital twins are an interesting and modern simulation technique that according to this author, could be implemented in the monitoring solutions available today. This concept will be looked into in the following chapter.

7.8 The digital twin concepts

As mentioned in the previous chapter, digital twins should not be mixed up with augmented reality. This is because a digital twin concept is *based on actual circumstances* and follows a specific counterpart in the real world that it was made upon, meaning that any changes or alterations to the real object will be reflected in the digital twin. The largest feature of digital twins is considered to be its ability to not only gather data but also create simulations based on the data. (Miskinis, 2018).

So, how could this be a part of a monitoring solution that support efficient and safe engine operations?

Below some aspects to consider that will support the digital twin concept as an effective addition for both on-site monitoring as well as remote monitoring, in accordance with this author´s interpretation of the subject. As a stand-alone solution the benefits of a digital twin concept is limited to pure visualization, according to this author´s understanding, but by adding this technique to an existing setup there could be use for this technique. For instance, when considering a traditional view of a monitoring system as in below Figure 64, the operator is alerted whenever there is a value out of range and an alarm is triggered as the value simply changes from green color to red.

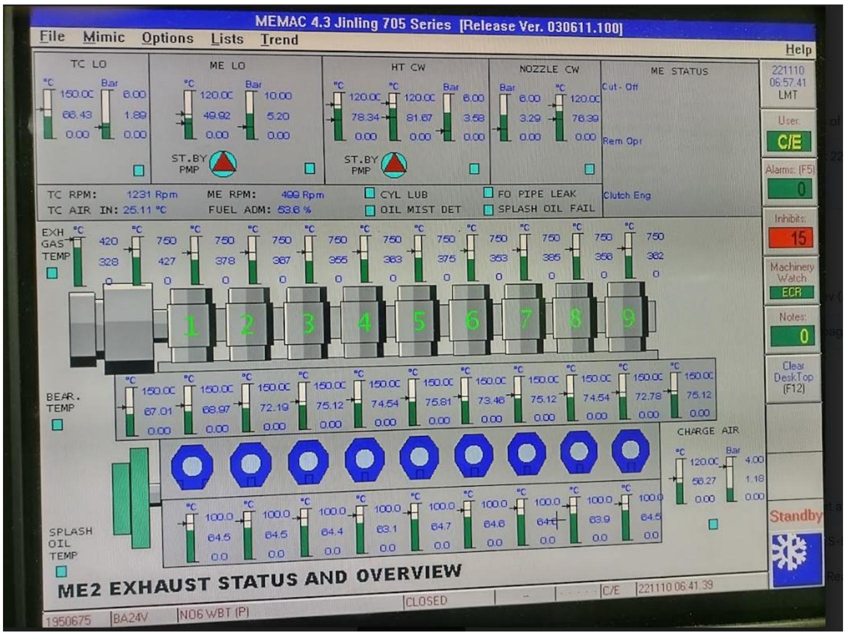


Figure 64. IAS Main engine 2 overview. (Author´s collection)

If one considers the above figure as a 3-dimensional X-ray view of the engine presented through a heat-map that represents the area where a possible deviation from average is shown

in relation to available parameters, it could with the suggested additions of sensors provide a larger perspective of the actual operating status and error. If referring to the piston seizure event described in Chapter 3.7 and Figure 65 below, a scenario where liner temperature and splash-oil temperature was affected it could show a hot area in red for instance.

Figure 65. Damages on piston of cylinder 7. Deep scoring and severe overheating. (Author´s collection).

As mentioned, this author finds this technique to be a visualization tool rather than any type of diagnostic concept. Anyhow, by using digital twins in combination with X-ray viewing and a heat-map setup it could certainly provide a high-level tool that point out the area of malfunction and parameter deviation effectively. Following Figure 66 is a simple three-dimensional engine section view and the purpose is to clarify the suggestion of implementing digital twins in monitoring. Relating to the case with the piston seizure and the resulting crank-case explosion, major red areas could represent affected assemblies such as liner temperature, splash oil temperature and possibly depending on the circumstances also other parameters. The known parameters after this incident is shown in the Figure 66 on page 80.

As mentioned, the author finds it necessary to involve advanced modelling of the engine and it should also be a 3-dimensional view to provide additional benefits. It should be possible to view different sub-assemblies of the complete engine in the same manner. To avoid providing too much information simultaneously, this author suggests that the error is illustrated through a heat map, but actual visualization of any values should appear once mowing the mice over the area of interest for instance.

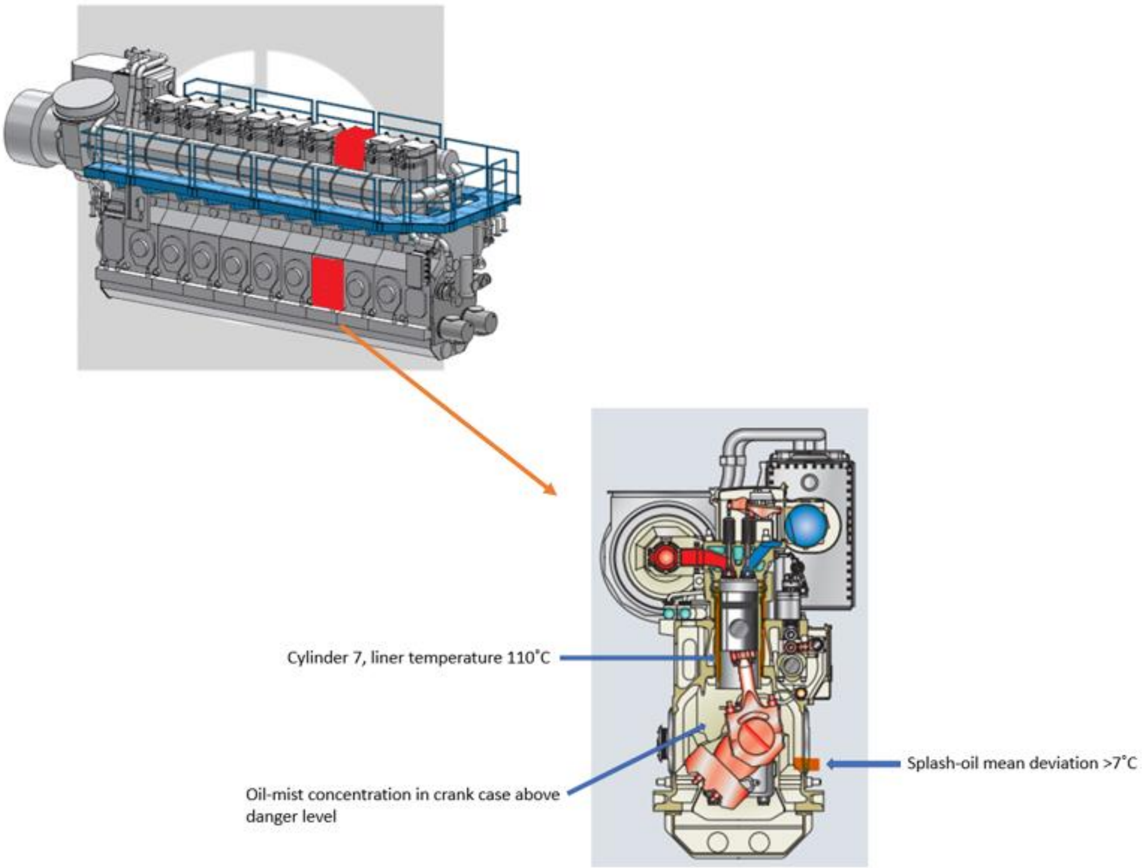


Figure 66. Cross section MAN 48/60 in-line engine.

7.9 Sensor Fusion

This is one of the most interesting features in terms of understanding equipment long time behavior as well as in terms of monitoring efficiency. Whenever there is an anomality inside the engine during operation, the anomality will most likely reflect multiple parameters. For instance, if there is an error within the fuel injection system this might appear as a deviation in the exhaust temperatures, fuel consumption, engine emissions and by this author´s experience, it will be indicated in the firing pressure of the specific cylinder. So, by combining not only different sensors but also different technique we can gain benefits through detecting performance and safety related issues before possible poor fuel efficiency and/or unplanned downtime takes place. In short terms, by using sensor fusion technology the operator as well as the remote monitoring center will be given a totally different view of the ongoing circumstances than with traditional monitoring where each sensor provides an own separate input.

“Sensor fusion combines sensory data to reduce uncertainty and help agents make more informed decisions”. (Udacity Team, 2021).

Currently sensor fusion can also incorporate Artificial Intelligence in different ways depending on actual usage. (Udacity Team, 2021). In terms of diesel engines and (remote) monitoring it could benefit to not only gather data and generate models but also automatically provide the essential and most important information for a given scenario. While involving more automation on-board, more data can be provided to the operator and remote monitoring centers and this can generate a confusing situation where many important inputs are risked getting lost in the large stream of informational flow that an event can generate. Several of these events were found in the event log used for this research and while these events appear somehow naturally as historical events, the scene on the site during an event is quite different. Large numbers of alarms might be triggered simultaneously causing confusion for the operator and making it difficult to understand the actual root cause of the event.

This author finds sensor fusion as a concept in combination with artificial intelligence and machine learning the most important modern contributor to achieve a close to ideal situational awareness in terms of engine monitoring. By combining all relevant sensor readings at any given circumstance, it is possible to alert the operator about the actual root cause of more or less any occurring anomaly related to engine operation. It is essential that machine learning would be utilized to benefit from this technique, as otherwise the operator

will most probably be overwhelmed with information instead of having an automated process that automatically alert the operator on what parameters are essential.

More or less all the suggested monitoring methods presented in this thesis can be used as contributors to this concept. Even while the individual methods does provide important inputs, combining them through artificial intelligence and machine leaning is obviously much more accurate and effective.

7.10 24/7 Technical Support

Currently MAN ES offer 24/7 instant technical support for all customers through a dedicated “hotline” as in the below Figure 67.

Figure 67. MAN PrimeServ emergency service. (Author´s collection).

As such, this service is not a part of a predictive maintenance concept but instead target emergencies whenever the customer is experiencing a major error in their equipment. According to this author´s genuine experience on-board various vessels, even with available state of the art technique, mankind will most likely never be able to predict failure of every piece of the sophisticated assembly that forms a diesel engine. We can through continuously learning about the different components find correlation between time aspects and wear but due to many contributors and circumstances during the lifetime of the equipment there might appear surprises. Load, fuel and lubricating oil quality are such main contributors but as

mentioned in the component failure and predictability sheet, failures related to manufacturing or material errors are difficult if not even impossible to predict. These kinds of failures are difficult due to the fact that the specific component has once installed on the engine cleared quality inspections at the manufacturer. Even while these types of failures are considered rare according to this author´s experience, they do occur.

As a part of predictive maintenance, the author sees definite importance that whenever there is a sudden breakdown, the manufacturer shall be alerted promptly in order to prevent similar failures. Further, by adapting remote monitoring, it can even decrease such failures as the dedicated expert at the PrimeServ Assist monitoring center might find small relationship´s in parameters that are not observed in time at site – given the equipment available at site.

MAN ES offer a web-based customer interface through the MAN CEON that is connected to the PrimeServ Assist service. By this service the customer will benefit from a more predictive approach as the intention is that the MAN expert will react to an anomaly before there is a major failure. Below Figure 68 presents the MAN CEON and PrimeServ Assist setup like it is intended to work. (MAN Energy Solutions, 2022b, p. 3)

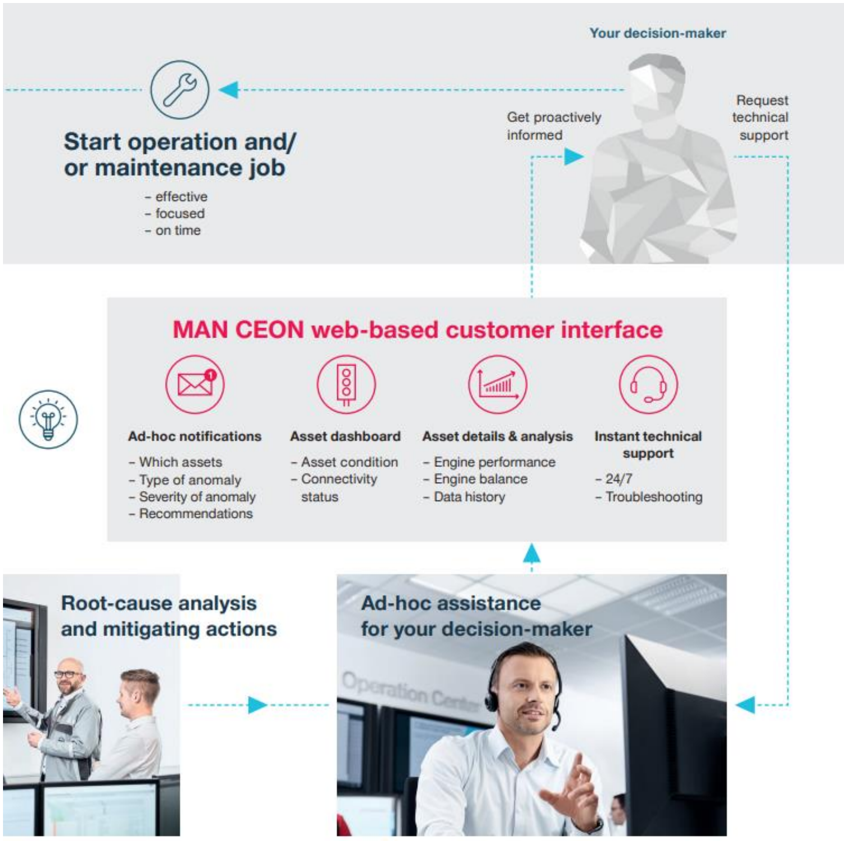


Figure 68. Customer interface by MAN CEON. (MAN Energy Solutions, 2022b, p. 5)

With all respect to the above Figure 68, this thesis must approach the subjects with a critical perspective, this author again wants to add the time perspective. If a component of the engine is suffering from some sort of material related fault, the resulting failure can develop very quickly. Is it then by even a dedicated expert behind a sophisticated (remote) monitoring system possible to react in time? The author cannot answer this question in a realistic way simply because it is highly dependent on the circumstances.

7.11 Automation and Emergency Operations

It is essential to understand the importance of being able to operate the engine during critical circumstances. By critical circumstances this author refers to situations when a major error is present, but the vessel must avoid further endangering human life, environmental pollution, or total loss of investment.

According to this author, such circumstances are for instance the following:

- disturbance or error in electrical supply required to operate the engine normally
- major error in control or monitoring system (automation)
- avoiding unnecessary shutdown due to single or multiple sensor errors
- different mechanical errors on the engine or within the auxiliary systems

With the technical advancement of today, where a constantly increasing number of processes related to the engine operation rely on automation systems it is important to remember that there are means implemented so that if there is a malfunction in the automation systems, the engine can still be operated. Obviously, this is highly dependent on the actual circumstances but according to this author´s experience, the means providing possibilities of emergency operation cannot be excluded as human will probably never be able to fully avoid failure occurrence. This is due to the large number of variables related to the processes connected to engine operations where some are mentioned in the following lines.

- human error
- material fatigue and manufacturing defects

- certain operating scenarios

Deciding by the inputs from the questionnaire, many of these “back-up” functions have remained the same even on more modern engines. Below a brief summary of different functions that allow emergency operation of the MAN 48/60 B engine in accordance with the operating instructions:

- Safety system override: a majority of the critical sensor inputs are blocked to prevent automatic power reduction as well as shutdown.

Figure 69. Safety System Override. (Author´s collection).

- Oil mist detector override: even when the oil mist detector triggers an alarm that normally result in an automatic shutdown, the signal is blocked.

Figure 70. Override Oil Mist in Crankcase. (Author´s collection).

- Electrical speed control system override: the engine has a mechanical governor as addition to the electrically controlled system to allow engine speed control if the control system suffer a malfunction. The mechanical governor also allows to set load limit.

Figure 71. Mechanical Governor control. (Author´s collection).

- Local engine start and stop.

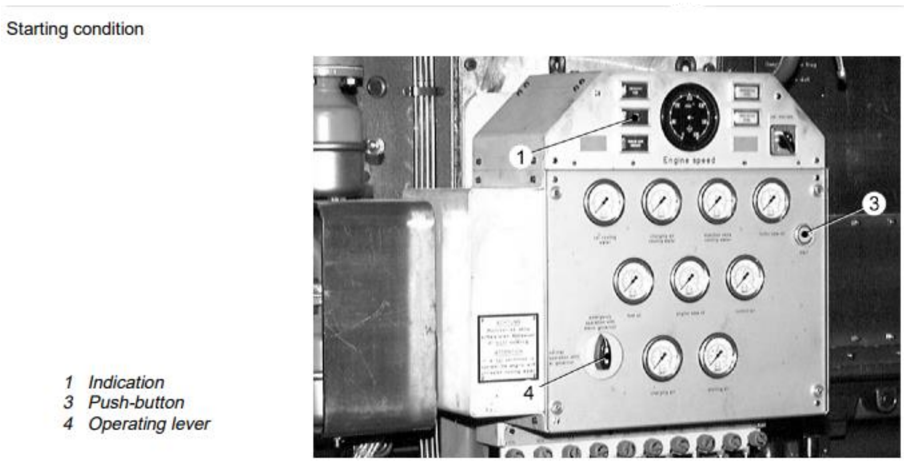


Figure 72. Local control. (MAN Energy Solutions, 1999a, p. 01/03)

8 Artificial Intelligence and Machine Learning

Because of the technical development and more sophisticated techniques in general, the terms artificial intelligence and machine learning has gained popularity. These concepts are important to consider when there are large amounts of data that require analyzing involved. Below lines aims to explain what these terms are:

- Artificial Intelligence is the simulation of human intelligence processes by machines or computers

- machine learning is an essential part of artificial intelligence and refer to the science on getting machines to take actions without programming

(Burns, 2022)

By involving additional monitoring, such as the ones suggested in this thesis, it will be challenging for the human brain to cope with all the information unless there is some level of artificial intelligence involved. This refers to technique that can filter the data and alert the operator on what is important information and additionally, predict outcomes. Artificial intelligence can be utilized by using machine learning algorithms to analyze and find patterns to predict future states. (Burns, 2022). Below Figure 73 aim to provide an example in understanding of how to benefit from machine learning in terms of predictive maintenance.

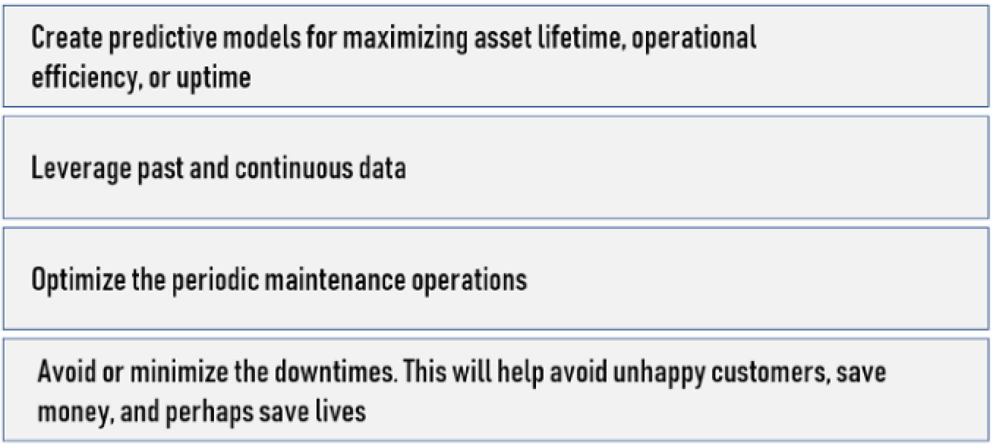


Figure 73. Advantages of Machine Learning. (Gonfalonieri, Towards Data Science, 2019)

When using artificial intelligence and machine learning as in above example, there is an initial process called learning process that involve data collection to create rules on how to convert available data to “actionable” information. This relates to the actual algorithms and

aims to provide instructions on how to manage a certain task. The learning process is followed by reasoning processes meaning that the algorithms are programmed into reaching a desired result or outcome. As a last step in the process there is the self-correction phase that adjusts and fine tunes the algorithms to ensure optimal result. There are three different main types of algorithms for learning: (Burns, 2022)

- supervised learning where the data is labeled to locate patterns
- unsupervised learning mean that the data is not labeled. This method categorizes the data in accordance with comparability
- reinforcement learning does not use labeled data but instead after conducting a task, the algorithm is provided feedback

(Burns, 2022)

Obviously in the context of this thesis and the different monitoring concepts included, the supervised learning should act as the basis due to fact that the data is concrete and connected to specific sensor(s) and functions (labels). Due to the complexity and overall width of this subject, this author cannot move too deeply into the theoretics of artificial intelligence but instead focus on a specific type of the subject that suits well considering the context of the thesis. This refers to neural networks that remind us of the human brain in the way they act by recognizing patterns and solving specific problems. Also, an important aspect of neural networking is that they rely on training data such as historical parameters to learn and improve accuracy continuously. (IBM Corporation, IBM Cloud Education, 2020) (IBM Corporation, AI in the enterprise, 2021). Many of the techniques and concepts presented in this thesis generates large amounts of sensor data over time and due to this reason, the neural network should be an effective way to benefit from the available data. We can illustrate the principle of neural networking by the following Figure 74.

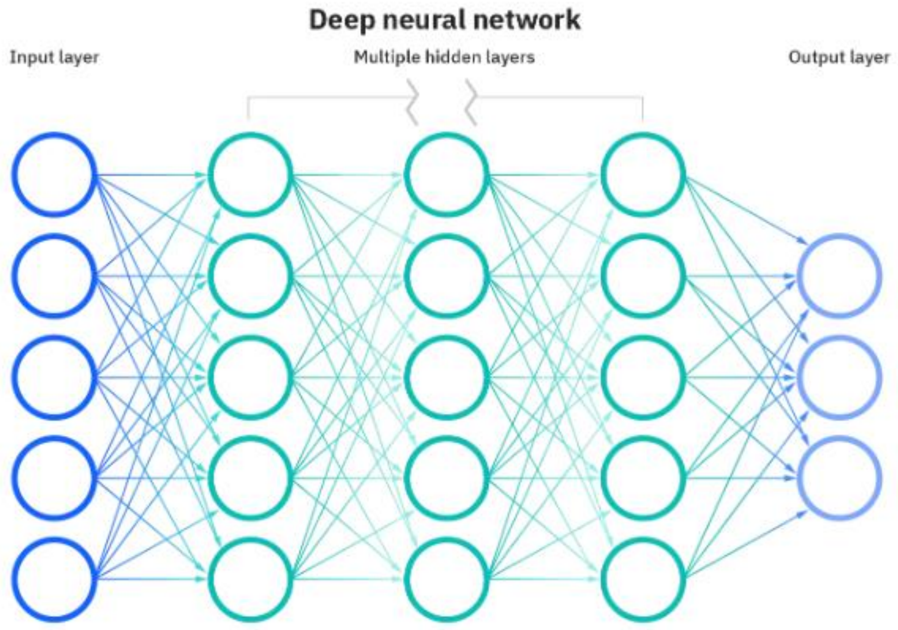


Figure 74. Schematic principle of neural networks. (IBM Corporation, IBM Cloud Education, 2020)

The circles are referred to as nodes or neurons in a complex network and, in Figure 74, there are several layers of nodes where the total number depends on actual task. Shortly, they are divided into input node layers, hidden layers of nodes and an output node layer. All of these layers are connected in a network, and each has an associated weight and threshold that makes them reveal additional features to determine output. Whenever one of the individual nodes exceed set threshold, the node will become active and pass data into the next layer. The function of the different layers can be described as follows and one can consider each node within the layers as a linear regression model. (IBM Corporation, IBM Cloud Education, 2020)

- Input layer is fed by raw sensor data and assessed. If thresholds are not exceeded, no data will be allowed to pass to next layer in the network.
- The hidden layers continue to assess provided data by additional criteria as a step-by-step process.
- Output layer will provide response in accordance with the programmed criteria and the given task.

(IBM Corporation, IBM Cloud Education, 2020)

So, briefly we can decide that neural networks rely on complex networks of nodes where each is activated by certain criteria. In the context of this thesis, we would like the neural network to predict a future state by using a large number of sensor inputs. The below Figure 75 aims to illustrate a neural network connected to the example cases I, II and III based on this author´s interpretation of the subject.

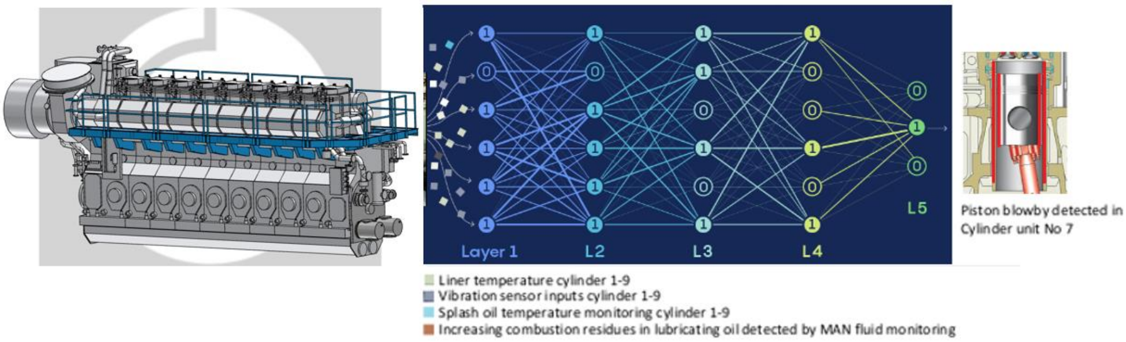


Figure 75. Neural networking and Sensor flow.

The algorithms have been trained to recognize what sensor values are considered as normal and what to see as an anomaly, and to identify output depending on information received. Each layer (L1-L5) response to available parameters in accordance to specified thresholds and in this example, we will get indications by several different inputs guiding us towards the actual error. We assume the engine is operating at a specific status in regards of load and ambient conditions. With the various sensor readings available, the triggered output in this case “piston blowby” is selected because of the below variables.

- Comparison of all cylinder liner temperatures against historical measurements at given conditions. Lacking cylinder lubrication due to blowby and the resulting increase in friction cause liner temperature on cylinder unit 7 to increase.

- Vibrations sensor inputs of all cylinders compared to historical measurements at given conditions. Lack of lubrication and resulting metal to metal contact reflect changes in vibration pattern in cylinder unit 7.

- Splash oil temperature increase on cylinder unit 7 because of increasing thermal load on engine lubricating oil. This is due to piston blowby.

- Continuously measuring lubricating oil condition provide indication as deviation to normal in amount of combustion residues.

We can illustrate the logic behind neural networking by linear regression. If we look at a certain scenario in a pure mathematical way, it can be illustrated through below formulas.

$$W_1X_1 + W_2X_2 + W_3X_3 + .. W_nX_n + bias = \sum_{i=1}^{m} W_iX_i + bias$$

Each node can be expressed by multiplying the individual input data (X) and a fixed weight value (W). These are then summarized to a determined “bias” or threshold.

Output:

For the next node to be activated, it is required that the current node exceed the determined threshold. This way the data will pass through the network.

$$f(x) = \begin{cases} 1 \; if \; \sum \; = \; W_1X_1 + bias \; \geq 0 \\ 0 \; if \; \sum \; = \; W_1X_1 + bias < 0 \end{cases}$$

(IBM Corporation, IBM Cloud Education, 2020)

By using linear regression, it is possible to predict an outcome by utilizing large number of different inputs. Once these learning algorithms are tuned, they will provide a powerful tool to classify and cluster data at high velocity which is considered as a presumption in predicting maintenance by performance. (IBM Corporation, IBM Cloud Education, 2020). According to this author, by utilizing artificial intelligence and machine learning as an addition to the different monitoring methods, the operators on-board could have received early indication of what the reason was for the resulting piston seizures.

9 Remote Monitoring

As described in previous chapters, the benefits of a remote monitoring service rely on real equipment expertise by the genuine manufacturer and custom-made monitoring software, and in this chapter this author would like to introduce some background aspects of remote monitoring:

- remote monitoring is provided by equipment experts on the OEM premises with experience gained over a long time (MAN Energy Solutions, 2022a)

- remote monitoring services offered today involve some level of artificial intelligence providing the ability to self-learn and find deviational patterns automatically after a certain time of system operation (training) (MAN Energy Solutions, 2022a)

- a remote monitoring service targets a specific equipment and is made for this purpose while the alarm and monitoring system currently on-board is adopted to suit all existing technical equipment that is being monitored on-board

- the existing alarm and monitoring system on-board are limited to alerting the operator once there is already an anomality as this system does not include any level of sophisticated long-term trending possibilities that would alert operators well before an actual alarm is triggered when the specific parameter is already out of range

- sensor data as currently available on-board for analyzing on daily a basis is considered as limited due to the fact that records are particularly recorded at high load conditions to see changes over time

10 MAN ES Services – Operational intelligence

MAN ES has a broad offering of industrial equipment and services. They also offer complete aftermarket sales and support for their customers in different segments of the industry and in following sub-chapters the content will target customer support by the perspective of remote monitoring and associated topics.

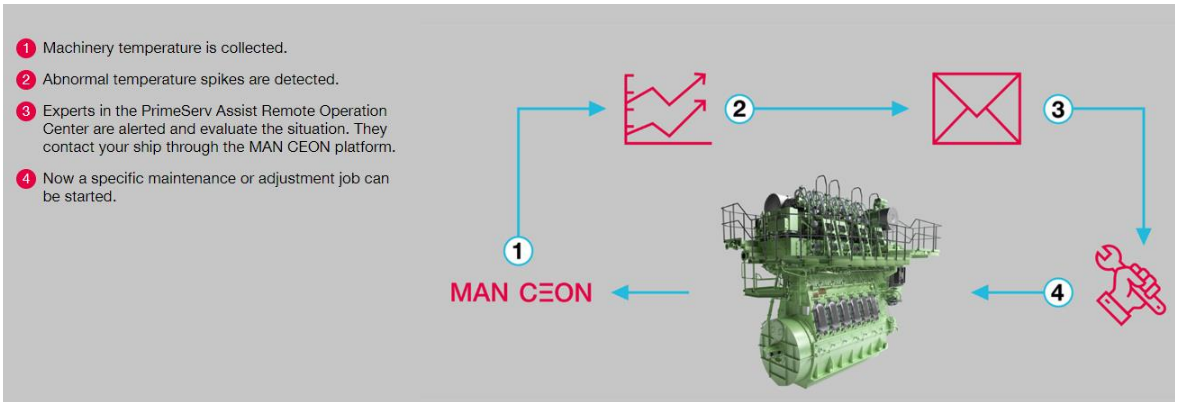


Figure 76. MAN Prime Serv Assist set-up. (MAN Energy Solutions, 2022b)

10.1 MAN PrimeServ

The brand MAN PrimeServ is responsible for the complete after-sales offerings by MAN ES. Everything related to maintenance, spare-parts and a various scope of digital services is available.

In this thesis the main target lies within the digital services, more specific the MAN PrimeServ Assist which is an essential part of the PrimeServ brand. The aim of PrimeServ Assist is to maximize equipment up-time through genuine MAN expertise by ensuring availability, safety and efficiency.

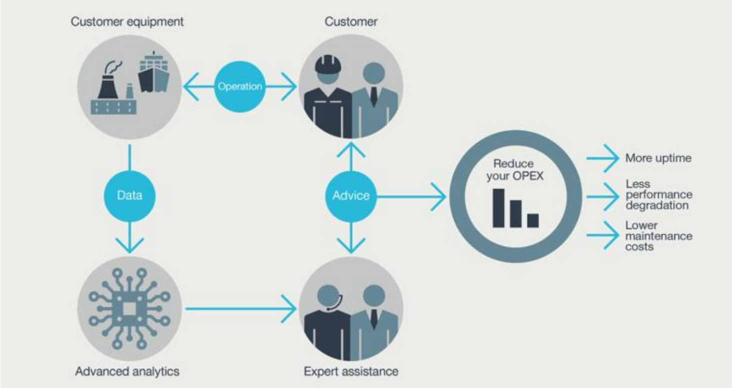


Figure 77. (MAN Energy Solutions, 2022f).

10.2 PrimeServ Assist

This service focuses on reducing the equipment OPEX by remote monitoring the data available from site. Target is on potential problems on the equipment being monitored to help the customer in decision making for preventing failures before they actually cause downtime, and simultaneously maintain equipment performance and efficiency while decreasing maintenance costs, and fuel consumption. All parameters available are being monitored on a dedicated MAN PrimeServ center 24/7 by any of the 100+ service centers globally. (MAN Energy Solutions, 2022e, p. 23).

The PrimeServ Assist is a tool for achieving a proactive approach on maintenance and operational efficiency optimization by pro-active expert assistance and advanced analytics. The following Figure 78 is to provide an illustration on the PrimeServ Assist setup, and to present a case that connects to the example cases in Chapter 3.4.3 and 3.4.4 of this thesis.

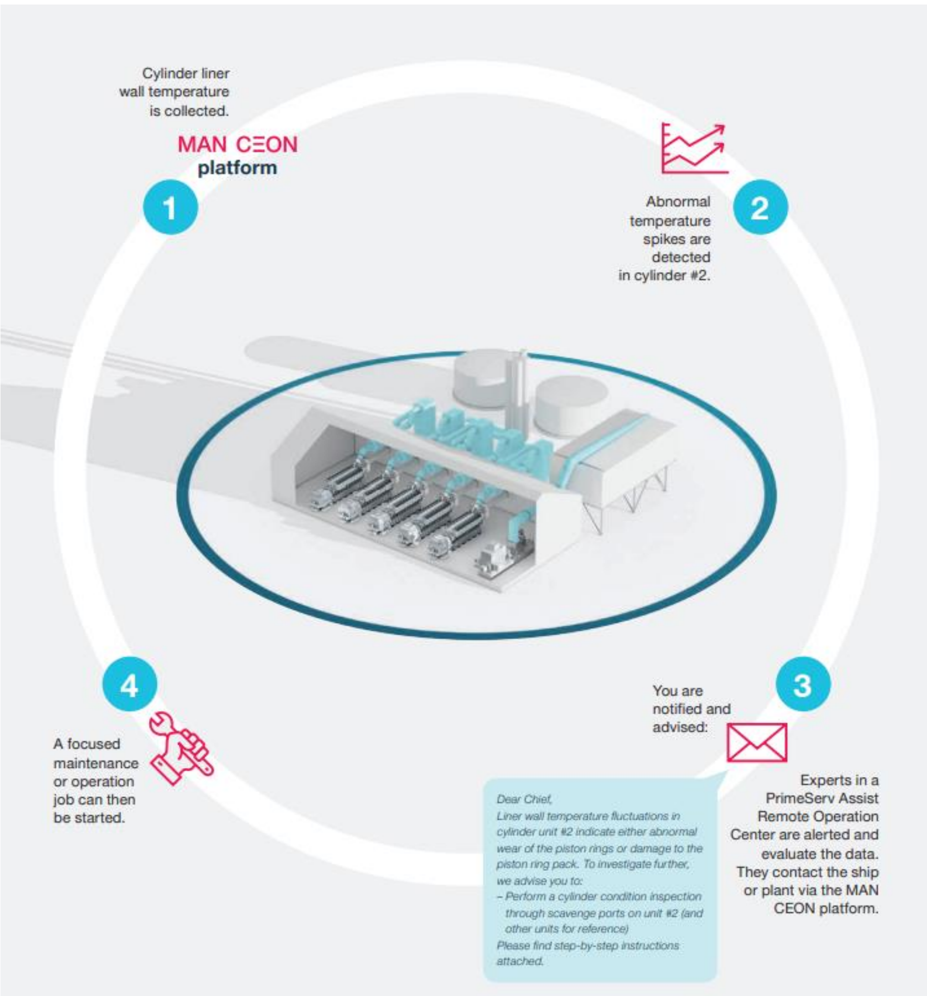


Figure 78. PrimeServ Assist – a proactive approach. (MAN Energy Solutions, 2022b).

10.3 MAN CEON and PrimeServ Assist

In order to utilize the PrimeServ Assist service, a connection is required to the MAN CEON platform. One can say that the CEON is the heart of the digital services provided by MAN ES. This platform is cloud-based and is used to transmit secure and actual data from the connected equipment for efficient storage and collection of the large data volumes involved. Furthermore, the MAN CEON is the interacting point for MAN designated equipment experts and the customer on site to elaborate via text or audio while the CEON intelligently collect and evaluate machinery data from site. (MAN Energy Solutions, 2019b).

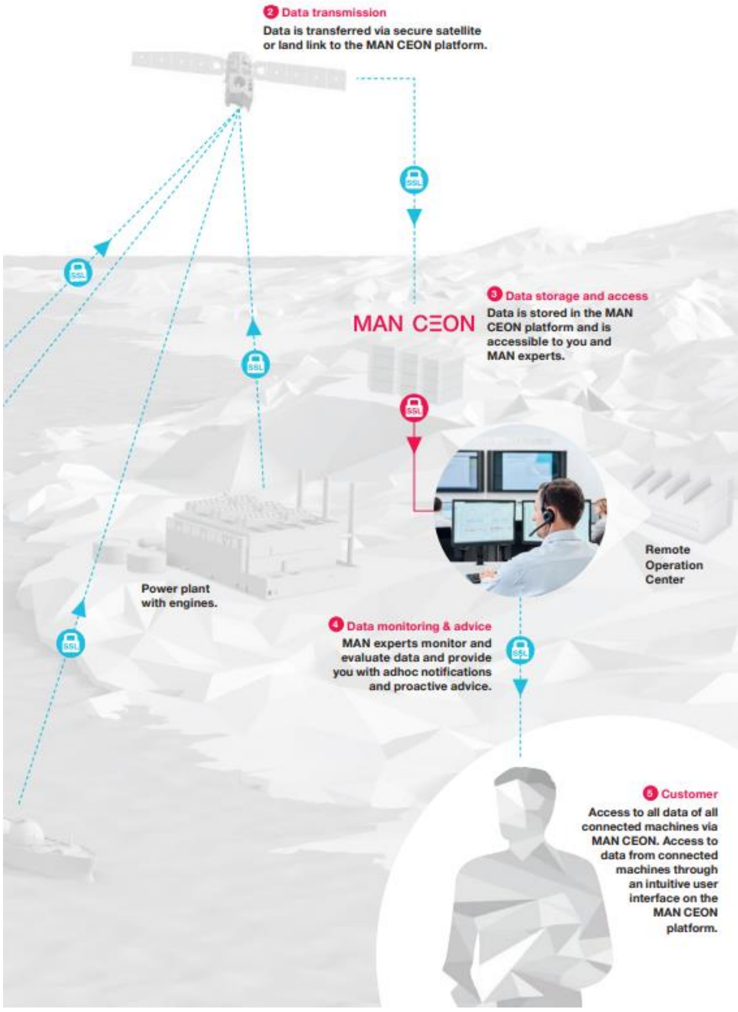


Figure 79. MAN CEON and PrimeServ Assist. (MAN Energy Solutions, 2022b, p. 7)

10.4 MAN ES Digital Services and Cyber Security

MAN CEON is accessible from a computer or through mobile-terminals. The CEON requires multi-level authorization and utilizes encrypted data transmission. MAN ES has stated “there is no possibility to interact with the control system” as this system contains a read interface only. (MAN Energy Solutions, 2022g) . All data transfer has end-to-end encryption by TLS[2] technology. TLS mean Transport Layer Security. Also, the used edge devices have no physical nor any digital way to interact from outside the system meaning no USB devices or login facilities can be connected.

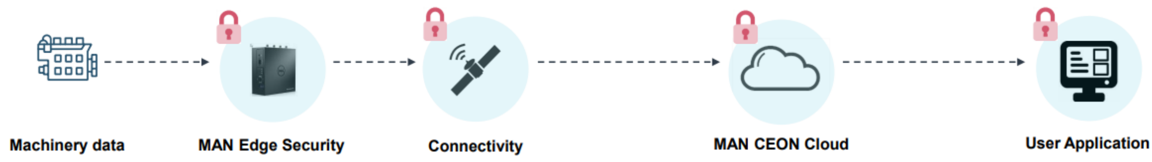


Figure 80. Cyber security setup. (MAN Energy Solutions, 2022g).

11 Critical discussion and conclusions

As previously described, this thesis made a somewhat large change in direction as the MAN PrimeServ Assist has not been implemented on Finnmill as of this date, meaning that the research relies on existing historical events only available in paper format (i.e., the printed event log). This material had to be analyzed manually which led to a considerable challenge in determining and connecting the actual cause behind each event in order to understand it, as no digital filtering was possible. This statement mainly relates to the fact that a relatively large number of events caused by disturbances in various auxiliary systems finally result in an error in the main engine.

If the research had relied mostly on digitalized input from the PrimeServ Assist, the workload of the research would have decreased drastically, and more focus could have been put on the different methods suggested for improvement. This is explained by the digital advantages of big data management. The current routes of the ship would also have contributed to a better result in this research because in the past this vessel had constant route changes affecting the engine operations to some extent as available parameters could not easily be compared, simply due to a limitation in parameter availability.

Despite the limitation, the research did provide a result through suggestions on various additions of technology to improve operational awareness, and the historical events prove the MAN 48/60 engine to be a superb and reliable performer. The various additions in technology requires testing already at the manufacturer. For instance, vibration monitoring or monitoring by ultrasound are highly sensitive methods that are to be tested on the manufacturer´s premises. To determine sensor location and how the component or assembly is affected by sensor installation might require changes to existing parts used in the engine to secure that initial component characteristics remain.

12 Final words

Although the technology has advanced remarkably since the year 2001 when the engines covered in this thesis were delivered, the cost aspect compared to actual benefits must be carefully considered when implementing new techniques - especially when retrofitting. This perspective was thoroughly discussed with MAN ES technical experts and even as some methods in terms of monitoring could provide additional value, the author agree that the MAN 9L 48/60 engines are very dependable as they were originally delivered. However, as the suggested additions require extensive investigations and testing at the engine design stage it is seen as only possibility to provide proof is by implementing the specific technique at the manufacturer´s premises, each as a specific test case. Also, the author would like to point out the importance of understanding that neither of the different techniques involved in this thesis is considered the “key to success”. We still need to rely on the basics like pressure and temperature sensors. Furthermore, by adding more sophisticated monitoring concepts to the existing setup, we can gain situational awareness to understand engine condition in order to maintain a reliable and efficient engine.

While considering the modern approach to engine operations in the maritime industry, where we rely on highly automated engine plants, this author finds it meaningful to investigate which automation is relevant – such as the monitoring perspective included in this thesis. This author sees no way around the term *prediction* and holds the view that the most important input should be a sophisticated monitoring system. If we take another step ahead, it is possible that the shipping industry will face changes in terms of decreasing on-board crew members. This would set even higher requirements on the monitoring systems in order to understand the situation on-board and to predict lifetime of the technology used. Due to this aspect, focus on the development of remote monitoring services is to be considered as the path forward.

During writing of this thesis, this author has strived to maintain a level of complexity to ensure that the context is understandable to everyone who finds this subject interesting as well as to maintain a certain path to ensure transparency that is easy to follow. Many of the headings within this thesis could constitute the undertaking of a number of separate researches simply due to the extent of each subject if one likes to find other perspectives or deeper information in the individual subjects. This contributes to excellent possibilities of further research on the topics included or to target other segments of on-board equipment.

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Appendix 1. MAN L-48/60 Specifications. (MAN Energy Solutions, 1997a, p. 2)

The L 48/60 engine

Power range: 6,300 to 9,450 kW

The 48/60 is also available as a V-configuration engine.
Power range: 12,600 to 18,900 kW

- sturdy
- of straightforward design
- heavy-fuel-oil compatible
- economical
- easy to maintain

Technical data

Working cycle:	Four-stroke
Combustion process:	Direct fuel injection
Number of cylinders:	6, 7, 8, 9
Cylinder bore:	480 mm
Piston stroke:	600 mm
Swept volume per cyl.:	108.5 dm³
Power/weight ratio:	MCR 15.6–16.6 kg/kW 11.5–12.2 kg/HP
Cylinder output: at 514/500 rpm	MCR 1050 kW/1430 HP
Coolants:	
Cylinders:	Fresh water
Charge air: (one and two-stage)	Fresh water
Fuel injection nozzles:	Fresh water
Starting:	By compressed air

Performance data: MCR

		kW/HP	kW/HP
6L 48/60	6 cyl.	6300 *8580*	6300 *8580*
7L 48/60	7 cyl.	7350 *10010*	7350 *10010*
8L 48/60	8 cyl.	8400 *11440*	8400 *11440*
9L 48/60	9 cyl.	9450 *12870*	9450 *12870*
Speed: rpm		514	500
Mean piston speed: m/s		10.3	10.0
Mean effective pressure: bar		22.6	23.2

Fuel consumption: MCR

	100 % P	85 % P
L 48/60	181 133	178 g/kWh 131 g/HPh

Lube oil consumption

L 48/60	1.0 g/kWh	0.7 g/HPh

Definition of engine ratings

Marine main engines

P = MCR = Maximum Continuous Rating (blocked at 100% power)

Reference conditions:

Air temperature	318 K (45° C)
Barometric pressure	1 bar
Cooling water temperature before charge air cooler	305 K (32° C)

The fuel consumption rates are based on ISO conditions (25° C ambient temperature, 25° C cooling water temperature before charge air cooler, 1 bar barometric pressure) and a net calorific value of the fuel of 42,700 kJ/kg.
tolerance: + 3 %.

Stationary plants (to ISO 3046/I)

Continuous rating with 10 % overload capacity for 1 hour within 12 hours of operation.

Reference conditions:

Air temperature	298 K (25° C)
Barometric pressure	1 bar
Cooling water temperature before charge air cooler	298 K (25° C)

The L 48/60 engine is one of our state-of-the-art medium-speed four-stroke engine types within the output range of 4200 up to 18900 kW, which to this date has logged over 6 million hours of operating performance based on its future-oriented design principle.
MAN B&W Diesel – one century of Diesel Engineering practice.

2

Appendix 2. Service report. (1/4).

Service Report 10.06.2022RD

Area: ME 1, MAN 48/60, CYLINDER 7 OVERHAUL
Owner: m/s „FINNMILL "
Order: FMIL/22/0151 45035
Period: 06.05.2022
Place: Travemunde, Germany. On board.

ME1 cylinder № 7 overhaul:

- ✓ **Cylinder head, piston, cooling water jacket and liner were dismounted by the vessel crew.**
- ✓ **Dismounted piston photo.**

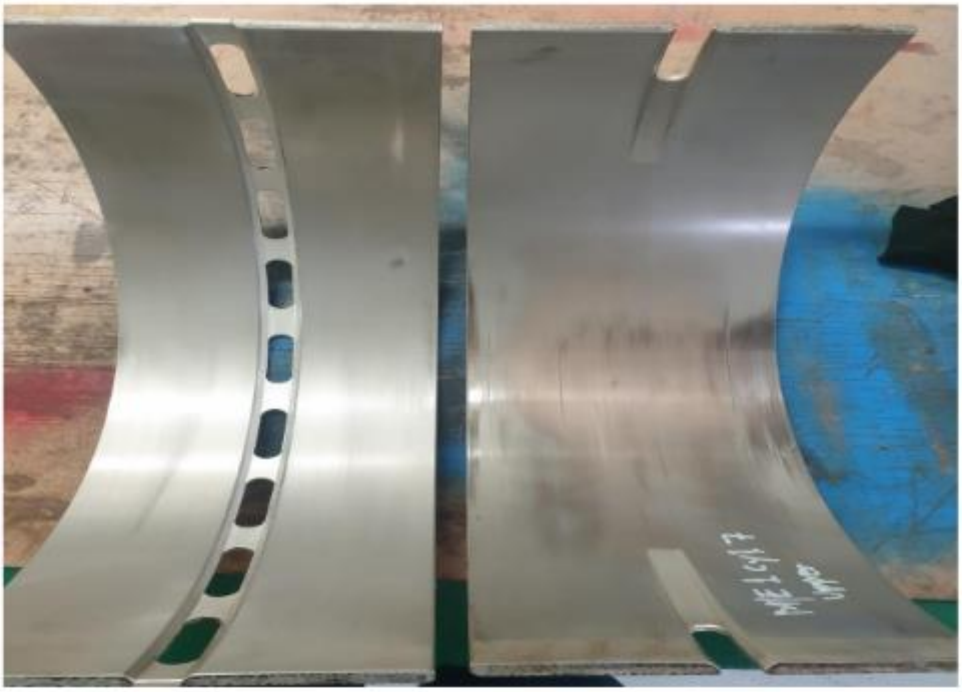
- ✓ **Liner dismounted together with cooling water jacket.**

Appendix 2. Service report. (2/4).

- ✓ **Landing surfaces cleaned and inspected. No remarks**

- ✓ **Connecting rod big end untightened. BEB shells replaced by new.**

Appendix 2. Service report. (3/4).



- ✓ Connecting rod big end tightened according instructional manual.
- ✓ New cooling water jacket was mounted to engine.
- ✓ New cylinder liner № 1970322 was mounted to the engine.
- ✓ Spare con-rod shank № 27808 with spare pin installed to the piston № 1712472
- ✓ Spare piston № 1712472 mounted back to engine with new piston rings and tightened according instruction manual.
- ✓ New anti-polish № 1970322 mounted to the engine.
- ✓ Spare Cylinder head № 6504862 assembled with spare fuel injection valve, used starting air valve, new HP fuel pipe was installed to the engine and tightened according instruction manual.
- ✓ Rocker arms installed back to engine.

Appendix 2. Service report. (4/4).

Remarks:

- The ME1 cylinder 7 has been completely reassembled after service in accordance to the maintenance instruction manual.
- All necessary O-rings, gaskets and spares provided by customer and replaced.
- The valve's clearances were adjusted according to instruction manual.
- The cooling, air, fuel and lubricating systems have been pressure tested by crew. No remarks.
- The ME1 is ready for trials.
- The spares (OEM) are provided by the Customer.
- The Customer has no claims.

Appendix 3. Service report. (1/2).

Service Report 02072022/VOLK

Area: ME 1, cyl.5, MAN 9L 48/60, emergency overhaul.
ME Running hours: 111527 hours
Owner: m/s „FINNMILL"
Order: 45115
Period: 01-02.07.2022
Place: Hanko, Finland.

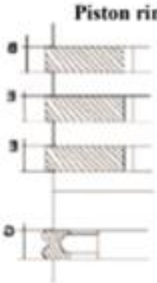
- The rocker arms housing, cylinder cover, top land ring, piston and cylinder liner were dismantled from the engine by the crew, due to damage on the piston (scuffs on the piston skirt and cylinder liner).
- The backing ring **nr.1725416** was replaced with a new one backing ring **nr.1130118**, due to the decision of the customer. No remarks.
- Spare cylinder liner **nr.1743011** was installed to the engine with new O-rings. No remarks.
- The BEBH has been opened and the crankpin and bearing housing have been visually inspected. No remarks. At the request of the customer, the big end bearing shells were replaced with new ones, BEB clearance = 0.52mm. No remarks.

Tightening of BEB bolts

Position:	not tightened	tightened	bolt elongation
Bolt 1 port side	829.50mm	831.80mm	2.30mm
Bolt 2 starboard	829.50mm	831.75mm	2.25mm

- The spare piston **nr.16112152** and conn-rod shank **nr.COC1033323** was mounted to the engine with new piston rings. No remarks.

Piston ring height clearance:



B	0.30
E	0.23
E	0.20
G	0.08

Appendix 3. Service report. (2/2).

- The spare top land ring **nr.1270769** was mounted to the engine with new O-rings. No remarks.
- The spare starting valve and fuel injection valve were installed in the spare cylinder head. The safety valve, indicator valve and connection piece to nozzle holder were reinstalled on the spare cylinder head. The spare cylinder head **nr.0275010** was mounted to the engine with new gaskets. No remarks.
- The rocker arms housing and air receiver were mounted to the engine with new O-rings. No remarks.
- The valve's clearances were adjusted according to instruction manual. No remarks.

Remarks:

- The ME 1, cyl.5 have been completely reassembled after service.
- The ME cooling, air, fuel and lubricating systems have been pressure tested by crew. No remarks.
- The ME 1 has been tested in accordance with the operating instruction manual within 02.07.2022 (without load). No remarks.
- The ME 1 is ready for the further normal working operation.
- The spares (OEM) are provided by the Customer.
- The Customer has no claims.

Appendix 4. Qestionnaire.

Main engine safety and efficiency

The aim of this questionnaire is to find possibilities on how to improve operational safety and efficiency of the ships main engines. Furthermore, the questions target four-stroke medium speed engines.

Please answer below questions and remember that only the main engines are targeted. Any auxiliary systems nor the propulsion system is considered.

FinnEco Engineers are kindly asked to consider your last vessel with four stroke main engines when answering.

1. Select engine manufacturer

1. MaK
2. MAN
3. Wärtsilä
4. Wärtsilä-Sulzer

2. Select engine type

1. M43
2. MAN 48/60
3. W46
4. ZA40

Appendix 4. Qestionnaire.

3. Select engine generation (Code letter)

1. B
2. C
3. D
4. E
5. F
6. S

4. Engine safety

Do You see possibilities to improve the operational safety of the main engine?
Please describe how and why. This may refer to both structural aspects and automation & control.

5. Engine safety

What are the means of emergency operation?
This question refers to both mechanical means as well as the engine control system.

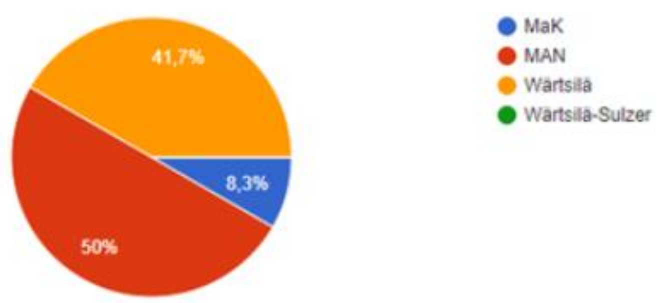
6. Engine efficiency and performance

Do You find it possible to improve operational efficiency of the engine itself?
Please describe. This refers to engine structure and automation & control.

Appendix 5. Questionnaire replies - brand and type summary.

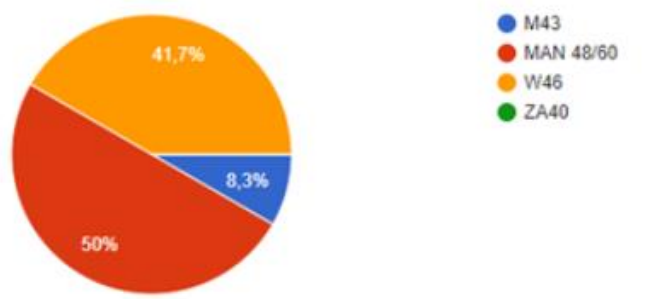
1. Select engine manufacturer

10 replies



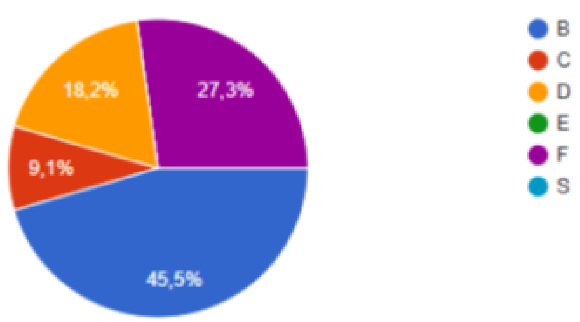
2. Select engine type

10 replies



3. Select engine generation (Code letter)

10 replies



Appendix 5. Questionnaire replies (1/10)

1. Select engine manufacturer *

Wärtsilä

2. Select engine type *

W46

3. Select engine generation (Code letter)

D

4. Engine safety

Do You see possibilities to improve the operational safety of the main engine?
Please describe how and why. This may refer to both structural aspects and automation & control.

Design could be improved so that parts would be easier/ faster to dismount/ install. At same time this would mean bigger engine room. Overall, quite reliable machines when maintenance programme with OEM spare parts is followed. Been onboard 8 years with only two major cases, where the repair of the engine took more than 3 days. And we have total four main engines that are all used daily.

5. Engine safety

What are the means of emergency operation?
This question refers to both mechanical means as well as the engine control system.

Mechanical + electrical overspeed devices, LO low press stop sensor, HT water high temp stop sensor, oil mist detector, cylinder liner high temp sensor

6. Engine efficiency and performance

Do You find it possible to improve operational efficiency of the engine itself?
Please describe. This refers to engine structure and automation & control.

With current propellers it is hard get out more power compared to consumption.

Appendix 5. Questionnaire replies (2/10)

1. Select engine manufacturer *

Wärtsilä

2. Select engine type *

W46

3. Select engine generation (Code letter)

F

4. Engine safety

Do You see possibilities to improve the operational safety of the main engine?
Please describe how and why. This may refer to both structural aspects and automation & control.

Wärtsila F series are forced engines with very high Pmax and sailing without load limits in bad weather condition and tight schedule stresses the engines and that the time, when engines problems started. Schedule need to be adjusted, that with good weather we have load 80-85% and when Autumn-Winter-Spring season bad weather starts, we still have spare 10-15% to be in time. Same time we reduce fuel consumption, emissions,high expensive spare parts.

5. Engine safety

What are the means of emergency operation?
This question refers to both mechanical means as well as the engine control system.

Emergency operation have a several meanings. 1) Operation of the engine with override mode, when vessel located in the narrow places and critical alarm appears, which can shutdown the engine without prewarning and these alarms are bypassed to get vessel out from narrows, where engine can be stopped for unplanned maintenance. 2) Operation of the engine without remote control and without automation system.

6. Engine efficiency and performance

Do You find it possible to improve operational efficiency of the engine itself?
Please describe. This refers to engine structure and automation & control.

1) As desribed previously, adjust the schedule and have a reserved 10-15% spare load of main engines for bad weather conditions. 2) Unmanned system to change for continous manned engine room with at least 1 duty engineer and 1 motorman.

Appendix 5. Questionnaire replies (3/10)

1. Select engine manufacturer *

Wärtsilä

2. Select engine type *

W46

3. Select engine generation (Code letter)

D

4. Engine safety
Do You see possibilities to improve the operational safety of the main engine?
Please describe how and why. This may refer to both structural aspects and automation & control.

Safety functions should be more simple all in 1 control unit same as sulzer had years ago.

5. Engine safety
What are the means of emergency operation?
This question refers to both mechanical means as well as the engine control system.

Overriding a sensor when mechanical gauge showing pressure.

6. Engine efficiency and performance

Do You find it possible to improve operational efficiency of the engine itself?
Please describe. This refers to engine structure and automation & control.

No , have to trust FAT are the optimal parameters to run engine.

Appendix 5. Questionnaire replies (4/10)

1. Select engine manufacturer *

Wärtsilä

2. Select engine type *

W46

3. Select engine generation (Code letter)

F

4. Engine safety
Do You see possibilities to improve the operational safety of the main engine?
Please describe how and why. This may refer to both structural aspects and automation & control.

Should be built in water% measuring and alarming system.

5. Engine safety
What are the means of emergency operation?
This question refers to both mechanical means as well as the engine control system.

Don't understand the question... local start and local governor control?

6. Engine efficiency and performance

Do You find it possible to improve operational efficiency of the engine itself?
Please describe. This refers to engine structure and automation & control.

Cant say ,

Appendix 5. Questionnaire replies (5/10)

1. Select engine manufacturer *

MAN

2. Select engine type *

MAN 48/60

3. Select engine generation (Code letter)

Välj

4. Engine safety
Do You see possibilities to improve the operational safety of the main engine?
Please describe how and why. This may refer to both structural aspects and automation & control.

Regular check of safety devices/alarms and shutdowns

5. Engine safety
What are the means of emergency operation?
This question refers to both mechanical means as well as the engine control system.

Crew must be aware on how to use equipment in emergency situations, CPP, steering gear etc., training's and familiarization to be done more often

6. Engine efficiency and performance

Do You find it possible to improve operational efficiency of the engine itself?
Please describe. This refers to engine structure and automation & control.

Engine and propulsion system performance can be optimized for changing requirements or upgraded to utilise to latest technologies. Engine performance can be optimized by upgrading the engine and propulsion components to newer technology that can offer efficiency and performance benefits

Appendix 5. Questionnaire replies (6/10)

1. Select engine manufacturer *

MAN

2. Select engine type *

MAN 48/60

3. Select engine generation (Code letter)

B

4. Engine safety
Do You see possibilities to improve the operational safety of the main engine?
Please describe how and why. This may refer to both structural aspects and automation & control.

In my opinion, MAN has a decent safety system - splash oil temp, temp. sensor on main bearings, oil mist etc. Regular diagnostic and measuring the tightness of the cylinders helps to ensure safety.

5. Engine safety
What are the means of emergency operation?
This question refers to both mechanical means as well as the engine control system.

In the event of an emergency, the "Override" system is helpful if used skillfully and wisely.

6. Engine efficiency and performance

Do You find it possible to improve operational efficiency of the engine itself?
Please describe. This refers to engine structure and automation & control.

It is possible to improve the efficiency of the engine by combining different operating modes - constant speed, combinator mode, etc.

Appendix 5. Questionnaire replies (7/10)

1. Select engine manufacturer *

MAN

2. Select engine type *

MAN 48/60

3. Select engine generation (Code letter)

B

4. Engine safety
Do You see possibilities to improve the operational safety of the main engine?
Please describe how and why. This may refer to both structural aspects and automation & control.

Yes. Always can improve more and usually if somethings happens after investigation they will improve it anyway

5. Engine safety
What are the means of emergency operation?
This question refers to both mechanical means as well as the engine control system.

To use engine in critical situation(lets say during maneuvering, or stormy weather) Like using override during maneuvering or offscan some critical item, which you know is really working but maybe sensor or something is just broken

6. Engine efficiency and performance

Do You find it possible to improve operational efficiency of the engine itself?
Please describe. This refers to engine structure and automation & control.

Yes. Elder engines can update automation and control to reduce fuel consumption. Newer engines same: engine structure-sure will come new materials which will increase engine overhauls hours between one overhaul to another..

Appendix 5. Questionnaire replies (8/10)

1. Select engine manufacturer *

Wärtsilä

2. Select engine type *

W46

3. Select engine generation (Code letter)

F

4. Engine safety
Do You see possibilities to improve the operational safety of the main engine?
Please describe how and why. This may refer to both structural aspects and automation & control.

More redundancy in the network connections between engine and outer controls

5. Engine safety
What are the means of emergency operation?
This question refers to both mechanical means as well as the engine control system.

Local control of ME start, bypassing the software. Local control of Governor

6. Engine efficiency and performance

Do You find it possible to improve operational efficiency of the engine itself?
Please describe. This refers to engine structure and automation & control.

Appendix 5. Questionnaire replies (9/10)

1. Select engine manufacturer *

MAN

2. Select engine type *

MAN 48/60

3. Select engine generation (Code letter)

B

4. Engine safety
Do You see possibilities to improve the operational safety of the main engine?
Please describe how and why. This may refer to both structural aspects and automation & control.

Prevent overloading the ME : the Captains, Deck officers need to know and respect the maximum rpm limits for Turbo chargers and maximum Charging air Pressure for example. These 2 readings represent a general load condition of ME. For quite a lot of Captains is the ETA the most important fact and not the keeping the vessel safely sailing. Reduce pitch in shallow water, prevent excessive vibrations (which in combination with material's fatigue generate in many cases disasters as Turbo chargers explosions for example as well as shaking electronic devices resulting in failures).

5. Engine safety
What are the means of emergency operation?
This question refers to both mechanical means as well as the engine control system.

Emergency operation... engine running with one less cylinder (fuel supply shut off for a cylinder), Or running with the Speed governor on Manual, By- passed safety devices, must be limited, specialized factory service must be directly arranged.

6. Engine efficiency and performance

Do You find it possible to improve operational efficiency of the engine itself?
Please describe. This refers to engine structure and automation & control.

Try to plan voyages as much as possible aiming the economic speed, Use good quality fuel, use OEM spares , again prevent vibrations. This will surely extend the life and efficiency of the ME.

Appendix 5. Questionnaire replies (10/10)

1. Select engine manufacturer *

MAN

2. Select engine type *

MAN 48/60

3. Select engine generation (Code letter)

B

4. Engine safety

Do You see possibilities to improve the operational safety of the main engine?
Please describe how and why. This may refer to both structural aspects and automation & control.

Indicator cocks are quite heavy, and they are only held by two bolts. There have been instances that 1 or both bolts break. Consequently, leading to fall-off of indicator cock from cylinder head. The release of hot air in the E/R could trigger fire if it hits directly a nearby combustible material. If not for the loud continuous noise, there's no way to tell that an indicator cock has fallen off already.
Suggestions for improvement: (1) use bigger bolts than the current size of bolt now, (2) if same size of bolt use 3 pcs, or (3) install a sensor in the indicator cock

5. Engine safety

What are the means of emergency operation?
This question refers to both mechanical means as well as the engine control system.

ECR – Overrides are activated during maneouvering to keep the engines running even when alarm setpoints were activated
Mechanical system – engines are started on the local stand whenever there's a problem with them from ECR

Appendix 5. Questionnaire replies (10/10)

6. Engine efficiency and performance

Do You find it possible to improve operational efficiency of the engine itself? Please describe. This refers to engine structure and automation & control.

For now all I can think of is to strictly follow the PMS of the engine. Once the part is due for replacement it should be done. It's not a good practice to not do the job and just wait for the part to start giving problem or worse wait for its breakdown. One more thing is the monthly performance test of engine to see that each cylinder unit is still efficient. The cylinder pressure balance is one important goal to improve the engine condition, enabling more efficient combustion. Peak engine efficiency is another important goal targeted by maximizing the ratio of maximum combustion pressure (Pmax) over the compression pressure (Pcomp), and subsequently the mean effective pressure (Pmep) within acceptable limits. Increased engine efficiency leads to reduced fuel consumption and a cleaner engine with less carbon deposits in the cylinders and turbochargers, thereby reducing the maintenance cost.

Appendix 6. Splash-Oil monitoring system CUS224 (2/2)

Diesel Customer Information Kunden Information

Six years of operating experience with splash-oil-temperature monitoring

Cus 224 • 05/06

Experience

MAN B&W Diesel AG introduced splash-oil-temperature monitoring as safety system on engines in 1999 (see figures 1 and 2). Since then, this system was subsequently installed in more than 150 engines and is also used as standard safety equipment in our four-stroke Diesel engines since the end of 2002. During the 6 years of operating experience, the splash-oil system proved to be extremely reliable and required only minor maintenance. More than once, it saved the running gear from severe damage. The special advantage of the splash-oil system is that any disturbance in normal operation, which causes an oil temperature increase, is recognised reliably and promptly. The splash-oil system is unable to prevent disturbances in normal operation, it is, however, able to minimise the extent of possibly severe damage.

Reason

Although the splash-oil system proved to be absolutely reliable in practical operation, we had to note now and then that the importance of the splash oil emergency stop is underrated. No matter how efficient a system may be, it only works if alarms and stops are taken seriously and promptly responded to.

Measures

We would like to point out that in the case of an engine stop, triggered by the splash-oil temperature monitoring system, exact examinations have to be carried out by the operators until the cause for the emergency stop is found.

Recommendation

For engines, which are not equipped with the splash-oil system yet, we would be pleased to submit you an offer for the subsequent installation of this system. In this connection, please see our Diesel Customer Information CUS 175 issued in 2000.

Contact

Should you have any queries, please do not hesitate to contact our Technical Service Department which is always at your disposal:

MAN B&W Diesel AG
86224 Augsburg
Germany

Tel.: +49 821 322-1075
Fax: +49 821 322-3838
E-mail: service-augsburg@de.manbw.com

Please forward this information to your technical operating personnel

MAN B&W Diesel AG · 86224 Augsburg · Germany
Tel. +49 821 322-0 · Fax +49 821 322-3382 · E-Mail: service-augsburg@de.manbw.com

1/2

Appendix 6. Splash-Oil monitoring system CUS224 (2/2)

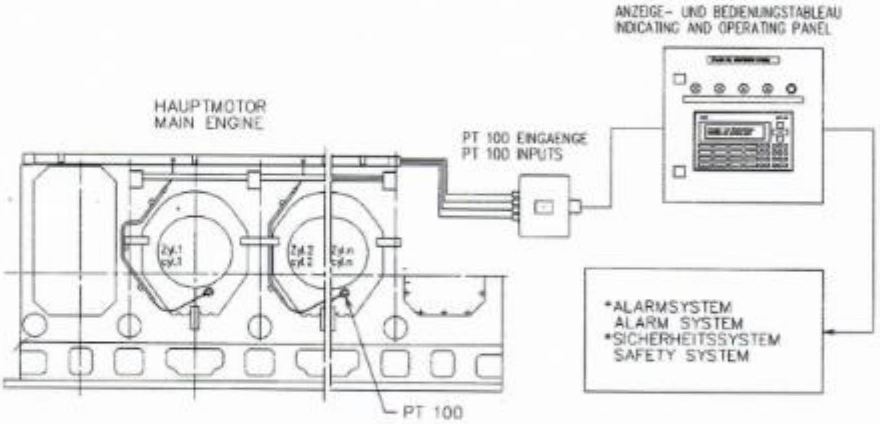


Figure 1: Splash Oil Monitoring System

Figure 2: Position of the temperature sensor in the crankcase cover