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AUTOMATED SYSTEM FOR FLEET BENCHMARKING AND ASSESSMENT OF TECHNICAL CONDITION

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ABSTRACT
On-board Energy systems in vessels have to use fuel efficiently to maintain ship speed at lowest possible costs. This paper describes how to use ship operational data to improve and maintain efficiency of the vessel's power production with respect to the condition and performance of equipment. The paper describes an overview of an automated Technical Operations Performance (TOP) Monitoring service. TOP monitors the performance of marine main and auxiliary diesel engines by use of the information collected onboard vessels at regular intervals. Performance data are stored in xml-reports sent as email attachments from ship to shore. This communication is reliable and cost efficient for merchant ships that are on-line only for shorter periods. Load, ISO and environmental corrections make results valid for benchmarking and trending. The service aggregates the hierarchical information obtained from different sources by transferring measurement readings into unified indicators, the Technical Condition Index (TCI) [1]. Experts manually check the automatically generated performance reports and add additional guidance on options to improve power production and machinery conditions analyzing the available data with respect to different targets, such as low engine degradation and high fuel efficiency. The performance reports then influence business processes indicating possible causes for loss of performance in equipment and possible erroneous instrumentation, and the need for maintenance actions. The obtained TCI values show the performance of individual units, or for a fleet/class of equipment and vessels.

ABBREVIATIONS

AHP	Analytical Hierarchical Process
EU	European Union
IMO	International Maritime Organization
KPI	Key Performance Indicators
MIP	Mean Indicated Pressure
MRV	Monitoring Reporting and Verification
OCIMF	Oil Companies International Marine Forum
SEEMP	Shipboard Energy Efficiency Management Plan
SFC	Specific Fuel Consumption
SFOC	Specific Fuel Oil Consumption
TCI	Technical Condition Index

[1] Earlier MARINTEK, SINTEF Ocean from 1st January 2017 through a merger internally in the SINTEF Group

TMSA	Tanker Management and Self Assessment
TOCC	Technical Operations Competence Centre
TOP	Technical Operations Performance
TeCoMan	Technical Condition Manager
VIT	Variable Injection Timing

INTRODUCTION

There is tonnage surplus in most segments of the shipping industry. Only ships that operate in the most effective manner will therefore sustain the current environment. Charterers will demand fuel efficiency. Those owner/managers that can demonstrate control and document specific fuel consumption, SFC/SFOC, as well as other verification documents may have a better chance of getting hire in the spot market.

In order to minimize operational costs it is essential that assets maintain good performance levels under a wide range of conditions and environments. This is particularly valid in the shipping, where the industry continuously works to improve profit margins.

In 2004, researchers and ship owners together established the project Technical Operations Competence Centre (TOCC). The TOCC mission was to improve the utilization of vessels' technical operational data and ship-shore interaction. The main purpose of TOCC was to establish a mechanism to improve the energy efficiency of ship operations and link that to a broader corporate energy management policy.

TOCC implemented a methodology focusing on the technical condition of equipment. There was a conviction that through systematic analysis and aggregation of data, availability would increase and costs would decrease. Reductions in fuel consumption also reduce CO_2 emissions and thus have a positive environmental effect. Information from different on-board systems would support this objective, though they missed the capability of integration of information from these systems, aggregation and benchmarking. The focus was to improve the monitoring and follow-up of main and auxiliary engines based on regular performance tests. The tests run at monthly intervals should lead to dimensionless key performance indicators enabling the benchmarking of vessels with different size and machinery.

Technical Condition Indexing (TCI) has successfully applied the concept to different areas [2] and developed the software tool TeCoMan (Technical Condition Manager), for collecting data and processing the TCIs. The project developed a method to assess a quantitative measure of a plant's technical condition, taking into account long-term degradations and influences of operation and maintenance. Condition data is in a hierarchy systematically aggregated from the lowest equipment level up to the top node, plant level, and gives a holistic overview of the plant.

TeCoMan was the tool used to process the underlying concept in TOCC. Its functionality has since then improved significantly, also during the TOCC project. TCI models were implemented for both main- (mostly two-stroke) and auxiliary engines (mostly four-stroke) to demonstrate the concept. Figure 5 gives a simple example of some of the information and the functionality that the TeCoMan software aggregates and presents.

The initial stage of the TOCC project included ship speed and consumption analyses but the project decided that further development should come at a later stage due to the complexity of the matter. The project stored data for speed and consumption analyses for later use. This subject has now developed by use of complex data analytics in the Norwegian "Smart Maritime" center, [6]. The important point of view was to demonstrate how the concept of TCI employed in a software tool could improve the performance of ships and make them stay on the top in this respect. The typical processing is as in Figure 1.

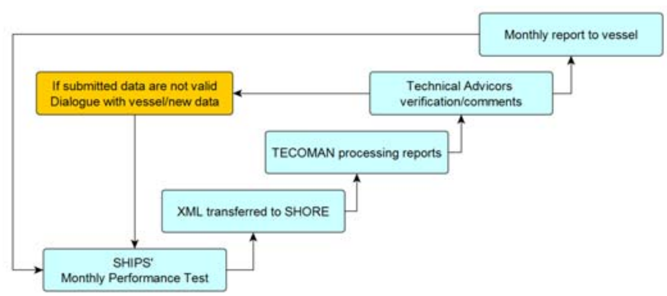

Figure 1: Reporting Process

The first results were promising the analyses were useful together with fuel analyses from laboratories. An important part of the work is to integrate the analyses in a holistic approach of awareness for corrective actions inside the ship managing businesses. Figure 4 shows some of the means used to implement the process for ship owner/managers. For such services to obtain good results they need to keep instrumentation calibrated and engine performance optimized. The way of monitoring and follow-up of ships performed in TOP/TOCC has been a useful stage towards more shore based monitoring and collaboration between ship and shore. This communication between ship and shore contributes to development of best practices that improve engines efficiencies and keep their performance reliable by proper and systematic observation and reporting that maintain their condition. Shore based monitoring is seen as a crucial part when vessels become more remotely controlled and even autonomous in the future. The TOP concept could be an integral part of IMO's Shipboard Energy Efficiency Management Plan, SEEMP [8], for ships and similarly the OCIMF's Tanker Management Self-Assessment, TMSA [9]. Recent developments in legislation and reporting requirement represent new challenges in ship operations demanding more monitoring, reporting and verification, MRV, by IMO [10] and EU [11].

TOP Monitoring could contribute to satisfy legislation and reporting requirements for better control of ships in operation by following up and documenting performance and assist in identifying possible improvements. The remaining chapters explain the TCI methodology, its application to marine diesel engines and the process of utilizing the results inside a ship owner company.

THE TECHNICAL CONDITION INDEX (TCI)

The concept of a technical condition index denoted TCI developed during 1996-1999 [1]. TCI aggregation uses a hierarchic structure from smaller objects at the bottom to the plant level at the top. SINTEF Ocean has published the concept for supervising the technical condition of complex process plants by use of TCIs in different contexts [3], [4], [5].

The capability of TCI is different from many other key performance indicators (KPIs) as budgets, regularity, accident and incident statistics are often lagging. I.e. they first give an alert long time after the technical system has degraded. Technical condition indexes alert management at an earlier state [2].

The Technical Condition Index defines the degree of degradation relative to the design condition. It takes values between minimum and maximum values, where the maximum value describes the design/ideal condition and the minimum value describes the state of total degradation.

The design condition is given the value 100, i.e. if a component obtains the TCI = 100 this means the condition is similar to when the component was new. The value of total degradation is equivalent to the TCI = 0.0. In TOP Monitoring TCI is an index that represents the overall performance of the engine based on Sea Trial conditions when the engine was as good as new and operated as good as it was meant to be.

The methodology basis is hierarchical aggregation of “Technical Condition Indices”, TCIs that are obtained from a set of initial measurement values. At the lowest level, the measurement values transfer into TCIs using a set of user defined transfer functions. These functions may combine several measurements or just use a measurement as-is, e.g. a temperature. To obtain TCI values at higher levels, sub level TCIs are aggregated using aggregation functions. In the TOCC application of the TCI principle, the aggregation functions have used weighted sums in each level of the hierarchy. Application experts have set the weight factors based on their knowledge of the supervised process (main engine and auxiliary engine). A more formal approach may assign weights like the “Analytic Hierarchy Process" [6]. AHP reduces the complexity of assigning relative weights by pairwise comparison. In general, the TCI aggregation does not put any restrictions on the aggregation functions in terms of algorithm so it is possible to investigate other principles.

In short, the configuration of a system to utilize the TCI methodology consists of the following steps:

- Establish a hierarchy sufficiently representing the actual system (main engine, auxiliary engine).
- Assign relevant input sources to the leaf nodes holding input functions as shown in Figure 2, define eventual normalization functions and configure appropriate transfer functions.
- Choose relevant aggregation functions for intermediate nodes according to their sub-nodes' criticality in the current context (environmental impact, availability etc.)
- Analyze a node’s TCI and assign an algorithm to obtain status value to it based on TCI trending and/or absolute TCI value.

Figure 2 outlines the calculation process. Status values serve as a quick indicator by performing an automated analysis of TCI trends and absolute values. Three states are displayed, namely red (alarm), yellow (alert) and green (ok).

One system hierarchy definition is possible to apply in several contexts to follow-up several properties of the system with respect to efficiency, environment, degradation etc. I.e. the system hierarchy is the basis structure for different performance/conditions hierarchies that follow-up of the systems'. As an example, it is interesting for the ship manager to both follow up on the energy efficiency of the engines and the degradation of them. Deviations in efficiency and degradation indicate deviations in costs that is of interest to investigate. Active use of the TCI creates profit for the user finding/comparing high and low performers by investigating/changing the causes for this.

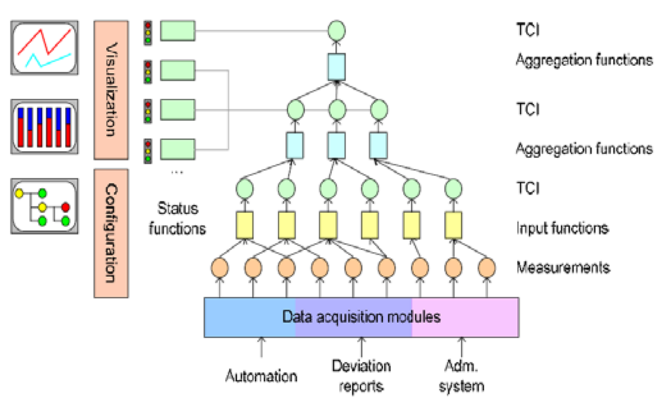

Figure 2: Aggregation of TCIs

There are several ways to acquire data from systems such as automation and monitoring, from deviation reports or from other administrative functions. One main point of view is that it is important to validate the data, and preferably, at the source to avoid unnecessary distribution and possible confusion based on erroneous data.

Modern ships are capable of providing a prodigious amount of data. Therefore, it is essential that ship operators require and implement information systems that present the data in a condensed way, and that rational tools are available that give the ship crew and on-shore support teams intelligent guidance.

It is of great value to apply the principles of TCI to follow-up different behaviors systematically and automatically. These behaviors can be like fuel usage relative to engine power, power usage relative to speed, power usage relative to trim etc.

The TCI becomes even more useful when complexity increases with more instrumented systems for sensing, monitoring and diagnostics. The TCI can be a contributor to provide decision support from complex analytics, and integrate ship and shore-based resources in a better way while reducing crews.

SHIP ENGINE PERFORMANCE CALCULATIONS

It was a target for the TOCC project to avoid the need to use additional software on-board the ships or onshore to follow up the conditions of the engines. One reason for this was to enable ships to obtain data without complications and cost to collect information from proprietary data formats. However, today it is a stronger demand that suppliers make data from their systems available for solutions that generate holistic views on the operations. Hence, the data from engines are manually from the instrumentation already available onboard and entered into an Adobe form, which can be filled in easily as the Adobe software is typically already installed and in use. This software can import data from e.g. xml when on-board systems offers this, which makes it possible to avoid manual registrations. Data validation and check of important correlations among parameters on-board by using the form removes erroneous inputs. Figure 6 shows one page of this form. By sending emails, data transfers from ship to shore with data attached as xml documents. Similarly, the crew on-board gets their feedback in Adobe reports showing the performance and condition of the engine together with hints regarding causes for the deviations.

Low TCI-values can originate from bad performance, defective instrumentation or result of wrong registrations. In order to have a good basis for performance monitoring it was important to emphasize the need for sufficient instrumentation to follow-up and improve the performance of the engines. At the time, when the project started in 2004 many engines where not equipped with torque meters. Similarly, many ships where not equipped with good quality fuel flow meters. These instruments are important investments to progress towards success in following-up energy efficiency of ships. The Mean Indicated Pressure (MIP) calculator is also essential as it will reveal the performance of the individual cylinders and in many cases contribute to find the root cause of performance losses. The instrument reveals the internal pressures in the different cylinders when pistons move as the crankshaft turns 360º.

To get an overall acceptable data quality, different engine power calculations use different sources like readings from shaft torque meter, MIP calculator and other indicators for validation. It is important to check correlations between instruments to prevent that instruments in bad condition do not contribute to erroneous analyzes of the engine condition. Erroneous instrumentation may confuse an operator. An important aspect to mention in this context is that engines have been equipped with temperature and pressure sensors for safety reasons. Some of these sensors have a tendency during time to provide less precise values. This does not matter so much as they are accurate enough within the safety limits. When the same sensors are used to follow-up energy efficiency it becomes a problem, as they then need to be more precise to provide value. Hence, when starting using a setup of sensors placed on an engine for safety reasons and they have been in operation for some time, they might need replacement for provision of data good enough to follow-up energy efficiency. The fuel's heat value and ignition properties are of vital importance, high quality fuel testing, and analyzes are essential.

Full-scale operational data influenced by complex inputs from sea and wind conditions make them more difficult to analyze than data from shop/laboratory tests due to the inherent uncertainties in the data. Hence, the data handling is a common challenge for shipping companies that want to analyze with more precise results than obtained earlier. Thus, the thought was that by applying experience, methods and tools on collected data from a number of shipping companies in a systematic way the competence and results should improve.

To assess specific fuel consumption (SFC) maximum pressures (pmax) for a short period is a good indication, and many times better than SFC with input from inaccurate fuel flow meters. A rule-of-thumb is that a 2-stroke slow speed propulsion engine uses 1 % extra fuel when pmax is 5 bars below the expected value relative the engine load.

To increase the competence on-board and on-shore, the concept stimulates for an educational dialogue with the ships for better data and analysis that includes expert evaluations mad by technical advisors on shore, in addition to auto-generated comments for technical support.

The operational data analyses are based on the principle of comparing the current condition of an engine and the input from the vessel, with the state when the engine was performing under optimal conditions; e.g. sea trials, shop test and speed tests. Operational conditions gives variation in performance that is possible to correct. E.g., mean effective cylinder pressure for an engine increases when a vessel with fixed pitch propeller increase its draft but still operates at the same rotational frequency (rpm). Similar will the relation between power and rotational frequency of the engine indicate the resistance on the ship and the load on the engine.

The measurements transform into index values that represent the main engine and its sub-components in a tree structure. Analysis of these data determines the Technical Condition Indices (TCI) of the engine in three dimensions, Efficiency, Balance and Degradation:

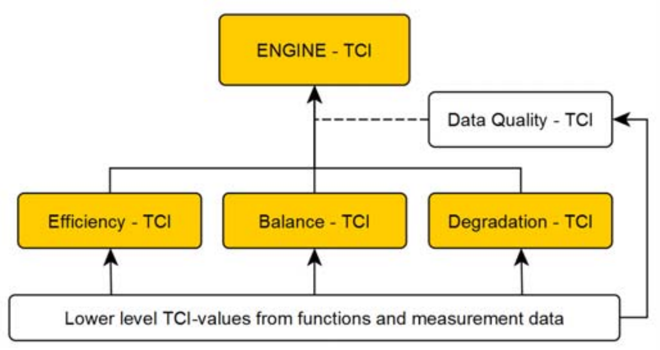

Figure 3: Engine TCI-values

- Efficiency assesses how well the engine converts fuel energy to shaft power.
- Balance compares readings from equal units like fuel pumps, cylinders, etc. to determine to which degree these units perform equally.
- Degradation assesses wear-out, clogging, etc. of systems/components

The aggregation hierarchy was developed and validated in TeCoMan based on internal project discussions on how to use measurements from engine performance tests. The model hierarchy and formulas was after a 3 years period with data from different ships finalized.

Performance assessment is carried out by comparing data from the vessel's monthly performance reports with a data set where the performance was optimal (i.e. Sea Trial).

The vessel's sea trial data registered in a computer model produces the TCI model (usually performance at 75, 90 and 100% load creates the model). These data named "static data" are systematics used to set up the model. The static data provides an xml that auto-configures the performance model for the engine in Tecoman, that at regular performance tests later on will use the model for comparison with ideal performance.

The model is by a vessel specific registration form supported. A form sent to the vessel for registration and validation of data. The vessel submits the engine data by e-mail every month. The submitted data is into a preliminary report processed.

The TCI calculations correct for ambient conditions, use ISO standard heat value, 42.7 MJ/kg, [12], and to 85 % load/power so that results are useful in trending and benchmarking of performance for tests taken at different times and loads.

The Technical Condition Index (TCI) range from zero to 100. When the TCI is 100, this considers performance equal with sea trial. The performance is easy to interpret due to standardization of the status of the TCI values as follows:

- Red 0-80 "Follow up recommended"
- Yellow 80-90 "Attention"
- Green 90-100 "OK"

If a red status occurs for lowest level TCI-values, reports comment possible causes and follow-up to improve results.

The performance data assessed and presented in the report is valid for an engine load of 85% (MCR) even though the engine load was different during performance tests. As an example, recording of an exhaust temperature reading at 90% load, a lower temperature is calculated and stated in the Main Engine Report adjusting it to 85% load.

Status will be green for a ship on a "good course" on the upper hierarchy levels TCI-Efficiency, TCI-Balance and TCI-Degradation, i.e. this indicates that a ship continuously does proper maintenance.

As technical advisors are looking at the automatically generated reports based on the data sent by the ships they get an impression of the current state of the ship's engine and compare it to the new (or modified/improved) state. The technical advisors add manual comments and store these to collect experience and develop competence for later use.

By evaluating the TCI trends and customized recommendations for continuous improvement, crew on-board ships initiate maintenance tasks. It has been important during the development of the tool that the service is not perceived as a control tool from office to ship but a support to their work, and to team up with the chief engineer as a partner and have a person-to-person dialog. This demonstrates to the engine crew that there are actually people ashore that follow-up the value in their work.

In order to have a good dialogue between ship and shore, technical advisors should avoid unnecessary scientific language and terms/expressions, to avoid possible contribution to confusion/irritation and misunderstanding. Similarly, Chief Engineers are encouraged to provide comments and feedback to the technical advisors. In this respect, the monitoring guideline booklet is also of support to clarify the systematic use of data and the encouragement to dialogue.

This monitoring contributes to ships' energy efficiency and maintenance plans and to their SEEMP objectives. The crew establishes a baseline for energy efficiency in order to determine improvement goals, from which, plans and actions all grow. In other words, they identify improvement potential and how much they can save and just as importantly, what initiatives they need to undertake to realize the improvements. They then put a plan into action and track performance using a variety of established systems/processes to help overcome resistance to 'new' initiatives using the TCI. This paper focuses only on use of TCIs to follow-up diesel engines, but the concept is general and possible to extend to any equipment onboard to follow-up properties as demanded.

To use SEEMP and TCI properly together they should regularly be evaluated/updated. By use of TCI, it is possible to obtain references for realistic development/targets from benchmarks/results from sister vessels, or defining how close to ideal condition the vessel should be. Hence, the results/progress of different improvement initiatives are by responsible persons/department regularly followed. This will harmonize the assessment of performance used to modify future goals and implementation tactics. In such a context, it is suitable to use monthly reports as the periodization to follow-up the engines/ships as a user-friendly method/tool for performance assessment to communicate main engine condition between ship and shore, and to give time for maintenance before next assessment based on TCI-values.

EXPERIENCE

Experience with TOP over the years with approximately 1000 performance reports from approximately 30 ships show that engine performance monitoring in average:

- Reduces fuel consumption with 1-2 percent due to better maintenance and tuning of 2-stroke engines
- Increases awareness/energy-culture among crews

There have been incidents with savings of up to 5% due to the installation of the TOP Monitoring system. TOP has identified equipment, which had been faulty for a long time such as a clogged charge air cooler and malfunctioning Variable Injection Timing (VIT) system.

Some typical examples listed below of how the system has contributed to improve engine maintenance, operations and cost based on VPS collection of experience.

Wrong T/C filters
Three sister vessels were identified using the wrong type of filters on the Turbochargers, significantly restricting airflow. These filters installed several years ago, by replacing these filters with the correct filter type the owner estimated a SFOC reduction of 1.5 – 2%.

Clogged air cooler
TOP Monitoring identified improper temperature relations that led to the discovery of clogged (corroded) charge air cooler. Repairs carried out and SFOC significantly reduced by 5%.

VIT malfunction
TOP Monitoring identified a drop in pmax of more than 10 bar, low compression pressures and that the VIT was not working properly. A locked control valve stated as the cause in MAN B&W's service report. The VIT repaired and SFOC reduced by 2%.

Wrong cylinder oil feed-rate
TOP Monitoring focus attention on cylinder oil feed rate. The vessel reported feed rates in the range of 1.8 to 2.3 g/kWh. By repeatedly commenting this excess cylinder feed rate the vessel and the superintendent reduced the average feed rate to 1.3 g/kWh.

Broken air cooler
Air cooler interior was broken without systems detecting the malfunctioning, before TCIs revealed it as an unacceptable condition.

CONCLUSIONS

Due to increased complexity in on-board systems, next generation ship operations must develop and use better technology and procedures to follow-up new regulations. The TCI principles can be very useful also in that context.

By combining the extensive experience in safe and sustainable ship operations and in-depth marine fuel quality knowledge from research expertise TCI is a powerful tool that delivers several benefits:

- Reduction in fuel consumption
- Savings in maintenance costs
- Reduction of off-hire costs
- Improved safety
- Relate fuel quality testing to engine performance and maintenance
- Increased TMSA rating

- Benchmarking of individual ships and within fleets
- Independent third-party performance assessment

The old saying “You can’t control what you can’t measure” is of vital importance and the keyword in this context is “precision”. Without accurate measurements from equipment, it is not possible to analyze its performance. Hence, it is worth investing in proper instruments and training of crew to obtain the most accurate data as possible to be successful.

Results reveal loss in ship/engines efficiencies and degradations and necessary actions to improve operation. In several cases, ships have reduced their fuel consumption of up to 5 % by maintenance actions initiated due to TOP performance analyses.

There are great possibilities to develop the concept of TCI in the future when more and more data for analytics, automation and robotics enter into the arena of shipping. The methods have shown to be valuable in demonstrating better collection and analyses that improves operations and reduces use of energy. Future development should implement solutions that avoids the necessity of manual inputs for data collection, include a wider scope of parameters to include weather and navigation information, and start to use methodologies within artificial intelligence to find/reduce sensor faults and increase/improve holistic analyses in the context of ship performance [13-15].

ACKNOWLEDGMENTS

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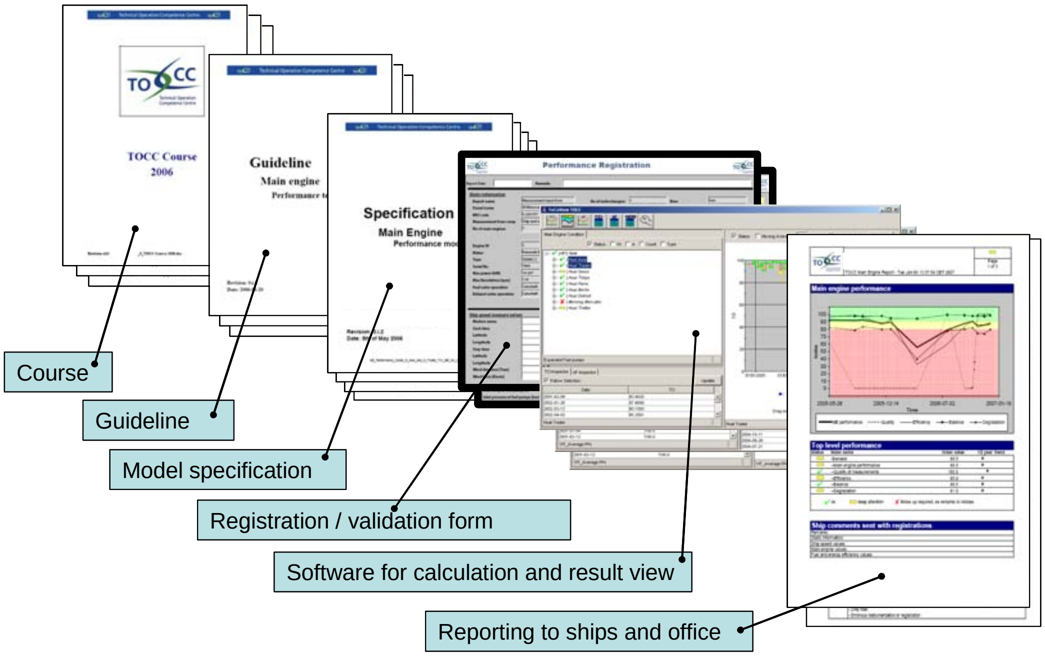

Figure 1: Documents and software applied in the TOP/TOCC concept

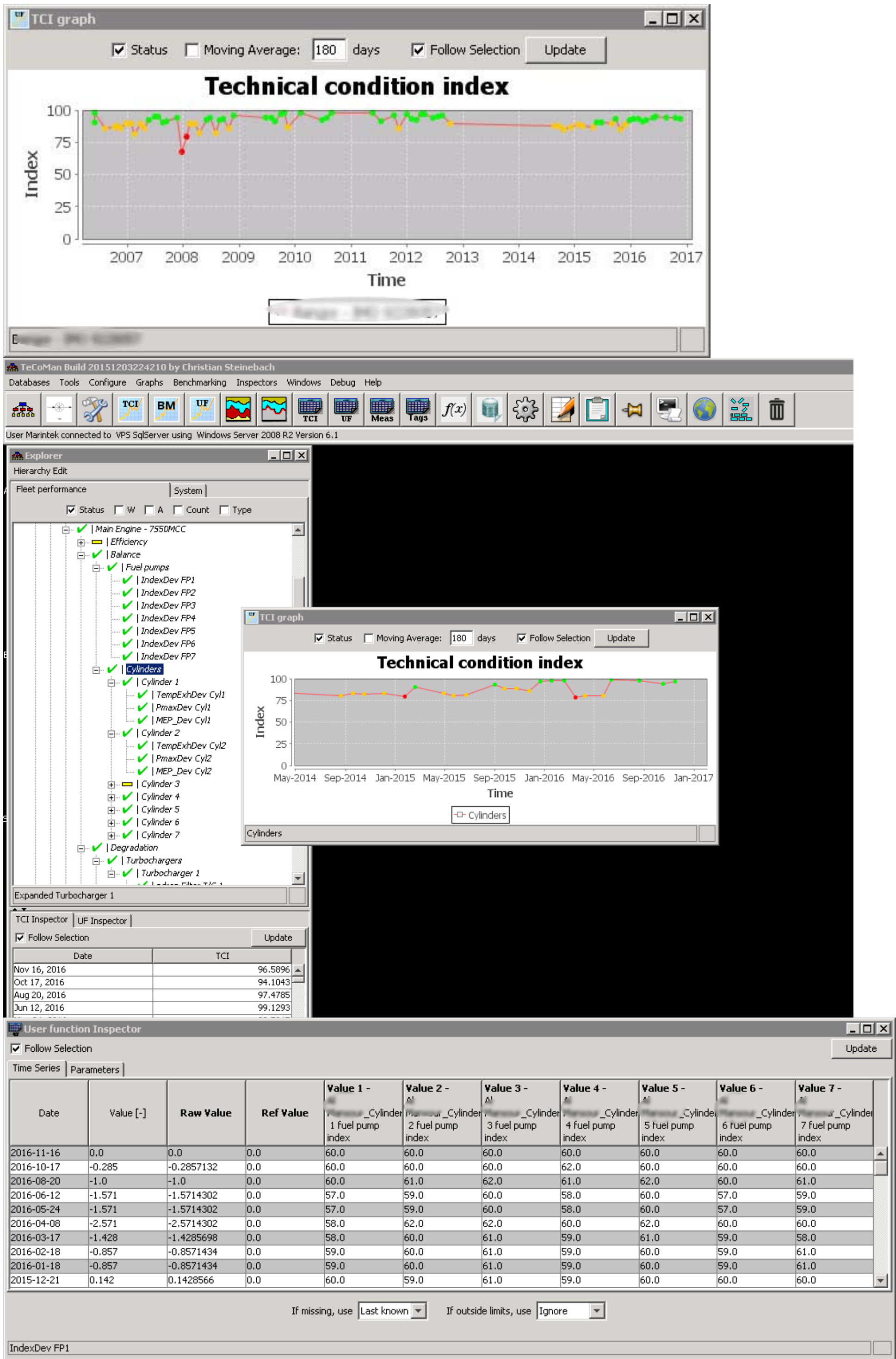

Figure 2: TeCoMan information for the TOP/TOCC concept

MPT Form (Monthly Performance Test) ME

VPS

Main Engine

Chief Engineers name	Demo Example
Total running hours	55 873
Start time	09:00:00
Stop time	11:00:00
Engine room temp [Deg C]	42

Scavenging receiver temp [Deg C]	40
Scavenging rec. press [barO]	1,5
Exhaust receiver press [barO]	1,2
Exh. gas economizer [mmWC]	0

Revolutions [rpm]	112,5
Fuel pumps index	77,0
Cyl.oil.cons [g/kWh]	1,9
Shaft power [kW]	0
Eff. power [kW]	7 519

OK

Turbocharger ID	1
Revolutions [rpm]	12 100
Air inlet [Deg C]	42,0
Air filter press. drop [mmWC]	42
Exhaust inlet temp. [Deg C]	453
Exhaust outlet temp. [Deg C]	335

Scavenging air cooler ID	1
Air inlet [Deg C]	128
Air outlet [Deg C]	39,0
Air pressure drop [mmWC]	160
Water inlet [Deg C]	35,0
Water outlet [Deg C]	45,0

Chief Engineers comments

E.G.E. no diff. press gauge fixed!

Cylinder ID	1	2	3	4	5	6
Compression pressure [bar]	84,0	82,5	80,7	79,5	79,8	82,9
Max pressure [bar]	133,6	134,9	139,3	135,2	134,7	137,8
Mean indicated pressure [bar]	17,5	18,2	20,0	18,2	18,3	18,7
Exhaust temperature [Deg C]	364	361	361	372	383	369
Fuel pump index	77,0	77,0	77,0	77,0	77,0	77,0
Revolutions [rpm]	112	112	112	112	112	112
VIT Index						

Fuel

Fuel sample no	nID
Bunkering date	2016-10-11
Supplier	nID
Bunkering port	nID
Heat value [MJ/kg]	40,56
Density at 15 c [kg/m3]	989
Viscosity at 40/50 c [cSt]	367,4
Sulphur content [%]	1,78
Inlet temp. fuel pump [Deg C]	128,0
Inlet press. fuel pumps [bar]	7,8

	Start	Stop
Fuel flow meter time	09:00:00	11:00:00
Fuel flow meter volume [l]	1	2970
Fuel flow meter temp [Deg C]	90,0	90,0
Shaft revolution counter time	09:00:00	11:00:00
Shaft total revolutions	81355750	81369250
Cyl oil flow meter time	09:00:00	11:00:00
Cyl oil flow meter volume [l]	420	450
Shaft torqueometer time		
Shaft total energy		

Density at flow meter [kg/m3]	939
Fuel consumption [l/h]	1 485
Fuel consumption [kg/h]	1 394
SFOC at ISO condition [g/kWh]	173,9

Fuel comments

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Figure 3: Performance test registration/validation form