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DIEM - A digital engine management platform for performance assessment and CBM for LNG fleets

Digitalizatiion, Connectivity, Artificial Intelligence & Cyber Security

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ABSTRACT

The LNG transportation market is undergoing significant changes driven by evolving regulatory frameworks for decarbonization, and heightened competition due to an influx of new tonnage. These factors have prompted the need to rethink asset management strategies to enhance operational efficiency and revenue generation. In response, an engine condition-based maintenance (ECBM) scheme has been developed through a collaboration of propuslion analytics with a major LNG carrier shipowner to optimize the performance and extend the maintenance intervals of their fleet's dual-fuel engines.

The ECBM scheme leverages continuous, high-frequency data collection encompassing thermodynamical, mechanical, tribological, and vibration criteria to ensure optimal engine performance and utilization. Key components of the scheme include the use of a digital twin performance assessment tool, lubricant monitoring systems, and comprehensive intermediate physical inspections. The scheme is being implemented in the purpose made platform DIEM-Digital Engine Management. The primary objectives are to reduce CO2 emissions, increase cost efficiencies through better planning, and extend overhauling intervals.

This initiative aims to create an early warning system for engine deficiencies, enhance cost-efficiency through strategic planning, and contribute to Energy Management Systems and Ship Energy Efficiency Management Plans (SEEMP). The scheme has been submitted to a classification society for review and approval, ensuring compliance with class rules and requirements. By implementing the ECBM scheme in the platform DIEM, the shipping company seeks to maintain competitive advantage, improve asset reliability, and navigate the evolving LNG transportation market effectively.

1 INTRODUCTION

The evolution of shipping companies and vessel types illustrates a continuous adaptation to the demands of global commerce, new capital financing, technological innovation, and environmental challenges. Shipping companies often manage a diverse fleet of ship types and sizes which on one hand allows them to remain competitive and flexible in a dynamic industry, while on the other adds complexity to fleet management and operational planning.

For many years shipping companies used the ship's crew for engine maintenance. However, the complexity of modern marine engines, with automation, electronic control systems and high-performance components, requires specialized skills and knowledge, which the crew may not possess.

Over the years the maintenance of machinery has evolved from a reactive process, performed after a functional failure, to an operation time-based preventive maintenance activity, where items are overhauled or discarded according to a time-schedule. Time-based preventive maintenance uses a prescriptive approach with equipment maker derived assumptions of component useful lifetime, after which its failure rate increases sharply [1]. However, estimates of lifetime often have large uncertainties, especially in relatively low sales volume machinery found in ocean-going vessels. Hence, scheduled maintenance is often performed too early, resulting in higher costs due to unnecessary replacements, or too late resulting in functional failures. Even worse, a component that cannot be inspected from the outside is often disassembled and inspected on schedule, with the risk of introducing faults during inspection or re-assembly.

To reduce the uncertainty resulting from time-based preventive maintenance, new approaches, based on the assessment of machinery condition, have emerged, which are collectively known as Condition Based Maintenance - CBM [2]. The benefits of implementing a Condition-Based Maintenance strategy for ship-owners are related to cost savings, decrease of equipment downtime, improved engine performance and the predictability of operations. A system for remote diagnostics and predictive maintenance may result in substantial reductions of maintenance cost through extended maintenance periods and associated costs, with a parallel increasing the safety and reliability and reduced CO_2e emissions footprint. Cost savings are also related to improved equipment performance that may lead to decreased fuel consumption [3,4].

Since the 1990's several ship operators have opted for Performance Based Contracts offered by the engine makers. These long-term contracts, often at fixed cost similar to aviation "engine leasing schemes" [5], shift the responsibility of system maintenance and support from the operator to the OEM, who is paid for achieving metrics like availability and reliability [6].

This approach has obvious advantages in simplifying budgeting and operations, but also some downsides, mainly due to the potentially higher long-term costs. In striving to reduce such costs, a ship operator needs to optimize procurement of engine maintenance, inspections, overhauls, and spares. This approach requires in-house experience and knowhow, combined with access to advanced software tools and diagnostic applications for performance monitoring, assessment, and condition-based maintenance. Such tools, linked to other enterprise applications within the shipping company, should also be able to support a diverse fleet of ships and engine types.

This paper presents the development and application of a digital monitoring platform on the fleet of major LNG Carrier shipowner GasLog, with the goal of applying a novel CBM scheme. The main novelty of the presented approach lies on the combination of different, independent condition monitoring and diagnostic methods, with the purpose of increasing the fidelity of diagnostics improving the soundness of overhaul extension decisions. The paper starts with background on the drivers for the platform development, then describes the platform structure and the principle of operation. The paper ends with some first results from the application.

2 BACKGROUND

The global and disruptive factors in both LNG freight market as well as the shipping regulatory framework in combination with a commercially volatile market has triggered the shipping company GasLog to re-think the current ship management strategies, targeting to optimizing Total Cost of Ownership (TCO), and increasing the reliability of the equipment. Within this context, GasLog decided to develop an Engine Condition Based Maintenance (ECBM) scheme for various engine types fitted in its vessels with a two-fold target:

- ensure that the engine performance remains optimal at all loads and engines are properly utilized, thus reducing CO_2 emissions
- extend maintenance intervals in a risk-based approach ensuring a more flexible overhauling planning, adhering to the strict trading profile of LNG Carriers with possible coordination (or

decoupling from) with scheduled technical stoppages such as Dry Dockings.

In the past, such a service was only possible with the use of long-term spare parts and service agreements with OEMs, in which they had the complete liability for engine management. Within this scope, condition-based maintenance approaches were also utilized for prolonging overhauling intervals. However, for engines not in such contracts, such an extension of overhauling intervals has not been feasible.

In view of this, GasLog has decided to develop its own, “in-house” Engine Condition Based Maintenance Scheme combining competitive supply of all spares and services, with prolonged overhauling intervals that have been traditionally offered by OEMs only. This ECBM will be applicable to all main and propulsion engines in the GasLog fleet and its main targets are the following:

1. Continuous monitoring of engine condition and creation of an early warning system of deficiencies or underperformance.
2. Facilitation of a better planning and coordination in accordance with Dry Dockings, by combining the overhauling intervals into two major overhauls.
3. Increase of cost efficiencies through effective planning.
4. Input to GasLog Energy Management system and SEEMP for effective monitoring and reduction of CO_2 emissions.

3 DIEM PLATFORM STRUCTURE

Within the context above, Propulsion Analytics was contracted to develop and host a custom-built digital engine management platform dubbed GasLog Digital Engine Management Platform – DiEM, for the purpose of monitoring engine performance of GasLog’s vessels. This platform builds on Propulsion Analytics’ core Engine Hyper Cube® application, which performs continuous engine performance analysis using intermittent or high-frequency data from onboard engine sensors.

Within the GasLog DiEM Platform, continuous engine measurement data is sourced via Kongsberg Digital’s Vessel Insight Vessel-to-Cloud infrastructure. The DiEM Platform will further incorporate vessel data from several other sources, such as the GasLog Planned Maintenance System, engine lubricant analysis, vibration data, thermography data and water chemical analysis.

By synthesizing continuous engine performance analysis with insights from various other data sources, the DiEM Platform empowers a comprehensive view and assessment of the engine condition, allowing improved maintenance planning. Recommendations from Classification Societies (ABS, DNV) will be incorporated in the DiEM Platform development to satisfy Class requirements for condition-based maintenance.

The primary objectives of the DiEM Platform are:

- Enhancing Engine Availability: Developing advanced diagnostics and predictive maintenance strategies to improve vessel reliability and reduce engine downtime.
- Optimizing Fuel Efficiency and Minimizing Environmental Impact: Reducing greenhouse gas emissions through improved engine performance.
- Data-Driven Predictive Maintenance: The coupling of continuous engine performance monitoring, prognostics and optimized operation with long-term statistics and reliability-based engineering principles, will lead to a more flexible overhauling planning, in line with LNG carrier trading profiles and drydock schedules.

The DiEM Platform and the included ECBM methodology involves the integration of 4 parallel pillars of engine condition monitoring (see Figure 1). The first two (Pillars A&B) are continuous; Pillar A utilises high frequency performance data and a continuous engine performance evaluation application, while Pillar B includes onboard measurements and sampling/analyses performed at regular intervals. The other two pillars are: (Pillar C) endoscopic examination and cylinder tightness test, that will be performed by the vessel’s crew and the other (Pillar D) is the opening-up and overhauling of one cylinder unit complete and associated parts by an approved service team.

All data and analysis results, including photos, endoscopic videos and inspection reports are included in the DiEM Platform along with interlinks to entries from lubricant analysis and computerized maintenance management system. The analysis from each pillar is combined using expert insights and machine learning/AI methods, in order to be combined in a single indication of engine health. Using multiple diagnostic methods to arrive at composite results has the following benefits:

- Increased diagnostic quality, leading to positive predictive value.
- Increased diagnostic accuracy, leading to earlier detection of faults.

The sections below describe the different pillars in further detail.

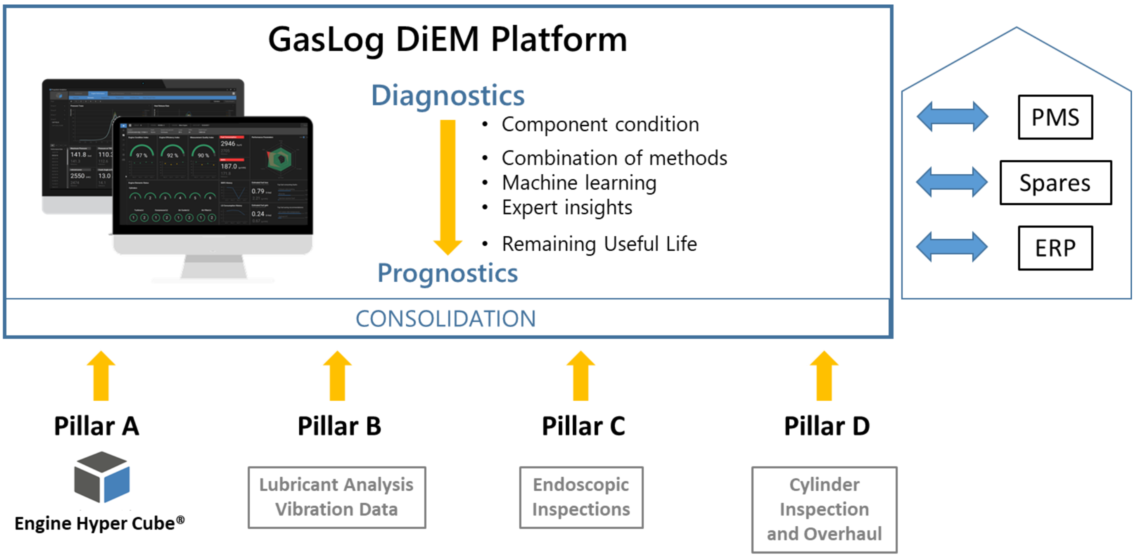

Figure 1. DiEM Platform Structure

3.1 Pillar A: Continuous Performance Monitoring using Engine Hyper Cube®

The continuous engine performance monitoring is performed using Engine Hyper Cube® (EHC) thermodynamic digital twins of each individual engine. EHC uses a detailed thermo-physical process model of the engine, custom-produced/tuned for each individual engine, which provides the "reference/healthy" engine performance for any possible engine operation setting, ambient conditions and fuel. The Engine Hyper Cube® can be applied to all conventional and electronic, 2 or 4 stroke, Diesel, Gas or dual-fuel marine engines.

Each EHC simulation model is built up and tuned separately. As a result, the model is a 'digital twin' of the actual engine in operation, reflecting the physical relationships of all primary parameters such as temperatures, pressures, rotational speeds as well as resultant values such as torque, fuel consumption, emissions etc. and internal parameters such as heat transfer, friction, etc. The ensuing specific engine model using the exact geometric characteristics of the specific engine, is calibrated using the recorded data from the engine shop tests and validated using actual measurement data [7,8].

Following the model calibration, Propulsion Analytics then performs a-priori a large number of simulations for combinations of all the possible engine operating conditions and settings. As a result, an engine hyper map is generated, which provides the "reference" values of all performance parameters at any operating condition (Figure 2).

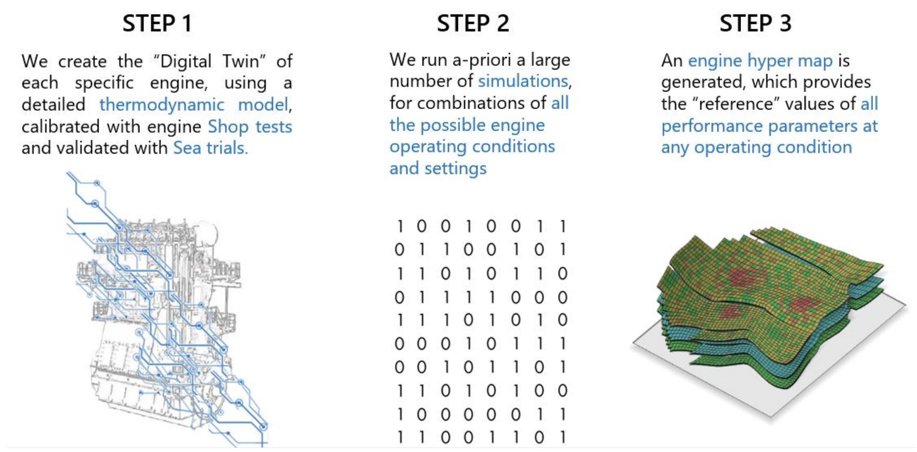

Figure 2. Engine Hyper Cube® creation steps

Finally, the engine hyper map database is utilized by the EHC software for the analysis, providing engine performance monitoring, fault diagnosis and optimization recommendations. The fault identification and diagnostics are performed by comparing engine measurement data collected from the vessels to the digital twin. Any deviation between real measurements and model values of the corresponding parameters as given by the digital twin at the same operating conditions, reliably leads to the engine status assessment. The digital twin can identify faulty/non-calibrated sensors and through advanced engineering rulesets, provides specific diagnostic findings along with actionable recommendations for each fault identified.

In the present case, the engine data is collected onboard through the Kongsberg Integrated Automation System (IAS) at a high frequency (1sec up to 1min), averaged to 5-minute data and transmitted ashore through Kongsberg Vessel Insight™. This data is made available to Propulsion Analytics through the Vessel Insight platform API (Application Programming Interface). This enables performance and consumption optimization along with trend monitoring and an early warning system based on the advanced fault detection algorithm within EHC.

The continuous engine data from the API is checked using a purpose-built vessel data filtering platform dubbed ADQM (Automatic Data Quality Management). ADQM checks data completeness and quality continuously, to ensure only high quality data is used for the engine performance analysis [8]. Within ADQM, measurement data quality is evaluated using four parallel evaluation methods:

1. Pre-processing (min/max and outliers): data is checked to be within pre-defined limits and to exclude abrupt changes in values
2. Engineering methods: engineering/physical relationships between measurements are used to check data validity
3. Statistical methods: Signals checked for long-term deviations (sensor drift or bias)
4. Machine learning methods: Signals are validated using outlier detection methods

Following the data validation, measurements are compared with the digital twin, with the residuals fed to a diagnostics ruleset. The diagnostics ruleset within EHC has been refined over the years, with applications on hundreds of installations, to discriminate between normal performance divergences due to outside conditions, versus abnormal behavior from incipient defects. In case of faults, the prognostic applications within EHC, provide predictions of the effects of gradual deterioration of performance over time and issue warnings and recommendations for inspection and repairs.

Prognostics of faults are made possible through extrapolation of observed measurement/residual trends, and the use of the digital twin for the analysis. The continuous data analysis process within the DiEM Platform is shown schematically in Figure 3.

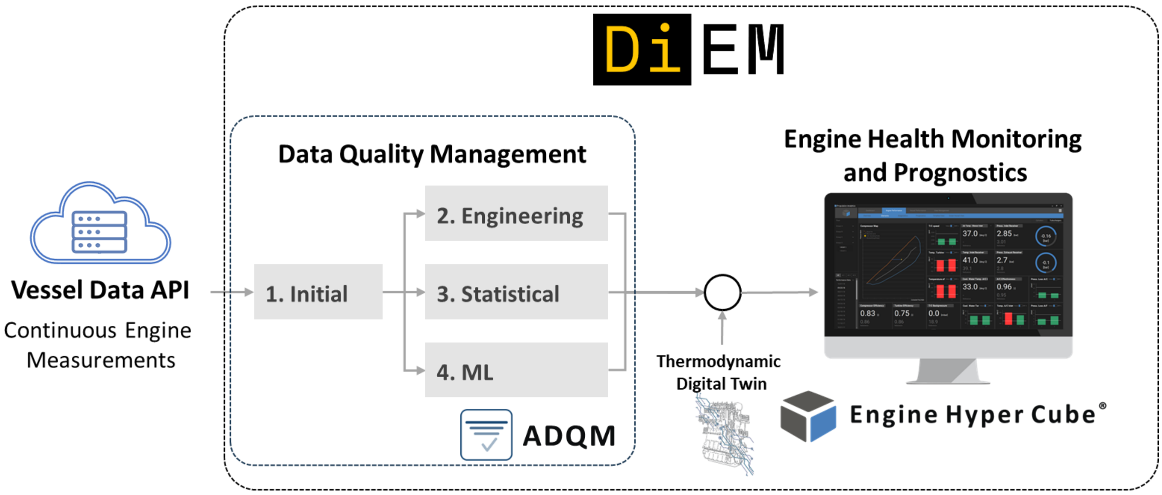

Figure 3. Schematic of Pillar A: Continuous Performance Monitoring using Engine Hyper Cube®

The following equipment can be assessed using Engine Hyper Cube®:

Table 1. Engine components covered by Engine Hyper Cube® and measurements utilised

Engine Component	Measurement
Cylinder, Piston, Piston Rings, Cylinder Cover, Intake/Exhaust Valves, Liner	Compression Pressure, Mean Effective Pressure, Max Pressure, Exhaust Gas Temperature, Crankcase Pressure
Fuel Pump, Fuel Injection Valve	Max Pressure, Mean Effective Pressure, Exhaust Gas Temperature
Gas Admission Valve	Max Pressure, Exhaust Gas Temperature
Main Bearings, Crankpin Bearings (Big End Bearings), Lower End Bearings	Bearing Temperature, Lube oil temperature
Turbocharger, Wastegate, Air bypass	Inlet/Outlet exhaust gas temperature, T/C RPM, lubricating oil temperature (inlet/outlet) etc.
Air Cooler	Intake Temperature, Cooler pressure drop

3.2 Pillar B: Lubricant and Vibration Analysis

Lubricant analysis and vibration monitoring methods are well-established for marine engine condition monitoring [9]. The DiEM Platform is to be connected through API to the Shell Lube Analyst [10] and GasLog Data warehouse for having all engine-specific lubricant analysis in the platform, cross-examine lubricant chemical analysis with operating temperatures in the crankcase, and store all historical data reports. The lubricating oil pressure are trended continuously from real-time sensor data, as well as the lube oil temperature. The above data, coupled with spot inspections, will enable Main Bearing overhauling extensions. The interaction of lube analysis and continuous performance monitoring is expected to provide a high-fidelity picture of the engine condition.

The DiEM Platform will also incorporate vibration data from continuous torsional vibration sensors, as well as vibration data from permanent 3-axis vibration sensors on turbochargers with the relevant expert analysis. The above aims to provide early identification of potential defects, improving reliability and further supporting decisions for overhauling extensions.

3.3 Pillar C: Endoscopic Inspections

Pillar C is comprised by the crew endoscopic inspections of each enrolled engine, which can be done on a regular basis. The crew endoscopic inspection scope includes the charge air cooler, cylinder cover, liner, piston, camshaft and crankshaft. In addition to the described endoscopic inspections, a cylinder pressure drop test (cylinder tightness as mentioned in makers manual) for all subject engine cylinder units will be conducted by the vessel's crew. From this test, the condition of the cylinder head valve and seats is crosschecked with data from Pillar A and validated. All Pillar C results are included in the DiEM Platform for ease of access.

3.4 Pillar D: Cylinder Inspection and Overhaul

The final decision for extending the overhauling is based on the results of the Pillar D which is the intermediate inspection and measurements. In this pillar, a team of engine service technicians will board the vessel, open up and overhaul one sample cylinder of each respective engine enrolled in the ECBM to validate condition and findings of the previous endoscopic inspection done by crew. Additionally engine alignment and main bearing clearances are going to be obtained. All inspection forms are included in the DiEM Platform for ease of access.

4 DIEM PLATFORM USER INTERFACE

The information from all pillars of the DiEM Platform is collected in a purpose-built user interface (UI). The UI hides the complexity and technical depth of the underlying engineering, mathematical, logical, and statistical calculations taking place in the background, so as to let the user to focus on the high value information.

The UI enables the user to monitor the fleet of vessels from a single dashboard, while also enabling in-depth investigations in data and diagnostics of all sub-systems. The UI follows two parallel structures:

1. Engines: here the user can navigate through all engines in the fleet, which are grouped into same engine family or same engine sub-types/models. The user can view performance and engine condition KPIs, faults per engine type/model, fault statistics and compare sister engine measurement data

2. Fleet/Vessels: the user can view groupings of classes of vessels, engines per vessel, and view performance and engine condition KPIs, faults identified and fault statistics

The user can follow either branch to drill down to the single engine level. The UI taxonomy is shown schematically in Figure 4.

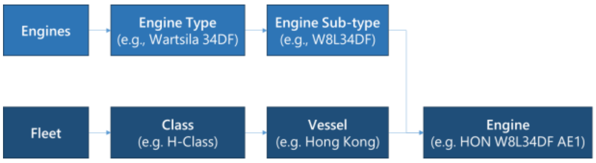

Figure 4. DiEM Platform UI taxonomy

On the engine level, the DiEM platform UI offers:

- high-level dashboard view of engine performance
- detailed diagnostics of possible engine faults together with recommended actions
- detailed diagnostics of possible sensor and/or measurement issues
- short-term and mid-term fault prognostics
- financial impact of faults and optimization options identified
- deviations from healthy state for a number of measured parameters
- detailed per-cylinder view and historical analysis on a number of engine parameters, as well as engine comparison between sister engines/vessels
- timeline view for all performance-related parameters
- in-cylinder pressure trace analysis

Figure 5-Figure 7 show exemplarily different views of the DiEM Platform UI.

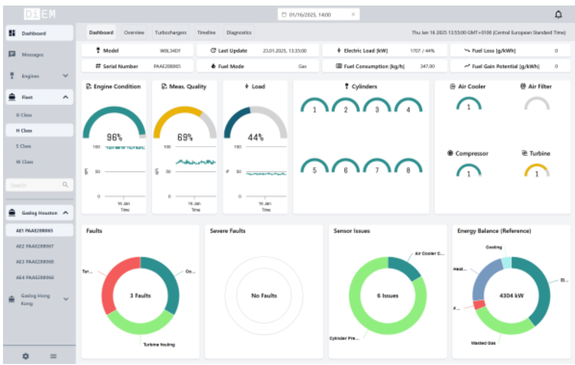

Figure 5. Engine dashboard, showing overall engine KPIs, individual component KPIs and active faults

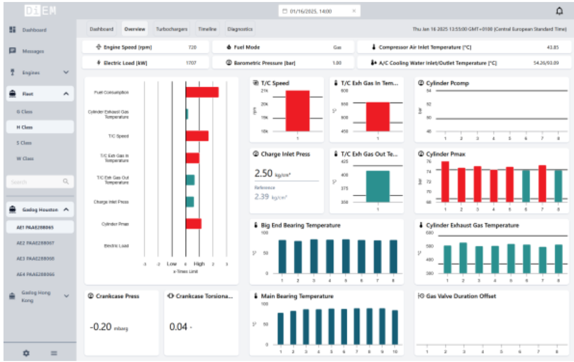

Figure 6. Engine performance parameters, showing a snapshot of parameters within and exceeding digital twin limits

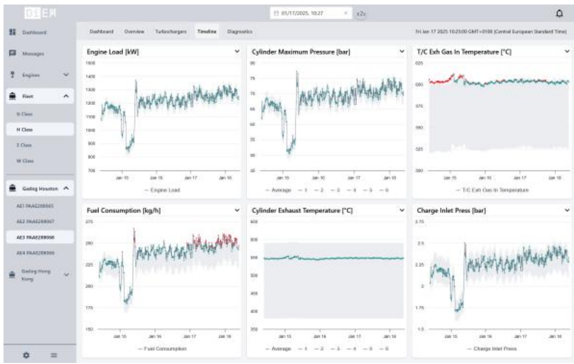

Figure 7. Engine performance parameter timeline, showing timeseries of parameters within and exceeding digital twin limits

5 DIEM DECISION PROCESS

The findings from the 4 pillars described in section 3 are combined for the determination of the engine health, and any decision concerning maintenance planning. The combination of the data is performed initially by Propulsion Analytics' experts, supported by engineering rulesets based on the input from GasLog experts – this combination of state-of-the-art performance monitoring tools combined with multi-year experience from GasLog experts is what enables this application. Final decisions for maintenance are taken by Propulsion Analytics' experts, based on all data evaluated – the decisions and underlying data are discussed with GasLog experts for each individual engine in monthly meetings.

Following the initial rollout of the DiEM platform, increasing decision-making and data evaluation/combination/screening processes will be covered by AI tools, specifically trained on the data produced by human experts. The focus of the AI tools is to increase accuracy and repeatability of decisions and reduce maintenance and service costs.

More specifically, Convolutional Neural Networks (CNNs), are being trained on past and new labeled endoscopic inspection images (Pillar C), in order to be incorporated to improve repeatability and reduce image processing cost. All data-based maintenance decisions taken by Propulsion Analytics' experts, are gathered and used to train decision-supporting algorithms (Gradient-boosted decision trees - XGBoost), in order to support decisions in the short-term and increasingly automate decisions in the medium/long-term.

In parallel to the maintenance planning support described above, all alerts arising from the Engine Hyper Cube application are sent to the shore technical team and crew for the specific vessel. This exchange is automated through the connection of the DiEM platform with the GasLog Planned Maintenance System, which enables the orderly exchange of information between the platform, Propulsion Analytics' experts and the crews. The connection of the two systems allows automated request of maintenance or inspection actions directly from the DiEM platform and receiving feedback on jobs completed by the crew.

6 INITIAL APPLICATION RESULTS

6.1 Past Fault Report Analysis

The starting point of the ECBM procedure was an in-depth analysis of service experience from overhauls conducted, as reported in the GasLog Failure Reporting, Analysis, and Corrective Action System (FRACAS). The FRACAS reports were grouped per system fault, and then cross checked with existing and adapted EHC rules for the particular cases, in order to ensure that all cases are captured by the diagnostics.

The FRACAS reports studied contained a total of 739 reported jobs on 32 engines in the GasLog fleet, out of which 214 were determined to be engine faults. Table 2 below shows the number of faults identified in the FRACAS reports for each component as well as which of the faults can be identified by the EHC application (EHC Rule).

The faults were also analysed in terms of their effect on engine efficiency. The estimation of the reduction in efficiency of the engines as a result of a fault is performed using the thermodynamic engine model used in the EHC digital twin; this model is used to simulate the performance of the engine with and without each fault, thus enabling the estimation of the effect of the fault on fuel consumption and CO_2 emissions. Such simulations have been conducted for all faults within EHC. The simulation results are tabulated and used within the application in order to quantify the increase in fuel consumption and emissions of any fault identified during engine operation, thus enabling improved maintenance decision making based on the actual effect of any fault on engine performance.

Table 2. GasLog FRACAS reports analysis: Number of faults found and fault EHC rules

Fault	No. of Faults	EHC Rule
Injection System Issue	48	Yes
Gas Admission Valve Issue	70	Yes
Turbocharger Issue	21	Yes
Air Cooler Fouling	7	Yes
Cylinder Compression Issue	18	Yes
Cylinder Pressure Measurement Issue	16	Yes
Wastegate Issue	9	Yes
Air Bypass Valve Issue	4	Yes
Combustion Issue	1	
Gas System Issue	1	
Oil Analysis	6	
VIC Issue	1	Yes
Sensor Issue	12	Yes
Total	**214**	

For this investigation, the severity of each incipient fault was chosen from experience from past observations in similar installations. The fault severity is depicted in terms of the variation in a significant measurement parameter – e.g. a fault in the wastegate controller is depicted in terms of the effects such a fault will have on engine intake pressure. Each simulated fault results in a reduction in engine efficiency and a corresponding increase in engine specific fuel consumption (in g/kWh) and CO_2 emissions (in %). The results of the investigation are summarized in Table 3.

The simulated results were also used to estimate the effect of incipient faults on total fuel consumption and CO_2 emissions in different GasLog installations. To achieve this, it is assumed that in the absence of an advanced monitoring system such as EHC, each incipient fault remains undetected for a period of time, resulting in an increase in fuel consumed and emissions emitted over that period. For the present investigation the following assumptions are made:

- Each incipient fault remains undetected and active for 2 months (60 days), as opposed to detected instantly using EHC and rectified.

- During this 2-month period, the impacted engine runs continuously at a constant load, which varies depending on the application:
    - 4MW Auxiliary Generator Engines operating at 50% of the Maximum Continuous Rating (MCR)
    - 12MW Main Generator Engines operating at 75% MCR

Using the simulated effect of faults, the total benefit of EHC continuous monitoring system from identifying incipient engine faults is estimated in terms of both fuel efficiency and CO_2e emissions (Table 4).

For assessing the total footprint savings, the instances are multiplied by the reductions of each fault and then extended to all engines in the GasLog fleet, to calculate fleetwide reductions of consumed fuel and emitted CO_2 annually. The findings (in tonnes per annum) shown in Table 4 highlight the importance of early identification of faults for both fuel cost and CO_2 reduction.

Table 3. Simulation results for effects of incipient faults on Specific Fuel Consumption (SFC) and CO_2 emissions

Fault	FRACAS Fault Instances	Effect on measurements	Effect on Significant Parameter	Effect in SFC	Effect in CO_2
Cylinder Compression Issues	18				
Exhaust Valve Closing Issue		Lower Pmax, higher Texh	P_comp: -3%	+1.1 g/kWh	+0.73%
Inlet Valve Closing issue		Lower Pmax, higher Texh	P_comp: -3%	+1.1 g/kWh	+0.73%
Piston Blow-by		Lower Pmax, higher Texh, higher crankcase pressure	P_comp: -3%	+1.1 g/kWh	+0.73%
Turbocharger Issue	21				
Turbine fouling		Tin vs Tout, TC speed, TC efficiency	Turb_eff: -3% eff	+1.25 g/kWh	+0.83%
Compressor fouling		P_in, TC speed, TC efficiency	Compr_eff: -3%	+1.3 g/kWh	+0.87%
Wastegate Issue	9	P_in, TC speed	P_in: -5%	+1.5 g/kWh	+1.00%
Air cooler fouling, air side	7	AC P_drop	P_drop: +6%	+0.3 g/kWh	+0.20%
GAV tuning/faults	70	Pmax, T_exh, GAV offset	P_max: -3%	+0.2 g/kWh	+0.13%
Injection System Issue	48				
FIV issues		Lower P_max	+6deg SOI, 0.8g/kWh	+0.8 g/kWh	+0.53%
Fuel Pump issues		Lower P_max	-5% Pmax, 0.35g/kWh	+0.35 g/kWh	+0.23%

Table 4. Total benefit of early identification of incipient faults on Auxiliary and Main 4-stroke generator engines

	4MW Auxiliary Engines		**12MW Main Engines**	
Issue	**Fuel Saved (tn/a)**	**CO_2 emissions Reduced (tn/a)**	**Fuel Saved (tn/a)**	**CO_2 emissions Reduced (tn/a)**
Cylinder Compression Issues				
Exhaust Valve Closing Issue	3.9	9.1	15.9	37.3
Inlet Valve Closing issue	3.9	9.1	15.9	37.3
Piston Blow-by	3.9	9.1	15.9	37.3
Turbocharger Issue				
Turbine fouling	4.4	10.3	18.0	42.3
Compressor fouling	4.6	10.7	18.8	44.0
Wastegate Issue	5.3	12.4	21.6	50.8
Air cooler fouling, air side	1.1	2.5	4.3	10.2
GAV tuning/faults	0.7	1.6	2.9	6.8
FIV issues (Fuel mode)	2.8	6.6	11.5	27.1
Fuel pump issues (Fuel mode)	1.2	2.9	5.0	11.9

6.2 Pilot Application

In the initial stage of this project and prior to full deployment, between September 2023 and March 2024, it was decided to perform a 2-step field assessment of Engine Hyper Cube®; in a first phase EHC would be tested with manual data input, before the full test of the application using high-frequency data. The vessel chosen for the pilot application is powered by twin dual-fuel 2-stroke main engines and four dual-fuel 4-stroke auxiliary engines. The vessel was already connected through the Kongsberg Vessel Insight platform; additional high-frequency engine measurement data was harvested from the IAS system of the vessel and connected to the Engine Hyper Cube® cloud server via API.

In the first phase, the application was evaluated using static, manually obtained engine data by crew measurements on the existing GasLog engine performance measurement form. The purpose of this initial test was to test EHC outputs, diagnostics and graphical user interface. Then, using high-frequency data would allow the test of the Engine Hyper Cube® algorithm in dynamic conditions and high volumes of data.

Already at the initial stages of the application, EHC® was able to diagnose an issue with a wastegate fault on one of the Auxiliary engines, which led to a 5% drop in engine intake pressure. This diagnosed fault, which was verified by the onboard crew, was persistent over a 5 month period and was only rectified after its identification using Engine Hyper Cube®. Rectification led to an estimated 1% reduction in fuel consumption and corresponding CO_2 emissions.

In the second phase, the overall functionality of the Engine Hyper Cube® was further assessed during a 2-month high frequency data trial. Results indicated that despite high volume of data and calculations, the code remained robust with no computing or lagging issues observed. Furthermore, the diagnostics capabilities of Engine Hyper Cube® have been validated.

During this phase the data acquisition flow was further optimized by Propulsion Analytics. A compromise between immediacy of diagnostics and computational resources was found, with the final application using 5-minute average values to run the diagnostics; the averages are computed within the Kongeberg digital Vessel Insight application from sensor data ranging from 1-0.0167Hz, and delivered to the Engine hyper Cube application via API. Along with the 5-minute average value, the API also provides min and max values for the period, as well as sample count; these parameters enable the evaluation of the signal quality.

7 CONCLUSIONS

A key element of the GasLog strategy is the optimization of the Total Cost of Ownership for its engines and assets. This includes the Lifecycle maintenance optimization made possible through a formal Condition Based Maintenance regime that will include continuous performance monitoring of the engines enrolled, in line with Classification Society requirements. Within this concept, the GasLog Asset Integrity team has developed, in conjunction with the technical software producer Propulsion Analytics, the Digital Engine Management DiEM Platform to provide:

- Engine Performance Monitoring: Continuous monitoring of engine performance with high-frequency data and a state-of-the-art thermodynamic digital twin model.
- Engine Condition Based Maintenance (ECBM) Scheme: overhauling interval combinations and extensions in line with the engine's actual condition.
- Fault Pattern Recognition & Early Warning System: With the use of powerful diagnostics, detect patterns leading to engine underperformance and faults in advance and before fault occurrence. Early detection leads to improved overall performance and CO_2 emissions reduction
- Overhauling Forecasting: Automated forecasting of spares and services, subject to actual component condition with advanced prognostics, determining the actual overhauling scope of the engine.
- Enhanced Troubleshooting Capabilities: Realtime key engine parameters monitoring along with advanced diagnostics with Automated Performance Reporting to enable faster and more efficient troubleshooting.
- Engine KPIs: Fleet engines Key Performance Indicators dashboards to ensure that a holistic overview of the engines' health at any given moment.

The DiEM Platform is presently incorporating the various pillars for both continuous and periodic monitoring, linking to external services, in view of gradual application fleetwide.

8 DEFINITIONS, ACRONYMS, ABBREVIATIONS

ADQM: Automatic Data Quality Management Platform

AI: Artificial Intelligence

API: Application Programming Interface

CBM: Condition-Based Maintenance

CO_2e: CO_2 Equivalent

DiEM: Digital Engine Management Platform

ECBM: Engine Condition-Based Maintenance

EHC: Engine Hyper Cube®

FRACAS: Failure Reporting, Analysis, and Corrective Action System

FMEA: Failure Mode and Effects Analysis

IAS: Integrated Automation System

IDM: Inspection Dependable Maintenance

KPI: Key Performance Indicator

LNG: Liquified Natural Gas

MCR: Maximum Continuous Rating

OEM: Original Equipment Manufacturer

PMS: Planned Maintenance System

SEEMP: Ship Energy Efficiency Management Plan

SFC: Specific Fuel Consumption

TCO: Total Cost of Ownership

UI: User Interface

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