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Wärtsilä Asset Diagnostic Configurator

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BACHELOR'S THESIS

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Abstract

The Wärtsilä Condition-based Maintenance (CBM) service is nearing 20 years in operation and no longer fulfills the service requirements based on customer demand and internal feedback. This thesis aims to describe the evolution of the CBM platform into the new Asset Diagnostic service and provide documentation relating thereto. The main focus is on the new Configurator tool, used for onboarding equipment to the remote monitoring service. Additionally, the goal is to develop a standard workflow with data normalization within the Configurator tool.

A theoretical foundation is established through a literature review of computer-based maintenance and related strategies. The legacy CBM system and Asset Diagnostics were subjected to a comparative analysis. A semi-structured interview of respondents from varying roles was conducted to provide a heterogeneous convenience sample of the perceived results and development requirements. The main improvements were found to be a more efficient workflow, enabling high-frequency data and daily condition notifications, scalability, improved analytics and response time, improved transparency towards the customer and a modern cloud-based service with improved cybersecurity. On this basis, it is recommended that the Asset Diagnostic platform keeps evolving to meet customer and Wärtsilä requirements of the future and that further research and development is devoted to improving the documentation and paving the way for service improvements.

Language: English   **Key words**: condition-based maintenance, asset diagnostics, remote monitoring, predictive maintenance

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EXAMENSARBETE

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Abstrakt

Wärtsiläs tillståndsbaserade underhållstjänst (CBM, Condition-based maintenance) har varit i bruk i nästan 20 år och uppfyller inte längre de krav som kunder och interna behov ställer. Detta examensarbete ämnar beskriva utvecklingen av CBM-tjänsten och dokumentera den nya Asset Diagnostic tjänsten. Huvudfokus ligger på det nya konfigurationsverktyget som används för att möjliggöra fjärrövervakning av ny utrustning. Därtill är syftet att utveckla en standardiserad arbetsmetod som innefattar normalisering av sensornamn i verktyget.

Den teoretiska grunden etableras genom en litteraturstudie kring datorbaserat underhåll och strategier som relaterar till detta. Det gamla CBM systemet och Asset Diagnostics utsätts för en jämförande analys. En semistrukturerad intervju av respondenter med olika roller inom Wärtsilä utförs för att ge ett heterogent bekvämlighetsurval av de uppfattade resultaten och utvecklingsbehoven. De främsta förbättringarna konstaterades vara ett effektivare arbetsflöde, ibruktagande av högfrekvent data, dagliga tillståndsmeddelanden, skalbarhet, förbättrade analysverktyg, snabbare respons, högre genomskinlighet gentemot kunden och utvecklandet av en modern molntjänst med förbättringar i cybersäkerhet. På basis av detta rekommenderas vidare utveckling av Asset Diagnostic plattformen för att svara mot kundens och Wärtsiläs framtida behov samt fortsatt forskning och utveckling för att förstärka dokumentationen och utveckla nya sätt att förbättra tjänsten.

Språk: engelska **Nyckelord**: tillståndsbaserat underhåll, utrustningsdiagnostik, fjärrövervakning, förebyggande underhåll

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Tiivistelmä

Wärtsilän kuntoperusteinen huoltopalvelu (CBM, Condition-based maintenance) on ollut käytössä lähes 20 vuotta, eikä enää vastaa asiakkaiden ja Wärtsilän sisäisiä vaatimuksia. Tämä opinnäytetyö pyrkii kuvailemaan miten CBM-palvelu on kehitetty uuteen Asset Diagnostic-palveluun ja dokumentoimaan tähän liittyviä prosesseja. Tärkein painopiste on uudessa työkalussa, jota käytetään uuden laitteiston konfigurointiin, jotta sitä pystytään etävalvomaan. Lisäksi päämääränä on kehittää normatiivinen työmenetelmä konfigurointityökalussa, jolla antureiden nimet voidaan normalisoida.

Tieteellinen perusta pohjautuu kirjallisuuskatsaukseen, joka käsittelee tietokoneavusteista kunnossapitoa ja siihen liittyviä strategioita. Vanhaa CBM- ja uutta Asset Diagnostic-järjestelmää vertailtiin analyyttisesti. Yrityksen sisällä suoritettiin puolistrukturoitu haastattelu, jossa vastaajat edustivat heterogeenistä mukavuusotosta projektiin liittyvästä henkilöstöstä. Tärkeimmät parannukset todettiin olevan tehokkaampi työnkulku, tiheästi poimitun datan hyödyntäminen, päivittäiset kuntoilmoitukset, skaalautuvuus, parannettu analytiikka, lyhyempi vastausaika, korkeampi läpinäkyvyys asiakasta kohtaan sekä modernin pilvipalvelun kehittäminen pitäen sisällään parannetun kyberturvallisuuden. Tämän perusteella suosittelen, että Asset Diagnostic-alustan kehitystä jatketaan, jotta se pystyy vastaamaan asiakkaiden ja Wärtsilän tulevaisuuden vaatimuksiin. Samalla tutkimus- ja kehitystyötä tulisi jatkaa, jotta dokumentointia voidaan parantaa ja palvelun uusia mahdollisuuksia kartoittaa.

Kieli: englanti **Avainsanat**: kuntoperusteinen huolto, asset diagnostics, etävalvonta, ennaltaehkäisevä huolto

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I would also like to acknowledge my father for offering his advice and time throughout the process of writing this thesis.

Glossary

API	Application Programming Interface
AWS	Amazon Web Services
CBM	Condition Based Maintenance
CSV	Comma-separated values
HMI	Human Machine Interface
Genset	Generator set
PlantNet	Wärtsilä internal server environment
PLC	Programmable Logic Controller
Repload	Report loader – Tagname definition list
RPA	Reference Performance Analyzer
SCADA	Supervisory Control and Data Acquisition
UNIC	Wärtsilä embedded engine automation control system
WDCU	Wärtsilä Data Collection Unit
WGDI	Wärtsilä Generic Data Interface
WIAS	Wärtsilä Integrated Automation System
WISE	Wärtsilä Information System Environment
WOIS	Wärtsilä Operator's Interface System

Table of Contents

1 Introduction

Wärtsilä was founded in 1834 with the construction of a sawmill in the county of Karelia in Eastern Finland. In 2019 Wärtsilä is celebrating its 185th year in business, through the years the company has evolved into an engineering innovator. Today, Wärtsilä is aiming to lead the industry transformation towards a 100% renewable energy future. Wärtsilä's purpose is defined as 'Enabling sustainable societies with smart technology' and this is reflected in the company strategy, split between smart energy and smart marine as observed in Figure 1. An indicator of Wärtsilä's commitment to the environment is the 2018 inclusion in the Climate Leadership Coalition (CLC) (Climate Leadership Coalition, 2018), a Finnish network of companies, research organisations and local government, aiming to mitigate the impact of climate change. Another example of this drive is the announcement of the Oceanic Awakening initiative (SEA20, 2019), a global movement focused on the transformation of the world's marine and energy industry into an efficient, ecologically sound and digitally connected ecosystem.

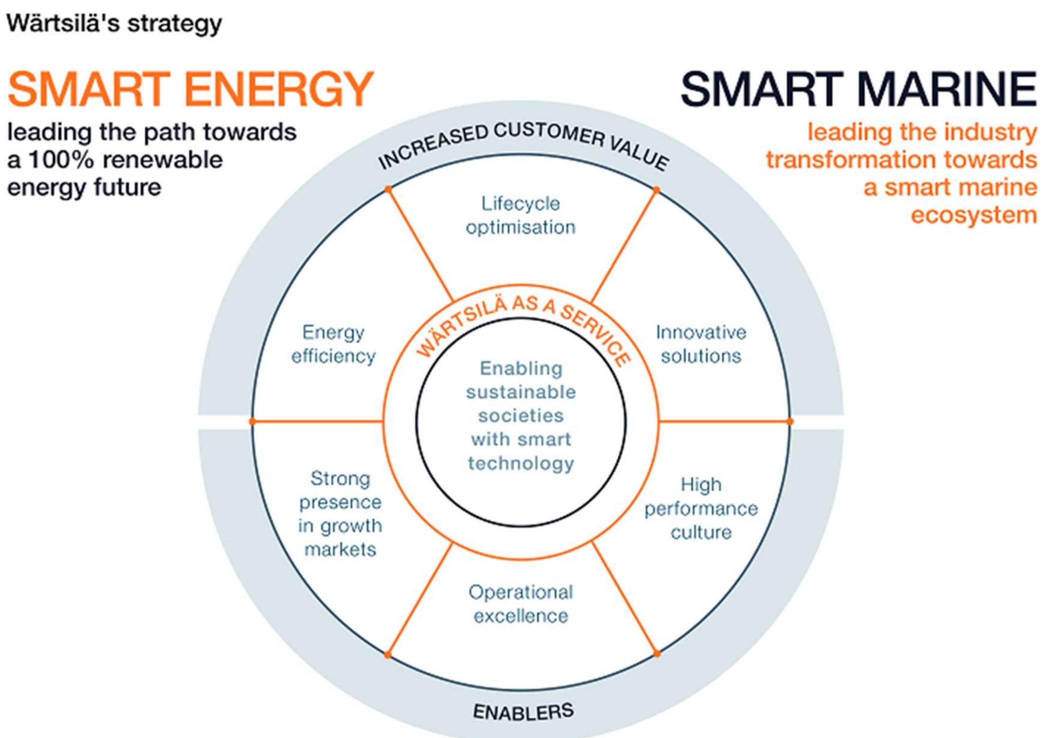

Figure 1. Wärtsilä Smart Energy and Smart Marine strategy (source: Wärtsilä)

1.1 Marine and Energy business

Wärtsilä employs around 19 000 people globally in more than 80 countries, with over 200 locations. Wärtsilä is listed on Nasdaq Helsinki with net sales in 2018 of EUR 5.2 billion, divided between Marine solutions, Energy solutions and Services. As of 2019 Wärtsilä has streamlined its business into two core businesses, Marine and Energy. In 2018 Wärtsilä was recognised by Corporate Knights in the Global 100 Most Sustainable Corporations in the World listing (Corporate Knights, 2018). In the energy sector for gas and liquid fuel power plants under 500 MW, Wärtsilä had a 13% market share in 2018. In the marine sector Wärtsilä is a top player in the gas carrier and cruise & ferry segments, a challenger in the traditional merchant and navy segments and a mid-player in the offshore and special vessels segment. For medium-speed main engines Wärtsilä had a market share of 47% in 2017 (Research and Markets, 2018) (see Figure 2). The Wärtsilä 31 medium-speed engine currently holds the Guinness World Record for most efficient 4-stroke diesel engine with a diesel fuel consumption of 165 g/kWh (Seatrade Maritime News, 2015). The Wärtsilä 31SG (Spark Gas) engine follows this evolution by raising the gas engine simple-cycle efficiency to over 50% (Wärtsilä, 2017). The current global socio-political and economic situation is delicate and this calls for companies to practise utmost sensitivity to maintain investor confidence while staying ahead of the competition. Concurrently, the regulations are changing in response to the increased environmental awareness and stringent standards such as the IMO global sulphur limit of 0,50% by mass coming into effect in 2020 (IMO, 2019).

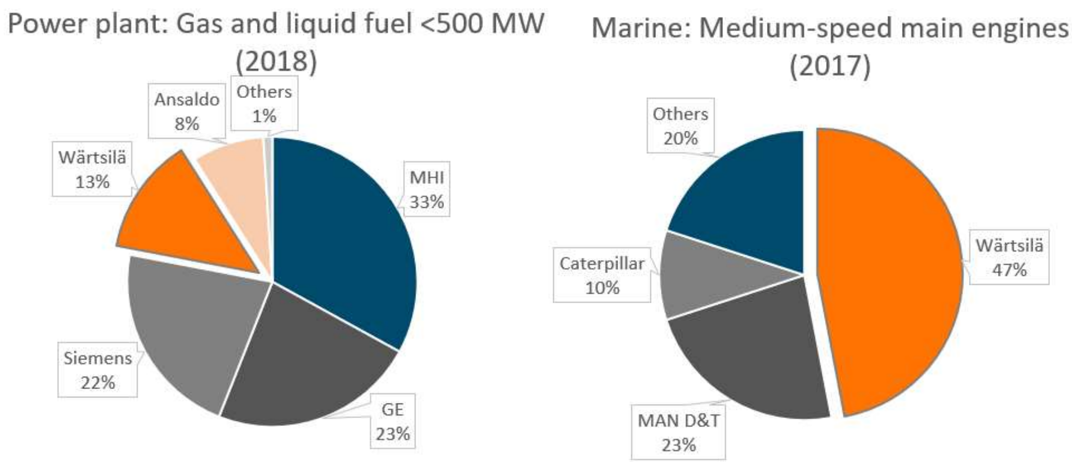

Figure 2. Market shares for (a) Energy sector and (b) Marine sector (Source: Wärtsila, adapted by author)

1.2 Maintenance strategy

Since 2000 Wärtsilä has been offering its Condition Based Maintenance system (CBM) which is a part of the dynamic maintenance planning concept that entails combining CBM with periodic inspections to extend the maintenance interval. CBM analyses aggregated data and generates reports based on smart analytics of the condition of the equipment. Currently there are more than 500 marine and power plant installations connected to the CBM centre, with a total engine count of over 2 000. For Wärtsilä to continue to maintain its competitive advantage, the company is now developing the next generation of Asset Diagnostics with increasing sensor amounts, data polling rates, live trend data monitoring and daily exception notifications. In addition, the new Asset Diagnostic service offers a streamlined equipment multi-portfolio monitoring tool. In conjunction with new smart algorithms, this offers the customer a new level of equipment monitoring and maintenance planning, with the goal of increasing customer profitability, increased sustainability and value proposition. Simultaneously, the ease of use is getting a major overhaul and the graphic design refreshed.

2 Disposition, purpose and methodology

This thesis is structured into ten chapters, advancing chronologically from the intended aims and objectives, to the desired outcome, or deliverables discussed in Chapter 8. Simultaneously the thesis aims to structurally document the Asset Diagnostic process and data normalization and mapping workflow – engaging in more detailed descriptions as the text progresses.

2.1 Disposition

Chapter 1 gives a brief introduction to Wärtsilä and their maintenance strategy.

Chapter 2 offers an overview of the content of this document, its purpose and the applied methodology.

Chapter 3 follows with a theoretical and historical review of the concepts of condition-based maintenance, condition monitoring and computer-aided equipment maintenance history. Further, attention is brought to the potential shortcomings of these systems through their limitations, assumptions and failure modes.

Chapter 4 describes the predecessor to the Asset diagnostics service – Wärtsilä CBM (Condition-based maintenance). This gives the frame of reference of how the services are arranged today and the present working condition of the systems originating from the early 2000s. The chapter details the original goals of Wärtsilä CBM and describes the legacy software: Reference performance analyser (RPA) and RPAViewer. CBM reports and the current CBM configurator tool are discussed in closing.

Chapter 5 introduces the reader to some fundamental concepts relating to engines and thermodynamics, in order to provide an understanding of the architecture in which the condition-based maintenance system operates. The principal concepts of the Carnot-, Otto- and Diesel-cycles are discussed together with an overview of 4-stroke and 2-stroke engines. The chapter concludes with a look at fuels and how fuel modes are processed by the system.

Chapter 6 outlines the development of the Asset diagnostic configurator – the replacement tool for the CBM configurator. This constitutes the major focus of the thesis, as can be deduced by the title. Initially, the functional requirements of the new tool are presented, followed by a functional description of the whole process of data collection, processing, storage and consumption. This is followed by a detailed description of the requirement for data validation and normalization and how the different data sources are treated to normalize them to the same baseline. Minimum sensor requirements for 4-stroke engines are discussed and general sensor guidelines outlined. The chapter concludes with a look at how diagnostics are performed, and a presentation of development versions of the visualization tools used in conjunction with the new configurator.

Chapter 7 is structured as a framework for the manual of the mapping and configuration workflow, along with details of the new configurator tool. This is specified as one of the major targets of this thesis. It includes a description of the standardization of tagnames to ISO codes, which is a big part of the rationale for the new tool. Finally, the chapter looks at the detailed installation configuration and sensor mapping process. These processes are integral to enabling the monitoring of new equipment.

Chapter 8 focuses the results of the thesis through the findings of the semi-structured interviews and the status of the main thesis goals. The original purposes are divided into four categories and specified under Chapter 2.2 Purpose.

Chapter 9 contains a discussion about the different aspects of the Asset Diagnostic service as a whole and the Configurator in specific. The discourse is divided into a look at the internal value proposition, external value proposition, potential threats and opportunities for development.

Chapter 10 concludes the thesis and summarizes the current status of the project and my personal thoughts on the process.

2.2 Purpose

The aim of this thesis is to describe the evolution of the CBM platform into the new Asset Diagnostic service, its background, project execution and possible future developments. To meet this aim, the following objectives have been set:

- Document the evolution of the Asset diagnostic project
- Formulate end-user documentation
- Develop optimized data normalization and workflow routines
- Acquire and asses user testing and future development opportunities

It is intended that the findings of this thesis will be used to develop documentation of the background and deployment of the Asset Diagnostic configurator and used to define development opportunities. This includes a description of the legacy software and process; comparing it to the new service offering. Further, it comprises documentation of the Asset diagnostic configurator use-cases, aimed to be structured into a manual for the end users. A substantial part of this documentation includes the data normalization process that is applied to the different data sources that feed the reporting platform. The workflow and rationale for data normalization is documented for the individual data sources with key differences being highlighted. Finally, the thesis provides feedback attained through user testing of the software and from practical experience of sensor mapping and equipment configuration. This feedback has been condensed and formulated into improvement requests for the configurator tool as well as for the entire process.

With the introduction of Asset Diagnostics, Wärtsilä has taken into use an automated and centralized platform to diagnose multi-portfolio product performance. This service includes event notifications, expert advice on exception cases, periodical reporting and long-term data trending visualization. Asset Diagnostics follows the natural progression from the foundation that was laid with CBM and expands onto this with a wider service offering, high-frequency data, cloud integration and data normalization. The service aims to provide Wärtsilä customers with:

- Daily anomaly notifications including Wärtsilä expert advice to provide early decision support with actionable advice
- Periodical condition reports
- Traditional calculations explicated with extended diagnostic logic and extended algorithms using pattern recognition from multiple data sources
- Optimized asset performance
- Increased safety, availability and reliability
- Optimized maintenance time and cost
- Long-term predictability and insight into asset condition
- Access to online diagnostics through Wärtsilä Online Services with a fleet overview
- Predictive maintenance strategy

The Asset diagnostic platform enables several internal key benefits for Wärtsilä. One of the key enablers is the ability to offer multiplatform reporting with the robustness of data conformed to a normalization process. In essence, this means that Wärtsilä can onboard new equipment types for reporting, whereas previously only 4-stroke engines were supported by CBM. These include 2-stroke engines, propulsion systems (PCMS) and any sensor-enabled hardware. In the past these equipment types had their own monitoring platforms. From a development standpoint, Asset Diagnostic gives Wärtsilä a solid new foundation for continuing service development. Some of the main technologies enabled by the new platform include an online service portal with visualization, including deviation notifications and trending capabilities. The service also offers advanced load level analytics and provides future options for custom fuel types like bio-fuels. Other key improvements include logging of both digital and analogue data and cloud data monitoring.

2.3 Methodology

The methodology of this thesis is structured around a literature review of computer-based maintenance and maintenance strategies. Following this, is a description of the Wärtsilä Condition-Based Maintenance and a comparative analysis of Asset Diagnostic and CBM. Descriptions of the normalization process and software functionality are subject to iterative documentation. The thesis concludes with a qualitative analysis of the project outcomes as discussed in the results. This includes a summary of the heterogenous convenience sample gathered through semi-structured interviews with key personnel involved in the project.

2.3.1 Protocol for semi-structured interview

The interview proceedings were initiated by agreeing on a convenient time for a face-to-face recorded interview session relating to the Asset Diagnostics project and its outcomes. The recordings were performed on an Android mobile phone, timestamped to later be transcribed and subsequently to have the recordings deleted. Initially the respondent was informed of the approximate duration and purpose of the interview and given key topics of what the interview would cover. The respondent was not privy to the exact questions prior to the interview to keep the response non-rehearsed and spontaneous. This information was again repeated in the e-mail invite for the appointment. The structure of the invitation letter can be seen in Appendix A, the pre-interview briefing in Appendix B and the interview questions are found in Appendix C. The abridged transcripts can be found in Appendices D-G.

The respondents chosen for the interview represent people from within Wärtsilä, consisting of representatives with variety in terms of experience, team, task and professional background. The purpose of this selection was to provide a heterogenous convenience sample of the perceived benefits and development needs of the Asset Diagnostic project. The respondents are listed in Table 1 with position, team, Wärtsilä work experience and comments.

Table 1. Summary of interview respondents

Role	Team	Exp.	Comments
Senior Technical Expert	Infra Hosting	6 years	Configuration mapping and end-user of the Configurator tool
Senior Technical Expert	Infra Hosting	1 year	Stream lead for the Asset Diagnostic Configurator and UI/UX design
Senior Technical Expert	Asset Diagnostics	24 years	Monthly reports and daily notifications to the customer
Manager	Asset Diagnostics	21 years	Technical experience as well as understanding of the business aspect

Before each interview the respondent was given a verbal briefing of the purpose of the interview and general guidelines for how the interview would take place. The interviews were conducted in closed offices with the interviewee and interviewer present. The respondents all gave informed consent before recording was initiated. A paper printout of the questions was handed to the respondent prior to the start of the recording, to make sure the questions were correctly interpreted. The interview followed the predetermined question sheet, with the interviewer probing for clarification on questions where necessary. Finally, the recorded interview was transcribed and abridged into appendices for inclusion into the thesis. The respondent was able to review the interview transcription to validate the content was in line with the informed consent provided at the outset of the interview. The original recording was subsequently deleted.

3 Theoretical foundation and history

The driving force behind all maintenance and asset management can be summarized as asset effectiveness. Every operator and owner wants to maximize the value that their asset can generate by maximizing the profit and minimizing the investment. This is where asset management comes into the picture by improving equipment reliability through predictive maintenance. The worst-case scenario for an equipment owner would be total equipment failure or a long-winded downtime. Predictive maintenance planning and effective scheduling of repairs aims to avoid these scenarios.

This has immediate financial implications as the reduction of maintenance hours with a condition-based monitoring system can maximize component lifetime. This is achieved through reduced maintenance intervals and early warning indications that can be used to intervene and prevent component failure by cost-effective means such as lubrication improvements. The added benefit of condition monitoring is to ensure maximized equipment performance whilst minimizing life-time maintenance costs (Dunn, 2015).

An instrument for accomplishing this goal is via the development of a holistic view of asset management as a driver to progress baseline operation into operational excellence (OE), with each step increasing the value retained. Figure 1 showcases how organizational change is pursued with continuous improvement (CI) valued at every level. The ultimate aim being operational excellence (Management Centre Europe, 2013). Regressive maintenance represents the lowest level of operation (baseline), whilst strategic maintenance signifies operational excellence.

Figure 1. Asset management driving Operational Excellence

The goal with regressive maintenance is to use the equipment until it fails because of staged decay (fatigue). This strategy can lead to short term savings but does not consider equipment longevity or the cost of a breakdown at all. The only goal is to meet a short-term budget.

Reactive maintenance responds to the equipment condition and fixes it after it breaks to achieve a strategy of theoretic bare minimum maintenance. From a life cycle perspective, this is the most expensive strategy.

Scheduled maintenance follows a predetermined schedule for when maintenance is due. This strategy is typically used in automobiles where the age or range determine the need for maintenance. This strategy can be competitive because it is easy to predict, but if the equipment fails to follow the anticipated degradation, the maintenance plan and budget can suffer.

Proactive maintenance goes beyond looking for errors and fixing them as they occur. This strategy seeks out competitive advantages by improving the equipment whenever possible. From a life cycle perspective, this is usually the lowest cost strategy.

Strategic maintenance, which represents the highest level, is a shift from a theoretical 100% failure detection rate to reducing the Mean Time Between Failure (MTBW), which improves equipment availability (see Chapter 3.4). Analytical data gathered through predictive maintenance is utilized to optimize equipment performance as well as error detection. The goal is process innovation and improvement to achieve *Best in Class* performance.

3.1 Condition Based Maintenance (CBM) as a concept

As the name implies, condition-based maintenance is the strategy of performing maintenance as-needed. It is a branch of predictive maintenance using computers, artificial intelligence and algorithms to detect indicators that the equipment is showing early signs of failure or performance deterioration. At this point, the condition-based maintenance system will infer that some maintenance work needs to be performed and sound an alert. Because of the time sensitivity, CBM relies on near real-time data to schedule the right maintenance at the right time, similarly CBM aims to prevent unnecessary maintenance. It is easy to deduce the advantages of CBM, reducing the costs from repairs and system downtime as well as improving the reliability of the equipment while at the same time removing the effect of human error in diagnosing faults. Naturally, CBM introduces a higher initial investment due to the monitoring equipment required and making sure that the monitoring equipment is performing as specified, otherwise the operator can face false positives due to sensor misreading. With information technology and sensors coming down in price, CBM is growing increasingly popular, especially for safeguarding the operation of expensive equipment. Another inherent drawback of CBM is that maintenance windows become quite unpredictable due to the lack of a schedule. Therefore, a common method is to use a selective maintenance strategy with a combination of scheduled maintenances and diagnostically identified maintenance needs.

3.2 Condition monitoring

CBM is sometimes used interchangeably with predictive maintenance but they are strictly not the same. Predictive maintenance uses predictability patterns based on mathematical models and statistical data to predict equipment failure and intervene before such time. Both CBM and predictive maintenance rely on qualitative operational data gained from condition monitoring. This is achieved by observing key parameters of the equipment using sensors and advanced diagnostics to identify patterns, changes and deviations that can be indicators of a developing fault. As a direct consequence of this, the data measuring rate correlates directly to the accuracy of the predictive maintenance but this causes challenges of its own.

There is a vast amount of data to keep track of and analyse and a lot of sensors that need to be kept in working condition. Some of the employed methods of detecting anomalies include vibration analysis, temperature and pressure measurements, lubrication analysis, infrared thermography and ultrasound testing (Limble CCMS, 2018). For a dual-fuel Wärtsilä 4-stroke engine the number of sensors can easily exceed 200. The final sensor count depends a lot on the engine type and fuel modes used. The CBM or predictive system should interface with existing Enterprise Resource Planning (ERP) and Computerized Maintenance Management Systems (CCMS) to provide the maximum benefit of a) cost reductions, b) inventory and asset management c) tracking and reporting and d) workflow improvements.

The more accurate a maintenance system is the earlier it will detect a potential developing fault and signal an alert. This can be graphically represented in a P-F curve (see Figure 2) which is a commonly used tool in condition-based maintenance. This curve displays the time interval between the first potential discovery of failure (P) to the actual functional failure (F) of the equipment. Therefore, the longer the PF-interval is, the more time the operator has, to intervene and schedule a maintenance break to rectify the situation (Blann, 2013). When setting up a CBM or predictive maintenance system the equipment to be monitored should be selected based on its functional importance, cost of repair or replacement and longevity. With the equipment identified, a Reliability-Centered Maintenance (RCM) analysis should be performed to highlight all the failure modes of the equipment to ensure the monitoring is covering it.

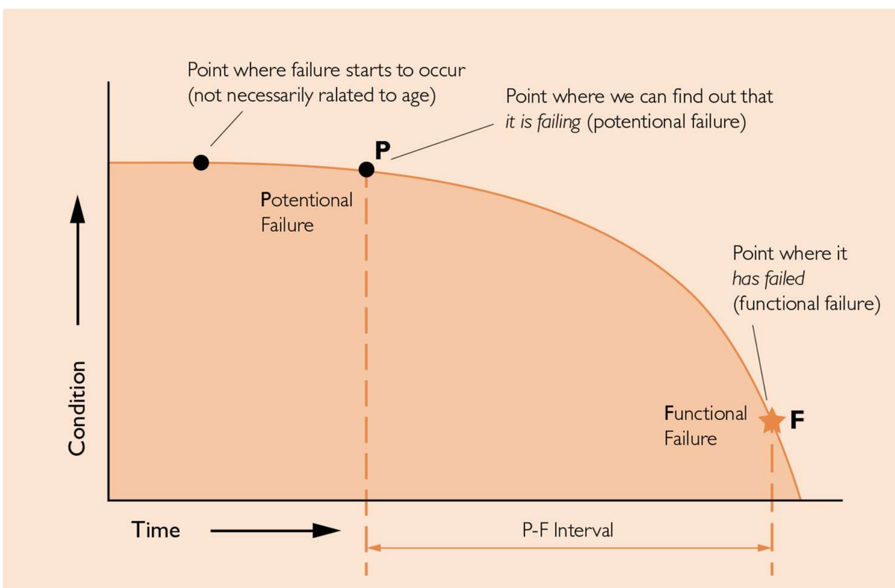

Figure 2. P-F curve showing the early indications of equipment failure (source: www.maintworld.com)

3.3 A history of computer-aided equipment maintenance

Traditionally the maintenance of engines and equipment has been performed on a scheduled basis, according to expected equipment wear patterns and best practices. There are several drawbacks to this kind of maintenance, due to the schedule typically not considering environmental factors or natural variances in material quality. This can lead to overdue maintenance or premature maintenance which can result in undue operational expenses, downtime or equipment failure (Shidong Fan, 1999). An alternative to this is a selective maintenance strategy that takes into account reliability calculations as well as equipment and environment variables. This strategy includes Breakdown Maintenance (BM), Scheduled Maintenance (SM) and Preventive Diagnostic Maintenance (PDM). The strategy revolves around the reliability theory, that only parts susceptible to wear-out failure are suitable for scheduled maintenance but parts that are prone to accidental failure need other methods of maintaining them. For these purposes the strategy employs fault diagnostics and condition monitoring, using collected data and computational power to calculate trends and predict failures. The goal of a selective maintenance strategy is to eliminate equipment failure, decrease maintenance costs, increase operational reliability and reduce downtime. A method of modelling maintenance and time to failure is the use of simple machine condition parameters and their statistical failure rates to ascertain optimal open-loop maintenance schedules. This methodology is known as proportional hazard modelling (Cox, 1972). The methodology has been tested in industrial and marine settings and has been proven to yield good results. (Love, 1991; Jardine, 2008)

The first notion of condition-based maintenance can be traced back to the 1940s when the American Rio Grande Railway Company developed a maintenance model called preventive maintenance (Prajapati, 2012). This method employed real-time analysis of pressure and temperature of the locomotive steam boiler to get early indications of developing faults before they degraded to critical status. The far-reaching distances that the locomotives covered often lacked maintenance support. This meant that it was imperative to detect failures before they became critical and could cause catastrophic events. The US Army was sentient to this development and quickly developed a condition-based maintenance system that evolved rapidly during WWII. Again, the criticality of a sudden failure was the driving force behind the development of a preventive maintenance system. The routines developed by the US Army became a fundament of what CBM stands for today. In the 1970s and accelerating fast in the 1980s the development of computers meant that calculating power quickly increased, which again leapfrogged the capabilities of CBM systems. In the past two decades, the most significant advancements in CBM have been in the scientific understanding of reliability engineering and the processing of massive amounts of data using advanced modelling and smart algorithms.

Historically, the sensory control process was looking at the regulatory feedback loop to maintain the process variables (PV) at their desired setpoints. These types of sensors measure things such as temperature, speed, volume, mass and pressure. With the rapid advancement of technology and sensor development, sensory supervision has taken a role beyond simply monitoring process value disparity. Modern sensory analytic systems can be used to measure the quality of the process. These types of systems are usually analytically complex to process and require specialized algorithms, video or audio processing or some other form of analytic tool beyond a static measurement. Figure 3 illustrates some of the development that has taken place in recent years under each of the typical regulatory control variables: temperature, pressure, flow, level, humidity, position and motion.

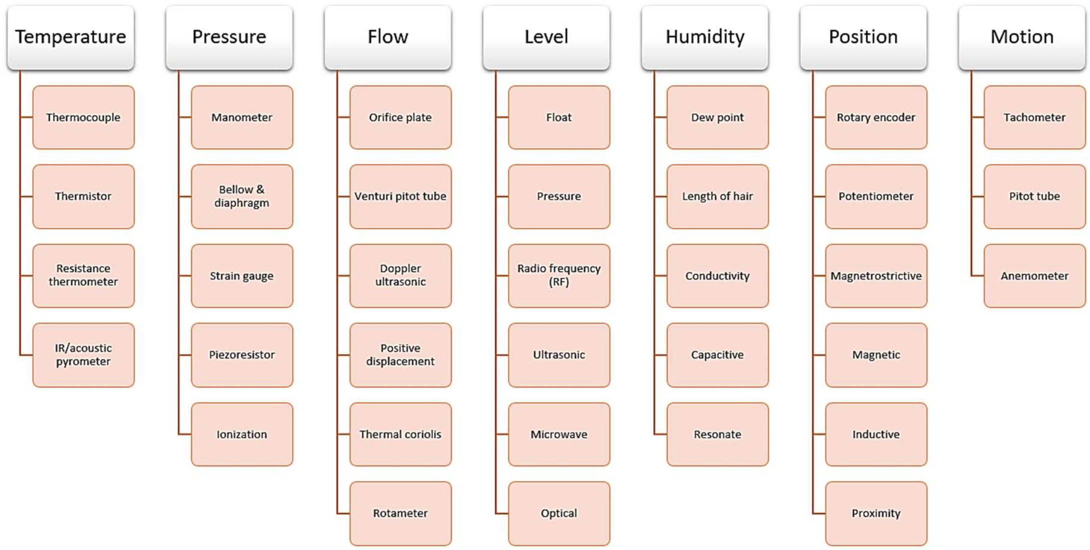

Figure 3. Development of regulatory control variables (source: Lee, 1999, adapted by author)

A major trend in computer-aided maintenance has been the introduction of smart sensors. These are sensors with a built-in logical function that goes beyond analogue signal measurement. This can encompass sensors that are connected directly to actuators to control the process, communication devices or logging and trending tools. With prices decreasing and sensor accuracy and complexity increasing, the latest development in this segment is the use of IoT (Internet of Things) sensor technology. The benefit of this type of sensor is that it can be completely autonomous, wireless and communicate high-frequency data to a control process, directly to an end-user device or the cloud, for generating trend data. A major design challenge for IoT sensors is the management of energy consumption. With a wireless design and with sensors located in hard to service places, the sensors need to be virtually maintenance free and collect their own energy. Battery technology has matured a lot and can be considered for these applications, but it is still a finite power source on its own. Instead, most IoT sensors rely on some form of energy harvesting to keep them powered.

The different methods of energy harvesting that are being used to power IoT devices include solar, piezo-mechanical, radio frequency (RF) and thermal collectors. These power sources can be used in conjunction with an on-board battery or supercapacitor to power the sensor continuously (Lea, 2018).

Another development in sensor analytics is the use of smart algorithms. These algorithms combine the inputs of several sensors and interpret the filtered result using pattern recognition. The algorithm looks for distinguishing features in the signal data coming from various sensors and pre-processes it to outline the pattern more clearly, the data is then partitioned into portions that are appropriately sized for analysis. This type of data may be simple measured process variables that are imported into an algorithm and collectively weighed against a predetermined threshold of normative values. Different methods used in smart algorithms include averaging, scaling, histogram modelling, cluster analysis and so on (Lee, 1999).

3.4 Reliability assumptions and computer-aided maintenance

The classical way to express reliability is the function (Narang, 2012):

$$R(t) = \int_0^\infty tf(t)dt$$

For any discernible failure prediction, the system is assumed to be operating inside of its expected life cycle with an average constant failure rate. This allows the function to be simplified as:

$$f(t) = \lambda e^{-\lambda t}$$

This means the Mean Time Between Failure (MTBF) is the multiplicative inverse of the failure rate of the system (λ). T represents the time the equipment has been in service.

$$MTBF = \frac{1}{\lambda}$$

For equipment that is not repaired but rather replaced at its end-of-life, MTBF can be replaced with Mean Time To Failure (MTTF). From the above formula can be deduced that the reciprocal relationship between the MTBF and the failure rate allows the other to be calculated if one is known and the failure rate is constant (O'Connor, 2012).

Establishing the MTBF of a system allows the probability of a system to be operational at a specific time to be calculated. The MTBF can also be expressed as:

$$MTBF = \frac{\sum(start\ of\ downtime - start\ of\ uptime)}{number\ of\ failures}$$

Looking at it from another perspective the mean downtime (MDT) can be expressed as:

$$MDT = \frac{\sum(start\ of\ uptime - start\ of\ downtime)}{number\ of\ failures}$$

Knowing both the mean time between failures and the mean downtime, the availability (A) of equipment can easily be calculated (Narang, 2012):

$$A = \frac{MTBF}{MTBF + MDT}$$

From a maintenance point of view, the factor that can be affected in the above calculations is the mean downtime through optimized and predictive maintenance to keep the availability as high as possible. It is possible to improve the MDT by several measures:

- Parts availability
- Repair personnel availability
- Diagnostics time (ease of fault finding)
- Ease of access (construction)
- Complexity of repair (construction)
- Proactive / predictive maintenance

For the complexity of an internal combustion engine, the potential fault scenarios can be in the hundreds and it takes highly qualified maintenance technicians to diagnose the exact cause of a problem. To circumvent the issue of prolonged downtime due to inability to diagnose the exact fault, due to maintenance personnel lacking experience or having to resort to trial and error, a heuristics system with the shared knowledge of very specialized maintenance experts can be proposed. This type of system is akin to the diagnostics process of a medical doctor, listening to and observing the clearly distinguishable symptoms of their patients. Having access to this kind of heuristics databank with typical fault scenario symptoms would aid maintenance technicians in their work. However, the inherent flaw of this system is the inability of people to discern the minute deviations that electromechanical equipment can display.

Having identified the shortcomings of human observations even by the most expert of technicians, the development of sensor-based diagnostics systems started to emerge on a broad scale.

- Expert systems that mimic the empirical knowledge of an expert panel of engineers to solve time-constraint or leverage the knowledge level for less experienced personnel
- Automated diagnostics to identify complex faults or faults which are hard to detect by human senses. Automates and further alleviates for personnel lacking experience.
    - Rule-based diagnostics to simulate the diagnostic process of a human expert
    - Maintenance consideration during equipment design by integrating sensors into hard to reach places

These factors have contributed to the development of CBM and the enormous data processing power that computers inhabit. The speed of delivery and detection is also greatly enhanced with computer-aided maintenance systems. Combining this with human expert advice, yields the most sophisticated maintenance system presently known.

3.5 Limitations and assumptions

While the concept of CBM sounds great in theory, studies have also shown that all the advantages expected with CBM are not always met due to issues with risk identification and detection algorithms. This has initiated research for more intelligent monitoring and detection solutions to pave way for the next generation of CBM. There are several parallel developments of next generation CBM systems but a noteworthy one is the CBM+ system developed by the United States Department of Defense (Office of the Assistant Secretary of Defense for Sustainment, 2019). Their definition of CBM+ is:

Condition Based Maintenance Plus is the application and integration of appropriate processes, technologies, and knowledge-based capabilities to achieve the target availability, reliability, and operation and support costs of DoD systems and components across their life cycle. At its core, CBM+ is maintenance performed based on evidence of need, integrating RCM[1] *analysis with those enabling processes, technologies, and capabilities that enhance the readiness and maintenance effectiveness of DoD systems and*

[1] Authors note: Reliability Centered Maintenance: A logical structured process used to determine the optimal failure management strategies for any system, based on system reliability characteristics and the intended operating context (US Department of Defense, 2019).

components. CBM+ uses a systems engineering approach to collect data, enable analysis, and support the decision-making processes for system acquisition, modernization, sustainment, and operations.

3.6 Failure modes

CBM often employs a failure detection identification system known as FMEA (Failure Modes and Effects Analysis) or FMECA (FMEA + Criticality Analysis). This is a procedure that aims to identify the following (Weibull, 2019):

- All different failure modes
- The criticality of each failure
- What are the causes of the failures?
- How are the failures and effects intertwined?
- Which physical failures are linked to functional failures?

A failure mode is defined as the inability to perform the function the equipment is designed for. The description of the failure mode should include information about how the failure is observed, a description of the failure process, a description of system impact of the failure and performance parameters of the failed item. A distinction needs to be made between a physical failure (for example a material fault) and a functional failure which is the result of physical failures. The complete failure mode list should be prepared by a workgroup or committee of experts that are well informed about the operation of the equipment and compiled into an FMECA report (Uhl, 2002).

An example of such a failure mode is illustrated in Figure 4.

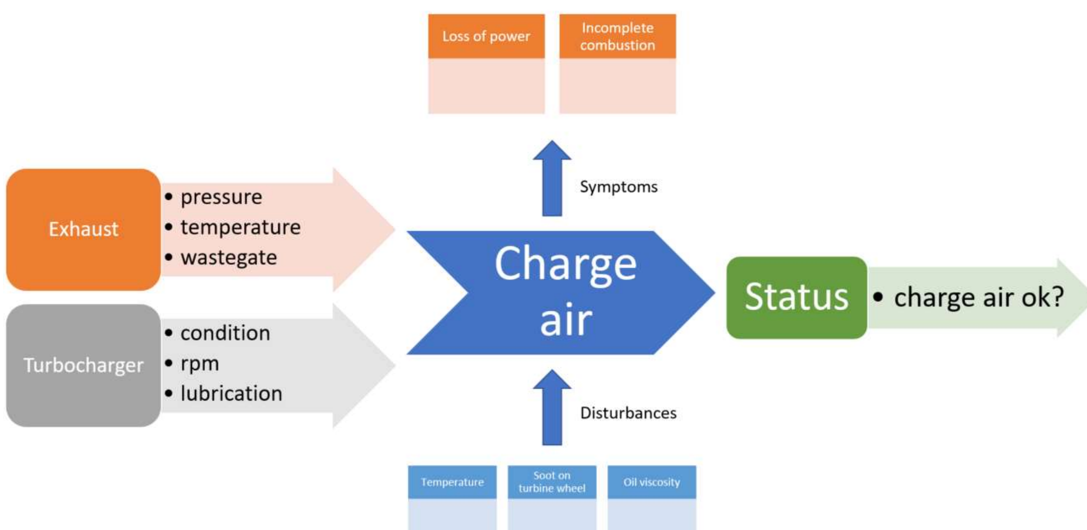

Figure 4. Failure mode process flow

The flow chart observes the performance of the charge air system of an engine. On the left side are parameters that affect the charge air: exhaust pressure, temperature and wastegate operation as well as turbocharger overall condition, rpm and sufficient lubrication. On the bottom are disturbance factors that can interrupt normal charge air functionality. These are temperature, soot on the turbine wheel or incorrect oil viscosity. If any of the disturbances are present, they will likely cause symptoms in the charge air system. The symptoms can be a noticeable loss of power or incomplete combustion. Constant monitoring of the parameters on the left is the key to avoiding potential failure modes. If all parameters are within their thresholds the charge air status will be reported as ok.

To counteract all the potential failure modes, CBM takes advantage of various sensors and diagnostics placed at strategic locations to have an early detection system for physical and functional failures. The shortcoming of CBM can then be two-fold due to:

1. The FMECA report can be incomplete or erroneous
2. Some faults are difficult or impossible to detect even with the most advanced sensors

CBM works on a system and subsystem level where each subsystem is equipped with the necessary sensors to detect and prevent physical failures which could result in a functional failure of the equipment. Each sensor typically has one specific job of detecting a symptom, abnormality or trend which is routed into the detection algorithms or analysed by system specialists. The problem with this approach is that sensor failure detections can be ambiguous because a failure can occur due to many reasons so there needs to be a systematic approach that relies on known dependencies between the subsystems and therefore, by extension, also the sensors. Compiling all the information together for the equipment, its threshold settings, algorithm accuracy and sensor reliability you can then make an estimation of the Probability Of Detection (POD).

In economic terms the Return On Investment (ROI) can be hard to measure for CBM because of the complex metrics in place, one has to consider the cost of constantly running the CBM system, cost of downtime, cost of lost opportunity, saving of reduced maintenance, reduction or removal of scheduled inspections, simplified logistics chain, consolidated maintenance and most importantly, preventing a catastrophic system failure (discussed in Chapter 9).

4 Engines, thermodynamics and fuel

A precursor to understanding the equipment and engine mapping process is to have a fundamental knowledge of the equipment itself and how the combustion process works. Knowing the integral parts of the process helps understand the component architecture and in turn the logical flow of sensors and their purpose. For the scope of this thesis a brief explanation is offered, but for a more in-depth discussion of the processes and the mechanical engineering please refer to dedicated technical literature (Mollenhauer, 2010 and Kuiken, 2016). A summary of frequently used terms to describe thermodynamic processes is shown in Table 1.

Table 1. Terms used for process descriptions

Adiabatic	A process where no heat is gained or lost by the system, entropy is constant
Isentropic	A process that is both adiabatic and reversible
Isothermal	A process where the temperature remains constant
Isobaric	A process where the pressure remains constant
Isovolumetric	A process where the volume remains constant, also called isochoric

4.1 Thermodynamic cycles

The dawn of the modern diesel engine can be traced to the late 19th century when German engineer Rudolf Diesel[2] invented a high efficiency, compression ignition, internal combustion engine. The diesel engine became a direct competitor with the steam engine, which was the prevalent power source at the time. Dr. Diesel applied the principles first proposed by French scientist Sadi Carnot[3] at the beginning of the 19th century to develop a patented cycle called the Diesel cycle. Another notable German engineer Nikolaus Otto[4] was a forerunner for the automotive industry during the late 19th century thanks to his work on a petroleum fuel based 4-stroke internal combustion engine. This engine type operates by what came to be known as the Otto cycle. Both the Diesel and Otto cycles rely on the foundations laid out by Carnot in the Carnot cycle described in his book Reflections on the Motive Power of Fire (Carnot, 1824). The process successfully theorized the maximum efficiency of heat engines and divided the process into four distinctive stages (Chemistry Library, 2019) described below and visible in Figure 1:

1. Isothermal expansion. Heat (q_{in}) is transferred reversibly from a high temperature source onto the gas, allowing it to expand and do work on its surroundings. The piston is pushed up by the gas. The temperature of the gas remains unchanged during this stage as it retains thermal contact with the heat source. Pressure drops as a result of the expansion.
2. Isentropic / Adiabatic expansion. The gas is thermally insulated causing a reversible adiabatic expansion. The temperature of the gas drops as it is no longer in contact with the source and the pressure keeps reducing as the piston rises.
3. Isothermal compression. With the piston in its top position, the gas comes into thermal contact with the cold source, causing a reversible heat transfer. The surroundings do work on the gas, compressing it as the piston moves down. Some heat energy (q_{out}) is released to the cold source.
4. Isentropic / Adiabatic compression. With the piston closing the gas is encapsulated again and becomes thermally insulated. For an ideal Carnot process, the engine is

[2] Rudolf Diesel was a German inventor and mechanical engineer, born 1858 in Paris and died in 1913. He is most known for the Diesel engine, which bears his name.
[3] Nicolas Léonard Sadi Carnot was a French military scientist and physicist, born in 1796 in Paris and died in 1832 in Paris. He is most known for laying out the principles of thermodynamics.
[4] Nikolaus Otto was a German engineer born in 1832 and died in 1891. He is most known for laying the foundation to the modern internal combustion engine through his development of the compressed charge internal combustion engine running on petroleum gas.

assumed to be frictionless, causing a reversible compression of the gas with the pressure and temperature rising. The engine is then in the same state as when it first started.

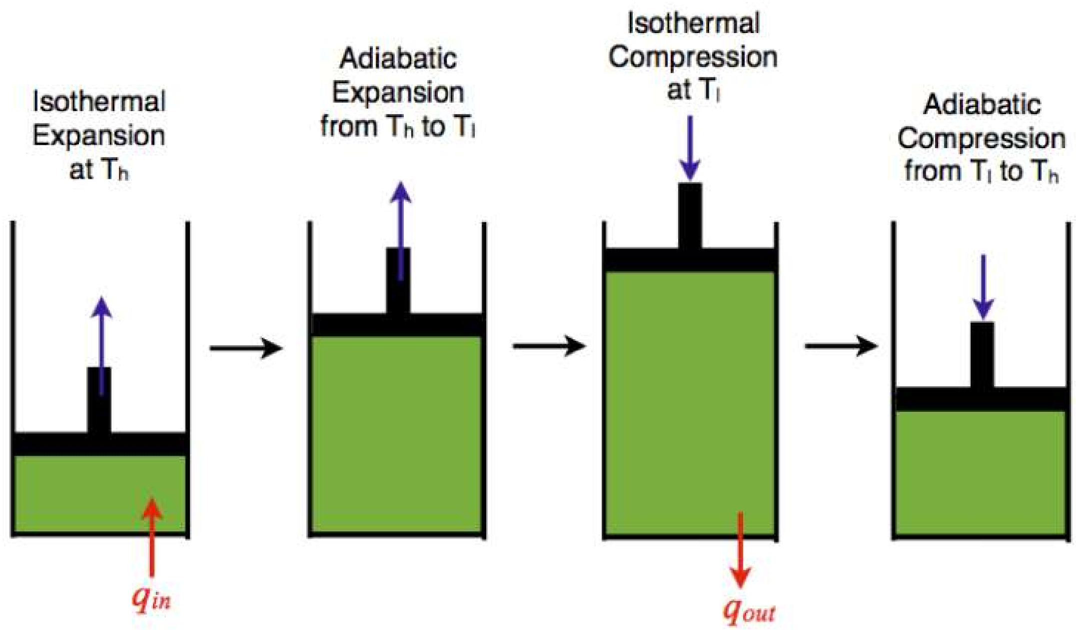

Figure 1. The four stages of the Carnot cycle (source: Chemistry Library)

Observing the pressure-volume diagram of the Carnot cycle during the first phase the isothermal expansion temperature is unchanged, but pressure drops, causing the volume to rise. In the second phase, the temperature drops from T_h to T_l and pressure reduces as the volume keeps expanding. In the third phase, the volume starts decreasing, causing the pressure to rise while the temperature remains constant. The fourth phase causes the pressure to rise rapidly while the volume is decreased. Temperature rises from T_l to T_h. The relationship between energy (q_{in} and q_{out}) and temperature is described by the entropy. The relationship is expressed through the formula below and is defined by Clausius inequality (Finn, 1993), a mathematical model for explaining the second law of thermodynamics[5]. The relationships between pressure-volume and temperature-entropy are visualized in Figure 2 and Figure 3.

$$\Delta S_1 = \Delta S_2 \ or \ \frac{Q_{in}}{T_h} = \frac{Q_{out}}{T_l}$$

[5] Sadi Carnot is first credited with formulating the second law of thermodynamics but it was later formalized by Rudolf Clausius and Lord Kelvin: “The total entropy of an isolated system can never decrease over time.”

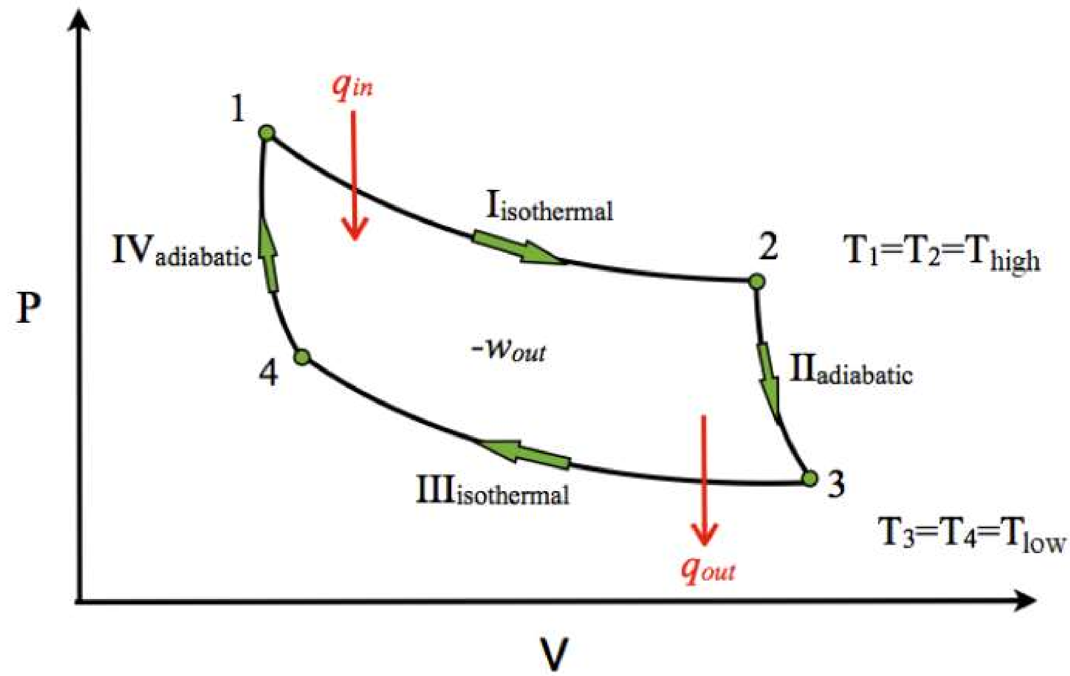

Figure 2. Pressure-volume diagram of the Carnot cycle (source: Chemistry Library)

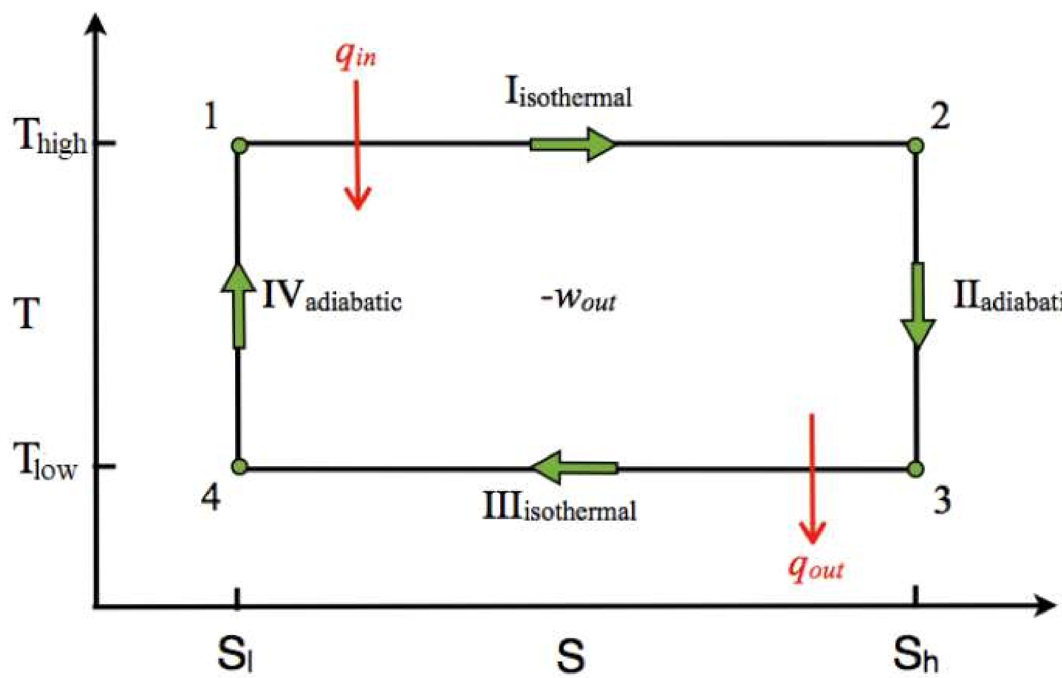

Figure 3. Temperature-entropy diagram of the Carnot cycle (source: Chemistry Library)

Both the Diesel and Otto-engine are heat engines that follow the general principles outlined by Carnot but refines them in different ways. The Diesel engine relies on the heat generated through high compression in the combustion chamber to ignite the fuel while an Otto engine ignites the air-fuel mixture by using spark plugs. Liquid fuel is provided through carburettors, fuel injectors or common rails while a gas-fuelled internal combustion engine typically uses a venturi system[6] to mix the fuel and air. The main difference between the Diesel and the Otto cycle, is that in the Otto cycle heat addition is isovolumetric, whilst in the Diesel cycle heat addition is isobaric.

Wärtsilä has been perfecting the technology of internal combustion engines for a long time and has been able to reach a claimed industry highest efficiency with the introduction of the Wärtsilä 31SG engine. This is a gas-fuelled version of the record-breaking Wärtsilä 31 engine, that holds the Guinness World Record as the world's most efficient 4-stroke diesel engine (Seatrade Maritime News, 2015). The Wärtsilä 31SG engine can achieve a simple-cycle efficiency over 50%, this figure is to be compared to around 40% for modern gas turbines. The gas engine works by combining multiple thermodynamic cycles to increase the overall efficiency. During liquid operation it operates according to the Diesel cycle with compression ignition. During gas operation it operates according to the Otto cycle and uses a small amount of liquid pilot fuel to ignite the gas. In a gas engine a heat recovery steam generator (HRSG) captures the exhaust heat from the internal combustion process to drive a steam turbine for additional power. Wärtsilä's Flexicycle[7] power plant can gain an additional 20% efficiency from the steam turbine process. This increased efficiency means reductions in emissions and cost savings for the operator. The efficiency can be calculated as the product of all efficiencies as seen in the formula below. Wärtsilä has been targeting to increase efficiencies across the board to bring the total efficiency as high as possible. This is achieved by the combustion shape combined with gas injection and higher cylinder pressure, reduced heat transfer in cylinders and the exhaust, reduced friction and parasitic losses, flow improvements and the use of 2-stage turbocharging.

$$\eta = \eta_{combustion} * \eta_{ther} \quad * \eta_{mechanica} * \eta_{gasexchang}$$

4.2 Equipment brief: four-stroke engines

The 4-stroke internal combustion engine is named after its working principle in which the piston does four strokes to complete a combustion cycle. Each stroke is the complete movement of the piston from one extremity to the other. The four-stroke engine has a camshaft gearing that is 1:2 that of the crankshaft. A full turn of the crankshaft is then equal to the piston moving up and down once, it takes another turn of the crankshaft or 720° to complete a full four-stroke cycle. Each of the strokes has a specific purpose to go through the combustion cycle: 1) Intake 2) Compression 3) Power 4) Exhaust (ODESIE, 2019). Sample running values for a four-stroke engine running at 500 rpm can be seen summarized in Table 1. These values can be compared to those of a two-stroke engine as seen in Table 2. Examples of four-stroke valve and injection timings can be seen in Figure 4. This can be compared with the two-stroke cycle as seen in Figure 7.

[6] The Venturi effect is achieved by flowing matter through a constricted choke point, causing a pressure reduction and a velocity increase

[7] https://www.wartsila.com/energy/explore-solutions/flexicycle-and-chp/flexicycle-power-plants

Table 2. 4-stroke engine speeds and stroke timing

Engine speed	500 rpm
Crankshaft speed	8.33 rps
Camshaft speed	4.17 rps
Strokes/s	16.67
Stroke time	0.060 s

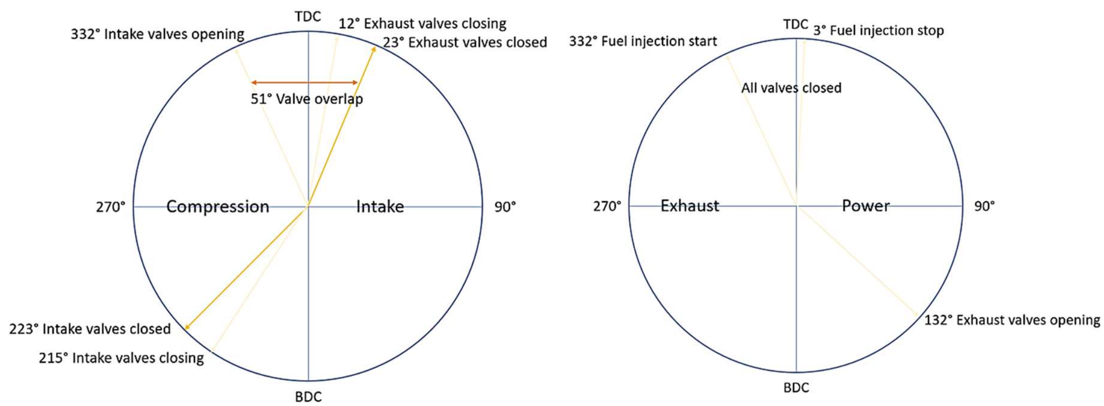

Figure 4. 4-stroke combustion timing (source: Odesie – Industrial Wiki, adapted by author)

1. Intake stroke

Just before the piston reaches the top dead center (TDC) of crankshaft rotation, the exhaust valve remains open and the flow of the exhaust gases escaping causes a low pressure to occur in the cylinder. With the intake valve opening, the low pressure helps to pull in fresh air into the cylinder and this suction is aided by the piston moving down to complete the intake stroke.

2. Compression stroke

The compression starts at the bottom dead center (BDC) after the intake suction completes. As the piston travels up towards TDC again the air inside the cylinder is compressed, causing it to increase in pressure and temperature. At the end of the compression stroke, the fuel is injected into the cylinder. The intake and exhaust valves remain closed.

3. Power stroke

Both valves remain closed as the piston passes TDC on the second revolution of the crankshaft. The air-fuel mixture is ignited causing pressure and temperature to rise. This forces the piston downward, exerting mechanical work to turn the crankshaft and generate power. A typical 4-stroke diesel engine has an efficiency of just over 40%, the remaining work is converted into heat losses that escape with cooling and exhaust gases.

4. Exhaust stroke

With the piston reaching BDC the second time, the exhaust valve opens to evacuate the hot spent air from the cylinder into the exhaust manifold. As the piston loses speed nearing TDC to complete its four-stroke cycle the exhaust gases escaping cause a pressure difference to develop which creates a suction when the intake valve opens.

The four strokes and six phases can be observed in the PV-diagrams of the Otto and Diesel cycles as can be seen in Figure 5. A simplified PV-diagram often omits the air exchange from the analysis (compare with Figure 2 of the Carnot cycle). The exchange of fresh and spent air can be seen in the isobaric in- and outflux of atmospheric air modelled in phases 0-1 and reversibly in phase 1-0 of Figure 5 and the whole cycle is comprised of the phases shown in Table 3. The four defining strokes of the 4-stroke engine are marked with red text. As previously mentioned the only discernible difference between the Otto and Diesel cycle occurs during phase 2-3.

Table 3. Otto and Diesel processes and types

Cycle	0-1 Intake	1-2 Compression	2-3 Heat Addition	3-4 Power	4-1 Heat rejection	1-0 Exhaust
Otto	Isobaric	Adiabatic	Isovolumetric	Adiabatic	Isovolumetric	Isobaric
Diesel	Isobaric	Adiabatic	Isobaric	Adiabatic	Isovolumetric	Isobaric

0-1: Intake of fresh air into the cylinder
1-2: Adiabatic compression (ideally isentropic) of the air
2-3: Reversible heating, Q_{in} is the heat introduced by fuel combustion
3-4: Adiabatic expansion (ideally isentropic) during the power stroke with work being done by the piston
4-1: Isovolumetric reversible exhaust, Q_{out} is the heat vented out
1-0: Isobaric release of air into the atmosphere

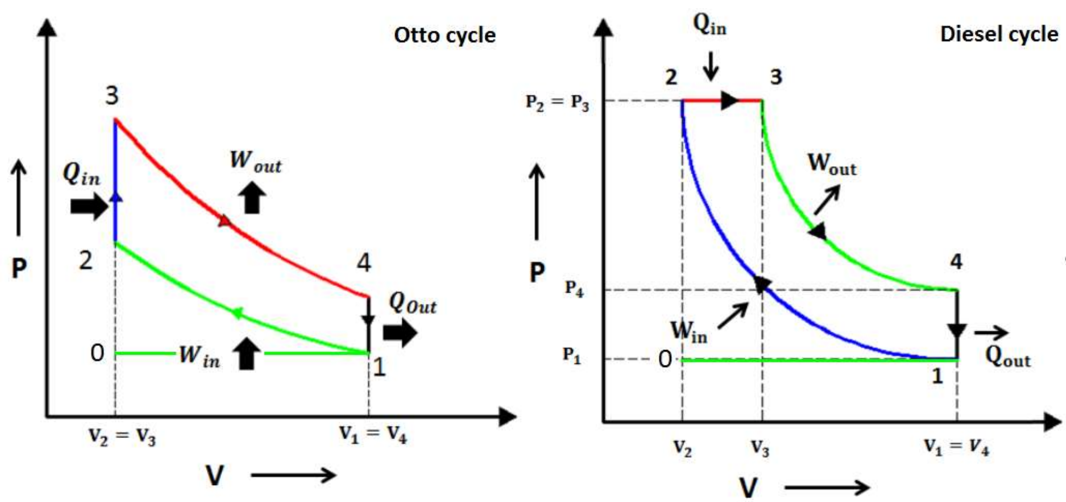

Figure 5. Pressure-volume diagrams of the Otto and Diesel cycles (source: mechanicalbooster.com, adapted by author)

A direct comparison of the idealized Diesel and Otto cycles display the similarities between them but also highlights a significant difference between them. Namely the different methods of ignition which can be seen in the isobaric compression ignition (Table 3, phase

2-3) of the Diesel cycle and the isovolumetric spark ignition (Table 3, phase 2-3) of the Otto cycle. Comparing both the Diesel and the Otto cycles to the most thermodynamically efficient heat engine cycle, the Carnot cycle, the similarities are apparent as they both follow the principles of heat engines. The compression and power strokes of both cycles are ideally isentropic. Equally, the exhaust strokes for both cycles are isovolumetric.

4.3 Equipment brief: two-stroke engines

The two-stroke engine completes the same four combustion events as the four-stroke engine, but it does so in half the time, or in one revolution of the crankshaft (360°). To achieve this, the two-stroke engine combines exhaust / intake into one stroke and compression / power into one stroke while omitting the need for a camshaft and valves. This relationship is evident in the example shown in Table 4. Comparing these values to Table 2, it is evident how much slower the crankshaft in a two-stroke engine is moving. A four-stroke engine is completing more than three times the number of strokes per second. The approximate valve timings and strokes are presented in Figure 6.

Table 4. 2-stroke engine speeds and stroke timing

Engine speed	167 rpm
Crankshaft speed	2.78 rps
Strokes/s	5.57
Stroke time	0.18 s

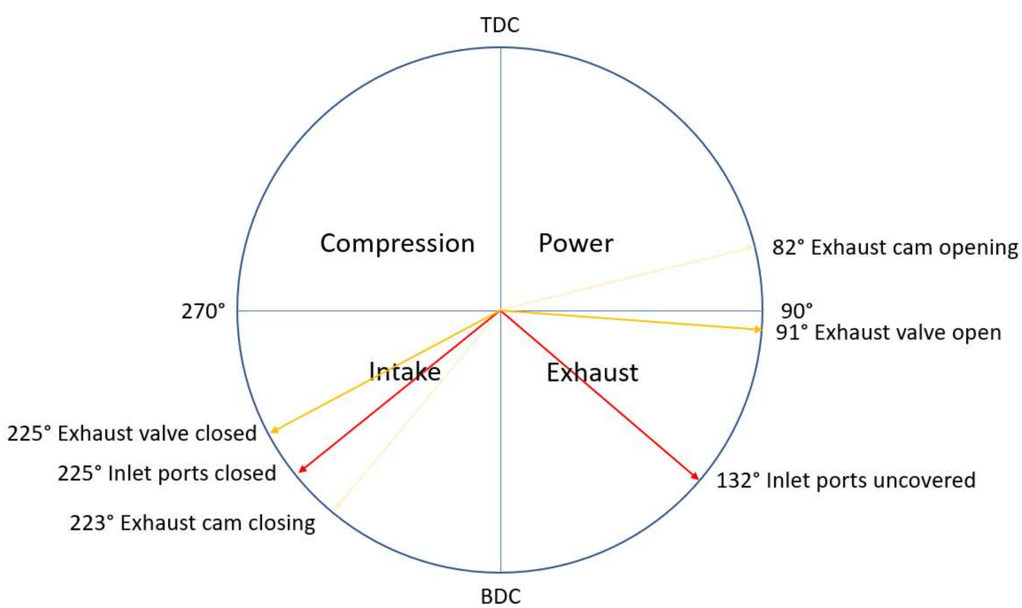

Figure 6. 2-stroke combustion timing (source: Odesie – Industrial Wiki, adapted by author)

With the technically more advanced four-stroke engines available, one can wonder why the two-stroke engine still lives on. The ocean-going market is a special segment in which the two-stroke engine offers advantages that make it an attractive proposition. Some of the reasons why two-stroke engines are chosen as the primary propulsion on ships over four-stroke engines include the size, power-to-weight ratio and fuel selection (Marine Insight, 2019). Two-stroke engines perform twice as many power strokes per revolution when compared to a four-stroke design, as described earlier in this chapter. Most two-stroke marine engines of today are large stroke and low-speed giving them high power-to-size ratio which can have relevance when it comes to ship architecture and cargo load capacity. Four-stroke engines have a larger footprint while two-stroke engines are taller due to the piston stroke. Observe some of the design differences between comparable power output two-stroke and four-stroke engines in Table 5. The two-stroke engine runs at less than a fifth of the engine speed, with five cylinders compared to 18 and a stroke length more than five times that of the four-stroke engine.

Table 5. Comparison of Wärtsilä (WinGD[8]) W5X72DF 2-stroke and Wärtsilä 18V50DF 4-stroke engines

Engine	2-stroke W5X72DF	4-stroke W18V50DF
Cylinders	5	18
Bore [mm]	720	500
Stroke [mm]	3086	580
Stroke / bore	4.29	1.16
Speed [rpm]	69-89	500, 514
Rated power [kW]	16125 [1)]	17100 [2)]
Length [mm]	8085	14180
Weight [t]	481	240

[1)] Nominal maximum continous R1 power/speed rating

[2)] Nominal engine output at 50 Hz

Another advantage is reliability which is a major concern when out at sea. Two-stroke engines have fewer moving parts, so they are more reliable by design, this also means that maintenance should be less. Thanks to the slow operating speed of two-stroke engines they also do not require reduction gears on the output shaft. Finally, two-stroke engines are simpler to run, and they can burn low-grade fuel which a four-stroke engine would not accept. This can reduce the running cost of the vessel and be a functional consideration in some parts of the world due to fuel quality. However, this is restricted by maritime legislation and is becoming less of an advantage. Naturally, four-stroke engines offer many advantages over two-stroke designs as well. These include longevity, the two-stroke engine lacks a dedicated lubrication system, so it consumes oil mixed with its fuel for lubrication. The two-stroke oil can carry a considerable price, so it must be offset against the cheaper fuel that the

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[8] Winterthur Gas & Diesel (WinGD), originally established in 1893 as Sulzer merged with Wärtsilä in 1997. In 2015 the Wärtsilä subsidiary merged with China State Shipbuilding Corporation (CSSC) and in 2016 CSSC took possession of remaining WinGD shares.

two-stroke can use. Four-stroke engines are more fuel efficient, more environmentally friendly and typically run quieter than two-stroke engines.

4.4 Fuels and fuel modes

The different variants of fuels used in power plants (PP) and marine installations can be seen in Table 6. Light Fuel Oil (LFO) and Marine Diesel Oil (MDO) are used almost exclusively for marine installations while Heavy Fuel Oil (HFO) and Liquefied Natural Gas (LNG) are shared between both. Some power plants can run on raw methane gas.

Table 6. Fuel types and properties (source: TheEngineeringToolbox.com and globalcombustion.com)

Fuel	Abbreviation	Type	Use	Density [kg/l or kg/m3]	Calorific value[9] [MJ/kg]
Light Fuel Oil	LFO	Fuel Oil	Marine	0,96	44,00
Marine Diesel Oil	MDO	Fuel Oil	Marine	0,98	42,26
Heavy Fuel Oil	HFO	Fuel Oil	Marine & PP	0,98	41,80
Liquefied Natural Gas	LNG	Gas	Marine & PP	0,43	55,20
Methane	CH4	Gas	Power plant	0,72	55,50

The calorific value (CV) expresses how much energy is contained in fuels by measuring the heat produced during a complete combustion of a specific quantity of the substance. The higher calorific value (HCV) is the sum of all heat extracted in the combustion, including all the water being condensed and recovered. The lower calorific value (LCV) measures the combustion including the water vapour escaping without recovering the heat loss. Regional variations in the calorific values between different fuels do occur.

For liquid fuels an important property is the kinematic viscosity, this is defined as the restrictive flow a fluid exhibits under gravity. The kinematic viscosity is often expressed in centistokes (cSt) where 1 cSt = 1 mm^2/s. The viscosity of fuel oil changes with temperature, so temperature should be mentioned in reference to viscosity. The relationship between viscosity and temperature has been classified by the American Society for Testing and Materials and is expressed as the Viscosity Index (VI) (American Society for Testing and Materials, 1975).

[9] Calorific value listed is the higher heating value (HHV) or gross calorific value (GCV)

4.4.1 Fuel Oils

LFO is a middle distillate largely used for medium to medium/high-speed marine diesel engines. It has a flash point of around 82 ˚C and qualifies as a marine fuel oil by the ISO 8217 (ISO, 2017) standard which requires a flash point of at least 60 ˚C.

MDO is also a middle distillate marine fuel that is created from a blend of marine gasoils (different distillates of MGO) with a small portion of HFO mixed in. MDO is not classified as a pure distillate like the ones used in for example diesel cars but it possesses similar properties with a higher density. Diesel oil has a density of 0,84 kg/l compared to 0,98 kg/l for MDO with a calorific value of 43,02 MJ/kg for diesel and 42,26 MJ/kg for MDO. A benefit of MDO compared to HFO is that it does not require preheating.

HFO is not a distillate fuel but rather a residual oil with a density of over 0,9 kg/l or a kinematic viscosity of over 180 cSt at 50 ˚C. A residual fuel is made up of materials that are left after finer crude oils have been boiled off – in essence, it contains a large percentage of heavy molecules of long-chain hydrocarbons, as well as some impurities like water and mineral soil. HFO needs to be preheated because of the high kinematic viscosity and filtered for harmful particles before use.

4.4.2 Sulphur content

The sulphur content in marine fuel oils are graded in classes:

- High Sulphur Fuel Oil (HSFO): 3,5% max
- Low Sulphur Fuel Oil (LSFO): 1,0% max
- Ultra-Low Sulphur Fuel Oil (ULSFO): 0,1% max

Typical marine fuel oils are classified as LSFOs with a sulphur content of less than 1%, examples of these types of fuels are IFO 180 (max 180 cSt, <3,5% sulphur) or IFO 380 (max 380 cSt, <3,5% sulphur). As of January 1, 2015, the MARPOL Convention Annex VI (International Maritime Organization, 2019) states that ship emissions must not contain more than 0,1% sulphur in emission control areas (ECAs – essentially shorelines) so LSFOs will largely be replaced by ULFSOs. An alternative to switching to an ultra-low sulphur fuel oil is to use exhaust scrubbers that can be retrofit to vessels. This technology enables the continued use of higher sulphur content fuel oils by injecting a water mist into the exhaust stream that binds sulphur and other emissions, so they cannot escape the flue. This way ships can continue using HSFOs even inside the ECAs (see IMO, 2019 and Wärtsilä, 2014).

4.4.3 Gases

LNG is a natural gas that has been frozen into the liquid state. It is mainly made up of methane (CH_4) but can contain other gases like carbon dioxide (CO_2), nitrogen (N), ethane (C_2H_6), ethylene (C_2H_4), propane (C_3H_8), butane (C_4H_{10}) and traces of noble gases. At around -160 ˚C LNG transforms into its liquid state which causes it to compress to around 1/600th the volume of its gaseous state. This yields a higher amount of non-flammable, odourless, non-toxic and non-corrosive fuel in a small space at near atmospheric pressure. Because LNG has to be kept at a low temperature it requires specialist equipment that decreases its price efficiency. Because of the high energy content and low emissions when compared to coal or other fossil fuels, LNG has become an attractive proposition both in marine and power plant applications.

Methane is the simplest hydrocarbon in the paraffin series of acyclic saturated hydrocarbons, meaning every carbon-to-carbon link is single. Methane is both odourless and colourless and is the main component of natural gas (60-90%). Methane or natural gas is sometimes labelled the world's cleanest fossil fuel (International Gas Union, 2019) but this has sparked controversy among politicians and legislators (Neslen, 2017).

4.5 Wärtsilä fuel mode processing

Fuel mode processing uses a filter class set defined for detecting fuel modes. CBM does not consider mixed fuel modes such as bio-diesels. This is an improvement that is to be implemented in Asset Diagnostics. Fuel mode detection is especially important for Dual Fuel (DF) engines, but diesel engines can function on different fuels (LFO/MDO/HFO) as well and it is important to know which one is in use to have the correct sensor thresholds. The detection of which fuel is in use can be achieved by looking at specific sensors which give tell-tale signs (Chevron Marine, 2012).

- If Global MFI (Multi-Port Fuel Injection) Demand is higher than 0 the engine is operating in gas mode
- For equipment missing the Global MFI Demand sensor, the Fuel rack control sensor can be used instead to detect the use of LFO or HFO, this excludes gas (LNG or methane) as a fuel
- The separation between LFO/MDO and HFO modes can be done by looking at the Fuel oil temperature sensor. HFO is a high-viscosity residual fuel and requires preheating, meaning it runs hotter than LFO and MDO.
- If the Fuel oil temperature is over 80 °C, then the fuel in use is HFO. A standard 380 cSt HFO fuel needs to be preheated to about 130 °C before its viscosity is low enough to be used.
- If the Fuel oil temperature is under 80 °C, then the fuel in use is LFO or MDO. MDO is a blend of heavy gasoil that can contain small amounts of black refinery feed stocks but has a viscosity that is low enough to omit fuel preheating. This means MDO and LFO can be treated under the same fuel mode.

5 Predecessor – Wärtsilä CBM

The CBM service has been in operation since 2000 and constitutes an engine management and surveillance system to safeguard against malfunctions and decrease maintenance downtime (see Chapter 3.1). The development of CBM as a service can be traced back to the Wärtsilä FAKS (Fault Avoidance Knowledge System) program that originated in the 1990s. This program ran on a local site computer that performed early edge computing for following up engine operation data. It was a computer program designed to help operators and service personnel with predictive maintenance and fault avoidance by providing condition monitoring, trend analysis and fault diagnostic capabilities (Vägar, 1999). FAKS lacked the option for remote monitoring and this is how CBM came to fruition.

CBM receives data from the engine and auxiliary automation systems and processes them through predefined algorithms in Wärtsilä proprietary software. The system works by calculating ideal operational parameters dependent on the engine type in use. These results are then filtered and corrected based on environmental parameters, such as ambient temperature, humidity and engine loads. The system operates by constantly monitoring key parameters and keeping a log of daily averages to trend how the equipment is performing. This data is automatically sent from the equipment supervisory computer to the CBM server once a day, which then processes the data. In some cases, for example when internet connectivity is poor or on customer request, the data is instead sent manually. This process is typically done weekly or monthly. Engine and installation reports are then generated based on the engine type and known optimal values for each equipment type. The processed values are analysed by an engine specialist and compiled into a monthly report which is part of the service agreement that Wärtsilä provides to its customers.

The Wärtsilä CBM system relies on data gathering from the site being pushed through for analytics at the CBM centre where it is populating an SQL database. This raw data gets processed daily and pushed further into an RPA[10] SQL database that holds the processed and filtered data. The data is then analysed in the RPAviewer (see Chapter 5.3) software and compiled into monthly CBM reports by Wärtsilä experts.

The data collection channels can be multiple, depending on the agreement and internet connectivity. In the case of poor internet connectivity or lower data polling frequency, the data is aggregated through the WISE[11] (Wärtsilä Information System Environment) service and sent to the server once a day. WISE is a reporting platform that relies on WOIS (Wärtsilä Operator's Interface System) as its primary data provider. With better connectivity and higher data sampling rates the system can use WOIS directly, to receive near-live data. Analog data is collected into historical trends (diagrams and tables) and digital values are stored as an archive list of events.

Figure 1 illustrates the circular flow of data inside the Wärtsilä CBM system. Operational data is collected locally and transmitted over a secure channel on the internet to the datacentre. Technical experts have access to this data and can in agreed cases, establish a

[10] Reference Performance Analyser, see Chapter 5.2
[11] WISE and WOIS are discussed in more detail in Chapter 6.

remote connection straight to the data source. Monthly reports are generated from this data, collected centrally and distributed to the customers, who can then use the suggested actions to improve their equipment performance.

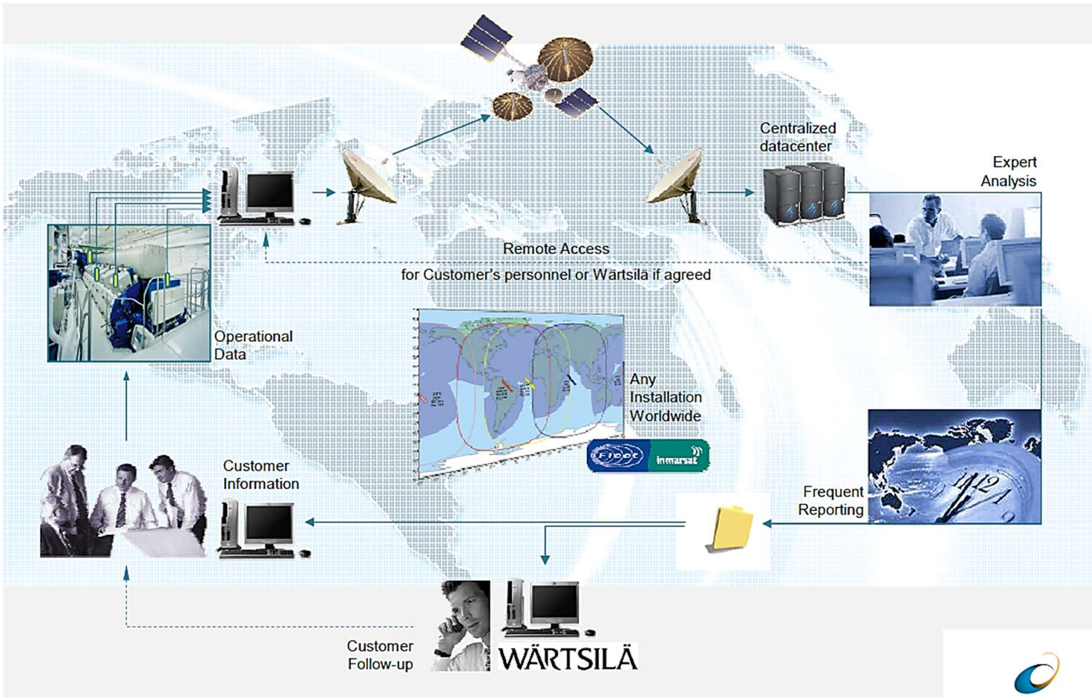


Figure 1. Data flow in CBM (source: Wärtsilä CBM)

The system works in conjunction with the operating crew reporting the plant or ship performance, inventory, any work performed, unscheduled maintenance and fuel / lubrication oil analysis. In addition, scheduled inspections are carried out and reported back to Wärtsilä. Based on all this data the system specialists can do dynamic maintenance planning that takes the aforementioned data into account and generates work orders and CBM reports. By using algorithms, the system can calculate ideal operational parameters for the equipment, taking into account the variability of environmental factors and also the interconnectivity of different parameters. Understanding this interrelationship between parameters is crucial for ensuring stable system operation. One example of this dependency can be seen in Figure 2. The inlet temperature of the air affects the turbocharger speed which in turn causes the charge receiver pressure to change. With the pressure changing the exhaust gas temperatures will also be affected, which has an effect on the wastegate / bypass valve position and this eventually leads to changes in the fuel consumption and emissions.

Figure 2. Parameter dependency

5.1 Targets

CBM is a tool used for supporting the dynamic maintenance planning to increase equipment availability and reliability. By supporting the operators of the installed equipment, the best possible performance can be reached. The overall goals that Wärtsilä CBM targets are:

- Reduce fuel oil consumption / emissions
- Reduce the maintenance costs
- Avoid unplanned stops
- Increase the total availability
- Predict the required maintenance
- Find critical cases in advance
- Offer life cycle support to the customer

Wärtsilä has been tracking the maintenance cost savings through follow-up of the dynamic maintenance planning. It is approximated that the cost savings for a predictive maintenance system are in the region of 10-20%, something which is backed up by the semi-structured interview presented in Chapter 8. Fuel consumption figures are not registered in most installations today. In certain cases, the customer is sharing the fuel consumption data with Wärtsilä. Some installations have mass flow meters installed before and after the engines to be able to measure the fuel consumption. On a general level, this is a metric that relates to the overall engine performance.

5.2 Reference Performance Analyser (RPA)

The Reference Performance Analyser is a Wärtsilä proprietary software used for performing equipment reference calculations. The RPA software is the backbone of the smart analytics used for generating CBM reports. Through the data processed by RPA in conjunction with input from engine experts, the system is able to compare actual installation data with Wärtsilä defined deterioration limits. These deterioration limits are calculated by RPA by accounting for a multitude of different parameters that can be broken down into three main segments: 1. Engine configuration 2. Installation configuration 3. Dynamic input.

5.2.1 Engine configuration

The engine configuration includes basic design parameters like cylinder count, cylinder orientation, nominal speed, engine rating, turbocharger type, fuel injection type, thermostatic valve set points, charge air cooler system and camshaft type among other things.

5.2.2 Installation configuration

The installation design criteria are also considered for subsystems such as cooling water, installation altitude, generator type, propulsion system, static water pressures and more.

Liquid input parameters like fuel oil quality, lubrication oil quality and cooling water quality are stored and used in the calculations.

5.2.3 Dynamic input

Dynamic site parameters that affect the calculations are added into the calculations. These parameters include load levels, ambient conditions, fuel selection, fuel oil viscosity, fuel heat value, atmospheric pressure and so on.

Based on the aggregated data and equipment configuration, RPA performs calculations to produce dynamic parameter reference points along with low- and high-spreads (tolerances) of what the values are expected to be. The actual site value for each sensor is then analysed and determined to be either inside or outside the threshold. If the value is within the threshold, the data is nominal and no action needs to be taken. If the value falls outside the threshold, it is compared against the yellow high- and low-spread (alert) and red high- and low-spread (action). This scale relates to the traffic light system in place in the CBM report and is a direct indication of how the equipment is performing on a sensor level.

To ensure data quality, operational data is also filtered according to the load level, as this has a direct correlation with measurement values. The load level is based on the customer's intended running profiles for the engine. The typical thresholds are a minimum of 20% power output for a 4-stroke engine and 5% power output for a 2-stroke engine, but it can vary depending on the equipment and customer needs. Figure 3 presents an example of the configuration parameters necessary for performing an engine analysis. In this case, the

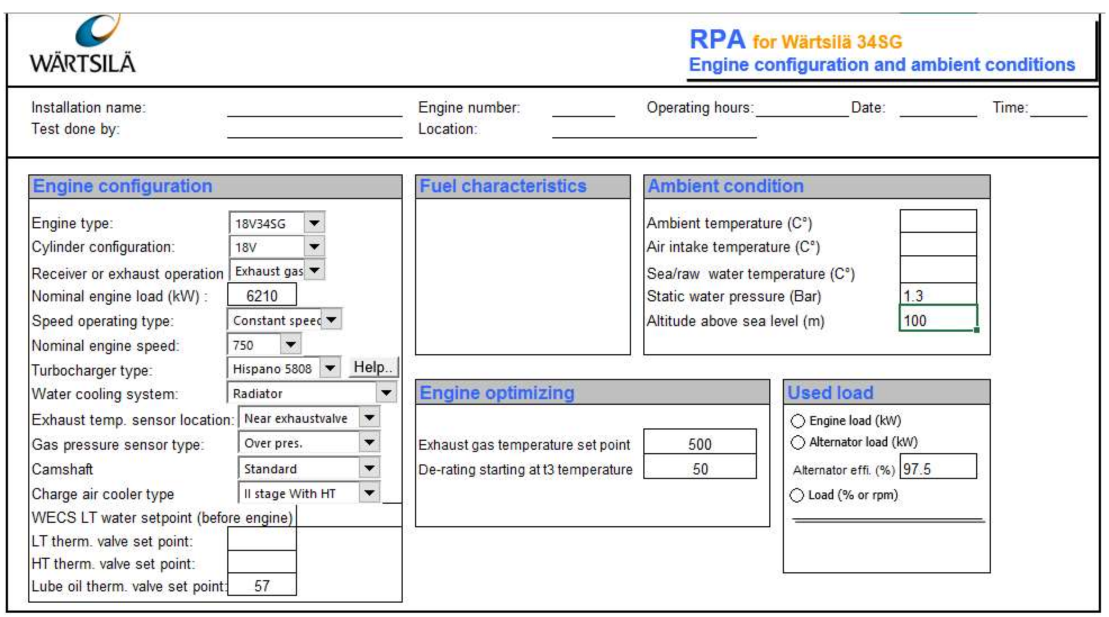


Figure 3. RPA configuration for a W18V34SG engine

engine type is Wärtsilä 34 Spark Gas. When you examine the configuration details you can ascertain this specific 34SG engine is an 18-cylinder version in V-formation, with an expected nominal load of 6210 kW. It operates at a constant expected speed of 750 rpm and has an alternator efficiency of 97,5%.

5.3 RPAviewer

RPAviewer is a proprietary software tool created with the purpose of simplifying the process of creating CBM reports by means of the Reference Performance Analyzer. The software aims to automate certain recurring events to aid the end user in data gathering and analysis. The RPAviewer project started in April 2003, shortly after the first power plants and ships were connected to the CBM service (2001 and 2002 respectively). The software has been continuously updated through the years but now nearing 20 years in service it is due for replacement. The program works as a front end for data collection and analysis from SQL databases.

The program layout can be seen in Figure 4. The main components can be identified as:

1. Connect / disconnect button for establishing an SQL connection to fetch the CBM data
2. Installation name, possible to select from a drop-down list or filtered text search
3. Calendar where the data analysis period is chosen by clicking or painting with the mouse cursor
4. Engine list that works as a drop-down list. It is also possible to filter by fuel mode (LFO/HFO/GAS) by using the drop-down list that appears under the Installation name. This is particularly useful for dual-fuel installations or installations with many engines
5. The Overview window is a status display of command responses
6. The selection window contains a list of the main analysis tools in the software

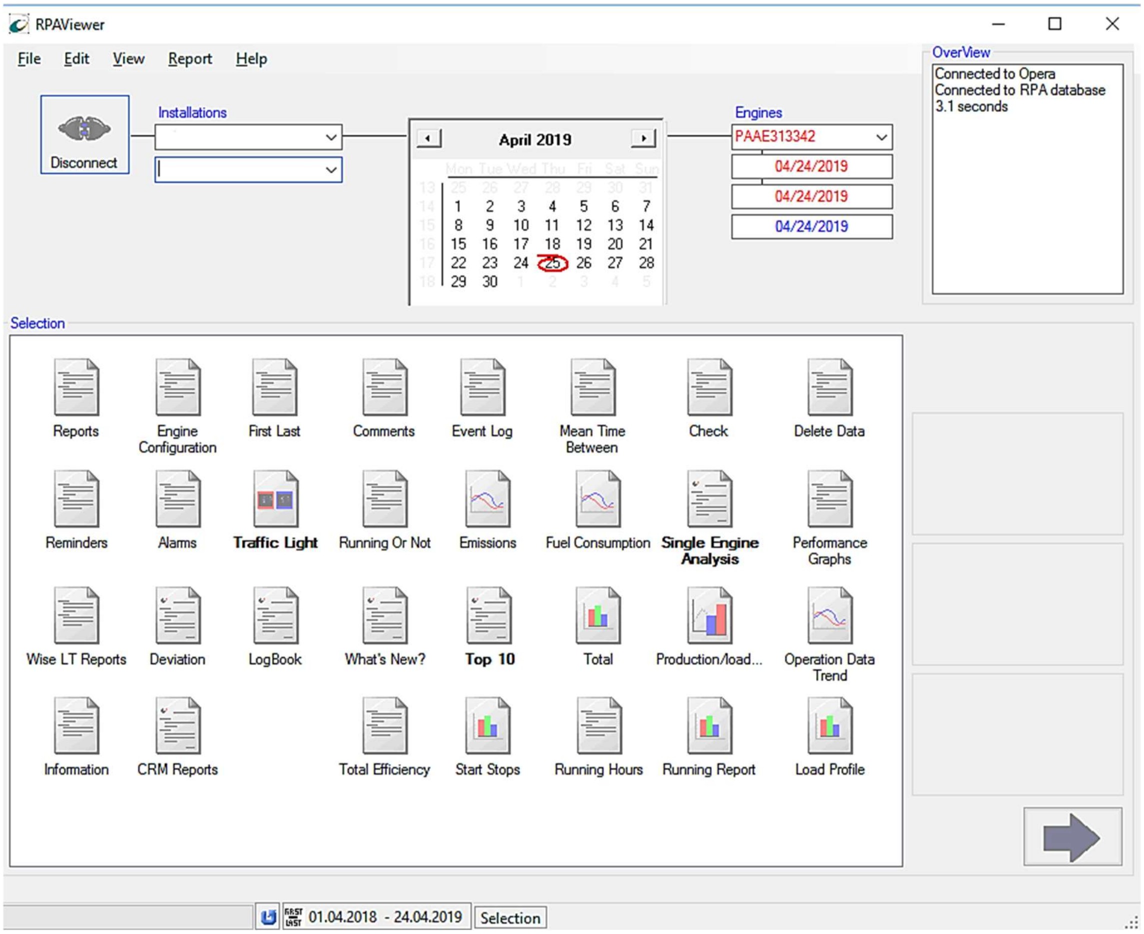


Figure 4. RPAviewer overall layout

5.3.1 Traffic light

Traffic light is a colour coded status indicator for all the engines in an installation. By selecting a date range and forcing the software to detect the last running date the report generates a list with the last running date info colour coded according to criticality:

- Blue: No or low load (below threshold)
- Green: Ideal operation
- Yellow: Alert (certain warning measurement thresholds breached)
- Red: Action (certain action measurement thresholds breached)

Figure 5 shows an example of a traffic light engine selection. Engine 1 PS LFO[12] and Engine 2 SB LFO are showing as blue or cold engines because there is no data present to process. This implies the engines have not been run or they have been run below their pre-set load

[12] PS and SB indicate portside and starboard in a marine environment. LFO and HFO indicate the fuel modes.

threshold. Engine 1 PS HFO is showing as yellow, meaning some operational data is outside the alert limit. Engine 2 SB HFO is green, meaning it is operating nominally.

Figure 5. Engine status in the traffic light report

5.3.2 Top ten

This list shows the top 10 most occurring alert or action measurements for each engine of an installation. The list will indicate how the equipment is performing and which measurements are most frequently outside normal operational values. This helps the analyst in assessing the actions to suggest to the customer. The list shows the total amount of days analysed and the frequency of deviations within this period, along with a percentage-based strength indication.

5.3.3 Single engine analysis

This report shows all the sensor measurements for a single engine and date. The high- and low-spread limits are also shown as well as colour coding of the measurements that fall outside of the alert and action thresholds.

5.3.4 Operation data trend

This is a trending tool that shows how a measurement has been operating for a prolonged period of time, as defined by the user. If only one measurement is selected, the high- and low-spread are also shown alongside the sensor values. If several measurements are compared in the same chart, the value limits are omitted. This graph can be subject to a load filter, which will disable output if values fall under the load threshold. Figure 6 shows an example of two similar engines running on Heavy Fuel Oil (HFO) being compared in the operation data trend. The x-axis represents the date and the y-axis represents the engine load in kW. This gives the analyst information on how an engine has been operating over time.

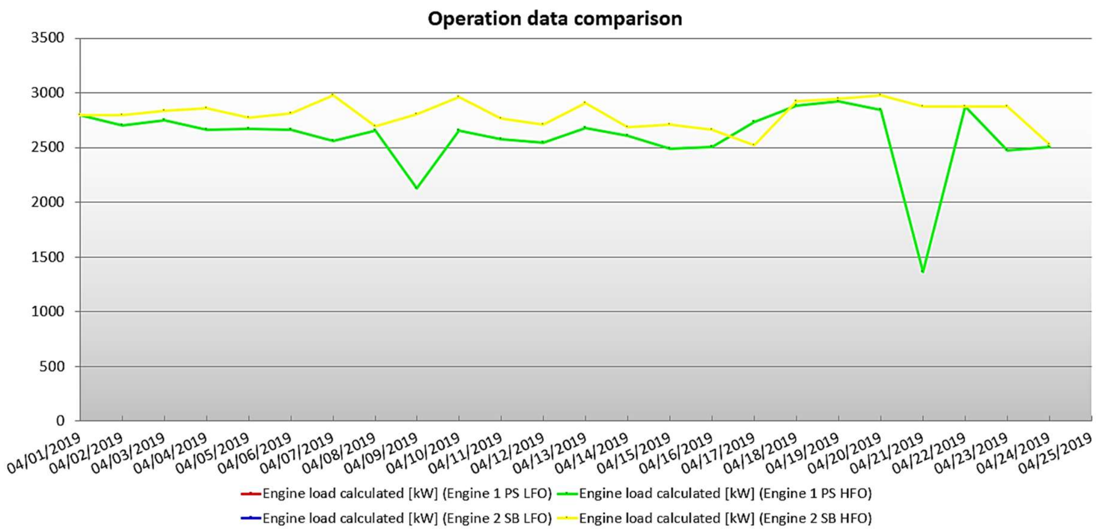


Figure 6. Operation data comparison of engine load between two engines

5.3.5 Production

This report shows a staple diagram of the 24 h megawatt (MWh) production for an installation, divided into month-sized periods with the fuel mode distribution displayed inside of each monthly staple. Figure 7 displays the electrical production of six engines that can run on three different fuels (light fuel oil, heavy fuel oil, gas), over a period of four months. The cumulative production can be seen in the total bar height, with the colours representing the engine and fuel distribution. In this example, only one fuel mode is being used, but there are a potential 18 different combinations available (3 fuel modes * 6 engines).

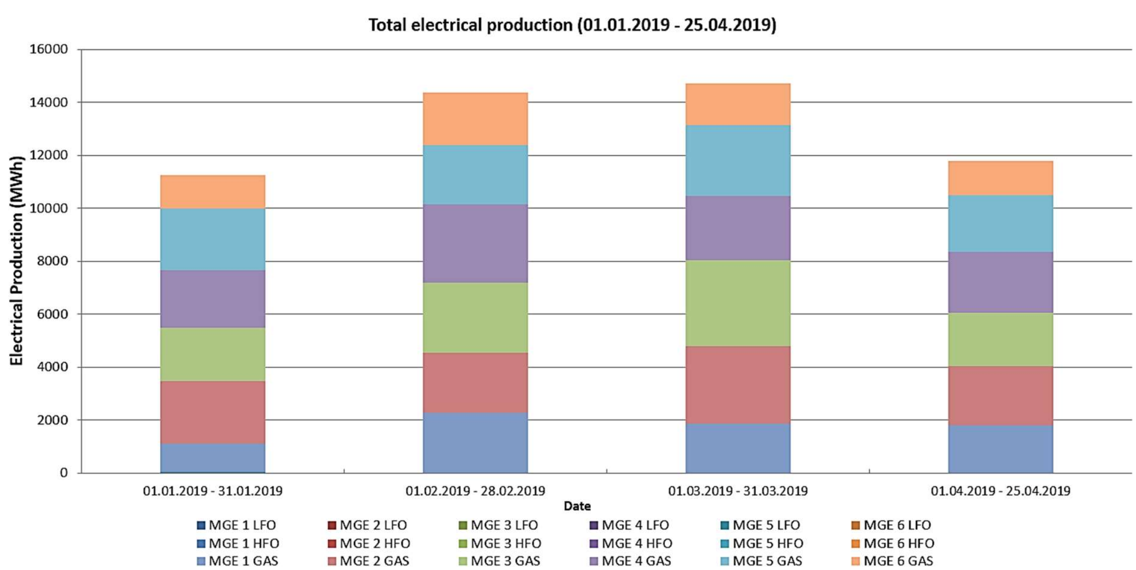


Figure 7. Electrical production break-down by month, engine & fuel mode

5.3.6 Start statistics

This is a statistical representation of how many successful and unsuccessful starts each engine in the installation has performed during the period selected by the user.

5.3.7 Other functionality

The statistical analytics only outline some of the features of the RPAviewer tool. It contains more specific tools for working with CBM report generation, installation and engine configuration, running hour reports as well as other technical functions.

5.4 CBM reports

The reports employ a traffic light system to highlight the status of the equipment with a quick visual overview. Each engine receives a traffic light and the subsystems each have their own condition rating which gives a more detailed insight into how the engine is performing and which parameters are outside the ideal threshold. This gives an opportunity for engine optimization and investigation into the cause for the deviation from ideal values. The scale of the traffic light report is the aforementioned Green / Yellow / Red. Green signifies an engine working in normal operational parameters, yellow indicates that one or several parameters are slightly outside the threshold and red indicates that one or more critical parameters are outside of limits. A blue engine in the CBM report signifies a 'cold' engine, one not running or below the pre-set load limit.

Typically, CBM is contracted for an engine or an installation containing a group of engines. The report is further divided into subsystems which the engine is dependent on. In each of these subsystems a number of sensors can be found that measure system operation. The main systems can be denoted as:

1. Engine control system
    - The engine control system is responsible for monitoring the operation of the engine through a multitude of sensors that are displayed on a control display. The system also operates with the engine safety system to issue automatic shutdowns or safety precautions.
2. Engine safety system
    - The engine safety system monitors critical function parameters to ensure the engine is not at risk of failure or imminent breakdown. Most critical operational values include lubrication oil pressure and engine main bearing temperatures.
3. Fuel oil system
    - The fuel oil system is responsible for providing the correct, clean fuel with a consistent temperature and pressure.

4. Lubrication oil system
5. Cooling system
6. Exhaust gas system
7. Charge air system

Figure 8 shows an example title page for a monthly CBM report. This page shows all the gensets (generator sets) and their running status as per the traffic light criteria. The subsystems of each genset are also evaluated and given a colour code.

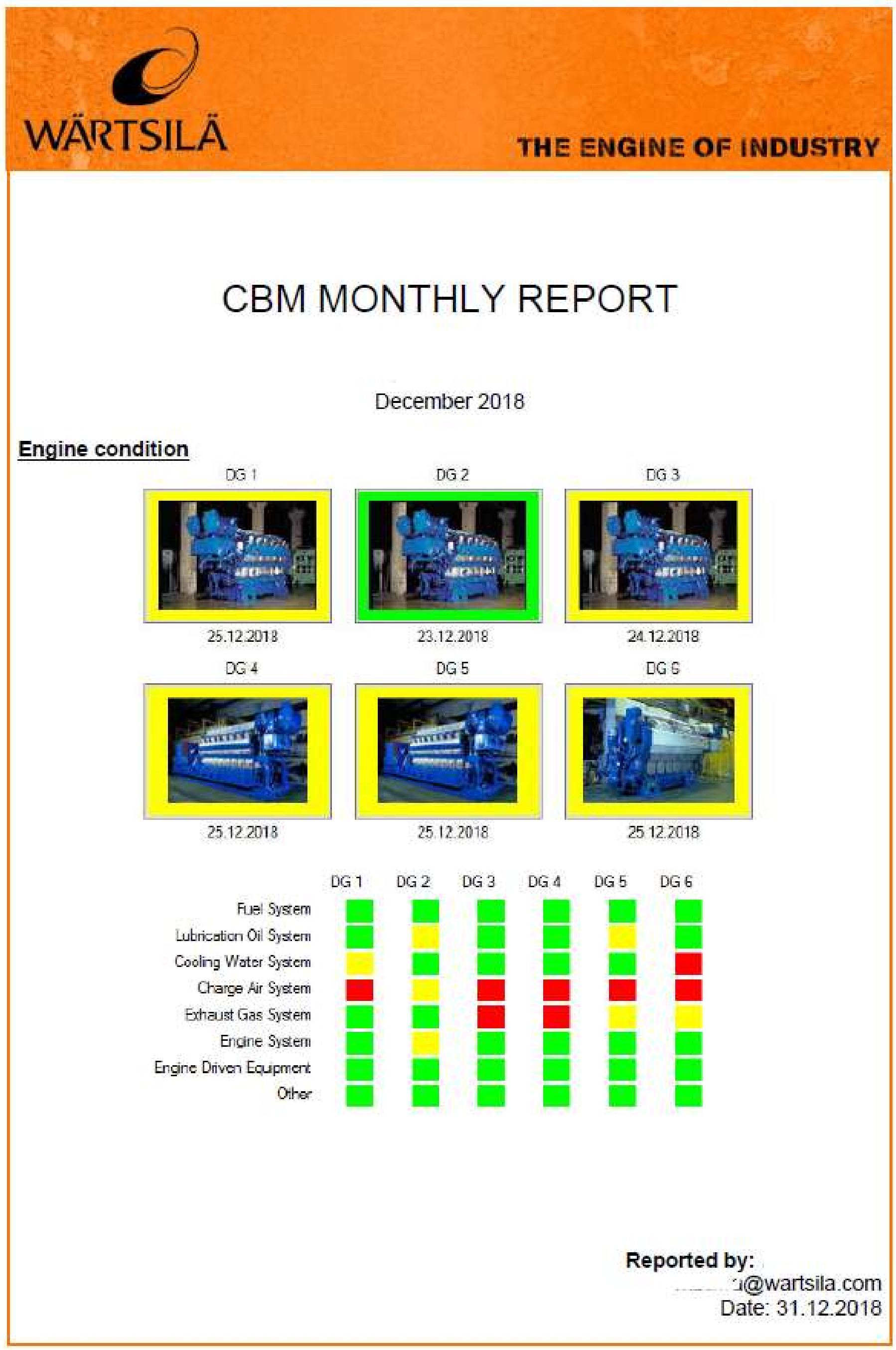


Figure 8. Opening page of legacy CBM report

The report contains a more detailed analysis of the potential faults and suggested actions. This is based on exhaustive equipment knowledge and the work of the human analyst who reviews the data and writes up the report. The analyst looks at the operational data and how the trend for that data is looking and presents causes and suggested actions to remedy the problem. The customer will get a detailed list of operational data values and highlights of those that are outside limits, which are calculated as a high / low spread of an engine running on 85% load. The high / low spread of an installation is set at a narrower gap than the alarm limits of the equipment to give an early indication of anomalies. An example of more in-depth sensor analytics can be seen in Figure 9. Deviations are highlighted in orange. Values in red are further outside the threshold. Depending on the circumstances and sensor in question, these can be actionable targets.

5.1 Complete operation data analysis, DG 1

Date/time:	25.12.2018			Installation:	
Load (kW):	5450			Engine no.	DG 1 (8389)
Load (%):	85			Run hrs.	0
				Air int. temp.	30.1
				Ambient	30.1

Operation data	Unit	Site values	High-spread	Low-spread	Comment(s)
Ambient temperature	°C	30	45	0	
Fuel oil pressure, engine inlet	bar	7.2	8.5	5.0	
Fuel oil temperature, engine inlet	°C	106	135	5	
Lubrication oil pressure, engine inlet	bar	5.1	6.0	4.5	
Lubrication oil temperature, engine inlet	°C	67	67	58	
Lubrication oil temperature, engine outlet (before LOC)	°C	81	82	68	
Charge air pressure	bar	1.9	2.3	1.9	
Charge air temperature	°C	59	60	43	
Pinch point, CAC-LT		6	15	11	
Engine Speed	rpm	720	735	705	
Turbocharger speed A	rpm	19517	19763	18263	
Turbocharger speed B	rpm	19504	19763	18263	
HT water pressure, engine inlet	bar	2.7	3.1	2.4	
HT water temperature, engine inlet	°C	79	82	77	
HT water temperature, A/B bank outlet (common)	°C	86	88	82	
LT water pressure, engine inlet	bar	2.6	3.1	2.4	
LT water temperature, engine inlet	°C	53	45	36	
LT water temperature, after charge air cooler common	°C	46	49	39	
LT water temperature, lube oil cooler outlet	°C	53	52	44	

Figure 9. Operation data analysis

The CBM experts analyse the operational data and react to anomalies and deviating trends. Based on their knowledge of the specific engines and their experience they give a technical brief of the issue and the problems it causes along with a recommendation on how to remedy the detected issue. Figure 10 indicates a sample technical conclusion of deviating sensor values. In this case the CBM expert advices a readjustment of the fuel pressure, with more detailed instructions accompanying the report.

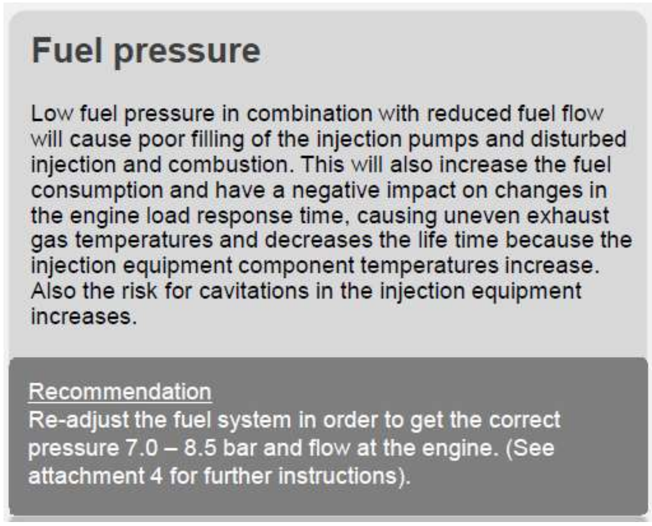


Figure 10. CBM experts advise

5.5 CBM Configurator

The CBM configurator is a tool designed for configuring metadata for installations and equipment as part of the RPA toolchain replacement. It was developed between 2017 and 2018 during the RPA Replica phase 2 project. Throughout 2018, testing and use of the tool has proved it lacks needed features and optimization for being able to on-board multi-portfolio installations. Therefore, the decision was made that the program should be evolved and developed into the new Asset Diagnostic Configurator (discussed in Chapter 6). The infrastructure and workflow would remain largely the same, but the new configurator would offer a wider range of functionality and have continued support and updates.

The hierarchy of how configurations are arranged is visualized in Figure 11. On the top level are the customer installations, this constitutes power plants or ships. Equipment belonging to each installation is listed on the next level, this is typically made up of engines. The lowest level is represented by sensors and parameters. Each equipment has sensors and parameters that are affiliated with it.

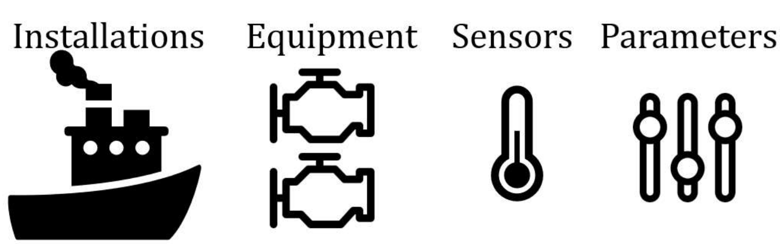


Figure 11. Installation and equipment hierarchy

The layout of the CBM configurator is split into three main views used for viewing and modifying installations, equipment and sensor mappings:

1. Equipment configuration (installation and equipment configuration)

2. Sensor mapping (mapping physical sensor tags to ISO codes)
3. Admin (administrator access for adding or modifying the system parameters)

5.5.1 Equipment configuration

In the equipment configuration tab, the user can view existing customer assets (installations) and their associated equipment, add new installations and equipment as well as modify existing configurations. If the user is tasked with mapping an entirely new installation the first step to take is to configure the installation details and add all the associated equipment with it. Existing installations can be filtered by searching for the installation name or the unique functional location.

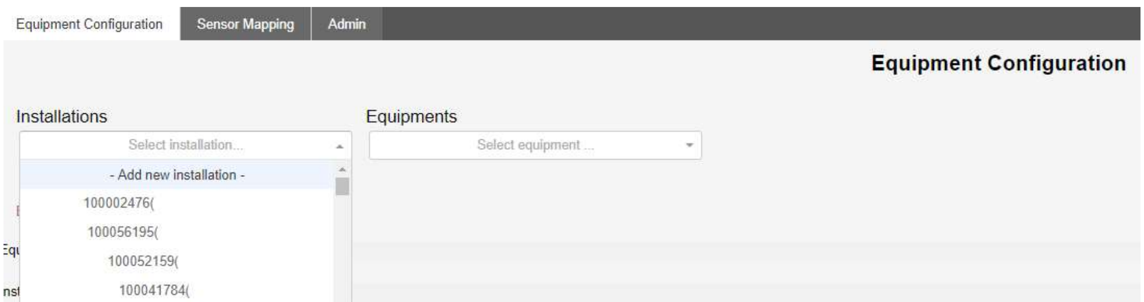


Figure 12. Adding and searching for installations

New installations can be added by selecting - Add new installation – at the top of the drop-down menu. When the user prompts for a new installation to be added they are presented with a window asking for the base installation details: Installation name, Installation ID and Functional location. The user can then opt to either save or cancel the operation. After the installation has been created some basic configuration details can be added: Altitude, Application category, Equipment category, Product line and Installation type (see Figure 13).

Altitude	8
Application Category	Energy
Equipment Category	Engines
Product line	4-stroke
Installation Type	Independent Power Produce

Figure 13. Installation configuration

Once an installation has been created the equipment list can be populated with new equipment. When viewing an existing installation, the equipment drop-down list will display all configured equipment and their type. New equipment can be added as well through using the – Add new equipment – option found at the top of the list. In Figure 14 you can see an example of a preconfigured installation with an equipment pool of several W18V46 engines.

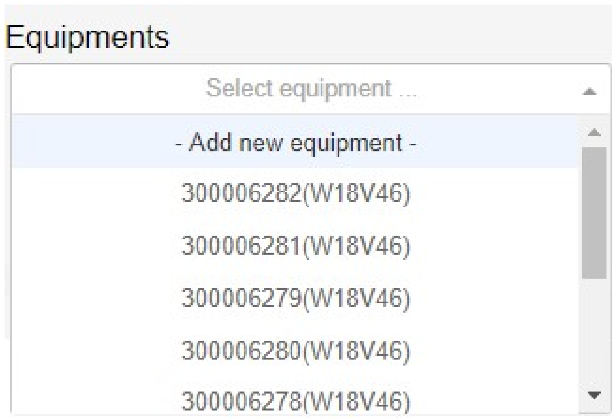


Figure 14. Populated equipment list with equipment numbers and types

If an engine is selected all the saved configuration details of that specific equipment are loaded and available for the user to modify. The required configuration parameters depend on the engine type but some of the commonly specified ones include base data needed for performing asset diagnostics such as:

- Engine load tag
- Engine order and identifier (nickname)
- Cylinder configuration
- Load filter limits
- Turbocharger and charge air cooler details
- Generator details
- Nominal power and RPM
- Low temperature (LT) & high temperature (HT) static water pressures and thermostatic valve set points
- Lubrication oil thermostatic valve set point
- Fuel type and quality

After adding or modifying equipment parameters the user has the option of enforcing the change to all equipment that is linked to the same installation by clicking the checkbox ‘Apply to all’ next to the text field input. When the update has been performed the user needs to manually save the changes by clicking ‘Save configuration’. One of the issues with the CBM configurator was that changes were not automatically saved and if a user waited too long before saving, the session could be timed out and the changes lost.

In addition to these parameters that the user can modify, add or delete there are some fixed equipment parameters that are always required for the system to know which installation the equipment is associated with. The fixed parameters are: Installation ID, Data acquisition type, Product type, Product reference type and Product serial number.

If a new engine being configured is of the same type as a previously configured one the user also has the option of copying the configuration from another engine, even if the source engine was linked to another installation.

5.5.2 Sensor mapping

The sensor mapping page is used for linking the physical sensor names that are coming from site metadata with the logical sensor ISO codes to be able to perform analytics and visualization on the data. This part of the process constitutes the normalization of the physical sensor data in order to harmonize all the data between different installations. The sensor mapping page works in a similar manner as the equipment configuration page. On the left-hand side are the name and functional location of the installation in question. When an installation has been selected, the list underneath it is populated with the sensor links that have been made. Figure 15 illustrates an example of a preconfigured installation. The list on the left represents all the physical sensors that have been mapped and the list on the right is the complete list of logical ISO codes. On the right-hand side you can observe that some ISO codes have been greyed out – this indicates that these codes have already been mapped. Both the left and the right side can be filtered by typing part of the sensor name at the top of the respective list. In addition, both sides can be filtered to only show unassigned sensors. As can be seen from the example, a lot of the logical ISO codes are not mapped. This is a normal occurrence as the number of sensors varies largely depending on the equipment type.

In the left-hand side list each of the sensor tagnames represents a group of sensors. This is automatically done to aid the mapping of several engines and/or fuel modes. It means that the same sensor for each engine and fuel mode would appear under the same sensor group and thus would only need to be mapped once instead of individually mapping all the engines and fuel modes. Sometimes this grouping causes undesired display effects in the CBM configurator, with different sensor types appearing in the same group. The grouping is primarily based on the sensor name following the six initial characters (filters out source and engine id). In some marine installations the sensor name is shorter than the standard naming scheme – in such an event only the first character is removed before sensor matching occurs. In some cases where the sensor name can not be used for grouping, the grouping is instead done based on the group ID that is present in the sensor definition list of an installation.

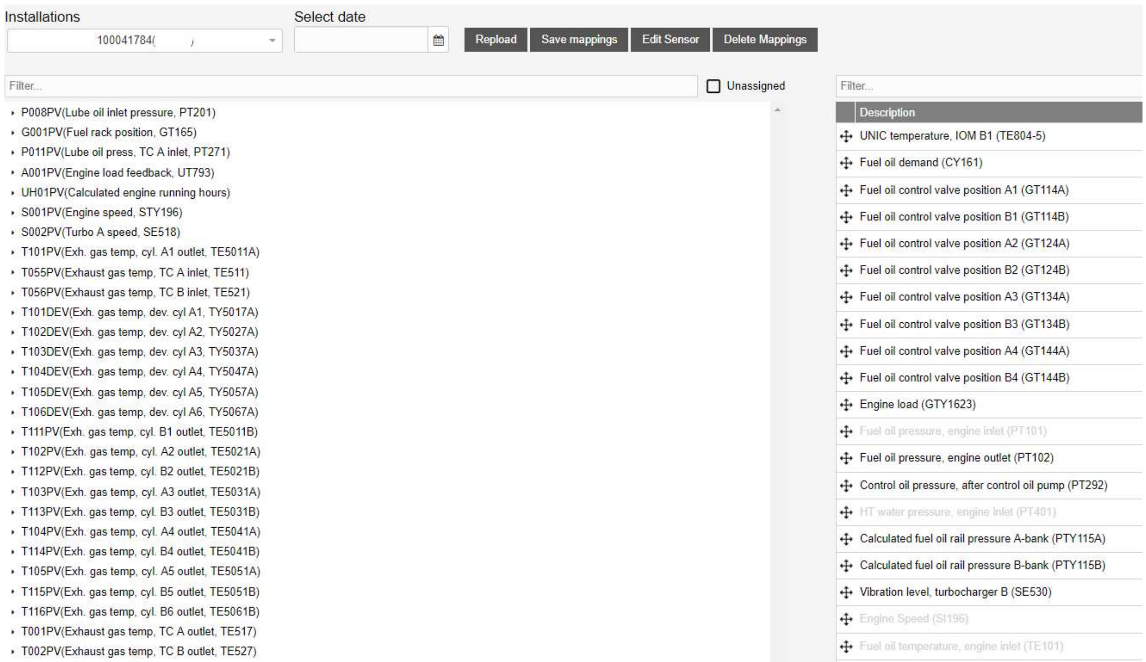


Figure 15. Sensor mapping list

Upon clicking on the small arrow next to each sensor group the subordinate sensors are revealed and greyed out to indicate they have been mapped. If a single sensor is selected the right-hand side list will highlight which logical ISO code the sensor is mapped to. Figure 16 shows how lubrication oil pressure (engine inlet) has been mapped for four different engines. This is indicated by the four sensors in the list, with each engine having its own SQA0X1P008PV code (X denoting the engine order). The 'KP' denotation indicates that this sensor has been tagged as a key parameter, giving it higher priority. By selecting a date at the top-right the list is updated with a reference value read from site data if there is data available for the selected date. This reference data is a good indication if the sensor is active, if the values are reasonable and if the relevant engine has been run at that time. The data in Figure 16 suggests Engine 2 has not been in operation because the oil pressure reads as 0.0.

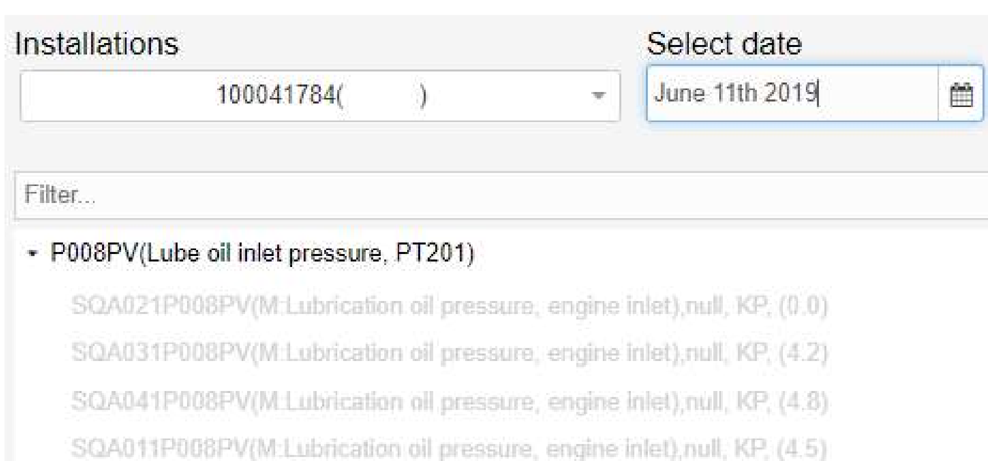


Figure 16. Sensor group list

5.5.3 New sensor map

When starting a new sensor mapping the list on the left will be empty as there are no links present. To populate this list the user clicks the ‘Reload’ button that prompts to load the sensor specification list into the program. This list contains all site-specific sensors and their parameters (reporting load). The program assumes the following standard column structure in the file to harmonize the data:

- Tagname
- Description
- EquipmentID
- FuelMode
- GroupID
- Unit
- Type
- ParameterPriority

After the list on the left-hand side has been populated with the physical sensors the user can proceed to link them with the logical ISO codes by first selecting the sensor or sensor group on the left side. The application will then attempt to find an automatic match based on the sensor name and matches done in the past. The suggestions are presented in a helper window and the user can elect to click on the suggestion to confirm the link. If no suggestions are found or the user cancels the suggested linking, a manual linking can be done by searching for the correct ISO code on the right-side list and clicking the ‘Link’ button located between the two lists. Conversely if a link has been made it can be undone in the same manner by pressing the same button which will then read ‘Unlink’. Figure 17 illustrates the manual linking of a physical sensor to the UH01 ISO code, which corresponds to engine running hours.

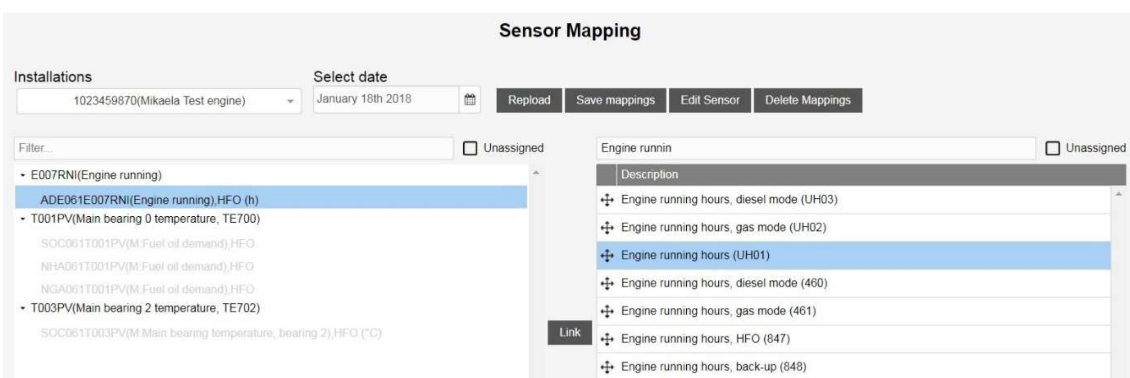


Figure 17. Example of linking engine running hours

An existing sensor can also be edited to some extent. This is performed by clicking the ‘Edit Sensor’ button at the top of the window. This allows the user to change the unit of the sensor from a drop-down list and to specify whether a sensor is a Key parameter. Key parameter sensors have a higher priority than regular ones. Figure 18 shows the detailed data of sensor P008 – Lube oil inlet pressure. Only the unit and parameter priority are editable, the other data is for information only.

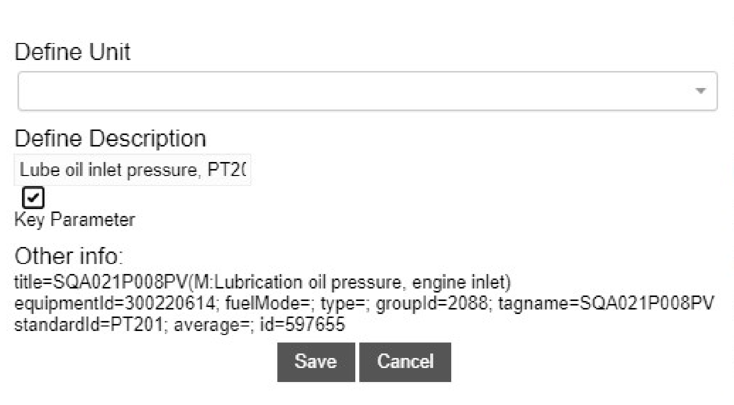


Figure 18. Edit sensor

5.5.4 Admin view

The admin view page of the CBM configurator allows administrators with sufficient privileges the option to add parameters to tables that are common for all installations. These parameters constitute the ISO codes, equipment and installation configuration parameters. The specifications of what the different fields mean for each of these metadata types is outlined in Sitedata API[13] (see Appendix H). The CBM configurator does not allow the modification or deletion of any parameters. This must be manually performed by an administrator.

5.6 Load level filtering

The equipment in CBM is mapped with a separate set for each fuel mode, inherently each sensor has a fuel mode parameter which allows it to be saved under different sets. The fuel mode sensor set is defined by the specific fuel mode selected and the load level of the equipment. Thus, the total number of sets is equal to the number of fuel modes times the number of load levels, barring any empty sets.

The load level definitions are expressed through a load level filter that can have upper and lower percentage limits of nominal power output. Examples of such load filters are:

- 20- (minimum 20% load)
- 73-78 (load between 73% and 78%)
- -80 (maximum 80% load)

[13] This is the application programming interface that serves the data to the configurator

6 Asset diagnostic configurator

The current CBM configuration tool (described in Chapter 5) is an evolution of the RPA configurator. It retains the overall concept of the old tool but brings improvements on a number of levels. The aim was to ensure the desired functionality through feedback from end-users while simultaneously enabling the platform to support multi-portfolio cases. In addition to this, the new configuration tool needs solid ISO code administration functionality, which is lacking from the current tool. The initial timeline for this project was set as December 2018 to June 2019.

The ISO code administration is the new functionality proposed to be included in the configurator tool and should include the ability to create, read, update and delete ISO codes that are used for normalizing the sensor data (more on this in Chapter 7.2 and 7.5). System administrators also need the ability to create, read, update and delete groups of ISO codes. These groups make it possible to create clusters of sensor data that relate to the same group and organize these in a logical manner. An example of this feature is organizing the ISO codes for 4-stroke engines under a common group and further organizing the fuel oil system of 4-stroke engines as a child group to the parent 4-stroke engines.

The overall requirements of the configurator development process can be summarized into the following steps:

1. Environment setup so the different endpoints can communicate with each other
2. Configurator API (application programming interface) for reading and writing configurations
3. ISO code API endpoints to read and write ISO codes
4. Application preparation that uses Azure AD (Active Directory) authentication
5. Configuration form templates for adding new and editing existing installations and equipment
6. Structuring of ISO code groups to enable logical grouping of different types of equipment and sensors

The program back end and detailed API endpoints are outside the scope of this thesis. The main focus lies on the technical implementation of sensor data normalization and the workflow of creating an analytical backbone for the system to rely on for enabling the new Asset Diagnostic service. This is described in Chapter 7.

6.1 Functional requirements

The design criteria outlined in Appendix I describe the required parameters and functionality for the Asset Diagnostic configurator based on the previous CBM configurator requirements and design improvements brought forth during the development of the platform. The rollout of the features will depend on the version of the configurator, but all items on the list are features to be implemented in the release. A concise recap of the requirements is offered here but refer the Appendix I for the detailed list with explanations.

- Master data fetching and synchronization.

- Equipment selection and creation
- Repository control
- Audit trails
- Copying functionality
- Auto saving
- Filtering
- Sensor selection
- Automatic or manual mapping
- User configuration with AD authentication
- Formal approval system
- API endpoints
- ISO code management
- Multiple workspaces with automatic triggering based on date
- Configuration templates
- Variable load limits
- Project export functionality
- Fuel mode selection, possible blends in the future
- Inclusion of both analogue and digital signals
- Batch updating of equipment
- Undo functionality
- Disabling equipment option
- Workspace lockout option
- Multiple data source support
- Time-zone handling
- Data clipping limits
- Error handling
- Handling of common sensors

6.2 Functional flow

The principal layout of the working methodology for the asset diagnostic configurator is illustrated in Figure 1. The process can be broken down into three main components:

1. Data collection
2. Data configuration and mapping
3. Data storage

6.2.1 Data collection

Installation data can be collected in a number of ways, depending on the implemented hardware and software solution. From a hardware point of the view, the data can either be collected at a site PC or in a data cloud solution, or both. The software format used for collecting data is based on the installed product on site. These formats are described more in detail in Chapter 6.3. The data stream is pushed to Wärtsilä's PlantNet or accessed through the cloud services from where it can be used as normalized data through the asset diagnostics service.

6.2.2 Data configuration and mapping

With the data stream established the Wärtsilä configuration expert can input the raw data into the Asset Diagnostic tool and configure the data to ensure the analysed data corresponds to reality. The expert configures the installation assets, equipment parameters and sensor mapping. By using multiple workspaces each installation can have several different sensor maps and multiple data formats. It also allows the user to save historical logs of previous maps.

6.2.3 Data storage

After the configuration and mapping process is completed the workspace gets saved as a sensor map under the installation. The process data is then pushed to storage from where it can be accessed for analytics.

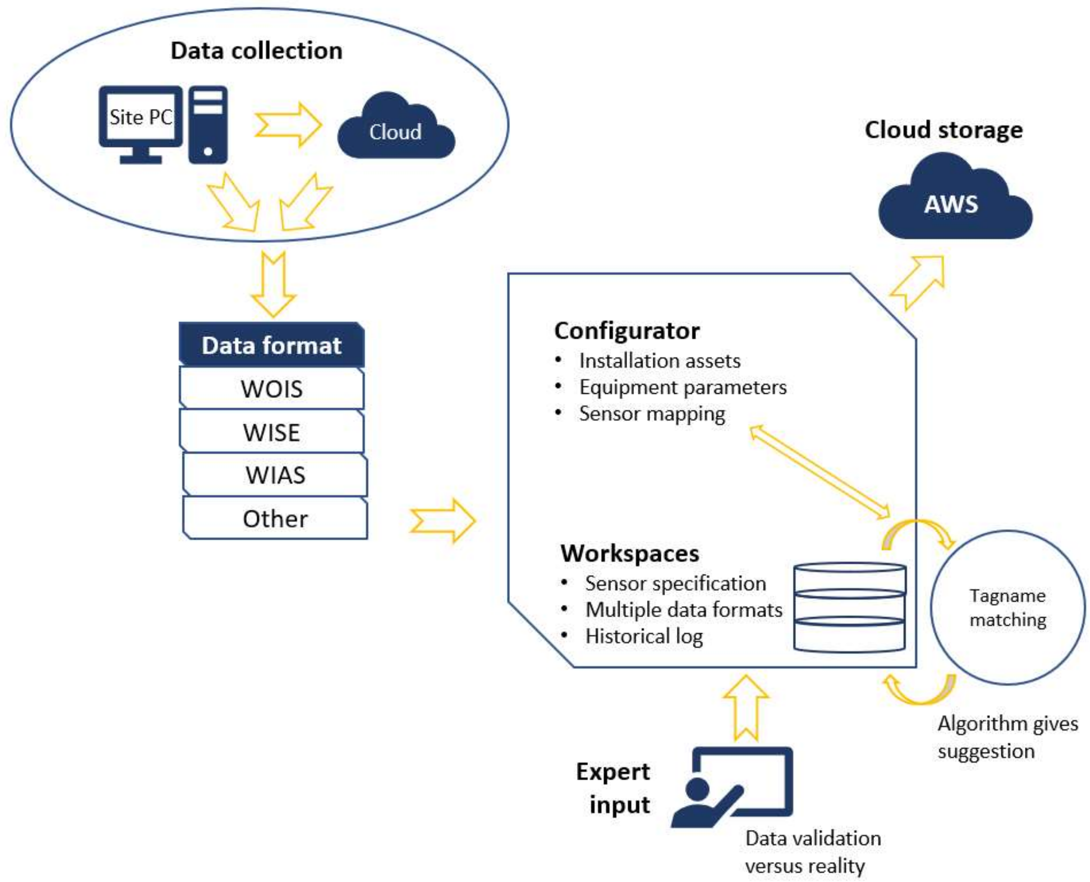


Figure 1. Data collection, processing and storage

6.3 Data handling and sources

The architecture of the data flow in the configurator is quite a complex process that involves a lot of different data sources and consumers, with a breadth of processes and APIs (Application Programming Interface) that handle the data between intermediaries. On a general level, the main structure can be divided into six segments according to their role as demonstrated in Figure 2:

1. Data intake
2. Data pre-processing
3. Data storage
4. Configuration & normalization
5. Data access / APIs

6. Data consumers / visualization

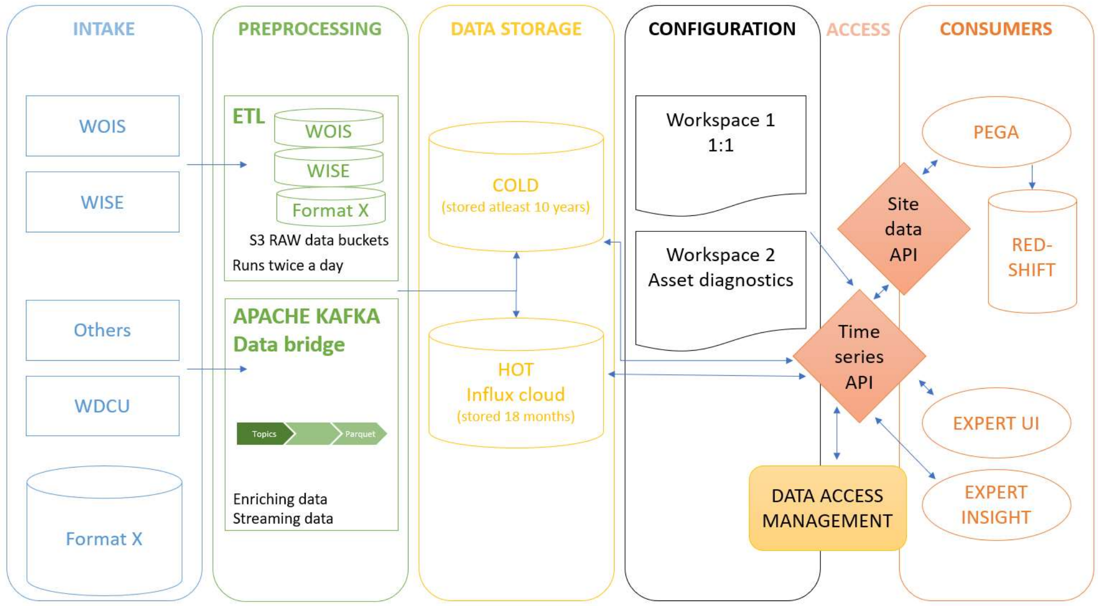


Figure 2. Principal data flow of the configurator

The data processing can be illustrated as a segmented flow chart seen in Figure 2, starting at the intake from various sources and ending at the data consumers that use the processed site data for different purposes. However, the process is not strictly linear and there are cases where cross-segment communication is needed to achieve the desired result. This is especially true when considering the function of the main APIs: Sitedata API and Timeseries API that communicate both with the configurator and end consumers as well as with the data storages. This places them in a space somewhere between the configurator and the consumers as they serve both processes. The different data processing stages are discussed more in detail below.

6.3.1 Data intake

In order to have any data to work with the process first needs to be populated with raw operational data. This data is collected from a multitude of different sources that each have their own characteristic data format and polling frequency. One of the main reasons for having the configurator is to enable this diversity of data sources whilst maintaining data coherence between the sources through normalization and validation. The main data intake sources are:

- WOIS / sWOIS

- WISE
- WDCU
- Others

The various intake sources and data formats and their normalization is discussed in more detail in Chapter 7.

6.3.1.1 Amazon Web Services (AWS)

AWS offers several cloud services, one of which is the S3 data lake. Amazon S3 (Simple Storage Service) is accessible from anywhere and works as a central repository that can store structured and unstructured data at any scale. Inside the S3 platform the user is able to create buckets – the fundamental containers for data storage in the S3 architecture. Every object in S3 is contained in a bucket. Objects are the containers for the data and consists of the following attributes (AWS, 2019):

- Key (name identifier for the object)
- Version ID (unique identifier along with the key, this can be used for object versioning)
- Value (the data that is being stored, size can vary from 0 to 5 TB)
- Metadata (name-value pairs that are attached to the object to store additional information)
- Subresources (a subordinate element to an object that can contain additional information like other objects or buckets)
- Access control information (options are resource-based access control, access control lists, bucket policies and user-based access control)

Amazon S3 storage is separated into different storage classes based on different use cases. Some data demands high availability while other data primarily needs long term storage. To cater to different needs Amazon has developed the following storage class policies:

- S3 Standard
    - General-purpose storage of frequently accessed data
    - High durability, availability and performance
- S3 Intelligent-Tiering
    - Intelligent algorithm for data with unknown or changing access patterns
    - Same low latency and high throughput as S3 Standard but with intelligent tiering to move objects to the most cost-effective tier
- S3 Standard - infrequent access
    - Long-lived but infrequently accessed data
    - Same low latency and high throughput as S3 Standard but for data that is less frequently accessed – this lowers the GB storage price and retrieval fees
- S3 One Zone – infrequent access
    - Long-lived but infrequently accessed data

    - Same low latency and high throughput as S3 Standard but for data that is less frequently accessed and only in a single availability zone[14] – this offers 20% cheaper prices than S3 Standard with a minimum of three zone availability
- S3 Glacier
    - Secure, durable, low-cost storage for data archiving
    - Retrieval times are configurable from minutes to hours, depending on the type
- S3 Glacier Deep Archive
    - Lowest storage cost option for data that is accessed very infrequently (maybe once or twice a year) but needs to be retained for 7 years or more
    - Retrieval time is within 12 hours

Figure 3 showcases how the data intake into the Wärtsilä AWS RAW bucket has grown nearly threefold over the last year (scales omitted for confidentiality).

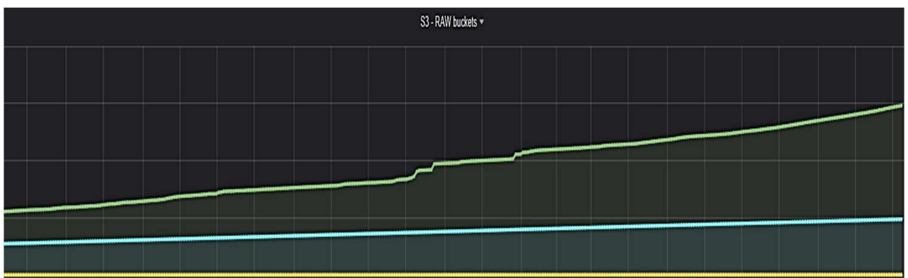


Figure 3. AWS RAW bucket size allocation from July 2018 - July 2019

6.3.1.2 WOIS and WISE data transfer to PlantNet

Before WOIS and WISE data are ready to be moved to their respective S3 buckets the data is brought into Wärtsilä's PlantNet environment for intermediate data storage before it is moved to the cloud service.

The WOIS data is fetched to the file server in the form of analogue and digital data. The LGH files contain the analogue signals and the TSV files contain the digital events. A dedicated application polls the files in a specific folder on-site and checks if there are new files present. If new files are detected, they are transferred to the jump server using the FTP protocol. This process is always postponed by a day due to the way the LGH files are constructed. The transfer waits for an LGH file to reach end-of-day before it is closed and

[14] AWS is structured into regions and availability zones. The availability zones are physically separated and isolated but interconnected with low latency and high throughput for increased availability, fault tolerance and scalability.

moved to the transfer queue the following day. Once the files appear on the jump server a similar application moves them forward to the appropriate bucket in the AWS data lake.

The WISE data is updated to an SQL database on the jump server. A dedicated application keeps track of each WISE installation and keeps an update log of the latest new data. If new data is found it is packaged in a JSON file by the AWS Lambda[15] function and transferred to the AWS data lake in the same manner as WOIS data. Data file operations are stored in log files.

6.3.2 Data pre-processing

The data pre-processing refers to the process that occurs to the data before it gets pushed to storage where data consumers can later reference this data through front end applications that communicate with the data storage through APIs. There is a clear distinction between two different types of data pre-processing that occurs, depending on the source of the data. These two processes are known as:

1. ETL (Extract – Transform – Load)
2. Kafka (Wärtsilä Data Bridge)

6.3.2.1 ETL

The ETL process is applied on WOIS, WISE and similar external data. The process is run twice a day, this means it has a limited intake and updating frequency. The data that is collected from the intake source is pushed into its own Amazon S3 raw data bucket and is moved into cold storage. Cold data storage refers to servers that are designed for data that is accessed less frequently. The optimization favours lower prices through lower hardware and operational costs while still maintaining a reasonable response time.

6.3.2.2 Kafka (Data Bridge)

The other data pre-processing process is known as the Wärtsilä Data Bridge. This process is constantly streaming new data through Apache Kafka. Kafka is known as a distributed

[15] AWS Lambda is a serverless computation service

streaming platform and is used as a real-time data streaming pipeline to reliably move data between systems or applications (Apache Software Foundation, 2019). Kafka is run as a cluster of one or more servers and stores the data streams in what are called topics. As a streaming platform, Kafka continually reads data from input topics, performs data processing and produces a stream of output topics. The way Data Bridge is set up Kafka is performing some calculations on the raw data but does not normalize it. The main input streams for Kafka are WDCU and Format Y. The data is passed through the Kafka topics and gets enriched, but all the raw data is retained. The data is then saved in Apache Parquet format in either hot or cold storage depending on the need. Parquet is a compressed columnar storage format (Apache Software Foundation, 2019). Wärtsilä implements this with data in hot storage being saved for 18 months in an InfluxDB cloud. Any high-frequency WOIS data is pushed to the InfluxDB cloud. Streaming data is continuously sent, and batch data is sent in packets with differing intervals. Both of these data types can contain low- and high-frequency data but streamed data can be received with a faster rate as seen in Table 1.

Table 1. Batch and stream data quality and speed matrix

	Batch data	Stream data
Data quality	High-frequency / low-frequency	High-frequency / low-frequency
Data speed	Daily / minute	Daily / minute / second

6.3.3 Data storage

As described in the data pre-processing the final data storage is separated between hot and cold storage depending on the data frequency. High-frequency data is stored in the InfluxDB cloud for a period of 18 months. Due to the design of this storage solution, existing data can not be overwritten – only new data can be added. InfluxDB is a managed database service that offers different components that run under the InfluxData platform (InfluxData, 2019). The data stream is acquired from the output topic of the Kafka enrichment process. Contrary to cold storage, hot storage is accessible right away and is more expensive to maintain. To avoid duplicate data accumulating and due to the restriction of data being locked for updates, a specific script is run occasionally that removes any duplicates to keep the data storage clean and efficient.

Lower frequency data resides in the cold storage where it gets stored for at least 10 years. Examples of cold data storage solutions include Amazon Glacier, Google Coldline and Microsoft Azure Cool Blob. The cold data is stored for a minimum of 10 years. Since there is no industry standard on what defines hot and cold data storage the terms can be confusing when comparing different services. The general differentiation is that cold data is accessed less frequently with trade-offs in performance and responsiveness.

6.3.4 Configurator

The configurator is split into different workspaces that use APIs to interface with the data storage and process the data in different ways. The workspaces fetch the installation master data from SAP (SAP, 2019) and populates the data into the configurator tool. Actual operational data is fetched from the cold storage through Sitedata API with a just-in-time data normalization. A 1-to-1 workspace exists where all the data points are retained. Asset diagnostics has its own dedicated workspace inside of the configurator.

6.3.5 Data access

Sitting somewhere in between the configurator and the data consumers are the different APIs that cater to fetching and processing the data the end-user wants.

Sitedata API has the capability to provide enriched data from WOIS (analogue/digital), WISE and other formats. The sensor data queries are enriched with installation and equipment metadata. Sitedata API reads data from cold storage and returns it to the consumer. The API can aggregate analogue data, perform load level filtering and has fuel mode detection algorithms. It can also populate data into the hot storage. Sitedata API has a non-SI-standard special unit list and performs unit conversions to standard units. Sitedata API only returns mapped data with just-in-time data normalization. Sitedata API allows the following parameter input to limit the response data set with optional aggregation and filtering:

- Installation name
- Installation functional location
- Installation ID (external format requirement)

- Timestamp start time (required)
- Timestamp end time (required)
- Product serial numbers
- Equipment identifiers (numeric)
- Fuel mode
- Digital or analogue signals
- ISO codes
- Tagnames
- Load filter

Timeseries API can read data from any data source (not just mapped data) and aggregates the data and performs unit conversions as required. The API works as a middleman between Sitedata API and the end consumer. It also works with a just-in-time data normalization, fetching the data based on the workspace in use and returns a response in the format that is required (can be aggregated or not). Timeseries API is capable of querying data based on fuel-mode and load level as is typically requested but is not limited to any specific tag query. There is a change request to add an enrichment topic to Kafka for calculating the fuel mode at an earlier stage in the data flow and associate it with its own ISO tag. This would mean the fuel mode would not have to be detected by the Sitedata API.

In the case of Timeseries API just-in-time processing not being fast enough to handle high frequency or live streaming data, the processing has to be moved to Kafka instead. Kafka then creates enriched data topics by checking which configurator workspace is in use and enriches the data with for example: unit conversions, ISO codes and tags. All the original data remains unchanged in the Kafka enrichment stream - it enriches the data but does not normalize it.

6.3.6 Data consumers

The Pega case worker is a reporting tool that can send queries to Sitedata API. Sitedata API, in turn, can query timeseries API about where to find the required data. Since Pega requires a specific format the data is always pushed through Sitedata API to process it correctly. Pega saves its data into an Amazon Redshift[16] database. Asset Diagnostics has a separate small API that allows access to the data that Pega is writing into the Redshift database.

Expert UI also has its own small API that reads data directly through the timeseries-API. The tool has the capability to combine raw data from InfluxDB with Pega populated data, from for example Redshift to add an overlay of sensor thresholds on top of the raw operational data. This can then be used in a customizable trending tool for making graphs.

6.4 Data validation

While working with a workspace in the configurator the responsible expert can load a predefined list of tags used at an installation. The configurator sends a request to Timeseries API to return all data for a certain date for the installation that is being worked on. Depending on the data acquisition method the data can be read either from the hot or cold storage. The expert also has the option of asking Timeseries API to aggregate the data, for example as daily data. The response from the API then populates the tables in the configurator with the sensor tags and operational values for the complete installation.

When the commissioning engineer of a new installation is on-site and requests for site data to be validated the expert working with the configurator needs to be able to use the Timeseries API response to read site data and verify to that commissioning engineer that data is being received for the associated installation and equipment. The configurator is requested to be able to display the sensor minimum and maximum thresholds as an overlay on the operational data, so the expert can ascertain if the site values are looking reasonable. Another function request is that the expert should be able to load site data for a period of a few days in order to determine which sensors are actually generating a data stream. This would help with removing sensors that are redundant or residual tagnames that have been left behind by the commissioning engineer. The reason for this is that the fundamental layout of the installation is often copied from a similar installation with the same engine type and this can have the effect of leaving behind traces of sensors that are not in use. For data clarity and reporting purposes, any such residual sensors should be removed. Another requested feature in the configurator is the ability to query site data and to have insight into the

[16] Amazon Redshift is a fast, fully managed data warehouse that offers Business intelligence, predictive analytics and real-time streaming analytics. It offers fast querying with SQL using ODBC and JDBC connections. Redshift can process data from the S3 data lake.

transaction log of the different APIs in order to troubleshoot different data processing scenarios. This would be useful for example if Pega seizes to auto process data for a site due to the load level being too low. Another useful scenario would be if a mapped sensor for some reason has the wrong associated unit and Sitedata API fails in the unit conversion, high transparency into the response would help with troubleshooting the problem.

6.5 General sensor guidelines

Regardless of the equipment category, there are certain baseline data required for all types of installations that are to be entered in the configurator tool. These parameters are common across the entire portfolio and help identify the specific installation and equipment that is being referenced. Another purpose of this is the ability to combine equipment from different categories into a multiplatform configuration of for example an installation with both 4-stroke and propulsion equipment.

The mandatory data for all installations are:

- Functional location (unique numeric identifier for each installation)
- Installation name
- Product line (for example 4-stroke, 2-stroke, LNGPac)
- Percentage of max load for load level filter (data measuring threshold)
- Load tag (tagname which is referring to the load level of the equipment)

On top of the base data comes the equipment configuration which specifies what hardware is in use and how it is being operated. The equipment configuration is specific to each equipment being run in the installation and for one installation there can be a multitude of configurations. This data includes:

- Fuel type (HFO, LFO, Gas, Liquid Fuel)
- Engine type (Wärtsilä specified product type code)
- Number of cylinders
- Nominal power & nominal speed
- Product extension (for example dual fuel, spark gas)
- In addition, equipment can include detailed information about turbochargers, temperature setpoints, propeller type, injector type, charge air systems etc.

Residing under the configuration data is a set of general information indicators that show the parent categories for the equipment:

- Nickname (for example DG1, Genset 1, ME1)
- Application category (Marine or Energy)
- Altitude (affects measurements)
- Installation type (for example Cruise vessel, Independent power producer)

This information is then further populated by sensor-specific data that is organized by load level and fuel mode. The sensor data will typically include:

- Tagname
- GroupID / Groups (sensor category or group identifier)
- ISOcode (normalized ISO sensor code)
- Description (long description of the sensor)
- Unit (data value unit)
- Sensor priority (is sensor a key parameter or not?)
- Values
    - Timestamp
    - Measured value
    - Min threshold
    - Max threshold

6.6 Minimum sensor requirements

From an analytics point of view more data is generally a favourable thing and Asset Diagnostics certainly benefits from a wide range of sensor data to provide the most thorough diagnostics. Wärtsilä however, has a wide range of equipment, ranging in age and specification. A baseline requirement is that lifetime support is being offered to all products. This raises the issue of establishing a bare minimum sensor set as a requirement for being able to provide Asset Diagnostic services. Some of the distinctions between equipment beyond their fuel modes and age are the application category (marine or power plant), various environmental factors, quality of fuel and the number of sensors installed on the engine. With the rollout of Asset Diagnostics during 2019, the initial focus lies on the inclusion of 4-stroke and 2-stroke engines and thus the initial sensor requirements are for these product families. A list of the base set of sensors for a Wärtsilä 4-stroke engine can be found in Appendix J.

6.7 Diagnostics

Once all the data has been collected, pre-processed and normalized it is ready to enter the diagnostics phase. This is where the collected data is compared against a set list of rules and algorithms. The data that is analysed is stored in the system infrastructure, through which it can be visualized using the front end UIs. The collected data is used to generate daily Asset Diagnostics Cases and any deviations that are detected get flagged as an Asset Exception Case (AEC). Experts are notified of any occurring deviations and they can enter advice into the system through the advice management system which the customer is then able to access. The exceptions and expert advice are distributed to the customer through the customer relation data connection with the Customer Relationship Management (CRM). In addition, the diagnostics is constantly used for populating data to the customer accessible online service portal, this includes timely data analysis and trending.

An example implementation of the event diagnostics service can be seen in Figure 4. The graph illustrates the running hours of a Wärtsilä 20V34SG engine. The event diagnostics monitor how often the engine is automatically stopped to give it a product reliability index. In the circles marked with red you can see how the reliability index (y-axis) has been lowered as a result of a detected automatic stop. The cumulative running hours are displayed on the x-axis.

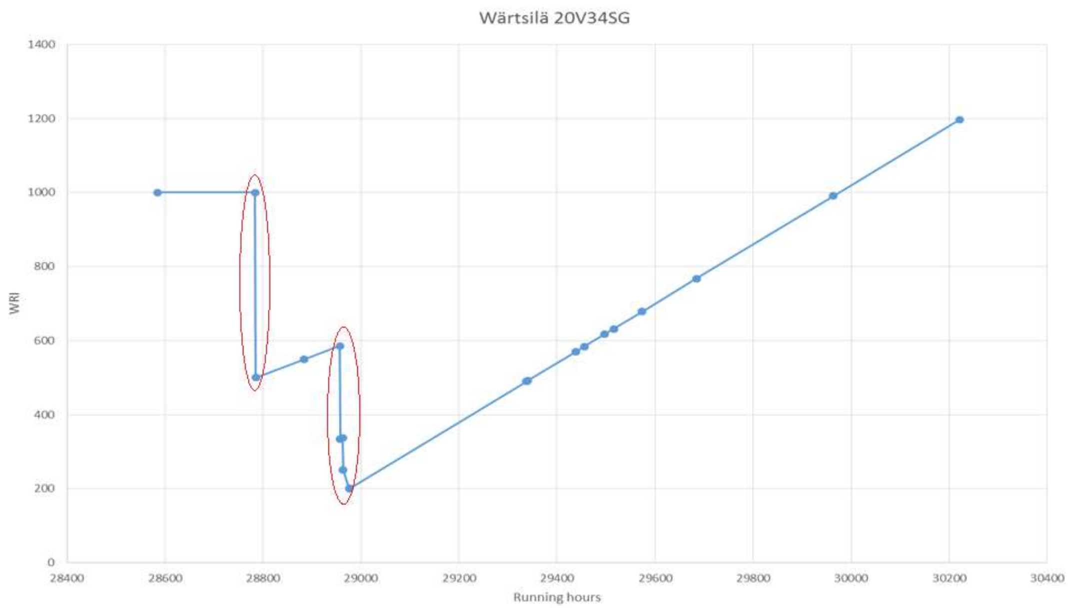


Figure 4. Product reliability index

6.7.1 Diagnostic requirements

The diagnostics work on both simple sensor thresholds as well as multi-sensor criterion and pattern recognition. The list of requirements contain specific rules for the diagnostics platform Pega, analysing the data collected into the Asset Diagnostic service. This list will be expanded as more product families are added into Asset Diagnostics. In the initial stage of starting up the service the focus is on 4-stroke and 2-stroke engines.

Moving forward, other equipment like LNGPac[17], scrubbers and propulsion systems can be added to enable a multi-portfolio platform. For future development, the diagnostics intend to on-board digital signals as well as load and fuel-mix specific diagnostics. The specific requirements can be found in Appendix K.

[17] Integrated fuel gas handling system (https://www.wartsila.com/products/marine-oil-gas/gas-solutions/fuel-gas-handling/wartsila-lngpac)

6.8 Implementation and visualization

The graphical representation of the sensor and diagnostic data is presented through two main user interfaces, Expert UI and Trending Tool.

6.8.1 Expert UI

Expert UI consists of a number of dashboards and a report generator. The reports are based on different templates to generate a PDF document that is ready to be sent to the customer. The report template defines which layout and content are to be included in the report.

Expert UI includes a number of different modules:

- PDF report generator
- Ad-hoc analysis
- Deviation detection
- Equipment health view
- Experts comments

The new Asset Diagnostics Report is comprised of an automatically generated segment that is based on a template of the desired data for a specific installation type, customer or equipment. These templates are configurable but serve as an overall design and data overlay to conform all the reports to the same Wärtsilä branding standard. On top of the automatically generated parts, the CBM experts have the liberty to influence dynamic content of the reports based on case reports that can be enriched with graphic overlays from the trending tool and comparisons between different sensor readings that can be overlaid or compared side-by-side. These custom views are also appended with Expert comments that are retained and can be included with the report.

The system allows the CBM expert to configure a data graph view template that can be used repeatedly but populated with new data each time the report is run. This is a powerful tool for generating custom views in for example the monthly report. In such a case the CBM expert could, for example, create a view where the interdependency of two sensors is clearly visualized in a graph that maintains its same exact parameters between several reports. This is important for ease of comparison and data conformity.

In addition to the normal monthly reports, the CBM experts can generate ad-hoc reports of highly specialized data which might be needed for the investigative purposes of cases that fall outside the scope of the regular monthly report. These reports are also saved and can be used to serve purposes outside of the Asset Diagnostic domain, for example for engine optimization purposes. The images presented in this chapter of the monthly reports and trending tool screens are all work in progress and do not represent the final product.

6.8.1.1 High-frequency data

One of the big improvements being introduced with the Asset Diagnostic service is the ability to analyse high-frequency data with improved processing rates. In the legacy CBM system, the analysed data was always aggregated daily data that was processed through the RPA tool. This tool had the restriction of never getting close to working with live data. In the best-case scenario, the RPA data would be at least 24 h old due to the way the data collection and aggregation was performed. A future development of this might be to utilize the Asset Diagnostic Expert UI tool to visualize data in the same near real-time fashion that current WOIS applications can do.

The overall information presented in the report would resemble that of the legacy CBM reports to maintain visual familiarity. Also, there is no need to modify most of the views of the CBM reports as they already contain the most relevant information for maintaining the client equipment. What Asset Diagnostic does offer is a larger breadth of information because more sensor data is being collected. The data analysis has higher sophistication and the accuracy of the analytic algorithms is improved due to higher data frequency, multi-sensor criterion algorithms and pattern recognition among other things.

At the time of writing, the final report templates are still in the stage of being created so all the graphical layout presented is a work in progress and as such only indicative of the final product. The opening page will include an installation overview of all installed equipment, fuel modes and running hours (see Figure 5).

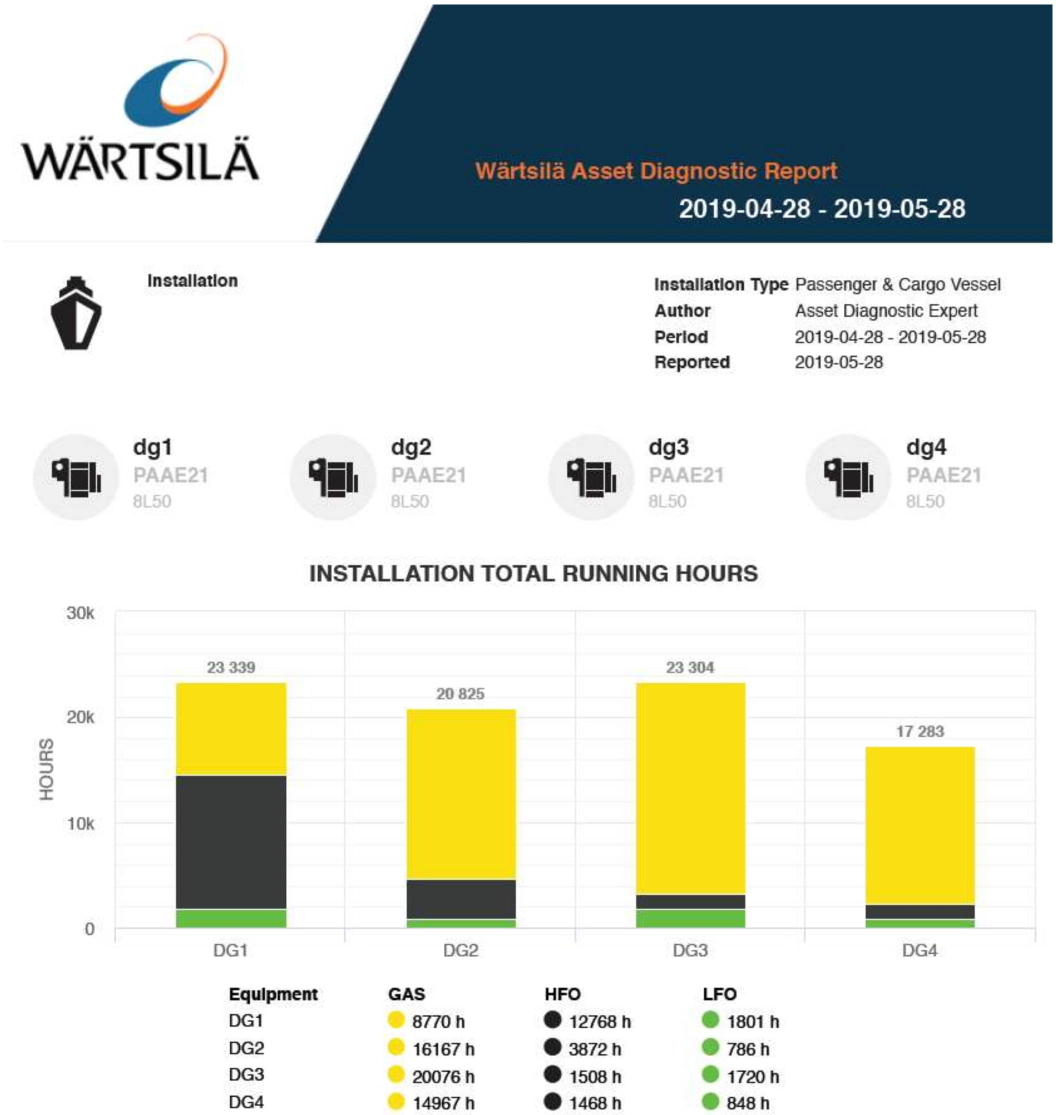


Figure 5. Asset Diagnostic Report opening page (work in progress)

Another example of the installation overview is the engine load data broken down into fuel modes and filtered according to the load filter limits as seen in Figure 6. This gives a quick insight into how the installation has been operated the previous month.

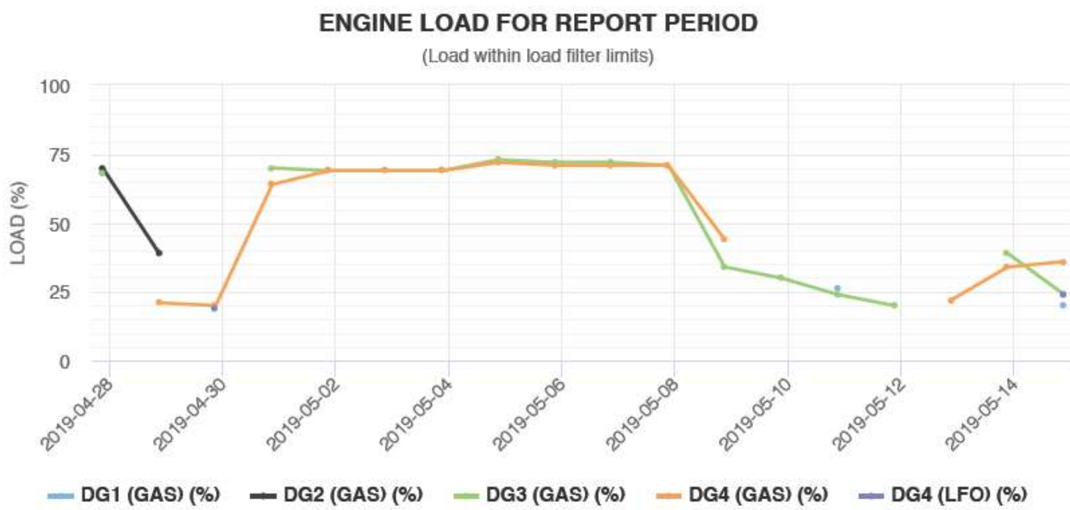
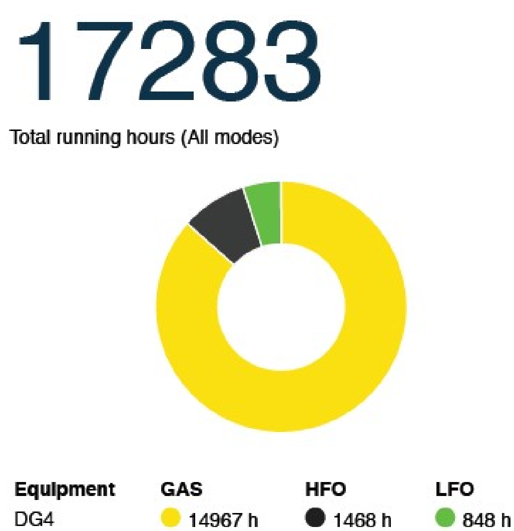


Figure 6. Engine loads by fuel mode and load filter

On an engine level, the initial overview presents information about fuel mode break-down, most recurring sensor warnings and engine running hour trends over the period of a month. This can be observed in Figure 7 with the fuel mode split of gas, HFO and LFO. In Figure 8 the running hour trends have been overlaid with a trendline of the DG4 Gas mode load level (%) as well, illustrated by the blue line, with the load-scale on the right side of the graph.



Sensors with most warnings

Description	Count
Wastegate actuator reference	3
Exhaust gas temperature, after cylinder A1	2

Figure 7. Engine fuel modes and sensor warnings

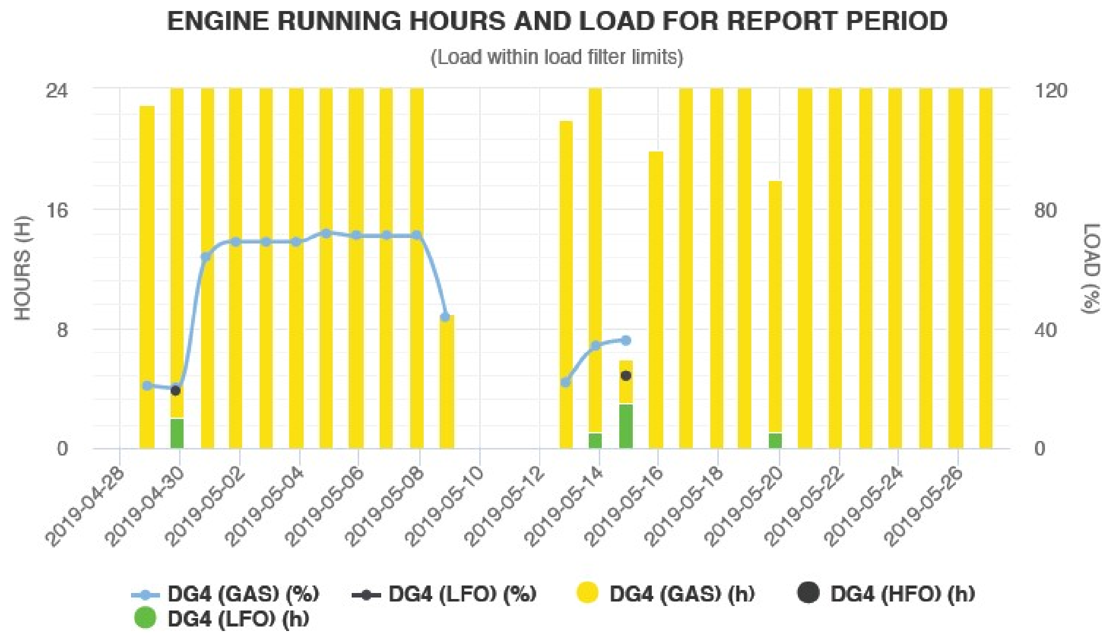


Figure 8. Running hour trend by fuel mode, superimposed with engine load level

6.8.2 Trending tool

The Trending tool is designed to visualize high-frequency sensor data in graphical form. The tool can adapt its data interval to the data collection rate of the source data and output trend charts as aggregated data if a wider timeline is selected. The aggregation is an arithmetic mean without dead-banding and the trending tool displays the difference between the minimum and maximum values as an opaque shadow around the trend line. Bundled into the trending tool is a trend data comparison tool that allows the user to compare different data sets.

Figure 9 shows a development version of the trending tool with a search bar at the top and a fleet view of installations that have been enabled in the trending tool. The name is represented by the functional location in this example.

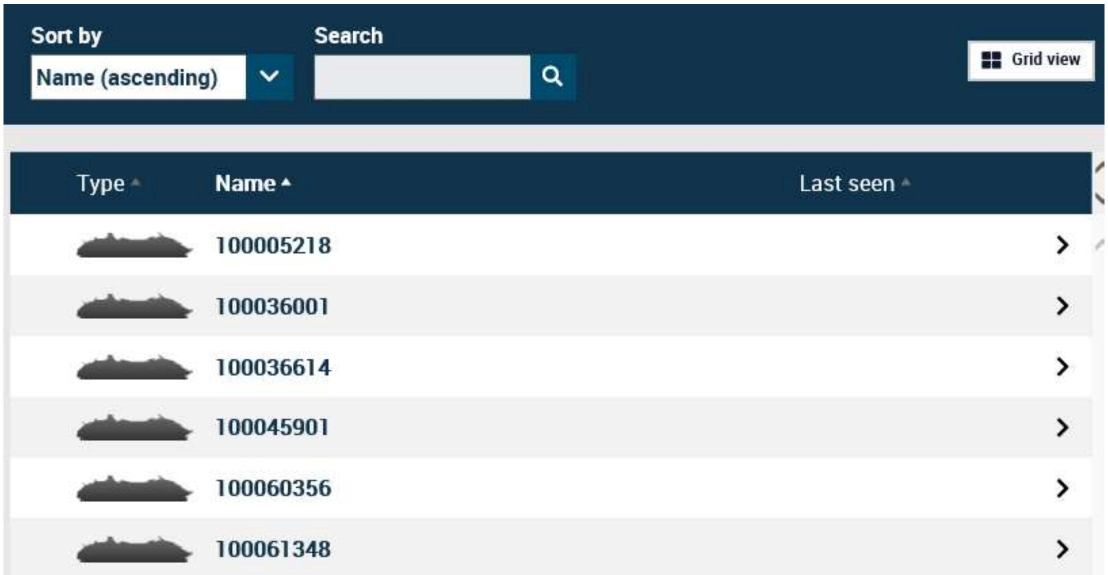


Figure 9. Trending tool example view

Observing the trending tool presents the view illustrated in Figure 10. The sensor selection is performed by clicking on a list of available measurements that are listed on the left sidebar. These are appended by the equipment number and ISO code and can be filtered by the search field at the top of the sidebar (see Figure 11). At the top of the main view of the trending tool the user can choose the date, time and timespan, save the current view as a preset, share the current view as a URL, enable/disable tooltips, turn on live view of sensor data and zoom in and out with the plus and minus keys. The menu key to the far right allows the user to export the trends as an image, document or as raw data in CSV format. Two measuring points can be selected with the 'A' and 'B' arrows at the bottom of the graph – these can be moved to points of interest. The view can be panned by using the mouse on the larger graph or by sliding the bottom view that displays the entire timespan from side to side. Moving the mouse cursor on top of a graph displays the point measurements of that exact time if tooltips are enabled. The live view button toggles live polling of new site data as it arrives and updates the graph correspondingly.

Figure 10. Trending tool output

The sensor selection list can be divided by equipment numbers into for example Genset 1, Genset 2 et cetera or as in the example seen in Figure 11, under a Common group. By filtering this list, the user can search for the sensors of interest and toggle their trend display, overlaid with the other sensors selected. By zooming in on the trend graph the data interval can be increased and the data frequency increases in response to this.

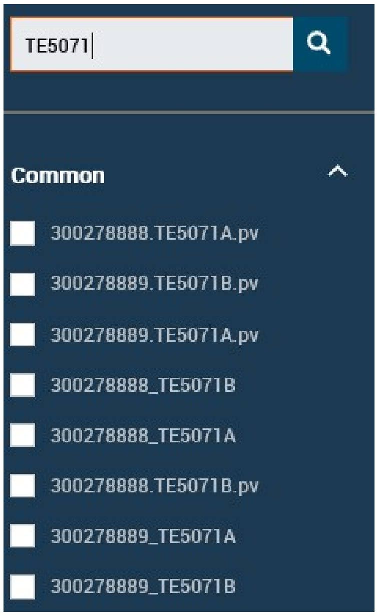


Figure 11. Side bar of the trending tool with sensor selection

By pinching the timeline at the bottom of the graph to a narrow area or by zooming in on the trend graph the data frequency increases. Figure 10 and Figure 12 show two different data frequencies of the same data with Figure 10 using a 15-minute data interval and Figure 12 showing data with an interval of 15 seconds. The sensors being polled in this case are GTY1623 for two different engines, equivalent to the engine load in kW. Point of interest ‘A’ is visible at the far left of the x-axis.

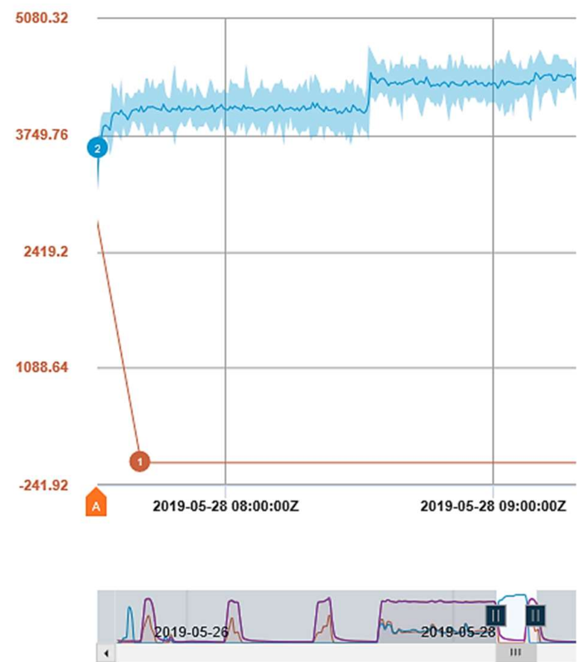


Figure 12. High-frequency data with the timeline at the bottom

At the very bottom of the trending tool is the list of all selected sensors in use, along with parameter values for the selected key points, average value and min/max value. Data interval is represented to the far right. The user can easily toggle the visibility of sensors by clicking on the eye icon on the far left or remove a sensor from the list by clicking on a trash can at the far right (not visible in the image). As more sensors are added the list grows accordingly up to a maximum of 12 sensors. Example output with two sensors is displayed in Figure 13.

	#	Measurement	Unit	Min	Avg	Max	A	B	Data Interval
	1	Common 300278889_GTY1623		0	1710	6501.747	3115.6125	1569.0419	15 minutes
	2	Common 300278888_GTY1623		0	516.9	6378.386	2554.2485	1348.3885	15 minutes

Figure 13. Sensor measurements with average and max values and point values for measuring point 'A' and 'B'

The trending tool also has a feature called Instant Report that is in the process of being implemented. This feature will visualize up to 200 sensor values for the latest received data or a selected point in time and present it in table format.

7 Asset diagnostic configurator workflow and manual

The intended use cases and documentation of the features of the new configurator tool along with its testing was defined as one of the initial purposes of this thesis. This chapter details the functionality of the Asset diagnostic configurator in its current state and describes the typical workflow that the Wärtsilä expert shoulder refer to when creating a new installation configuration. Additionally, the normalization process of each of the data sources is discussed in detail. This material is intended as reference material to later be shaped into a finalized user manual.

7.1 Workflow overview

The condensed mapping workflow that the Wärtsilä expert follows when using the configurator for initiating a new installation can be broken down into the following consecutive steps:

1. Installation creation. The user starts the process by creating a new installation based on the functional location (unique identifier) for each installation. Master data is fetched through an API into the configurator where it can be validated.
2. Equipment configuration. The user configures all the existing equipment that belongs to an installation asset. This equipment configuration can be selected from predefined sets or copied from existing ones to help the user. This is helpful since many installations use similar equipment (engine setups) but the editing of these configurations is also required.
3. Installation base-data entry. The user uploads the base configuration file that contains all the sensor and other installation details into the configurator. The configurator parses it into the relevant data fields (see Chapter 7.4).
4. Installation base-data analysis. The configurator analyses the uploaded file, compares it against other existing installations by looking at the tag names and descriptions to find matches. The analysis can be rule-based or rely on a machine learning algorithm to find the most likely sensor matches.
5. Suggested equipment mapping. The configurator presents the mapping that is has come up with through its rulesets, based on previous installation configurations.
6. Editing the mapping. The user is given the task of correcting possible mistakes in the mapping and validating that the configurator automated mapping process has done the correct linking of tag names and ISO codes.
7. Saving the mapping. The user can opt to save the mapping as either a draft or as ready for review. A draft is saved as a work in progress while a ready for review mapping will get automatically forwarded to a reviewer for a second validation.
8. Accept or reject. The reviewer has the option of either accepting the mapping as it is, in which case the status is changed to completed and the installation is flagged as production-ready. If the reviewer rejects the mapping it is sent back to the original user who mapped it, along with a comment on what needs to be revised. This process is repeated until the mapping is accepted.

In the case of production-ready installations, the Pega case worker platform can automatically mark sensors as misconfigured. Asset diagnostic experts also have the option of flagging sensors as misconfigured. These sensors get saved as a list and presented in the configurator as a list of sensors that should be remapped. The configurator automatically sends a notification to the expert responsible for mapping the installation that there have been reports of misconfigured sensors. The mapping expert is presented with a shortlist of all the misconfigured sensors and given the option to edit their respective mapping. This functionality is intended to assist the expert and expedite the task of making corrections.

7.2 ISO Codes

One of the cornerstones of normalizing the sensor data that is flowing into the system from multiple different sources is the unification of the sensor names (tag names) and to which measurement they point. The ISO descriptions are unique for the different equipment types such as 4-stroke and 2-stroke engines but uniform across the board within the equipment group. The ISO codes define the scope of signals that are obtained from various installations and they form the analytic backbone upon which the algorithms rely for reporting. On the left-hand side of the configurator the menu options visible in Table 1 are presented.

Table 1. Configurator menu options

Units
Unit Groups
Sensor Types
Equipment Types
ISO Codes
ISO Code Groups

7.2.1 Units & Unit Groups

In Units, sensor measurement units like bar, rpm and °C can be viewed and added. Previously entered units can also be edited. Unit groups organize the units into logical groups such as temperature, pressure or time. New groups of units can be created, and existing ones managed. In this capacity, units can be added or removed to groups. For instance, the process of creating a Pressure unit group would be:

1. Open the Units tools and create all the pressure units that need to be added to the group. For example: bar, mbar, Pa, atm.
2. Open Unit Groups and create a group called Pressure.
3. Click on Manage under the Pressure group. On the top is a list of units included in this group. On the bottom is the list of all existing units.
4. On the top row in the lower part of the screen units can be looked up on the blank line. Type in the full or partial name and the unit list will filter according to the selection. Find all the units added in step (1) and click on Add to Group.
5. The units will appear at the top of the screen.

7.2.2 Sensor Types

This display lists the various measurements that are taken from sensor data. New sensor type can be created, or existing ones edited. Every sensor type has to be linked to a unit group, this is done by selecting the unit group when creating the sensor. Thus, a unit group needs to be created prior to creating a sensor type so it can be assigned. Alternatively, if the sensor type is assigned to the wrong unit group, a new unit group can be created, and the linking corrected retroactively.

7.2.3 Equipment Types

This listing defines which product family the equipment belongs to and is one of the major filters for organizing the ISO codes since they are unique inside the equipment types. This list will expand as more products are taken onboard in the multi-portfolio. At the time of writing this, the list includes:

- 2-stroke
- 4-stroke
- PCMS
- LNGPac

7.2.4 ISO Codes

The complete list of all existing ISO codes in the system are listed in this view. Sensors can be added, edited and deleted. There is also the option to copy an existing ISO code. This option copies all the information of the ISO code, and opens a new entry window with pre-filled information that can be altered. Note that the ISO codes must be unique. When a new ISO code is created the following information needs to be included:

- ISO name
- Short description
- Long description
- Abbreviated description
- Sensor type (drop-down selection from previously configured types)
- Unit (drop-down selection from previously configured types)
- Equipment type (drop-down selection from previously configured types)

An example of the ISO code list can be seen in Figure 1. In this instance, the list is being filtered by sensor types that include the word 'Pressure'.

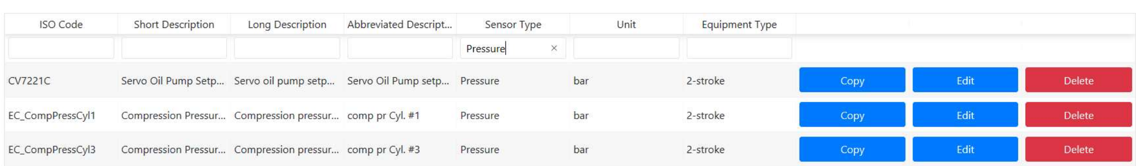


Figure 1. View of the ISO code list

This list can be filtered by entering requirements into the top row, such as only listing pressure ISO codes or only listing 2-stroke codes.

7.2.5 ISO Code Groups

The code groups organize the ISO codes into logical clusters with big numbers of similar sensors that measure the same data type at multiple points on the equipment. An example of this are all the sensors that are repeated across all the cylinders of an engine. The requirements when adding a new ISO code group are:

- Group name
- Short description
- Long description
- Group parent (optionally no parent)

As an example, the cylinder liners of a 4-stroke engine could be organized into a group called 4s_cylinder_liners and this could be the subordinate group to the parent: 4s_engine. This way a logical flow of the sensors can be created, and multiple sensors grouped together.

After the group has been created, it can be managed by clicking on the appropriate button for the group. This presents a list of all existing ISO codes and gives the option to add them to the group. In case of a mistake, the ISO code can always be removed from the group.

7.3 Installation configuration

At the top of the screen is the main division of the tools offered within the configurator. Next to the ISO code admin is the Installation configuration. This tool gives access to adding a new installation or editing an existing one. Similar to the ISO code tools, the results can be filtered by entering data into the top row. A new installation entry requires the following information:

- Functional location (numeric identifier of the installation that can be found in CRM)
- Installation name (textual identifier of the installation, also found in CRM)
- Category (Energy or Marine, listed in CRM as Application category)
- Type (listed in CRM as Installation type, for example: Independent Power Producer IPP)

Note that all the data fields are required before committing the entry. After successful entry of a new installation, it can be opened to look at the installation details. This view is divided into two main categories: (1) Installation equipment and (2) Installation workspaces.

7.3.1 Installation equipment

This view lists all the equipment associated with the installation. It allows the user to enter, edit and delete equipment. It is suggested to add the equipment to an installation before starting configuration on the workspaces since the equipment is not dependant on the workspaces and can exist in several workspaces concurrently. Adding new equipment requires the following information:

- Product number (found in CRM as equipment number, for example 300508787)
- Product reference type (found in CRM with the same name, for example W50 for a Wärtsilä 50 engine)
- Equipment type (drop-down selection of equipment types defined in the ISO code segment)

7.3.2 Installation workspaces

The workspace defines a parent entity for the equipment to exist in and allows for the same equipment to have multiple configurations. All installations need to have at least one workspace for a configuration to be able to exist. The workspace is directly related to the data acquisition type, for example, WOIS or WISE. This indicates the data source to be used for the installation workspace. The required information when creating a new workspace is:

- Functional location (see above)
- Name (workspace name, for example, WOIS config)
- Description (additional information about the workspace)
- Data acquisition type (drop-down selection)
- Altitude (height above sea level)
- Activation date (activation date for the workspace)
- Expiry date (expiry date for the workspace)

After adding the workspace, it can be opened for configuration. When opening a new workspace, it will be void of data, so the relevant equipment needs to be added to it. At the top of the screen, is the list of equipment included in the workspace. At the bottom is the complete list of equipment that belongs to the installation. If the installation equipment has already been added it can be linked to the workspace by clicking on the Create Configuration button. A sample workspace can be observed in Figure 2. At the bottom, four engines can be seen that have the options to create configurations for them within this workspace.

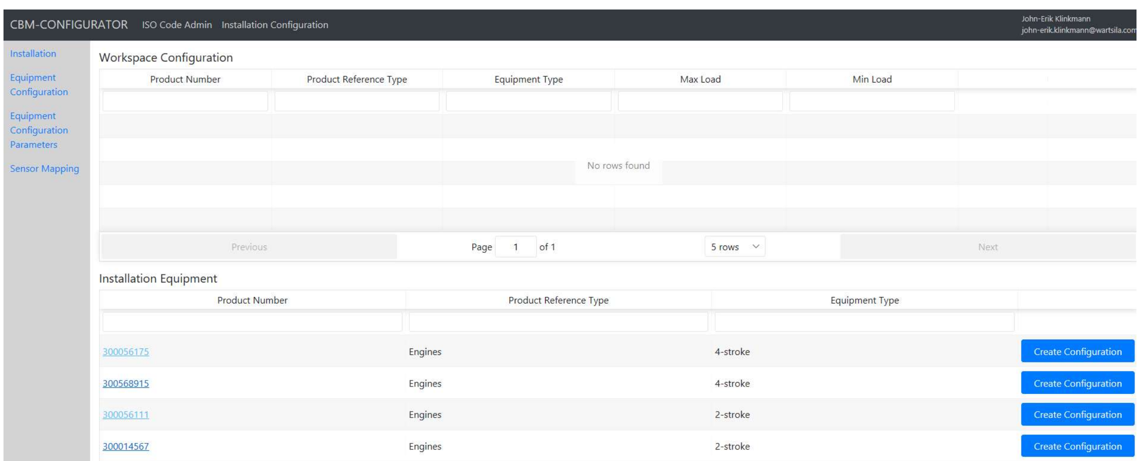


Figure 2. Workspace configuration

The configuration window can be seen in Figure 3. Creating the configuration for the workspace asks for a minimum and maximum load. This is a percentage-based load filter and can be for example minimum 20 and maximum 100. After the configuration is created it can be edited and equipment can be swapped from the installation equipment bank to the workspace configuration bank.

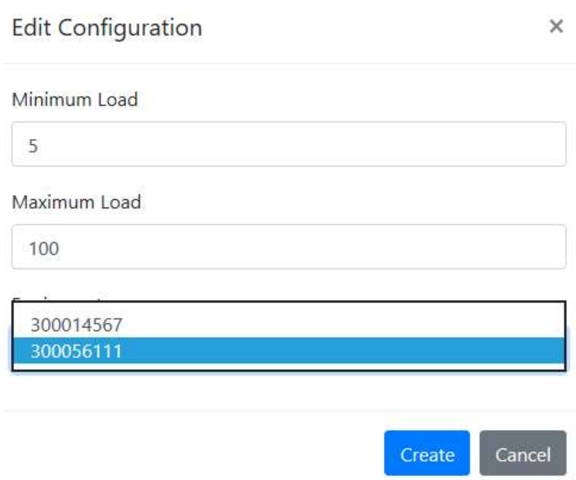


Figure 3. Swapping equipment of the same type from the drop-down

7.3.3 Equipment configuration parameters

With equipment linked to the workspace configuration parameters can be added. This is a free text field entry with Parameter name and Parameter value, outlined in Figure 4. Here, the setup includes details of turbocharger, engine, generator and charge air cooler types.

Equipment Id: 300056175	Setup
Equipment Type: 4-stroke Product Number: 300056175 Product Reference Type: Engines Minimum Load: 20 % Maximum Load: 100 %	Turbocharger type - TPL76 Engine type - Wärtsilä 50DF Generator type - Other 97% Charge air cooler type - II-stage

Figure 4. Parameter list

If there are several engines of the same type with the same configuration parameters, it only needs to be added once. The configuration can then be copied using the Copy Setup button on the far right. The below figure illustrates the copying feature. Clicking on Copy Setup presents a list of engines that can be used to copy the configuration from (see Figure 5 - this pre-release version is not showing the correct engine identifier on the list, it will show the equipment number in the release version).

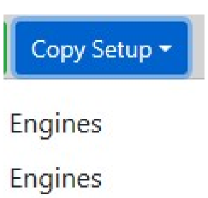


Figure 5. Copy configuration setup

7.4 Sensor mapping

With the equipment added, workspaces and equipment configured the sensor mapping can proceed. The task is initiated by clicking the *Submit Mapping* button. This allows the user to select the source of the sensor data. The data sources can vary between WOIS, WISE, WDCU and others. The configuration tool is made to automatically detect the type and parse the correct information from the file when the mapping is submitted as can be seen in Figure 6.

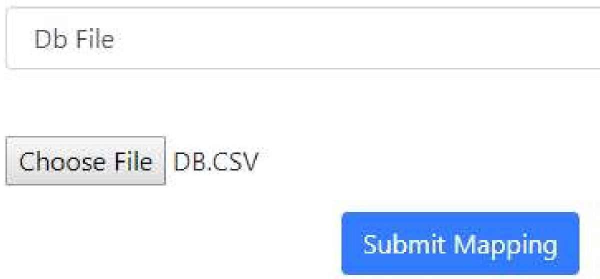


Figure 6. Submit mapping view

7.5 Normalizing data sources

The concept of normalization is to bring all the installations to the same baseline of measurements. In practical terms, this means that the diverse pool of tagnames that are being used on both marine and power plant installations across the world need to be unified to a common standardized ISO code. This ensures operational comparability moving forward with the Asset Diagnostics service. All sensors of the same type use the same name and description, which is of importance for a standardized data workflow. The tagname matching algorithm is providing a normalized template of each installation that is loaded into the Asset Diagnostic configurator. The input can vary depending on the source, as defined by the following chapters, but the output should always be of a similar format with standardized ISO codes and descriptions. Figure 7 displays an example of the sheer variance that can presently occur in tagnames that describe the same parameter. In this case, the tagnames are all linking to the High-temperature water cooling engine inlet pressure, which has been normalized to ISO code PT401. The reasons for such a wide variance in the tagnames used for the same measuring point are many:

- The installations represent a broad time scale, some of them can be over 20 years old
- The installations are spread across the globe with different local Wärtsilä offices and commissioning engineers being responsible for the equipment configurations
- Marine and energy businesses have different naming conventions
- Some Wärtsilä customers have their own naming conventions that must be followed
- Differences between equipment types can cause naming disparities

ISO code	Description	Unit	Tagname
PT401	HT water pressure, engine inlet	bar	PIAL-011604
PT401	HT water pressure, engine inlet	bar	651_DG1_PT401_PV
PT401	HT water pressure, engine inlet	bar	SCA011PT401PV
PT401	HT water pressure, engine inlet	bar	45MJG40CP010PV
PT401	HT water pressure, engine inlet	bar	DG1_HT_INLET_PRESS
PT401	HT water pressure, engine inlet	bar	SVH011P003PV
PT401	HT water pressure, engine inlet	bar	O8020505
PT401	HT water pressure, engine inlet	bar	611110010PIAL

Figure 7. Variance in tagnames call for normalization

This is an example of the broad spectrum of naming practices that are in place, but for the most part, the naming schemes follow the same guidelines. This structure of naming sensor tags is used in determining what the tagname describes and the logic behind it can be broken down into segments. Most of the presently supported installations use the tagname format of SCA011PT401PV. Examining this tagname structure in detail, it can be broken down into the components evident in Figure 8.

SCA	011	PT401	PV
SCADA	Engine	ISO	Function

Figure 8. Tagname break-down

The first part of the tagname describes what sort of measurement it is. SCADA is short for Supervisory Control and Data Acquisition. This means it is part of the supervisory monitoring system. The following three digits indicate which engine this tagname belongs to. The numbering format is such that the first engine in an installation has the number 011, the second 021 and so on. PT401 is the ISO code part of the tagname, so in most cases, the ISO code can already be determined by looking at the tagname. The ISO codes can be found directly in the tagname when the reference is made to Modbus[18] or WDCU (see Chapter 7.5.3). However, as Figure 8 shows, this is not the case across the board. PT401 can be broken down further with PT indicating a pressure sensor and 401 signifying its identifier. The function PV is short for Process Value – which means it is an analogue measurement.

After the tagname matching algorithm has provided a template recommendation of how the tagnames should be mapped, it is the responsibility of the Wärtsilä expert working on the installation to ensure the mapping is done correctly and validate all the links done. Figure 9 displays the difference on a general level between WOIS, WISE and WDCU, discussed in more detail below. The tagnames for all the plants differ and it is the purpose of the configurator to normalize this data, so all the installations map this sensor measurement to the ISO code *"TY500",* which is indicative of engine average exhaust gas temperature.

[18] Gould-Modicon serial communications protocol fieldbus for PLC automation

WOIS	DB.CSV	
Tagname	Comment	Group
SCA011TAVG	Exhaust gas average temp.	Genset_1

WISE	Repload	
Tagname	Description	Goupid
SCA011TY500PV	Exhaust gas average temp. [°C]	1025

WDCU	Unictool.CSV	
ISO code	Description	Plant code
TY500	Exh gas temp, engine average	SCAPAAE240669TY500PV

Figure 9. WOIS - WISE - WDCU comparison

7.5.1 WOIS

The Wärtsilä Operator's Interface System[19] is a human-machine interface that plant operators, managers, supervisors and engineers use to view plant live- and long-term performance. WOIS is built on Wonderware's InTouch platform (Wonderware by Aveva, 2019) and uses a Wärtsilä developed BaseWOIS application that gets customized for each individual customer's needs to create a bespoke plant management and supervision software. WOIS uses a graphical user interface complimented with alarms, reports and trend data to provide the user with a complete picture of how the plant is operating.

Wärtsilä has introduced a WOIS upgrade project called sWOIS (server-based WOIS) which operates slightly different to a traditional WOIS. The system is intended to mitigate obsolescence issues causes by Microsoft operating system (OS) lifecycles by virtualizing the WOIS visualization on a Windows server with the latest OS. This allows the user to interface with the WOIS through a web interface that is isolated from the internet. From a data perspective, sWOIS is treated the same as a normal WOIS installation.

The field engineer in charge of the PLC commissioning of a plant issues a backup of the custom WOIS application along with a DB.CSV file that is an export of all the digital and analogue data present in the installation. The DB.CSV file has the complete list of tagnames, descriptions and additional data embedded. When the algorithm parses the file, it links the tagnames with the standardized ISO codes. The WOIS data is aggregated from data collected with a sampling rate of 1s with a dead-band function.

The WOIS sensor data is stored in a large database dump of all the analogue and digital signals that are utilized inside a WOIS application. This data is stored inside a dump file that the user can request through the WonderWare InTouch Application Manager. The output is a comma-separated value file (CSV) with the name standardized as DB.CSV. The data structure of the file is separated by commas as the name suggests and it can be opened for viewing and editing in Microsoft Excel or any editor capable of parsing CSV. Inside the file there are separations of different keywords denoted by semi-colons. The keywords indicate what type of memory variable type the tagname is and to which group it belongs. The main segments of the CSV file are presented in Table 2. A general separation can be done between

[19] See Appendix L for an example of a WOIS application

the access names, alarm groups, memory tags, I/O[20] tags, indirect tags and tags related to historical trending and group variables (Aveva Group, 2018).

Table 2. WOIS DB.CSV structure

Keyword	Function	Attributes
Mode	Mode selection of how duplicate tag names are handled during DB import	
IOAccess	Access names as defined in the WOIS application	
AlarmGroup	Alarm groups as defined in the WOIS application	
MemoryDisc	Memory discrete tags (On/Off)	16
IODisc	I/O discrete tags (On/Off)	21
MemoryInt	Memory integer tags	55
IOInt	I/O integer tags	62
MemoryReal	Memory real tags (Analog)	55
IOReal	I/O real tags (Analog)	62
MemoryMsg	Memory message tags	10
IOMsg	I/O message tags	14
GroupVar	Group Var tags	3
HistoryTrend	Historical Trend tags	3
TagID	Tag ID tags	2
IndirectDisc	Indirect discrete tags	6
IndirectAnalog	Indirect analog tags	6
IndirectMsg	Indirect message tags	6

Without going into the detailed functionality of each of the tagname groups the most significant one for the purpose of the mapping process is the IOReal group. This group contains the analogue Input and Output tagnames of data type ‘Real’. This is synonymous with floating-point numbers. Because of the sheer amount of tagnames from analogue values, digital events, alarm events and other data the DB.CSV file is of considerable size. A multi-engine installation can easily contain in excess of 10 000 rows of data. This makes it very difficult for a human to process. Figure 10 shows example output from a DB.CSV file with each row populated by a unique tagname. For each tagname there are also a large number of columns containing different data attributes. Table 1 gives a numeric representation of the parameters associated with the different types of keywords. These parameters include things like: logging, event logging, alarm values, threshold values, unit, dead-band information, access names, read-only flag and other settings used inside the WOIS application.

[20] Input/Output, this is a tag that communicates directly with the UNIC system or PLC

:IOReal	Group	Comment	Logged	EngUnits	AccessName
SCA011TE600PV	Genset_1	Air temp, TC inlet	Yes	°C	WECS011
SCA011OT160PV	Genset_1	Analogue synchroniser	Yes	rpm	WECS011
SCA011PDY601PV	Genset_1	CA press dev. from ref.	Yes	bar	WECS011
SCA011PT601PV	Genset_1	CA press, engine inlet	Yes	bar	WECS011

Figure 10. DB.CSV filtered and condensed example of tagnames found under :IOReal

For sensor mapping purposes the tagnames that are of utmost importance are those which are flagged as logged sensors as seen by the yellow colour in Figure 10. Any sensor that is logged will have its operational data continually stored in LGH container files that are fetched from the on-site WOIS computer to the Asset diagnostics team for monitoring engine performance. Thus, the typical second step of establishing a sensor map after isolating the IOReal group is to sort it according to whether the tagname is logged or not. To maintain mapping simplicity a lot of the columns of the DB.CSV file can be disregarded. The condensed list of the most significant parameters can then be broken down according to Figure 11. The remaining information is in order: Tagname, Group, Comment, Logged, EngUnits and AccessName. After the excessive columns have been filtered out the data is sorted according to three factors in decreasing priority:

1. Logged
2. Group
3. Comment

:IOReal	Group	Comment	Logged	EngUnits	AccessName
SCA011TE600PV	Genset_1	Air temp, TC inlet	Yes	°C	WECS011
SCA011OT160PV	Genset_1	Analogue synchroniser	Yes	rpm	WECS011
SCA011PDY601PV	Genset_1	CA press dev. from ref.	Yes	bar	WECS011
SCA011PT601PV	Genset_1	CA press, engine inlet	Yes	bar	WECS011
SCA011TC01CVO	Genset_1	CA temp controller, actual control	Yes	%	CFC011
SCA011TC01SPO	Genset_1	CA temp controller, actual setpoin	Yes	°C	CFC011
SCA011TE601PV	Genset_1	CA temp, engine inlet	Yes	°C	WECS011
VCL012TC02GAN	Genset_1	CA valve controller, gain	Yes		CFC011

Figure 11. Filtered and sorted list of tagnames

The group shows which equipment the tagname belongs to. If it is a general measurement such as ambient temperature, the group will be listed as Common. Most of the sensor measurements will be directly related to an engine-generator set (genset). The comment field describes the function of the tagname. EngUnits shows the engineering unit that is associated with the tagname. This is site-specific as some sites can use imperial units. AccessName indicates which subsystem of the SCADA is responsible for generating the signal.

An important point to make here is that due to commissioning errors the settings for the tagnames can be wrong. For example, a key parameter might have logging turned off when in fact it should be turned on. Running hours is a parameter that always should be logged. It is the task of the experts mapping and validating the equipment to notice and correct problems like these as soon as possible. Because of differing tagname naming schemas and variances in equipment configurations, it is difficult to establish a hard baseline of which tagnames should be present on the map. It is the intent to improve the clarity through normalization of tagnames and harmonizing installations.

After an initial sensor list has been established by the above steps, the mapping expert proceeds with analysing the list of remaining logged tagnames. For efficiency, it is recommended to group engines of the same type into clusters, so they can be mapped simultaneously and compared for disparities in sensors. For an installation consisting of for example 10 engines, it is a considerable time-saving procedure to compare the engines and establish an engine standard mapping instead of doing 10 custom maps for the same engine type (which might have minuscule differences). Figure 12 exemplifies en masse engine mapping with each engine being horizontally synchronized so the tagnames correspond. Any disparity needs to be removed or corrected before proceeding with the mapping.

ISO	Tagname	Grc	Comment	Tagname	Grc	Comment	Tagname	Grc	Comment
TE600	SCA011TE600PV	1	Air temp, TC inlet	SCA021TE600PV	2	Air temp, TC inlet	SCA031TE60	3	Air temp, TC inlet
OT190	SCA011OT190PV	1	Analogue speed reference	SCA021OT190PV	2	Analogue speed reference	SCA031OT19	3	Analogue speed reference
TE7016A	SCA011TE7016APV	1	Big end bearing temp, cyl 01A	SCA021TE7016APV	2	Big end bearing temp, cyl 01A	SCA031TE70	3	Big end bearing temp, cyl 01A
TE7016B	SCA011TE7016BPV	1	Big end bearing temp, cyl 01B	SCA021TE7016BPV	2	Big end bearing temp, cyl 01B	SCA031TE70	3	Big end bearing temp, cyl 01B
TE7026A	SCA011TE7026APV	1	Big end bearing temp, cyl 02A	SCA021TE7026AP	2	Big end bearing temp, cyl 02A	SCA031TE70	3	Big end bearing temp, cyl 02A
TE7026B	SCA011TE7026BPV	1	Big end bearing temp, cyl 02B	SCA021TE7026BP	2	Big end bearing temp, cyl 02B	SCA031TE70	3	Big end bearing temp, cyl 02B
TE7036A	SCA011TE7036APV	1	Big end bearing temp, cyl 03A	SCA021TE7036AP	2	Big end bearing temp, cyl 03A	SCA031TE70	3	Big end bearing temp, cyl 03A
TE7036B	SCA011TE7036BPV	1	Big end bearing temp, cyl 03B	SCA021TE7036BP	2	Big end bearing temp, cyl 03B	SCA031TE70	3	Big end bearing temp, cyl 03B
TE7046A	SCA011TE7046APV	1	Big end bearing temp, cyl 04A	SCA021TE7046AP	2	Big end bearing temp, cyl 04A	SCA031TE70	3	Big end bearing temp, cyl 04A
TE7046B	SCA011TE7046BPV	1	Big end bearing temp, cyl 04B	SCA021TE7046BP	2	Big end bearing temp, cyl 04B	SCA031TE70	3	Big end bearing temp, cyl 04B
TE7056A	SCA011TE7056APV	1	Big end bearing temp, cyl 05A	SCA021TE7056AP	2	Big end bearing temp, cyl 05A	SCA031TE70	3	Big end bearing temp, cyl 05A
TE7056B	SCA011TE7056BPV	1	Big end bearing temp, cyl 05B	SCA021TE7056BP	2	Big end bearing temp, cyl 05B	SCA031TE70	3	Big end bearing temp, cyl 05B
TE7066A	SCA011TE7066APV	1	Big end bearing temp, cyl 06A	SCA021TE7066AP	2	Big end bearing temp, cyl 06A	SCA031TE70	3	Big end bearing temp, cyl 06A

Figure 12. Batch engine mapping

Once a standard sensor set has been established the expert only needs to define the ISO list and units once for the entire cluster of engines. At this point the tagnames and comments need to be matched against the normalized ISO list. In many cases the majority of sensors can be mapped according to the SCADA naming convention, but this is not always the case. On top of that, a lot of the sensors might not be recognized as belonging to the normalized sensor set of the ISO table. These types of tagnames need to be removed from the map.

Having arrived at a condensed and normalized list of sensors the proposed mapping still has to be checked and validated to ensure data is actually flowing in from all the linked tagnames. This is accomplished by superimposing operational data from the LGH source on top of the mapping and observing the output. An example of this can be seen in Figure 13 where a three-engine installation has been successfully mapped and the tagnames STA0X1P005PV have been linked to the ISO code PT311 – pertinent to control air pressure. Similarly, tagnames SOB0X1P001 have been linked to ISO code PT700 (crankcase pressure). The site operational values can be read inside the brackets for each engine.

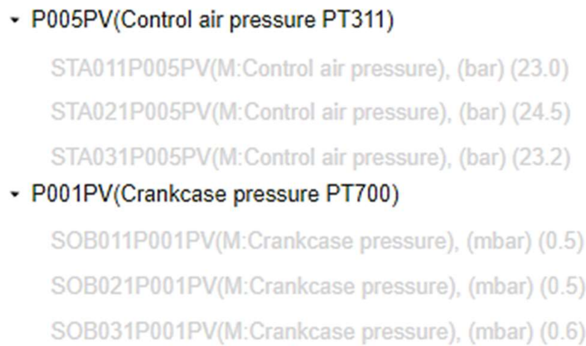


Figure 13. Observing tagname operational data values

If a sensor is reading as continually null – it is very likely that the sensor does not actually exist on-site but rather is a remnant left in the DB.CSV file from the process of it being templated from another installation. These types of tagnames should be removed to defeat null values in the final report. In the current configurator, the sensor operational values can be checked for a single date, for each sensor individually. This is something that is in the scope for improvement in the new configurator. There needs to be a tool to batch process many sensors at once and to look at a wider period of time, to establish if a sensor is in use or not.

7.5.2 WISE

The Wärtsilä Information System Environment is a plant management tool that enables operators, managers, supervisors and engineers to view the long-term performance of a plant. WISE can generate genset and common technical reports, production reports and provides remote reporting capabilities for CBM in the form of aggregated daily reports that get sent to the CBM centre for analysis. The WISE data is stored in a database that communicates through an ODBC-32[21] interface to generate daily and production reports.

The field engineer in charge of the PLC commissioning of a plant issues a report loader from the WISE system. This report loader (Repload for short) is provided to the CBM centre that coordinates the remote monitoring and data collection. The Repload file contains a list of plant tagnames, descriptions and analogue signals but lacks information about all available sensors or digital signals. This is where the algorithm of the Asset Diagnostic configurator comes into the picture, its job is to normalize the tagnames received from the Repload into a normalized set of sensor data, or a package. This sensor package is linked with standardized ISO codes to create a unified installation template. This algorithm looks for tagname matches based on previous installations and provides a recommendation. There is also an on-going machine learning sandbox of looking for new ways to link these sensors.

The Repload has tagnames similar to a WOIS installation but additionally has group ID (IN_GROUPID) numbers for each sensor, as can be seen in Figure 14. These group IDs are unique for each sensor and fuel mode. In a typical installation, each increment in the group

[21] Open database connectivity

ID by one thousand signifies the start of a new engine. The group IDs have no strict rules so the WISE Reload needs to be normalized to link the tagnames with the correct ISO code.

IN_INSTALLATIONID	IN_TAGNAME	IN_DESCRIPTION	IN_GROUPID	IN_MEASI	IN_REPTYI	IN_CALCT	IN_DEPENI	IN_DEPENI	IN_VALIDL	IN_SCREEI	IN_COL	IN_DESCRI	IN_UNIT	IN_FETCH
20V34SG	NGA011T002PV	Air temp., TC B inlet	1148	0	1	0	ADE011E(	2	0.01	2	1			0
20V34SG	SNB011P002PV	Charge air pressure, CAC outlet	1149	0	1	0	ADE011E(	3	0.01	2	1			0
20V34SG	SNB011T004PV	Charge air temp, CAC outlet	1150	0	1	0	ADE011E(	2	0.01	2	1			0
20V34SG	Group name	WECS SYSTEM	100	0	0	0		0	0	2	1			0
20V34SG	SCX011T001PV	MCM 700-1 Internal temp	1151	0	1	0	ADE011E(	2	0.01	2	1			0
20V34SG	SCX011T101PV	SSM 701/CCM10 Internal temp, 1	1152	0	1	0	ADE011E(	2	0.01	2	1			0
20V34SG	SCX011T102PV	SSM 701/CCM10 Internal temp, 2	1153	0	1	0	ADE011E(	2	0.01	2	1			0
20V34SG	SCX011T103PV	SSM 701/CCM10 Internal temp, 3	1154	0	1	0	ADE011E(	2	0.01	2	1			0
20V34SG	SCX011T104PV	SSM 701/CCM10 Internal temp, 4	1155	0	1	0	ADE011E(	2	0.01	2	1			0
20V34SG	SCX011T105PV	SSM 701/CCM10 Internal temp, 5	1156	0	1	0	ADE011E(	2	0.01	2	1			0
20V34SG	SCX011T106PV	SSM 701/CCM10 Internal temp, 6	1157	0	1	0	ADE011E(	2	0.01	2	1			0
20V34SG	SCX011T107PV	SSM 701/CCM10 Internal temp, 7	1158	0	1	0	ADE011E(	2	0.01	2	1			0

Figure 14. Reload output of sensor list

The Wärtsilä reporting system is divided into two parts: 1) calculations and 2) viewing. The calculations are handled by WGDI (Wärtsilä Generic Data Interface) that stores all the necessary values on a sensor level. WGDI gets its raw data from the WOIS workstation. The interrelationship between WOIS and WISE is explained by this connection. They are both reliant on the same data but WOIS data is richer and has a higher frequency. WISE data is aggregated from the data acquired from the WOIS workstation. WGDI stores its calculations in a database. WISE is the software used for viewing the data in the database through ODBC. WGDI has a standardized design where it assumes all entries with a groupID between 0 and 49 999 are WGDI calculations. Within this group, anything between groupID 1 000 and 19 999 is engine related and groupIDs 20 000 and up are common measurements. This gives the option to include up to 19 engines in a single installation reload. GroupIDs between 50 000 and 99 999 are WISE initialization parameters. For the purpose of data intake, the groupIDs of interest are those below 50 000 – they constitute the WISE calculations. There are specific recommendations in place how a reload should be structured but they only serve as guidelines and thus there are deviations to these recommendations due to various factors. In essence, this means that each reload should be treated as its own entity – differences are always present.

The general ruleset is that each engine is allocated a number series of 1 000 unique values ranging for example from 1 000 to 1 999. In WISE the fuel dependency is defined in the reload with duplicate tags for each fuel mode of the same engine. This means a dual-fuel engine that can run on LFO, HFO and GAS will have three duplicates of the same tagname, one for each fuel mode. Some sensors are fuel mode specific and do not follow this pattern. Examples of these types of sensors are gas and fuel oil sensors. The numbering logic for a multi-fuel engine can be seen in Table 3. The fuel dependency is split into three groups of no specified order, with each group representing a fuel mode. In the Reload you will find some rows with a group ID of 100, these identifiers are purely used for informative purposes and do not affect the report.

Table 3. WISE group ID logic (fuel modes do not have a designated order)

Group ID	Depend tag	Description
1000 - 1299	CFC011RUNGAS	Technical report measurements when running in GAS mode
1300 - 1599	CFC011RUNLFO	Technical report measurements when running in LFO mode
1600 - 1899	CFC011RUNHFO	Technical report measurements when running in HFO mode
1900 - 1919		Production report total (non-fuel mode dependent)
1920 - 1939	CFC011RUNGAS	Production report measurements in GAS mode
1940 - 1959	CFC011RUNLFO	Production report measurements in LFO mode
1960 - 1979	CFC011RUNHFO	Production report measurements in HFO mode
1980 - 1998		Dependency tags
1999		Reserved for genset 100% load value

The WISE sensor list is stored in the report loader configuration file that is created during the commissioning of the installation. This file bears similarities to the DB.CSV file of the WOIS data soure. The tagnames are following the same logic and since several sites support both WISE and WOIS data – the tagnames are in fact identical. The structure of the repload file is different in that it does not contain anything besides the base set of tags for each engine along with some general installation details and comments. The typical size of a repload file is a few thousand rows as opposed to tens of thousands, as is the case for the DB.CSV files. The parameters that are defined through the columns in the repload are standardized and the same for all installations. A sample output of some sensor tagnames can be seen in Figure 15. This group of sensors are the active and reactive power, power factor and frequency of the generator.

Tagname	Description	Group Id	Measure Group	Rep.Type	Calc.Type	Depend Tag	Depend Type	Valid Limit
ADE011E007RNI	Engine running	1000	20	1	0		0	1
BAG011UP01PV	G1. active	1001	0	2	1	ADE011E007RNI	3	2
BAG011UQ01PV	G1. reactive	1002	0	2	1	ADE011E007RNI	3	-1000
Group name	**ELECTRICAL SYSTEM**	**100**	**0**	**0**	**0**	**0**	**0**	**0**
BAG011UP01PV	PMU, Gen. Active power	1004	0	1	0	ADE011E007RNI	3	-4.1
BAG011UQ01PV	PMU, Gen. Reactive power	1005	0	1	0	ADE011E007RNI	3	-4.1
BAG011UC01PV	PMU, Gen. Power Factor	1006	0	1	0	ADE011E007RNI	3	0.01
BAG011UF01PV	PMU, Gen. Frequency	1007	0	1	0	ADE011E007RNI	3	0.01

Figure 15. Example Repload output

Starting from the left the standard information included in the repload is: tagname, description, group ID, measure group, rep.type, calc.type, depend tag, depend type, valid limit, screen, column, description 2 (2nd language) and unit.

The initial step of establishing a baseline map for a WISE installation entails filtering the repload according to the group ID, so that any group ID below 1 000 or above 19 999 can be removed. Most of the attribute columns in the repload are not of interest during mapping so they can be disabled. Those which take priority are: tagname, description, groupID, depend tag and unit. GroupID serves the purpose of identifying to which engine each sensor belongs and the depend tag describes what fuel mode each of the groupIDs indicate. Unlike a WOIS mapping, the WISE mapping includes duplicate sensor tags for each fuel mode. WOIS handles the fuel mode processing by looking at certain criteria of operational values (see Chapter 4.5). Similar to a WOIS installation the WISE tagnames follow the same structure and the standard ISO code can be ascertained by looking at the tagname and description. If the tagname deviates from the norm, the ISO code has to be determined by looking at the description or by looking at tagnames of previously mapped installations of the same type. Figure 16 is an example of the filtered reload output with the initial tags of engine number 1 (groupID 1 000 – 1 999). The depend tag states the first fuel mode is gas. According to the groupID logic described above, the assumption is then that groupIDs 1 000 to 1 299 are all gas sensors for the first engine. However, due to differing practices and the groupID logic not being a hard rule, this assumption can-not be taken for granted. Exceptions do exist, and every installation has to be checked and verified before it is processed. This is an improvement request that is also in the pipeline for improvement in the future. With increased data frequency the prevalence of WISE installations is decreasing.

IN_TAGNAME	IN_DESCRIPTION	IN_GROUPID	IN_DEPENDTAG	IN_UNIT
SCA011GTY1623PV	Engine load, relative kW [%]	1000	SCA011GASRNI	
SCA011GTY1623PV_C	Engine load calc. [kW]	1001	SCA011GASRNI	
SCA011GTY1624PV	Engine load, relative BMEP	1002	SCA011GASRNI	
SCA011STY196PV	Engine speed [rpm]	1003	SCA011GASRNI	
SCA011SE518PV	Turbo A speed [rpm]	1004	SCA011GASRNI	
SCA011ST173PV	Engine speed 1	1005	SCA011GASRNI	
SCA011SDY169PV	Engine speed dev from rated [rpm]	1006	SCA011GASRNI	
SCA011TE700PV	Main bearing 0 temp. [°C]	1007	SCA011GASRNI	
SCA011TE701PV	Main bearing 1 temp. [°C]	1008	SCA011GASRNI	

Figure 16. Initial WISE mapping

After the tagnames have been successfully linked to their respective ISO code, fuel modes added in place of the depend tag and unique equipment id appended the sensor list is prime for mapping. In Figure 17 the repeated sensor behaviour can be observed, with the only difference between them being the fuel mode and groupID. Essentially this differentiation works like having multiple placeholders of the same engine – one for each fuel mode.

ISO	Tagname	Unit	Description	equipment	fuelmode	Group Id
TE7501	SCA011TE7501PV	°C	Generator bearing temp, DE [°C]	300527046	GAS	1002
TE7502	SCA011TE7502PV	°C	Generator bearing temp, NDE [°C]	300527046	GAS	1003
TE7501	SCA011TE7501PV	°C	Generator bearing temp, DE [°C]	300527046	LFO	1302
TE7502	SCA011TE7502PV	°C	Generator bearing temp, NDE [°C]	300527046	LFO	1303
TE7501	SCA011TE7501PV	°C	Generator bearing temp, DE [°C]	300527046	HFO	1602
TE7502	SCA011TE7502PV	°C	Generator bearing temp, NDE [°C]	300527046	HFO	1603

Figure 17. Final WISE map with examples of repeated sensors across three fuel modes

Similar to WOIS installations, it is logical to batch map engines of the same type to save time and detect possible variances between them. Harmonizing the engines of an installation makes it easier to process them and benefits the readability of the report. Most importantly, this step can pick up on sensor omissions that might be present. The goal with the new configurator is to automate the batch mapping of engines as far as possible and highlight differences between them.

7.5.3 WDCU

The Wärtsilä Data Collection Unit is a unified data collector that allows high volumes of data from a broad range of equipment and sensors to be efficiently captured for live and historic analysis. It allows near real-time insight with flexible maintenance planning and adaptability to a wide range of circumstances and requirements. It uses a Modbus plugin to read data from the Wärtsilä UNIC system and streams it through the Wärtsilä Data Bridge[22], where it gets enriched by Kafka and outputs it through an influxDB database (InfluxData, 2019).

The structure of the WDCU data is different to the WOIS/WISE channels, in that it already contains the ISO code data and Modbus registers in the output. Modbus addresses can quite easily be linked directly to ISO codes, so it does not require the same kind of tagname to ISO code translation. However, it presents other challenges due to ISO codes and Modbus registers not being strictly unique without considering the internal function of the tag. As can be seen in Figure 18 the ISO code PT102 can be linked with three separate functions: PV (process value), SF (sensor failure) and ALM HIGH (alarm high). Simultaneously, the Modbus TCP address of 41058 relates to both PT102SF and PT102AH. The ISO codes need to be separated so that only the analogue values remain in the map. Plant code shows the standard naming convention which is what most power plants follow with an example value for the number one engine being SCA011PT102PV.

Modbus/TCP Address	Bit	Function	ISO code	Description	Plant code
41057		PV	PT102	FO press, engine outlet	SCA0_1PT102PV
41058	0	SF	PT102	SF, FO press, engine outlet	SCA0_1PT102SF
41058	2	ALM HIGH	PT102	ALM, High FO press, engine outlet	SCA0_1PT102AH

Figure 18. Modbus addresses and ISO codes

Process values are the analogue signals that are of interest for mapping an installation. Initial filtering can be made by excluding everything except PV ISO codes. In Figure 19 a selection of sensors can be seen. Out of these sensors, the only ones relevant for the mapping process are the sensors with the -PV appendix in their name. Another distinguishing factor is their type: float (floating point), i.e. they are analogue signals.

service	equipment_id	display_name	name	type	deadband	gain	min_value	max_value	unit	register	bit_field	sample_rate
modbus	300483976	DG1	CV124-PV	FLOAT	0.5	0.01	0	100		41111		1000
modbus	300483976	DG1	CV130-STATUS	BOOLEAN	1	1	0	1		41002	5	1000
modbus	300483976	DG1	CV161-PV	FLOAT	0.5	0.01	0	100		41180		1000
modbus	300483976	DG1	CV161-SF	BOOLEAN	1	1	0	1		41181	0	1000
modbus	300483976	DG1	CV161-SF LMP	BOOLEAN	1	1	0	1		41182	2	1000

Figure 19. Sample WDCU output

Due to misnomers or incorrect function types, some sensors can present as process values but when observing their type, it states they are Boolean, as is the case in Figure 20. Boolean values represent discrete data types with a state of either ON or OFF, so they are not analogue signals. These types of signals need to be removed from the map. An alternative approach is to filter the sensors by the type instead and exclude everything but floating values. A considerate approach should be employed as human errors are always possible and there might exist errors in the WDCU sensor list. The expert doing the mapping needs to make the judgement call if the sensor is of a critical type or if it can be left out.

[22] Wärtsilä Data Bridge is an integrated technology stack that connects Marine and Energy business to provide the customer with an adaptable platform

name	type	ISO	register	description
OS7306-PV	BOOLEAN	OS7306	47003	Stop/shutdown override status
GS7610-PV	BOOLEAN	GS7610	47011	PTO clutch status
OS7611-PV	BOOLEAN	OS7611	47011	PTO clutch-in requested
CV947-PV	BOOLEAN	CV947	49001	MCC, degassing valve control
OS931O-PV	BOOLEAN	OS931O	49001	Open gas supply
GS947C_1-PV	BOOLEAN	GS947C_1	49006	MCC degasing valve 1 pos, closed
GS947O_1-PV	BOOLEAN	GS947O_1	49006	MCC degasing valve 1 pos, open

Figure 20. Process values of type Boolean

For the other parts, the mapping process is similar to mapping a WOIS installation. The analogue signal list can be directly translated to ISO codes through the inclusion of the ISO codes in the sensor names in WDCU. The only difference is in the transposed WDCU tag – it prefixes the ISO code and PV suffix with the equipment ID as can be seen in Figure 21.

ISO	WDCU tag	Unit	Description	Equipment
CV124	300483976_CV124-PV	%	Pilot FO press control	300483976
CV161	300483976_CV161-PV	%	Fuel rack control	300483976
CV432	300483976_CV432-PV	%	HT cooling water thermostat control	300483976
CV493	300483976_CV493-PV	%	LT cooling water thermostat control	300483976

Figure 21. WDCU final sensor list

7.5.4 Format Y

Format Y uses a format that is similar to WOIS data in nature. The main difference between WOIS data and Format Y is that Format Y utilizes a generic TSV (tab-separated values) data format that is sent in batches, whereas WOIS is using the designated daily LGH format of InTouch. An example output from a data file can look like Figure 22. The sensor uses the same SCADA format as described for the WOIS data and the value is a numeric representation of the sensor data for the timestamp that is defined by the UNIX Epoch in column 1.

unixepoch	sensor	value
1566882307000	BAG011AC01PV	-22515
1566882307000	BAG011AC02PV	12
1566882307000	BAG011UE22CV	9311

Figure 22. Format Y TSV data file

The UNIX Epoch is a UNIX operating system specific time designator that is also known as POSIX time. It works by counting the cumulative time elapsed in seconds minus leap seconds since 00:00:00 Thursday January 1, 1970, in the UTC time zone. This date and time are defined as the epoch (second 0) of when time counting first was initiated on UNIX systems. It is a widely used standard in computer systems. Using a UNIX time or UNIX Epoch converter this figure can be translated into what we regard as normal human time. The time format of the Format Y data uses a higher accuracy, so the timestamp is expressed in milliseconds, instead of the conventional seconds. Figure 23 shows that the timestamp in the example equals August 27th, 2019 05:05:07 GMT.

Figure 23. Unixepoch to normal time (source: epochconverter.com)

7.5.5 Format X

Format X data is customer-specific cloud-data in CSV format with a sampling rate of 30 s. This is treated as a separate cloud-to-cloud data source where the daily backup bucket is used for processing data. It is treated similar to WOIS data and gets put through the ETL process (Chapter 6.3) twice a day and converted into parquet format before it is stored. The process of configuring the installations is similar to a WOIS configuration, with the main difference being in the tagname convention (discussed in Chapter 7.5). Figure 24 gives a sample of the final configuration list of a Format X installation. The tagname logic is different from the SCADA standard used in WOIS applications. Instead, tagnames have a prefix of the DG (diesel generator) they belong to followed by an underscore and a more immediately obvious naming scheme compared to the use of abbreviations. For example, DG1_DE_BRNG_TE can be translated into Diesel Generator 1 – Drive End – Bearing – Temperature. However, the naming schema is not always consistent, and the sensor names tend to become very long. For instance, pressure can be indicated by both PR and PRESS, temperature by both TE and TEMP.

ISO	Tagname	Unit	Description	equipment
GTY1623	DG1_ACTIVE_POWER	%	DG Active Power	300137207
TE601	DG1_CHARGE_AIR_IN_TE	°C	Charge air temperature inlet	300137207
PT601	DG1_CHARGE_AIR_PR	bar	Charge air pressure	300137207
TE7501	DG1_DE_BRNG_TE	°C	Generator bearing temperature, driving end	300137207
TE5011A	DG1_EXH.GAS_CYL1_OUTA_TE	°C	Exhaust gas temperature, after cylinder 1 (L engine)	300137207

Figure 24. Format X final engine mapping

To align Format X installations with all other data, the same normalization takes place and the sensor tagnames are linked to the relevant ISO code. The DG-prefix of the tagname essentially becomes superfluous as the equipment number indicates which genset is being referred to. It needs to be retained though to ensure the linking chain is unbroken.

8 Results

Reviewing the original purpose of this work, the focus shifts back to the finalized proposal for the thesis. This was filed during the first quarter of 2019, with the intended purpose and objectives being outlined in Chapter 2 as follows:

- Document the evolution of the Asset diagnostic project
- Formulate end-user documentation
- Develop optimized data normalization and workflow routines
- Acquire and asses user testing and future development opportunities

These objectives will be covered point-by-point with my personal findings during this project and supported by the conclusions attained from the semi-structured interviews.

8.1 Evolution of the Asset Diagnostic project

From the outset, one of the main goals was to document the development and use cases of the Asset Diagnostics project, with the main emphasise being on the development of the configurator tool, as the thesis title states. The documentation process has been continuous, trying to capture the environment in which the configurator works, its enablers and dependencies. In addition, the target was to provide a wider picture of the theoretical boundaries of what condition-based maintenance and predictive maintenance entails as well as their added value both internally and externally.

Documentation remains an on-going process as the project is still in development but for the purposes of a printed document about the history and current status of the configurator, in my opinion, the purpose has been met. A large part of the rationale for initiating the Asset Diagnostic service was to evolve the service offering in response to internal and external demands. This is strongly highlighted in the findings of strengths and weaknesses found during the interviews when comparing the CBM and Asset Diagnostic systems.

8.1.1 Strengths and weaknesses

A major problem area with CBM is identified as the system requiring a lot of manual work from the experts. Improving the report generation process will free up the experts to focus on problem solving for the customers. Another problem is configuration changes occurring during a product’s life-cycle lacking in transparency, with the information not always being relayed forward which would equate to errors in the analytics. One of the major drivers for introducing Asset Diagnostics is the customer expectations or demand for more high-frequency reporting and direct input from Wärtsilä. On the technical side the CBM data output is hard to use for anything other than the CBM template and it relies heavily on doing calculations on the client computer. A modern system would utilize cloud components more for this purpose. Another major problem is the need to support a wide array of installations, ranging in age up to 30 years, with all that this entails in terms of difference in automation systems. The same variety is experienced as a challenge during the commissioning of installations. The industry is also perceived to be moving ahead quickly and the pressure to stay technologically up-to-date underpins the need to abandon the legacy CBM system. In conclusion, the main elements that Asset Diagnostic can provide are: faster workflow, scalability, daily notifications, high-frequency data that leads to improved analytics quality and response time, improved transparency toward the customer with more communication options, cloud-based data handling and improved cybersecurity.

8.1.2 Predictive maintenance

The backbone of CBM and Asset Diagnostic is a predictive maintenance strategy as outlined in Chapter 3. It could be said that maintenance is a necessary evil – ideally it would be avoided entirely. The purpose of predictive maintenance is to enable time and money savings. With increased data intake and diagnostics, the reporters can better help optimize the customer assets and decrease the maintenance need. Predictive maintenance also considers environmental variables, something which traditional maintenance often does not. It also depends a lot on what the customer wants.

Interview comments pointed out that some customers are happy to try to balance maintenance costs and reliable operation by using a more traditional maintenance schedule. However, predictive maintenance can offer benefits on top of traditional maintenance, like catching risk factors ahead of failure events. One aspect that is mentioned is the desire to avoid unnecessary maintenance in order to lower the risk of maintenance related errors. Predictability is important in trying to optimize operating costs. Predictive maintenance is estimated to be able to save 15-20% in direct maintenance costs but potentially even more in fuel savings through efficiency improvements. Fuel consumption equates to around 75% of a customer's total operating cost so that could equal a considerable amount.

8.1.3 Environmental focus

The new Asset Diagnostic service adds the opportunity for more advanced load level and fuel mode processing as mentioned in Chapter 4. The significance of the service offering in regard to environmental impact was brought to the interview respondents. The response was that the service is seen as an open book that can be developed in any which way Wärtsilä wants. In fact, one of the design criteria early on in the project was to build a system that can cater to different equipment and work on different levels in order to future-proof it. The service can and should be used as a means to improve engine efficiency. Sometimes it is seen as a hindrance that the operator might not follow Wärtsilä recommendations. This is an issue that is hard to circumvent as Wärtsilä only has an advisory role. Improving fuel efficiency has been a top priority for Wärtsilä for a long time. Optimizing the performance and overall operation of an engine usually has the added benefit of reducing the environmental footprint as well. With access to more high-quality data and more advanced diagnostics, Wärtsilä has a stronger case to present to the customer on how to operate their equipment more efficiently. This gives the opportunity to reduce fuel consumption and carbon emissions. Another opportunity comes from the hybrid solutions that are coming to market. Wärtsilä already has customers that are using hybrid solutions and the advisory role of helping enable more optimal operation of equipment gives the opportunity to improve performance and in turn lower emissions. One of the challenges with hybrid technology is overcoming the scepticism which might be present, educating experts of older technologies such as diesel engines on how to operate the new systems.

8.2 End-user documentation

As previously stated, the work on the configurator continues and as such the structuring of a user manual is a work in progress, but substantial elements of the workflow, the capabilities of the tool and their intended function have been covered. These segments of the thesis will be directly in line with the intended use cases and structuring the end-user documentation. This will be an on-going process that will be maintained online, to enable updates and easy insight.

Chapter 7 of this thesis is a description of the workflow and configuration process while Chapter 6 contains the functional requirements and a description of the configurator and supporting systems. Combined with the history of RPA and RPA toolchain replica project detailed in Chapter 5, the progression and similarities as well as changes to the workflow have been outlined. Continuous practical testing of these systems and working with actual configurations have also enabled the adaptation of real-world scenarios. This process has brought forth change requests and highlighted some inherent weaknesses with the legacy systems. These considerations have been reflected in the design of the new tool. As a result, it has also presented improvement opportunities which are described in more detail in Chapter 9.

8.3 Data normalization and workflow

The need for data normalization is outlined in Chapter 4 and further detailed in Chapter 7 with the different data formats described elaborately. The workflow of data normalization and achieving a uniform sensor map across multiple data sources has been covered. Principally, data normalization has been a key component and a driving force in the development of the configurator. It provides a harmonized equipment base that can be treated and analysed by the same platform by providing data conformity, comparability and future proofing. This leads to the opportunity of being able to offer a software solution that can cater to a multi-portfolio of equipment.

The need for normalization and a standardized method of working will continue to grow in the future. With more complex installations on the horizon, the requirements on data quality will become stricter and stricter. Another important factor is the internal and external transparency of making the big data easily comprehendible while extracting as much useful information from it as possible. This is discussed in the external and internal value proposition segments in Chapter 9.

8.3.1 Customer transparency

One significant aspect that the workflow needs to reflect is a high transparency towards the customer. This question was polled with the respondents of the interview and the results were mixed. Some of the respondents have not had any feedback on the service as it is still in its pilot stage. The feedback that has been received has been mixed, there have been both positive, negative and a lack of feedback. For the reporters the new system has meant that report generation is an easier proposition, but instead they have to monitor the daily notifications and provide insight in that capacity. Some customers have provided positive feedback on the monthly reports, especially on the higher-frequency reporting and the day-to-day feedback. Other customers have expressed wishes for improvements in the reports; saying they expected more detailed analysis and overviews of equipment performance. That is feedback that Wärtsilä needs to pay attention to and implement better trending graphs and other improvements to satisfy customer demands. The customers that do not give any feedback are usually not detail-focused on the technical implementation of the service delivery but rather focus on their business and the savings that Wärtsilä can achieve for them. This is something Wärtsilä should capitalize on and showcase the benefits of the diagnostics system, acting as a technical buffer for the customer.

8.3.2 Communication channels

When it comes to the communication channel for relaying information between Wärtsilä and the customer the development requirement is seen as high. One problem is that there are a lot of contact surfaces – different organizations within Wärtsilä that communicate with the customer. These include the contract managers, reporters, remote support and so on. The need to develop a structured ticketing system where cases and feedback can be collected is seen as imperative. The current system is based on e-mail communication and the risk is always that the chain of communication is broken when a message gets stuck in a mailbox. It is an issue that is familiar from CBM, so it is essential that the feedback channel is improved into a structured system that can also be connected to the maintenance planning systems and include data like equipment numbers, sensor names and other required records that can be linked to the master data. The development of Expertise Centres is aimed at improving this situation.

8.4 User testing and future development opportunities

One important aspect of the user testing for enabling an efficient system is the context of a timeline. The test user needs to understand the background of the process, its purpose and requirements. Having the context of the legacy system is key in being able to identify development opportunities and weaknesses of the current system. In this domain, experience of RPA configurations (Chapter 5.2), the CBM configurator (Chapter 5.5) as well as test cases with the new Configurator (Chapter 6) provide the best possible baseline for optimizing the workflow.

In regard to user testing of the new Configurator, the task is constantly on-going with requests for change being filed so the back end and front end as well as the APIs perform the tasks that are required of them. This includes, but is not exclusive to bug detection, feature testing, requesting new features and quality-of-life improvements. Most of the functionality is mirrored from previously known good practice from the CBM configurator but with the undesired functionality changed or removed. The additional features and ease-of-use of the new configurator is what should really set it apart from the legacy system looking at it purely from an end-user perspective. From a broader perspective, it is an enabler for a much wider span of installations, as previously mentioned.

8.4.1 High-frequency data

An important functionality enabled by the Asset Diagnostic service is the ability to process high-frequency data. The respondents of the interview found two interesting aspects of approaching this topic. The first being in the amount of sensors being included with new installations. The trend of adding more sensors to engines is seen as mild. Traditionally it has been hard to outweigh the cost with the benefits of fitting more sensors. In the last ten years gas engines have got a fair number of new sensors and diesel engines a few, for example big end bearing temperatures. New measurements can be incorporated with the addition of sensors, but if the business proposition is not profitable the sensors are left out. Cost-effectiveness in construction during recent years has meant that additional sensors are often one of the things omitted in a cost-saving scenario.

The second aspect that came to light during the interviews was the frequency of data being collected and processed. When it comes to data frequency the trend shows an increased frequency and the opportunity to diagnose data more than once daily is seen as a possibility. In addition to this, there is an opportunity to diagnose streaming data. The configurator tool needs to provide the functionality of safeguarding the data quality and limiting the data response so as not to drown the process with unnecessary data. With increased data frequency comes increased demands on the internet services. This means bandwidth use needs to be kept efficient, especially for the marine segment that represents 70% of the connected equipment and where the satellite technology is still lagging behind a bit. Edge computing is seen as an opportunity with light calculations being performed on site to keep the data packets more efficient. Another optimization possibility could be the use of filtered data packets where only the most critical data is sent during times of poor connectivity.

Another consideration to make is the option to send data in batches, for example in 1 to 10-minute intervals, as opposed to streaming the data continually. Data frequency is not expected to grow at such a pace that it would be likely to see a remote alarm and monitoring system that works on the edge in the next five years. This would require more computational power.

Customer demand for more time-sensitive data is a demand that needs to be met. This is mirrored in our society with the social pressure to always be connected and it translates to the industry as well. It is more of a requirement today to have a direct line of communication with the equipment manufacturer. This will also mean that the reports and customer deliverables can change in response to more direct feedback.

8.4.2 Legacy formats

Legacy reports like aggregated WISE and WISELT formats are expected to decrease and there is a wish to phase them out with the introduction of Asset Diagnostics. However, there are customers that are content with a more rudimentary type of report that may want to retain this service. The problem with the legacy reports is that they put additional work on the crew or operator of the equipment. Importantly, they can provide some valuable data that is not possible to collect automatically yet, so the rationale for keeping them around is noted. A higher degree of automation in the generation of these reports would be desired. With the increasing complexity of new installations and automation systems improving it is expected that legacy reports will vanish on a longer timescale. A web portal that can service the customers as a communication channel is seen as an enabler for phasing out these legacy reports, but the price of the service will always be a consideration as well.

9 Discussion

Based on the results attained and presented in Chapter 8, the strengths, weaknesses, opportunities and threats of the project are discussed below.

9.1 External value proposition

The condition monitoring of Wärtsilä connected equipment enables a predictive maintenance strategy as explained in Chapter 3. That constitutes a condition-based maintenance program with expanded mathematical complexity and statistical analysis. This allows equipment condition prediction and alignment of the maintenance with other schedules to enable the most cost effective and least intrusive maintenance strategy. The aim is to increase reliability and availability while maintaining performance and reduce unplanned maintenance and downtime. This can ultimately lead to lower life-time costs, more effective inventory and asset management, improved tracking and reporting as well as workflow improvements. For the customer this has the following key benefits:

Decreased downtime. As explained in Chapter 3.4 the availability is a product of the mean time between failures divided by the sum of the mean downtime and mean time between failures (relationship between expected aggregates of uptime and downtime). Lower downtime means increased availability and reliability, which are key parameters for maximizing equipment utilization.

Predictable maintenance schedule. This is a key factor in enabling a proactive and strategic maintenance strategy as defined in Chapter 3. By aligning the maintenance windows, coordinating support crew, spare part availability and operational downtime, the highest possible asset availability can be achieved with the lowest life-time maintenance cost. This offers long-term predictability with a high degree of insight into asset condition.

Decision support and actionable advice. Traditional calculations are extended with diagnostic logic and multi-sensor criterion algorithms (see Chapter 6). This enables new fault detection possibilities like pattern and deviation detection (outlined in Chapter 3). The statistical and mathematical models paired with expert advice give the customer early decision support.

Timely information. The Wärtsilä Online services gives the customer access to a wealth of asset performance information in a timely fashion. This offers an asset overview with streamlined data management, online diagnostics, trending capability and daily anomaly notifications including expert advice.

Optimized performance. The advantages of advanced analytics go beyond traditional fault detection. It can also be used for optimizing asset performance and reduce operating costs.

Higher accuracy. Increased data flow rate and speed of analysis increases the accuracy of fault detection while added data measuring points can increase the breadth and complexity of the analysis. The difference can be as dramatic as historically daily aggregated data that is analysed twice a day and reported monthly. At best Asset diagnostic can support high-frequency data that can be updated and viewed in near real-time with daily exception notifications and monthly summaries.

Familiar design. The support channels should remain the same but be even more customer centric with the overall layout presenting the customer an easily comprehensible and familiar view, with a modern layout and the statistical and analytical benefits of higher data frequency and advanced analytics.

Return on investment. A goal of the process is to improve the customer return on investment as outlined in Chapter 3. To quantify this benefit, a multitude of factors must be considered. The costs of the monitoring system have to be taken into account, both the initial investment and the running costs of enabling constant monitoring. This cost should be weighed against the alternative - repairing equipment when it breaks. The implications of this are many: savings on reduced maintenance and a reduction or removal of scheduled inspections. The cost of lost opportunity or reduced asset availability due to downtime also must be factored in. Savings can be achieved through a simplified logistics chain with more effective spare parts ordering and storage. In addition, the predictive maintenance strategy enables consolidated maintenance through prognostics and planning. Human resources can be more efficiently utilized, and several maintenance actions coordinated. Finally, and most essentially, the predictive maintenance reduces the risk of a potential catastrophic system failure.

9.2 Internal value proposition

Internally the changes introduced with Asset Diagnostics and the value added is multifaceted. These include structural changes like enabling cloud services, data normalization and high-frequency data, infrastructure design changes and partial rewrites of the codebase with increased internal control over the software tools. On a system level it allows for more advanced fuel mode processing which enables future analytics of different fuel blends such as bio-diesel (previously not possible, see Chapter 4.5). This is also a change that is market- and policy driven and of interest to external clients as well as Wärtsilä. Another added value is a more advanced load level filtering with virtually unlimited options with the possibility of quick and easy swaps between configuration sets (workspaces). This seamless switching can even be performed automatically. Old configurations are preserved, which was not the case in the legacy system. Other improvements can be summarized as:

- Multi-portfolio. Onboarding of more equipment types, initially 2-stroke and 4-stroke engines, PCMS and LNGPac with the opportunity to add more in the future. This also means reports can be consolidated across the range.
- Continuous improvement of Wärtsilä proprietary software.
- Load specific diagnostics, for several load ranges if desired.
- Digital event diagnostics (previously only analogue). The new configurator will add support for more function types, besides process values (PV) it will also support digital events and alarms (see Chapter 6.1).
- Cloud data monitoring for lifecycle support.
- Replacement of legacy RPA software with modern software solutions that offer more intuitive and easier workflow with increased options for data monitoring and analysis (Chapter 6.4). The original codebase was lacking the desired functionality and contained undesired features and issues that remain unsolved in the interim RPA replica project. A complete rewrite of the code base allowed for a fresh start while also allowing for testing and user input during the implementation phase.
- The new platform offers improvements in the robustness of the ISO code administration as well as general system administration.

The configurator offers many quality-of-life improvements for the user as well as sanity checks to ensure data quality and allow for improved validation methods. The specific technical and detail focused improvements are listed in Appendix M.

9.3 Potential threats and weaknesses

Most of the potential threats are common for Condition-based Maintenance and Asset Diagnostics. In this light, the threats and considerations are not new or exclusive to Asset Diagnostics. However, with the increased data intake and analytics being introduced and more equipment being onboarded, this is even more relevant looking ahead.

The potentially underlying threat of a condition-based maintenance system is discussed in Chapter 3.5 and 3.6. In summary the systems can be prone to issues relating to risk identification and the intelligence of the detection algorithms. The condition-based system is entirely dependent on the accuracy of the data that it is monitoring. If a failure mode is not included in the detection algorithms it can cause the equipment to experience physical failures that go undetected. If the detection algorithms are not sufficiently comprehensive they might omit reporting undesired equipment behaviour. On the other hand, if the detection algorithms are too strict, they can flag false positives, undermining the reliability of the entire detection system.

The system can be prone to sensor faults and through complexity of its design it can be hard to distinguish the difference between an actual potential equipment fault and a sensor fault. In most cases, this ambiguity can be eliminated through cross-referencing data but there is still a slight risk of the sensor data being erroneous, causing the report to be inaccurate.

Further, some faults can be such that they are hard or impossible to detect even with the most advanced monitoring systems. These kinds of faults can be very hard to avoid and require the most advanced type of asset diagnostic, with a hybrid approach of both data analysis and a holistic view where expert experience can play a large role.

Wärtsilä wants to offer lifetime support for its products and this makes it difficult to maintain a harmonized minimum sensor set when dealing with a wide array of equipment. The equipment age and specification can vary a lot and there are situations where equipment is converted or retrofitted to add new features. This also has to be reflected in the equipment monitoring and it is a constant challenge to guarantee that the configuration is up-to-date. The lifetime aspect of customer support is a big undertaking and goes far beyond equipment monitoring. To ensure business rationale for maintaining the Asset Diagnostic service, appropriate contracts have to be made with customers so that the agreement is beneficial to both parties. The cost of maintaining and constantly updating the Asset Diagnostic service is something Wärtsilä has to consider. Offering advanced equipment monitoring and expert service needs to add business value, not be a complementary service upheld by goodwill.

Another difficulty that can surface lies in the use of varying types of fuel and above all, varying or subpar fuel quality that can cause the diagnostic tools to trigger warnings. This is expected behaviour and can provide useful information, but sometimes it can present a situation that can-not easily be remedied due to regional differences in fuel quality. In such a case the Asset Diagnostics will flag warnings, but no actionable solution might be possible. This could potentially be detected and accounted for in the algorithms by chromatography-mass spectrometry and oil fingerprinting.

Different threat scenarios were also discussed during the semi-structured interviews and respondents had differing outlooks on this question, pertaining to their varying professional roles. One threat scenario that is discussed is the potential for customers to be reluctant to installing a monitoring system or sharing data with Wärtsilä. In actuality this has been a very rare occurrence so far and most customers have the opposite attitude and welcome the advice. Sometimes specific customers may have the wish for their data to be kept anonymous. This is something that also needs to be considered. One of the continual processes that is already present in CBM is the investigation of data quality and correction of software bugs that can occur. This situation is seen as improved with Asset Diagnostics thanks to more advanced algorithms and the inclusion of digital events, which can be cross-referenced to the analogue data. Wärtsilä should also look at the internal authorization process and review how the operational data access is granted, to ensure the right people gain access. Another threat scenario that is discussed is the pricing policy and how to best package Asset Diagnostic in order to sell it to the customer. Wärtsilä needs to define the service in such a way that it is apparent what value it adds, while keeping the overall price in check. This relates to the bigger picture where Asset Diagnostic is one part of a larger service contract. Wärtsilä should not aim to sell Asset Diagnostics as a stand-alone service but rather include it in a wider scope of services. The price increase of Asset Diagnostic is quite moderate when you compare it to the complexity of the systems. The actual service being provided through Asset Diagnostics with more frequent feedback and utilizing Wärtsilä experts daily has increased the price roughly 50% compared to CBM. In the scheme of total running costs for an installation, the additional cost for Asset Diagnostics is very small. Still, when service contracts are bundled together, and different modules added on top of each other the price tag goes up. This delivery cost can become too high, so there is a challenge in how to package the service. Thanks to its design Asset Diagnostics can form the common system for all linked equipment to keep the cost down. To be able to provide a service contract today, Wärtsilä requires to have access to operational data. That data can originate from Asset Diagnostics or other sources, however, operating in the blind is not an option.

9.4 Opportunities

The development opportunities are numerous and an important point to make is that the Asset Diagnostic platform is a constantly evolving service where new algorithms are tested and added. New equipment is tested and onboarded with specific analytics for each equipment type. Much like the evolution of CBM, Asset Diagnostics will continue to build on that strong fundament and remain in constant development. This is a necessary strategy in a rapidly changing world where equipment keeps getting upgraded or retrofitted, algorithms grow smarter and customer and internal demands become ever more stringent.

Some of the major improvement opportunities that came to light during the testing and development of the configurator and its related workflow include the visibility into data quality during commissioning. There is an improvement request to add the necessary tools to look at custom timelines of raw site data with the possibility to overlay sensor thresholds on top of that data. Additionally, including the necessary tools to easily identify redundant sensors that are present on newly commissioned installations (this is discussed in Chapter 7).

Another requirement that became obvious during testing was the inclusion of tools to add higher transparency into the data flow and processing (outlined in Chapter 6.7). In the current iteration of the configurator the end-user has very little insight into what the different APIs are doing, and possible fault scenarios are not immediately obvious. Therefore, a transaction log of some kind would be of use.

A general opportunity and a development which is naturally taking place is the decreased reliance on aggregated data sources (WISE). Thanks to infrastructure improvements and especially with internet speed and reliability improving in the future, the potential for high-frequency data is increasing. This has the direct impact of improving the analytic accuracy and response time. The customer will benefit from more immediate response and less delay in fault detection. For Wärtsilä internally this will mean that over time the support for RPA can be phased out as installations are moved over to the new platform. This will mean interim savings in both time and money by removing redundant legacy systems. In the grand scheme Asset Diagnostics has a higher cost related to it.

One of the big improvements enabled by the new configurator is the potential for true multi-portfolio installations with each equipment segment having their own harmonized ISO code groups. The possibility exists to accommodate any kind of equipment that has monitoring sensors attached to it. The first installations to benefit from this possibility will likely be marine vessels that have both 2-stroke and 4-stroke engines onboard. They can now have a consolidated report that covers all equipment. Looking toward the future, the configurator provides the necessary tools to broaden the equipment base.

Another potential development for the future is the use of Expert UI to present near real-time data, accessible by the customer on a large scale anywhere in the world (see Chapter 6.8). This would enable a visualization option similar to what WOIS Connect remote monitoring is offering today, with the bonus of being multi-platform and multi-portfolio capable.

9.5 Limitations

Because the project still is on-going and due to the large scale that this thesis has attempted to cover it can fail to cover some aspects. Part of the software solution is still under development and not available for testing. This presents challenges as the complete validation and configuration workflow can not be established with absolute certainty. This is a process that needs to evolve along with the continuation of the project. Issues which surely can and will surface along the way also need to be addressed. Another aspect is the large variety in formats that are planned to be supported by the new configurator. Some of these are yet to be tested. However, this is a question of technical implementation and making sure different software solutions can communicate with each other. As previously mentioned, this is not within the scope of this thesis as the purpose was to establish the working principles of how the actual configuration should take place. Simultaneously, this offers an opportunity for further research and documentation of the technically more intricate layers of program and platform functionality. The other possible limitation is relating to the extent which this thesis attempts to cover. Due to the constraints in time and space for this thesis, prioritisations had to be made in regard to what should be included.

10 Conclusion

Nearing two decades in operation the age of the CBM system was starting to show. Even though the system has been updated throughout the years, it was due for a modern replacement. Looking back at the inception of this thesis work at the end of 2018 and contemplating it today, nearly a year later, the work has evolved a lot and taken more time than expected to finish. While the project is still on-going, the goals for this thesis have been met. It has been a constant consideration since the very beginning of how to appropriately narrow down the reach of the project while allowing enough peripheral vision to give a historic perspective and offer a holistic view of the interdependent systems. While delving into the project it became immediately obvious it was easy to get side-tracked by the breadth of information in terms of products, services and other tangents. The results presented in this thesis are those that I believe are the most notable. The interviews conducted added a lot of rich data to analyse and at times yielded unexpected results due to the widely varying experience and background of the respondents. This was the exact type of results that I was hoping for and it serves to give a broader perception of the entire platform. The main findings as far as improvements brought by Asset Diagnostics and the challenges to look out for during development and in general terms are outlined in Table 1.

Table 1. Major improvements and challenges to consider

Improvements	Challenges
Meet external & internal demands	Configuration changes
Improved workflow	Wide array of installations to support
High-frequency data	Ensuring commissioning quality
Response time	Mixed response to services
Cloud computing	Structured communication channel
Cybersecurity	Mild trend of adding new sensors
Scalability	Internet bandwidth requirements
Daily notifications	Support for legacy formats (WISE)
Transparency toward customer	Data anonymity
Failure detection	Data quality
Time and money savings	Internal authorization
Platform to enable future needs	Added value of Asset Diagnostics
Multi-portfolio	
Enabling hybrid solutions	
Sensor normalization	
Data validation	
Edge computing	
Batch / streamed data	
Online service portal	
Digital events	

As work is still on-going on the configurator and the Asset Diagnostic platform as a whole, certain aspects of it are hard or impossible to describe in detail. At present time the Configurator tool is prime for quality assurance testing which will offer the opportunity to further enhance the software tools. The continued testing and feedback to the developers is expected to help continue to develop new areas of improvement.

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Appendix A. Interview invitation letter

I would like to extend you an invitation to a semi-structured interview for charting the present state of Asset Diagnostics and its outlook for the future. This information will be used in my bachelor's thesis "Wärtsilä Asset Diagnostic Configurator" and used in the discourse of the outcome of the project. Your name and role in the project will be visible unless you expressly want to remain anonymous. The interview will be recorded and is expected to take around 30 minutes. Please find the key topics covered below.

Key topics:

- Current CBM system
- Benefits of Asset Diagnostics
- Future trends
- High-frequency data
- Environmental aspect
- Threat scenarios

Appendix B. Pre-interview briefing

Thank you for taking part in this semi-structured interview for charting the present state of Asset Diagnostics and its outlook for the future. This information will be used in my bachelor's thesis "Wärtsilä Asset Diagnostic Configurator" and used in the discourse of the outcome of the project. Your name and role in the project will be visible unless you expressly want to remain anonymous.

This interview aims to capture the perceived goals and outcomes of the Asset Diagnostic service from a heterogenous convenience sample of key persons involved in the project. If you find some questions difficult to answer or far-fetched from your field of expertise, do not worry but try to answer them to your best ability. There are no right or wrong answers as this interview aims to collect opinions and personal experiences. If at any point you have comments or questions regarding something, feel free to address the issue openly. With your permission I will start recording the interview for the purpose of creating an interview transcript to be appended to my thesis. The original recording will be disposed of upon receiving formal consent to include or exclude the material in my thesis.

Please start with a short introduction of yourself and your experience within Wärtsilä and explain your role in the Asset Diagnostic project.

Appendix C. Interview questions

1. In your opinion, what are the biggest problem areas with the current CBM system?
2. What do you feel are the biggest improvements that the Asset Diagnostic platform enables? In your opinion how will a Wärtsilä customer benefit from this?
3. What does the future look like for Asset Diagnostics? Do you believe that there is a trend of increased usage of predictive maintenance?
4. Can you offer some predictions of what the data frequency will look like in the next five years?
    a. Has there been a lot of customer demand for more time-sensitive data and prompt deviation response?
    b. How do you see the future of legacy aggregated data sources? Will traditional reports like WISELT and WISE diminish or vanish altogether?
5. Has there been any external feedback on how the Asset Diagnostic service is working from the pilot cases that are running today, and what is the general reception of the service?
6. Can the Asset diagnostic platform be seen as an enabler for more environmental operation of equipment? For example, more advanced load diagnostics, hybrid fuel compositions or possible other features planned for the future?
7. What do you see as the biggest potential threats for the Asset Diagnostic service; today and moving into the future?

Closing remarks: Thank you for your time and insight. Do you have any final comment or opinion relating to the Asset Diagnostic project that you would like to highlight?

Appendix D. Abridged interview transcript I

Position: Senior Technical Expert

Team: Infra Hosting

Date: 20.8.2019

Introduction

Overall, I have a little bit over 6 years of experience in Wärtsilä. I started in Field Service as a service engineer. After a change of jobs, I returned to a new role in Wärtsilä in the newly formed ICT-team (later Infra Hosting). Now I have nearly 3 years of experience in that capacity.

Interviewer: **You have quite a lot of experience with sensor mapping procedures and the general preparation work for being able to produce the CBM reports.**

Yes, the old reporting tool was arranged in such a way that the person who was in charge of that particular work later changed his position in the organization and I kind of took over after him when he left. Having the practical field knowledge has been helpful in the sensor mapping process. After joining the ICT-team I have gained knowledge in the IT-field as well.

1. In your opinion, what are the biggest problem areas with the current CBM system?

The biggest issue is that there is so much manual work that needs to be done. Following this also some sites are updating their configuration and the information is not relayed forward. The disparity is only noticed when the reporter comes and asks why the data is not valid. When the case is investigated the site engineers might have already left and the issue cannot easily be resolved.

Interviewer: **If you think about it from a customer perspective, is this something they have noticed? Have customers demanded more of the service?**

Since the data is based on daily averages (aggregated data) the customer might want more and more (near) real-time data. Of course, data can never be truly live but the demand for more up-to-date data is one thing. Now the reports are monthly so there is always a delay in responding to events. Of course, the reporter can see some different things that would otherwise be missed – more long-term trends. For example, a gradual rise of the turbo speed can be detected by the reporter. The Asset diagnostic service can react to events quicker.

Interviewer: **Do you feel these are the same reasons why the Asset Diagnostic service was introduced?**

Probably some of the reasons and also getting out of the old legacy systems. Even though they are working quite nicely, every software solution has a lifetime and CBM has reached its end-of-life.

2. What do you feel are the biggest improvements that the Asset Diagnostic platform enables? In your opinion how will a Wärtsilä customer benefit from this?

Hard to answer at this time because the response from the reporters has been pretty limited so far. The project is still on-going, and testing is in the early phases. The biggest thing is that the data quality is improved, and the response time is better.

Interviewer: **What if you look at the question from an internal end-user perspective?**

The amount of manual work should improve with the new tools, but they are still in development. The first version of the updated configurator tool (RPA replica phase 2) was not very well designed. I didn't like that version a lot and didn't end up using it a lot. I'm anticipating the new updated configurator to be a big step forward. When you are developing something, and you have a deadline it can be easy to get into a tunnel vision, so some important things can be missed.

3. What does the future look like for Asset Diagnostics? Do you believe that there is a trend of increased usage of predictive maintenance?

Definitely, for the end customer point of view it's a big thing. Maintenance is basically an unwanted for the end customer, but a more predictive schedule reduces the negative impact of time and money being spent. With better understanding of the engine operation the maintenance can be lowered. In some cases, it can be the opposite so that maintenance is higher, for example if the load is very low on one engine it will require more maintenance. But in this instance the reporters can give advice to the customers to optimize their asset usage to avoid low-loading scenarios. There are so many environmental variables (temperature, fuel quality, air quality) that affect inlet filters and all kinds of maintenance related parts. A more traditional scheduled maintenance swaps out parts according to a worst-case scenario without taking into account the actual equipment condition. This can mean unnecessary expenditure for the customer.

4. Can you offer some predictions of what the data frequency will look like in the next five years?

The amount of raw data and sensor amount has increased and will keep on increasing. Nowadays more sensors are installed in the engines and it's a really big step with the Asset Diagnostic service in data amount compared to the legacy CBM system.

Interviewer: Do you think the development will continue or accelerate even more in the future?

Maybe not so much. Of course, when engine control systems are updated, more data will be required. There are so many different things that can affect this. Every time when a discovery is made that a sensor can be used to detect different things – they can be incorporated into the service. One problem can be if you have too much data and don't know how to use it. You need to be able to weigh the quality of the data.

  a. **Has there been a lot of customer demand for more time-sensitive data and prompt deviation response?**

Not directly. There has not been that much response yet. Sometimes the customer has reacted that the data is not actually responding to what the reports are saying. This can lead to an investigation into the root cause, which can be an incorrect sensor mapping or a sensor problem. This varies a lot from customer to customer – some want a lot more transparency into the data.

b. How do you see the future of legacy aggregated data sources? Will traditional reports like WISELT and WISE diminish or vanish altogether?

I don't think that it will vanish because it's only a small part of what we offer. I haven't really thought about this scenario.

Interviewer: Do you think that it will decrease with Asset Diagnostic being sold with more complex analytics?

There's a delay if its disappearing, it will not happen straight away. It also depends on the customer, some might be happy with the aggregated data of the legacy reports while others want the latest and greatest.

5. Has there been any external feedback on how the Asset Diagnostic service is working from the pilot cases that are running today, and what is the general reception of the service?

It's an important thing to discuss. A lot of the time, maybe in Finnish culture overall, if there is no feedback it can be seen as good feedback. This might be better to ask from the reporters' point of view, they have direct communication with the customer.

Interviewer: Do you feel that there is a robust channel for feedback of the service?

I think they normally contact the contract manager, but it depends on the customer. Some are in direct contact with the reporter.

6. Can the Asset diagnostic platform be seen as an enabler for more environmental operation of equipment? For example, more advanced load diagnostics, hybrid fuel compositions or possible other features planned for the future?

Definitely, there are possibilities to get more efficient engine operation. Especially some of the shipyards are not worried about how much fuel they are using. They do not pay for the fuel so it's not a consideration to them. Wärtsilä can still try to help them with lowering the fuel consumption and efficiency, which is beneficial. Sometimes old habits of the crew can be hard to break, for example when a Wärtsilä expert gives recommendations to a captain with decades of experience. The same goes for power plants, they don't always realize they can stop an engine and spread the load to other engines. This depends on how good the load-balancing system is. Of course, this is also a part of the legacy CBM system, but Asset Diagnostic has more possibilities. This is true also for biofuels, CBM does not presently support them.

7. What do you see as the biggest potential threats for the Asset Diagnostic service; today and moving into the future?

What kind of threats do you mean?

Interviewer: Cybersecurity, for example.

It is probably a threat if the customer does not want to install any monitoring system. If they start to think that Wärtsilä is a threat and don't want to share any operational data.

Interviewer: **Is this something that you have experienced or that is common?**

Not so much but there is a potential that customers don't want to share the data.

Interviewer: Another threat for all diagnostic systems can be the data quality. How can you trust the data being received, especially with more data coming in. How can Wärtsilä trust the quality?

It's a situation I haven't thought about. Investigating possible faults is a part of daily work and it might be a possibility that it will increase with more data. But we should also get more algorithms and cross-referencing to detect these situations. Another thing is that we can now capture the digital events and with time synchronization, these can be compared with the analogue data to detect things like this.

Do you have any additional comments or questions?

I think these were good questions because it covers both customers, ICT and reporters (CBM / Asset diagnostic) perspective to give a wider view of the situation.

Appendix E. Abridged interview transcript II

Position: Senior Technical Expert

Team: Infra Hosting UI/UX design, Asset Diagnostic Configurator stream lead

Date: 20.8.2019

Introduction

I have been working for Wärtsilä for a little over a year, my role here is stream lead for the Asset Diagnostic Configurator as well as Expert UI. My role in the Asset Diagnostic project is doing visualizations both in web applications and in PDF reports that are sent to customers.

Interviewer: **Is it fair to say you have a pretty good overview of the development process of the configurator tool?**

Yes, absolutely. I have been writing the specifications for the configurator and looking into what needs to be done in the new configurator that was not available in the old system.

1. In your opinion, what are the biggest problem areas with the current CBM system?

One of the major issues with the current CBM system is that it's relying heavily on doing calculations on the client computer, not utilizing cloud or server technologies like a modern system should. Also, it has more to do with the general data handling, but everything is built only for the CBM template outputs so it's difficult to utilize the data for other purposes.

Interviewer: **Do you see Asset Diagnostics as one of the main drivers for enabling a multi-portfolio with unified reporting?**

Yeah, Asset Diagnostic has a key role in Wärtsilä. Especially because of the number of existing contracts. Meaning, there is a user-base and a customer deliverable that Asset Diagnostics needs to provide. Of course, there are a lot of other things happening at Wärtsilä that is utilizing the same sensor data. Asset Diagnostic's role in that sense may be seen as one of many data consumers. Whereas previously, the CBM system was one of the only data consumers.

Interviewer: **Do you see these reasons as the same as to why Asset Diagnostic was introduced?**

I think the key is to provide better scalability and faster workflow. Having the experts focusing more on the problem areas as opposed to putting in hours to produce a report. The time-cut in creating reports and making the deliverables are the key features, in my opinion. Also, the daily expert cases are a completely new thing that was not present in the legacy CBM system.

2. What do you feel are the biggest improvements that the Asset Diagnostic platform enables? In your opinion how will a Wärtsilä customer benefit from this?

What the customer wanted was a faster response from Wärtsilä, they didn't want to wait two weeks for the monthly report. Also, when something happened on-site they wanted Wärtsilä to address that immediately. With the new daily cases created and more automated report generation, we can achieve these goals and provide the customer with our expertise when they require it.

3. What does the future look like for Asset Diagnostics? Do you believe that there is a trend of increased usage of predictive maintenance?

It's a bit outside my field but I would assume this is what Wärtsilä should strive for and the value that the customer wants. They want the overhauls done as needed and Wärtsilä should be able to deliver the best fuel efficiency and so on. If we notice that some key component is starting to fail earlier than predicted it's a win-win situation for everyone. This is what we should aim for.

4. Can you offer some predictions of what the data frequency will look like in the next five years?

The future depends on the timespan that we look at, but at least one simple thing that we can do with data acquisition being improved - is that diagnostics can be run more than once daily. Also, the possibility to do some diagnostics on the streaming data. These are the main things I see in the future for Asset Diagnostics.

Interviewer: **With increased high-frequency data and increased sensors, how can Wärtsilä ensure the data quality and give relevant data?**

It's a good question. The configurator is the key here; one of the most important things is that we don't provide the data consumers with more data than they actually need. The configurator can limit the data response and amount when a query is performed. That also makes it a little bit easier to validate that the data is what we are looking for. I would say that we need to collect as much as possible and specify for the data consumers what they actually need. The bandwidth should be limited to what is required which makes it easier to validate what is being consumed. I don't see it as a problem of collecting too much data, rather what we do with this data. It's always more difficult to retrofit equipment or change how we collect data.

Interviewer: **Do you see it as a potential drawback or problem for the customer that their internet speed requirements will increase?**

It's a good point. We need to make sure we are efficient in bandwidth during the transfer process. One thing that we need to look into is edge computing. Meaning we do calculations on-site in a larger scale than we are doing today. For example, there might be 20 sensors we need in order to calculate one certain thing, and the calculation itself might not be that heavy to run. This calculation could be performed on-site and compressed to decrease the bandwidth requirement. Another point is that we could differentiate between what is required to be sent daily and what could be sent whenever the internet connection is better. In essence, during poor internet connectivity only the most critical data could be sent. This is a possibility.

a. **Has there been a lot of customer demand for more time-sensitive data and prompt deviation response?**

The reports and the customer deliverables will change. The daily cases will then be the action points that will prompt the customer to react.

b. **How do you see the future of legacy aggregated data sources? Will traditional reports like WISELT and WISE diminish or vanish altogether?**

It really depends on the customers desires. Some customers are happy with a broad overview of how the system is performing. Some users demand a deeper analysis of problem areas. I think the current CBM reports will vanish as soon as we get a web interface where the customer and Wärtsilä can communicate on demand rather than the current monthly reporting.

Interviewer: **Do you see Asset Diagnostic as replacing CBM reports entirely on a fairly short timescale?**

I would assume so, of course one aspect for the customer is the price point. Wärtsilä must consider: Are we bringing the value to justify the service for customer? It is obvious Asset Diagnostic will be more expensive than the current CBM.

5. Has there been any external feedback on how the Asset Diagnostic service is working from the pilot cases that are running today, and what is the general reception of the service?

I have been in a meeting with one customer where we went through the monthly report for their vessel. They had some feedback on what they wanted to see and what the layout should be like. All in all, the feedback was positive. I haven't heard any feedback on the daily cases (daily insight), I don't know how much feedback we get on that. During the aforementioned meeting, the customers' technical experts were of the opinion the monthly reports would be great to put on their manager's desk because it wasn't too technical in nature. It contained details about running hours, what components have been failing as well as what the fuel mode and load levels have been. It was quite interesting to hear from the crew about the more practical side of how the vessel had been performing during the month and actually comparing that experience with the monthly report findings. To me the graphs and bar charts don't really tell a story but for the customer this could well be the case.

Interviewer: **Can you give any more specific details as to what the customer liked about the new system? As far as I understood the PDF report is not that different from the legacy CBM report.**

Actually, they differ quite a bit. The PDF reports of Asset Diagnostic are quite static, there are no comments from the experts under the graphs as there are in the CBM reports. Instead, it just lists the technical data, the failing sensors and a list of cases of what has been reported during the time period. In this regard, they are much more static. Our fear with this was that the customer would ask why there are no comments from the experts. However, when you pair it with the daily insights and the experts commenting on occurring events, the monthly PDF report is sufficient. The benefit is that the report can be created with one click instead of the expert spending a couple of hours on making it.

Interviewer: **Is there a robust channel for feedback about the service?**

This is a big area where we are lacking today. We do need a better ticketing system for presenting the cases to the customers, getting feedback from the customers and allowing internal users to comment on the development needs. Presently, it's mostly e-mail communication, and this requires that you know exactly who to contact. For CBM reporting, the contact has traditionally been between the reporter and the customer. This is also changing within Wärtsilä towards having the Expertise Centres tasked with customer contacts. We see more and more workflow where Asset Diagnostic reports do not end up at the end-user (the customer) but rather this information is sent to the Expertise Centre, who can forward it to the customer if they see fit. That part will change quite a lot and the ticketing system and feedback flow are really important parts of this. The Expertise Centre will work as a kind of filter between different Wärtsilä solutions and the customer. The problem can occur when Wärtsilä has a lot of different solutions like Expert Insights, Asset Diagnostics and so on that generate cases to the customer, we might end up in a situation of information overload. In the worst case Wärtsilä could end up sending contradictory information to the customer if different solutions report different things. This is where the Expertise Centre will come into the picture.

6. Can the Asset diagnostic platform be seen as an enabler for more environmental operation of equipment? For example, more advanced load diagnostics, hybrid fuel compositions or possible other features planned for the future?

I wonder if Asset Diagnostic as such, is the right tool for it. We need to be able to find the formulas for improved fuel efficiency and so on. We would be able to detect this in Asset Diagnostic and tweak the parameters but I'm not entirely sure if Asset Diagnostic is the right platform for it.

Interviewer: **If I'm understanding you correctly you mean that Asset Diagnostics is used for fault detection rather than equipment optimization?**

That's my understanding but I'm not in the Asset Diagnostic team. Optimization might be done elsewhere. The analytics are rule-based, and someone has to define these rules.

7. What do you see as the biggest potential threats for the Asset Diagnostic service; today and moving into the future?

I think Artificial Intelligence could be used within the Asset Diagnostic service, transforming it into something else than what it is today. One threat might be if the customer is not willing to pay for the service. Ultimately, this would mean that Wärtsilä would not get any data from the customers. It's up to Wärtsilä to define a service that Asset Diagnostics is a part of. If Wärtsilä fails to bring the value to the customer – that would pose threat of not being able to sell the service. Another threat could be political in nature, if the customer refuses to share data with Wärtsilä.

Interviewer: Have you heard of any cases where the customer would be unwilling or worried about sharing data with Wärtsilä?

Not really, I think the customer also sees the value in sharing the data and they are themselves interested in the data. We actually have cases where the customer wants to have Asset Diagnostics, but they want the service to be anonymous by removing the identifiers of the installation. This way the data analytics could be provided without identifying the customer or the installation.

Interviewer: **Do you see any increased threat in terms of cybersecurity with Asset Diagnostics?**

No, I see Asset Diagnostics and the new ways of getting data as more secure than the older systems. In that sense, it’s a step in the right direction. I don’t see the sensor values or the data that we collect as very critical data that external sources would be that interested in for illegitimate purposes. There is no way of sending data or manipulate what is on-site, Wärtsilä is purely a data recipient. The problem that I see today is that Wärtsilä has previously had a very open mindset regarding asset data. This needs to be tightened up so that only the relevant experts have access to the data they need.

Interviewer: **So more internal restrictions within Wärtsilä?**

Yes, we are introducing authentication in the first stage to target this issue. This means we know who consumes the data and we need to build an authorization system, so we can enforce the right policy to only provide the data to the people that really need it.

Do you have any additional comments or questions?

No further comments.

Appendix F. Abridged interview transcript III

Position: Senior Technical Expert

Team: Asset Diagnostics

Date: 22.8.2019

Introduction

I started in Wärtsilä 24 years ago, I worked in the product factory in Vaasa as well as the test laboratory. After that I worked for 10 years in field service, five years in service sales and now I'm on my sixth year in the CBM or Asset Diagnostic team. The last five and a half years I have been working with the CBM system, creating traditional CBM monthly reports for approximately 35 installations.

Interviewer: **And you also have some experience in the last year of the new Asset Diagnostic service?**

Correct, I have been working on the first pilot case. This came to my table some months ago and now we have started the daily reporting and follow-ups with this installation.

1. In your opinion, what are the biggest problem areas with the current CBM system?

When the current CBM system came about almost 20 years ago it was a huge leap in development of the digitalization of Wärtsilä services. Maybe the biggest problem is that the customers are feeling that they are only getting feedback from Wärtsilä once a month. That is often seen as a bit of an old-fashioned system. The customers clearly think that Wärtsilä should be able to respond to all problems more or less immediately. Daily follow-ups have been desired based on discussions that I have had after doing presentations about the CBM system to customers. Generally speaking the requirement for constant feedback is coming from the environment we are living in today. Everything is expected to happen instantaneously, and solutions must be available 24/7. This gives Wärtsilä huge business potential if attractive solutions are available.

Interviewer: **As a reporter, do you get a lot of direct feedback from the customers or indications that competitors to Wärtsilä are offering more comprehensive services?**

Actually not, I have never received this kind of feedback. However, I assume that there is a lot of different solution providers for equipment condition and performance monitoring.

Interviewer: **Like you said, the CBM system is almost 20 years old. Are the mentioned reasons the same why Asset Diagnostics was introduced?**

Having the Asset Diagnostic system and daily follow-ups are answers to customer wishes to be connected all the time and have daily feedback of engine performance. That is the clear message we have been receiving from the customers – they want Wärtsilä to monitor the equipment condition and performance 24/7.

2. What do you feel are the biggest improvements that the Asset Diagnostic platform enables? In your opinion how will a Wärtsilä customer benefit from this?

Now we can see how an installation or equipment is performing on a daily basis. For example, if there is a deviation in a certain parameter, we are able to follow-up on that deviation from day to day and see how it is developing. Also, we can see customers response to our comments on specific parameters and how they are receiving and acting on our actionable advices. We can also see a bit how the customer is behaving in regard to Wärtsilä recommendations. Sometimes we can notice the same deviations for longer periods, which can indicate the customer is not reacting to Wärtsilä expert advice. We have to remember that we in the office can not see everything that is going on at an installation level. There are many factors that we are unaware of, but we can make recommendations based on the received parameter data. However, it is always the operators on-board that need to have the bigger picture of everything that is going on and make a decision for themselves how they should react. We can only provide recommendations on what to do but never force anybody into action.

Interviewer: **If we compare the monthly reports from the legacy CBM system with the Asset Diagnostic reports. How much would you say has changed?**

To be honest, the monthly reporting with Pega (Asset Diagnostics) is so new that I have not yet had time to produce a monthly report. Therefore, I cannot give a comparison at this time.

Interviewer: Can you see any additional benefits of the Asset Diagnostic platform?

With the new system, customers and Wärtsilä have a great opportunity to work together. The received data can be shared within Wärtsilä with different actors like technical services, contract management and maintenance planning. This is an opportunity with both systems that fresh data could be shared with different actors within Wärtsilä. There are many good sides to the old CBM system as well that should carry over to Asset Diagnostics.

3. What does the future look like for Asset Diagnostics? Do you believe that there is a trend of increased usage of predictive maintenance?

In my opinion, it depends a lot on the customer attitude. It varies how the customer wants to take care of their equipment. If they are looking to save money, they usually tend to not do a lot of predictive maintenance but rather balance maintenance cost with securing reliable operation. It’s not a black or white situation. The customer maintenance budget has a lot to do with this.

Interviewer: Would you say you can notice an increased reliance on predictive maintenance?

It’s very good if predictive maintenance is possible and a clear message from Wärtsilä is communicated to the customer for optimal equipment operation. Traditional maintenance schedules still give quite a good guideline for base maintenance that offers operational safety. Predictive maintenance works on top of this system and can catch events that the traditional system cannot, even if you follow the maintenance schedule perfectly. Predictive maintenance can catch risk factors and rectify them before an unplanned stop happens.

4. Can you offer some predictions of what the data frequency will look like in the next five years?

Regarding the sensor amount, in gas engines it has increased and also in some extent in traditional diesel engines. For example, sensors like big end bearing temperature sensors have been added. However, the sensor amount has not increased or decreased because of a CBM system or any type of monitoring system. In my personal opinion, we are utilizing the sensors that are planned to be in the engine, regardless of the monitoring system.

a. **Has there been a lot of customer demand for more time-sensitive data and prompt deviation response?**

I would compare it a bit to elders becoming very reliant on mobiles phones. If they find themselves without their phone for a few minutes, it can cause a slight panic. I think this trend is also translating to the industry where the customers want to be connected to the equipment manufacturer all the time. There is a big attitude change that has taken place due to mobile devices in the last decade. The psychological effect of being connected all the time is an important aspect in this.

b. **(Interviewer: Question skipped as respondent had no comment)**

5. Has there been any external feedback on how the Asset Diagnostic service is working from the pilot cases that are running today, and what is the general reception of the service?

So far, I haven't had any concrete feedback. This system is so new to me that I have not heard anything.

Interviewer: **In your opinion, is there a robust enough channel to communicate feedback about Asset Diagnostic, both external and internal?**

That has already been a problem with the legacy CBM system, there has not been a formal channel where to issue feedback. Therefore, we seldom get any feedback from customers. There are a lot of actors involved in this like account managers, contract managers, maintenance planners and remote support. This equates to a lot of contact surfaces where the customer can direct their feedback. I don't know how much feedback is received through the other channels.

Interviewer: **This can be a problem with a big organization and many actors communicating with the customer. If there is not one consolidated channel for feedback, it easily gets lost?**

Correct, as you say there as so many organizations and the communication between them might get stuck in a mailbox. It would be helpful to have a comment box where the customer could give their feedback on our observations, for example some specific parameter deviations. The customer could then give immediate feedback to explain why these parameters are out of bounds to help the reporter understand the bigger picture.

Interviewer: Would it also be useful for you to see the perspective of the customer and have that direct line of communication?

That's absolutely essential in my opinion. We easily end up a bit in the periphery here in the office. We don't know what actually happens on the ship, why it happens and what the action plans are. Sometimes, the way ships are designed some parameters like for instance LT water temperature can be slightly outside bounds and it's not possible to tweak them to optimal thresholds. It's not critical if this is the case but it would be useful information for us to know this is by design. As reporters we have to understand what the different parameters are doing and how they affect each other and the engine operation.

6. Can the Asset diagnostic platform be seen as an enabler for more environmental operation of equipment? For example, more advanced load diagnostics, hybrid fuel compositions or possible other features planned for the future?

There are no limits to what we can develop. We can develop a system towards any direction that the customer wishes as long as there is a market for it.

Interviewer: **If you look at fuel consumption, do you as reporters come with recommendations to the customer?**

Fuel consumption is a hot topic today because of environmental reasons and the cost involved. It has always been on top of the priorities in our work, in the legacy CBM system as well. We are looking for example at exhaust gas temperatures and parameters affecting these to understand how the engine fuel economy is performing. If combustion related parameters are outside of ideal values, it is an indicator of the engine not working optimally and the fuel consumption may be higher. We know that carbon emissions are a hot topic as well and to cut these we need to make sure that the engines are working at an optimal level.

7. What do you see as the biggest potential threats for the Asset Diagnostic service; today and moving into the future?

Can you elaborate on what kind of threats you have in mind?

Interviewer: **If you look at it from the customer's perspective. Have you had any experience of customers being negative towards sharing data with Wärtsilä?**

No, I don't have that kind of experience. It would ruin the concept of CBM or Asset Diagnostic altogether.

Interviewer: **Finally, how can we trust the quality of the data that we are receiving? As a reporter your job is to analyse and understand the data that we are receiving so you are relying on it a lot.**

There can always be bugs present in the system, this is not something new. We have already noted bugs in the Asset Diagnostic system, but we are constantly working to get them fixed as soon as possible. This is continuous development work. There are many actors present that can complicate the situation. For example, a service engineer working on an installation can introduce a new bug into the control and operation system when they are making modifications. They might be unaware of the issues and we must detect and correct this as soon as it is noticed.

Do you have any additional comments or questions?

No further comments.

Appendix G. Abridged interview transcript IV

Position: Manager

Team: Asset Diagnostics

Date: 26.8.2019

Introduction

Presently I'm the manager of the Asset Diagnostic team, consisting of 17 people. I started in Wärtsilä in 1998 as a summer trainee in Field Service, where I worked for a couple of years. Following this I took an assignment in Bangladesh, where I lived for one year and took part in the operation of a floating power plant. After I returned from Bangladesh I joined the Technical Service product team Vasa 32 engine types, where I worked for a couple of years. Since 2002 or 2003 we founded the CBM function within Wärtsilä. During that time, it was an independent function within Technical Service. I worked in the team as an expert until 2011 at which time I took over the role as team manager.

Interviewer: You have been involved with CBM since its very start?

Actually, my bachelor's thesis marked the start of the CBM system for Wärtsilä. That is an interesting point of view in this case.

1. In your opinion, what are the biggest problem areas with the current CBM system?

I would see it as a challenge more than a problem that today we are supporting a very wide range of applications. Age-wise we have ships that are 20-30 years old and at the same time we have brand new installations. Since the CBM system is all about gathering and transferring data, the variety in automation systems on the field that we rely on for supplying data presents a challenge. One solution does not fit all. This is also mirrored in different kinds of problems and challenges during the commissioning of different types of systems. We need to have highly experienced people for commissioning these systems. Another matter is that we are living in a very hectic industry today, things are happening very fast and it's not that easy to keep up with new technologies all the time. The big variation in applications that we need to be able to support is what I see as the biggest challenge.

Interviewer: CBM is nearly 20 years old now and like you say software systems develop very quickly and hardware advances too, but at a slower pace. Do you see this as one of the reasons why the Asset Diagnostic service was needed?

Definitely yes, but perhaps even more because of the customer expectations. We had been running this legacy system for almost 20 years and the capabilities of the system are not in line with what the technology of today can offer. With the legacy setup we are only able to deliver a monthly type of service to the customer. With the new Asset Diagnostic platform, we have a much bigger capability of going into much more frequent follow-ups of the equipment. Simultaneously, it's very much regarding cybersecurity and these kinds of areas, that are very important today. Upgrading the legacy system was definitely a must in order to survive in this area today.

2. What do you feel are the biggest improvements that the Asset Diagnostic platform enables? In your opinion how will a Wärtsilä customer benefit from this?

Clearly the biggest improvement is to have the higher frequency of reporting, going from the monthly reporting to daily feedback, or in the future even more frequent. Close to 24/7 follow-up could be the next step. Transitioning to a cloud-based platform with data pre-processing and storage being in the cloud gives the customer a higher level of transparency of the data we are collecting from their assets. We can for example share results from our data processing on the Wärtsilä online portal, this means a more interactive access to the data for the customers. Thanks to the online portal development the customer can sign in at any time and have a look at the data. Everything we are doing with the Asset Diagnostic development is an enabler to be more transparent toward the customer.

Interviewer: And this is also a customer demand?

Definitely yes, it has been a continuous request that they would like to get a glimpse at the data that we are collecting from their assets.

3. What does the future look like for Asset Diagnostics? Do you believe that there is a trend of increased usage of predictive maintenance?

I would say yes in general. Throughout the industry today the customers are changing the way they are doing maintenance on their equipment. Trying to avoid opening engines if it’s not necessary is getting more common, because the percentage of equipment failures or errors happening due to failures during maintenance is quite high. Getting rid of the maintenance tasks that are not really necessary is definitely a positive thing for the customer. Customers today are also very cost conscious, due to competition they try to save as much as possible in the operating costs of their assets. Everything that can be foreseen in upcoming problems, possible component changes or time schedule constraints is a direct cost saving for the customer.

Interviewer: The literature talks a lot about predictive maintenance being more cost effective than traditional maintenance. What is your experience?

I’m not sure if we have direct figures from customers but we have made internal investigations into this matter, comparing a scheduled maintenance with a more flexible condition-based maintenance. The figures have been in the realm of 15-20% savings in maintenance costs for a CBM system. On the other hand, if we look at an installation today, whether marine or power plant, around 75% of the customer’s cost is originating from fuel. In this light, Asset Diagnostics and analysing equipment performance is also very much in the interest of improving efficiency, decreasing fuel consumption and so on.

4. Can you offer some predictions of what the data frequency will look like in the next five years?

If we talk about the number of sensors connected to an engine, this has been on the agenda in the past quite frequently as well. Every now and then a customer is looking into new types of sensors that provide new measurements. Looking at the past examples, it has been very difficult to come up with benefits that outweigh the investment needed to enable these measurements. In this sense, I don't see that the sensor amount will increase a lot in the next five years. Also, a trend in the recent years has been that we need to build the equipment very cost-effectively. Normally when the costs get squeezed, one of the things that are left out are the 'extra' sensors. It's an additional cost to the equipment if savings have to be made. If you consider a retrofit of sensors after the equipment has been built the cost will be ten-fold.

Interviewer: One could assume then that retrofitting sensors is a very rare occurrence?

I would say during my 20 years there are only a handful of cases where this has happened.

Interviewer: What is your view on data frequency, do you think it will keep on increasing?

I would foresee that it will grow, but from my personal point of view I don't think we will build a secondary alarm or monitoring system because the equipment we are delivering today has a control and alarm system 'on the edge'. If something critical is happening to any of the sensor values, the equipment will automatically shut down or sound an alarm. If we would like for example 1 Hz follow-up of data that would mean that we need processing power that I don't think we can afford in the next five years. I don't foresee that we would have a remote control and alarm system anytime soon. Some critical components could be considered being incorporated in such a system, but I still foresee we will have people on-site that respond to these types of critical situations. As far as predicting problems and what we can support with Asset Diagnostics, we always benefit from higher frequency data to process and predict equipment condition. In my eyes, this only improves the quality of our diagnostics. In this sense, I see that more high frequency will come but perhaps not always as a continual flow of high frequency data but rather in batches of data. For example, every 1-10 minutes a data package could be sent. In general, we want higher frequency data to do more and provide better diagnostics, but it doesn't necessarily have to be streamed data.

Interviewer: One thing that comes into the picture is the internet speeds and connectivity. How can this affect Wärtsilä?

All of that plays a part and especially as over 70% of our connected equipment today is on the marine side. There are still some years to go before we can reach the desired availability and bandwidth on these remote installations. Satellite connections are improving, and the cost is coming down, but it still will take some years, in my experience.

a. **(Interviewer: Question already covered)**
b. **How do you see the future of legacy aggregated data sources? Will traditional reports like WISELT and WISE diminish or vanish altogether?**

I would like to see them vanished to put the least amount of additional work on the crew or the operator. The customer does not have extra resources to spend on manually collecting data, so this is not something we should strive for. On the other hand, we have data that we are not able to collect through sensors today and probably not in the next five years. There is data that would be very important to have for high quality diagnostics of the equipment, so I see the importance of the manual more traditional reporting. However, I would like to see this carried out in a smarter way, for example with incorporating mobile technology through pictures and increased levels of automation so the crew would not need to use a pen and paper to take notes. Ideally a picture sent through a phone would be recognized by the analytics system and processed automatically, instead of resorting to manual labour.

Interviewer: Do you foresee a situation where some customers might feel that it's sufficient to have these more traditional reports instead of all the features of Asset Diagnostics?

Of course, there are costumers like this as well and I would say the marine segment is not prioritizing digitalization that highly yet. Looking at it from this perspective, we have customers that would like to have a basic support from Wärtsilä. Analysing their assets through low-frequency data or more traditional reporting. These are becoming fewer and fewer as the delivered equipment is getting more and more sophisticated. For example, we have software that digitally controls the combustion process. The new equipment deliveries are very sophisticated.

Interviewer: It makes sense to have the more advanced analytics on all the newer deliveries?

Exactly, it's all very highly automated. It's a different story if we look at a 30-year old ship with a very rudimentary automation system. A lot has already happened in this field if you look at the history of the past ten years. In the past, marine chief engineers didn't want to have any supervision but if you ask the same question today - they are positive for the insight.

5. Has there been any external feedback on how the Asset Diagnostic service is working from the pilot cases that are running today, and what is the general reception of the service?

We have had experience of both positive, negative and lack of feedback. For example, one of our marine customers has been very positive of the more frequent follow-ups. They actually get a notification if something untoward is taking place. They have also had rather positive feedback on the summary reports that we create on day to day events, based on the previous period. Simultaneously, they also have comments on what they would like to see improve. One of the things they have asked for is improvements in the reports, so there we still have work to do. In this particular case, the diagnostics have been based on low-frequency data, but the customer would like to see the diagnostics run with high-frequency data. This is further proof from the pilot cases that we would need to go for high-frequency data, even if we would then have to resort to collecting batches of data instead of streaming it.

We have received negative feedback as well in respect to the reports. Another client was not entirely satisfied with the content of the report that we have been creating for them. They were expecting more statistical information in the report and updates on how the equipment has been performing. I would say on this part, that including trending graphs in the reports is something we have to work on. From our own point of view, one issue is that the daily notifications are delivered by e-mail to the customer. This means there is not a structured way to answer on the daily notifications. Naturally, they can reply to the e-mail, but this means that the reply may be stuck in a single e-mail box and not collected in a central database.

Interviewer: This is actually something I was curious about. How can the feedback channel for the Asset Diagnostics platform be structured so that the communication possibilities between Wärtsilä and the customers are best maintained?

Definitely this needs to be developed but it can be tricky to say exactly how it should be carried out. We do need the feedback from the customer when we give actionable advice to them. If we do not receive any reply, we don't know how the recommendation was received. Has anything been done or has the customer not reacted at all? We would need the feedback from the customer to know what has been done or what is planned. That way we could further troubleshoot problems. This would also need be quite a structured feedback because we would want to get this information into the maintenance planning systems as well. For this reason, the structure would need to be more than just chatter but instead be clear with equipment number, sensor name and everything required to be stored as part of the master data records. This is something we need to look into.

Of course, we also have the third type of customer that hasn't really given much feedback. This is usually a customer that has signed a service agreement with Wärtsilä, but they are not detail-focused of what Wärtsilä is delivering. The customer is interested in the business and savings they can achieve but do not care so much about the technical aspect of how Wärtsilä is fulfilling the agreement. It's up to us to make sure we keep the customer happy by showing them the benefit of the diagnostic system.

Interviewer: Maybe it can also be a good thing for Wärtsilä to act as a buffer between the equipment and client, so the customer can focus on business?

Exactly, we take care of the technical side and are paid for that by the customer and this supports the customer in their business and improved profits.

6. Can the Asset diagnostic platform be seen as an enabler for more environmental operation of equipment? For example, more advanced load diagnostics, hybrid fuel compositions or possible other features planned for the future?

The environmental operation aspect is definitely tied to fuel efficiency. Optimizing the performance and operation of the equipment and fuel consumption has a positive impact on the environment by reducing emissions at the same time. By doing more advanced diagnostics of the equipment we would be able to provide more proof to the customer how they can better operate their assets, to reduce fuel consumption and the environmental footprint.

A topic very much on the agenda today is different kinds of hybrids. This is something Wärtsilä offers in the form of battery and other kinds of hybrid solutions. In this field we are playing an important role as well with different kinds of analytics and diagnostics to look into how well these hybrid systems are working. For example, we have one costumer where we run the Asset Diagnostics service with a hybrid battery system installed as part of their equipment. However, the operator is a little bit afraid of using the battery system, so they run the equipment in a conventional manner with diesel engines on low load. In this case it would be advisable to rely on the batteries instead. In this situation, we have been showing the customer's technical department what the load levels have been like and suggested that it would be in their benefit to utilize the batteries. We are working on supporting the customer to have more insight into how they should operate the ship optimally.

Interviewer: Would you say the reluctance to rely on the battery system is due to not being familiar with the technology?

I would say so. This kind of hybrid system is still rather new technology. With competent people on-board that are used to operate diesel engines it can be quite a steep step to start utilizing these new systems. I would compare it to the situation when the diesel engine first came to market. At that time steam was the prevalent means of propulsion and people were hesitant to transition to diesel.

Interviewer: In essence, Asset Diagnostic can be developed in any direction that Wärtsilä decides?

It was the standpoint we took early in the project that we need to build a system that can be used on different equipment and on different levels.

7. What do you see as the biggest potential threats for the Asset Diagnostic service; today and moving into the future?

Today we have competitors that we previously did not have. Wärtsilä is changing in regard to who our competitors are. Historically the competitors have been engine manufacturers but now we are competing with automation system providers as well. Keeping up and staying ahead of these competitors can be a challenge since it's a new area of business. It will require a change of mindset on all levels. It's not only related to the delivery of the Asset Diagnostic service but also how it is promoted and how the sales are reaching the customer. In the end, the Asset Diagnostic service is one part of a larger service contract we sign with our customers. Selling Asset Diagnostics as a solitary service is not something that Wärtsilä wants to do, in my opinion. What we strive for is to have a bigger scope towards the customer - that includes spare parts, delivery, maintenance work and so forth.

Interviewer: Should Wärtsilä try to bundle Asset Diagnostic as a service that is included as a soft requirement for new equipment?

More or less, I would say this is the case today. We are not signing any service contracts without having access to data. It doesn't necessarily have to be Asset Diagnostics but some type of monitoring service and access to the data, so we don't operate in the blind.

Interviewer: Have you heard of any cases where the customer has been negative towards sharing data with Wärtsilä?

Very few of these cases. Normally it is seen as a positive thing to get the support and improvement on equipment operation and performance. Some special segments are maybe not reluctant to share the data, but they want to ensure no third parties have access to the operation data. This is data that is being kept anonymous.

Do you have any additional comments or questions?

I think we have covered a big part of relevant topics with these questions, nothing more to add.

Appendix H. Sitedata API metadata structure

Installations
ID
Name
Functional location
Installation ID

Equipments
Equipment ID
Functional location
Installation name
Product number
Data acquisition type
Product type
Product reference type

ISO codes
Standard ID
Name
Description
Old ID
Unit

Sensor mappings
ID
Standard ID
Group ID
Tagname
Start date
End date
Equipment ID
Fuel mode
Old ID
Unit
Description
Parameter priority
Type

Equipment parameter types
ID
Name
Description
Type

Equipment configurations
ID
Equipment ID
Parameter ID
Parameter value
Start date timestamp
End date timestamp
Start date
End date

Installation parameter types
ID
Name
Description

Installation configurations
ID
Functional location
Parameter ID
Parameter value
Start date
End date

Appendix I. Configurator functional requirements

1. Setting up the application, repository (version control - tracking changes), deployment and Azure AD authorization
2. Program front end reading and writing data through an application programming interface to a PostgreSQL database working as the data source.
3. Creation of new configuration based on functional location
4. Installation master data is automatically fetched from SAP to ensure data conformity and save the user from having the insert the data manually
5. The user needs to have the option to select only the relevant equipment that is to be mapped in the configurator. Often times an installation can have additional equipment that should not be saved unnecessarily
6. Sometimes SAP data is incomplete or mismatching with the data that the user wants to enter into the configurator. In these instances, the user needs the liberty to create new equipment
7. Some equipment may share a common sensor. In these cases, the user needs to be able to select which equipment share common sensors
8. The user needs to be able to decide the component parameters for the equipment so that analysis is performed with the right criteria
9. If equipment are missing parameters, the user has the option to add new parameters
10. Many equipment setups are identical or similar. Having the option to copy the setup from a sister installation can be a big time-saver as well and helping ensure the correct parameters are configured
11. Copying equipment setups should be limited by type, for example engine type to prevent wrong setups from being copied. This functionality is to help the user with filtering the results when copying setups. For example, the engines can be filtered by type so only W20 engines are displayed
12. The configuration and mapping process can be lengthy, so the user needs to be able to save the progress at any point to eliminate the risk for losing work progress. In addition to manual progress saving, the configurator should perform automatic saves to avoid potential data loss
13. The user needs the option to load a sensor list by selecting a reload or other similar configuration list to start the sensor mapping. This loads the installation configuration data into the configurator along with available sensor lists for each equipment that is a part of the installation. Moreover, the configurator needs to be able to parse the reload and display a table of tagnames, descriptions and so on for the user to be able to verify the data is correct. This allows the user to validate the mapping is correct by comparing to the data present in the Reload tagnames or descriptions. When a Reload file is uploaded it should be saved with functional location and date as a reference file. Reloads serve as data sources for the mapping so they should be saved in their original form as a reference
14. The user can decide to map any tagname to an ISO code manually. The configurator aids the user by autocompleting the ISO code and displays the description in the results so provide a secondary error check

15. The user can select a date and the configurator fetches sensor data from the database for all the sensors. This allows the user to verify that the sensor values are inside the expected threshold of what is being mapped to ensure data validity
16. Audit trails are stored to display a historical log of changes and users affiliated with them. This is a functionality lacking from the current system. A complete action log allows users to see what changes have been made, by whom and when
17. The configurator offers different functionality based on which user is logged in. This is driven by the Azure AD authentication
18. The user can submit an engine configuration and sensor mapping for approval for the admin. The administrator is presented with a list of pending approvals and the ability to review them before deciding to approve or reject a configuration. The system sets the status to approved or rejected, in which case they are returned to the original user
19. The configurator should allow the user to create Jira (Atlassian, 2019) tasks with task titles, description and functional location that are automatically pushed to Jira via API
20. The API needs endpoints for getting complete installation configurations with all equipment and sensors. The API also needs an endpoint for requests of specific sensors or ISO codes and responds with a complete list of installations and equipment that match the request
21. With regard to ISO codes the configurator needs to enable admins to create new ISO codes, edit existing ones, create new ISO groups and edit existing ones. In addition, admin users need to be able to add or remove sensors to an ISO group and specify in which order they should be displayed. Admin users also need to be able to select key sensors and “Wärtsilä standard” sensors with checkboxes. The user also needs to ability to search for ISO codes and look at different ISO code types, for example: temperature, pressure or alarms. Each ISO code is associated with a predefined unit. On an installation level there exists a disparity in which units are used due to differing international standards. For example, pressure might be measured in Pa (Pascal) or PSI on-site but needs to be converted to bar in the configurator. The user needs the ability to see both site and ISO defined units
22. Each view in the configurator should give the user the option to leave comments that are timestamped and signed. This can provide instructions or serve as a note for future reference
23. The old system only had the possibility of running one configuration at a time and a new mapping always overrode the old one. If the user did not manually save the old configuration before an update, it was lost in the process. The new configurator can run multiple instances of configurations (workspaces) that can each have different sensor setups and data sources. Seamless switching between workspaces allows for multiple configurations
24. The user has the option to load a configuration template with a predefined set of sensor requirements to assist with the mapping task. This is a tool to help the user with sensor mapping by providing a working template of a sensor set that should be included for a specific engine type
25. Load limits can be applied to any equipment with a load tag, this allows the filtering of the results below (min) or above (max) a set threshold. Fuel modes are included in the load limits and there should be no limit on how many load filters can be added.

This is an improvement over the legacy system where load limits and fuel modes were restricted

26. The entire project configuration file can be exported with equipment configuration and sensor mappings as a CSV file
27. WISE installations are dependent on the fuel mode being explicitly set, this must be considered in the sensor mapping table. In addition, there is a future request to include quality classes of fuels to accommodate varying fuel qualities and blends. This is a future improvement that enables a previously impossible analytic option of running on different fuel blends, for example, partial bio-diesel
28. Both analogue and digital signals should have the option to be mapped. This is an improvement over the legacy system where digital events were not being mapped. Digital events are Boolean triggers (0 or 1) while analogue events are typically sensor readings within a pre-set range
29. Installations that have several pieces of the same equipment type need to be able to update simultaneously, as opposed to enforcing the update to each equipment individually
30. There is an ongoing sandbox project with a machine learning (ML) algorithm that attempts to match the tagnames with an ISO code through pattern recognition. The algorithm should display the proposed match and display the percentage of reliability. The ML algorithm has specific requirements implied on its functionality:
    - Front end application setup
    - Tag list parser to read the different file formats and normalize them
    - Machine Learning code
    - Training set database for storing the learning data set
    - Mapping output of the automated mapping results in a JSON file
31. The user needs the option to undo changes
32. The user needs the option to disable equipment of an installation if for example an engine is scrapped
33. Implement a lockout so several people cannot work on the same installation workspace
34. If new equipment is added in the configurator or a change is introduced that contradicts with SAP or CRM (Salesforce, 2019), an automatic data update request should be fed back to the source
35. The tool needs to support different workflows depending on the data acquisition type. This includes DB.CSV, UNICTOOL.CSV, Repload.xls.
36. If there are sensors in the Repload that remain unmapped, the user needs to have the option to view a list of these as well as the mapped ones
37. With installations ranging all over the world the time zone handling and time stamp accuracy need to be considered to ensure data validity and comparability
38. The data acquisition type determines the data source that is being analysed. A single installation can have several data acquisition types by enabling multiple workspaces (see Chapter 6.3)
39. Research and development has a code tool that could be used for future enhancement of the configurator to directly fetch the ISO codes
40. Administrator user need to approve or reject changes that are done in the configurator before they are implemented
41. EDW (Enterprise Data Warehouse) integration

42. Options to enable different limits for data clipping of events
43. Error handling needs to be implemented. A minimum requirement is to include an error log for every stream
44. Every user can define their own default workspace
45. Workspace start- and end date selection is a setting to activate a certain workspace inside a time frame. This could be used to enable automatic switching between for example two different data acquisition types
46. Offer the option to select which ISO standard is being followed
47. Offer the user the option to add relations to the ISO code to signify relations to other standards
48. The user needs to be able to select which workspace to use or edit. A single installation can have several workspaces, for example, 2-stroke, 4-stroke, PCMS
49. The user needs to be able to specify the rules for fuel mode detection on an installation level. A default template will be offered if no changes are required
50. The user needs to be able to select which equipment are sharing common sensors

Appendix J. Minimum sensor requirements for a Wärtsilä 4-stroke engine

The following list summarizes the minimum set of sensors required from a Wärtsilä 4-stroke engine to be able to provide a reliable Asset Diagnostic service. The specific sensors depend on the engine model (for example: common rail, dual-fuel, spark gas) and not all sensors apply to all engine models.

- Engine running hours (total / gas mode / diesel mode / HFO mode / back-up)
    - Running hours under all the different fuel modes, typically for a dual fuel engine this will include Light Fuel Oil (LFO), Marine Diesel Oil (MDO), Heavy Fuel Oil (HFO) and Liquefied Natural Gas (LNG) as well as a back-up mode
- Engine or generator load
    - Engine or generator load in kW or %
- Fuel oil pressures & temperatures
    - Fuel pressure and temperature is imperative to ensure the right fuel flow. For fuel oils the temperature affects the viscosity which in turn affects lubrication properties of the fuel.
- Pilot fuel oil pressures
    - Engines running in gas mode use a small amount of marine diesel oil as pilot fuel to ignite the main gas.
- Fuel rack position
    - Controls the amount of fuel being injected. Adjustable depending on the engine power, fuel oil quality, injection pump values and charge air measurements
- Timing rack position
- Calculated rail pressure A/B-bank
    - Fuel oil rail pressure is calculated based on the engine load
- Fuel injection pump temperatures
    - Used for common rail engines
- Fuel oil control valve positions
- Control oil pressure
- Main gas pressures & temperatures
    - Measured pressure and temperature of gas-burning engines, usually compared against a reference value
- Main gas injection duration reference
    - A reference value of gas feed duration based on the engine load, ambient conditions and gas quality
- Gas injection duration offset
    - Cylinder specific offset of gas feed duration from the main gas injection, affected by cylinder knock and firing pressure
- PCC gas pressures
    - Pre-combustion chamber gas technology used for spark gas engines
- Lubrication oil pressures & temperatures

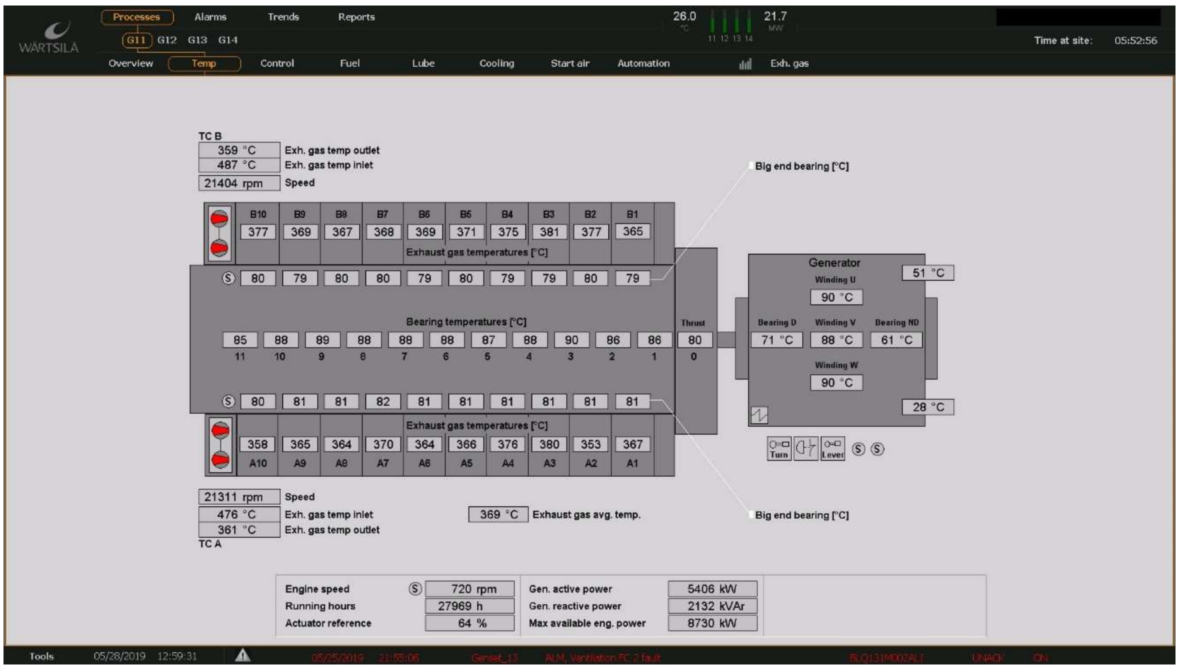
- Main bearing temperatures
  - Main bearing temperatures are one of the vital measurements for engine health. This is also stipulated as a mandatory measurement for marine installations by classification societies. This is a relatively new measurement as it relies on wireless data from the rotating assembly.
- Starting air pressure
- Control air pressure
- HT (high temperature) water pressures & temperatures
  - The HT cooling circuit circulates around the cylinder liners and heads
- LT (low temperature) water pressures and temperatures
  - The LT cooling circuit circulates through the charge air cooler and lubrication oil cooler
- Charge air pressures & temperatures
  - Charge air is the volume of air being pushed by the turbocharger to complete the combustion
- Air intake temperature
  - Measured at the intake port and practically synonymous with the ambient temperature
- Turbocharger speeds
  - Depends on the exhaust gas velocity and how clean the turbine wheel is
- Turbocharger vibration levels
  - Excessive vibration can be indicative of bearing wear
- Exhaust gas temperatures
- Wastegate actuator reference
- Exhaust gas wastegate position
  - This is measured behind the cylinder exhaust gas valves or cylinder heads as well as before and after the turbochargers
- Generator bearing temperatures
- Generator winding temperatures
- UNIC temperatures (engine automation system)
- Engine speed
- Engine room air pressure
  - Indexed against the crankcase pressure
- Cylinder firing pressures
  - Measured in the cylinder as the peak combustion pressure
- Cylinder liner temperatures
  - Cylinder liner temperatures are vital to monitor for engine health and often a cylinder can have two or even three temperature sensors per cylinder for redundancy. Mandatory for marine installations.
- Connecting rod temperatures
- Crankcase pressure
  - Measuring small over-pressure compared to normal atmospheric pressure to detect blow-by (exhaust gases leaking past pistons)
- Torsional vibration level
  - Indicative of angular vibration of drive / prop shaft

Appendix K. Data diagnostic requirements

1. Wärtsilä 31 rules and algorithms
2. Wärtsilä 50 SG rules and algorithms
3. Load tags to be investigated for all equipment
4. Extended algorithms that have been tested and approved for exception detection (8)
5. Extended algorithms that need to be tested and approved for exception detection (14)
6. Extended algorithms in the pipeline to later be tested and approved for exception detection (~50)
7. Implementation of digital signals
8. Load specific diagnostic
9. Data streaming for high frequency data
10. Situation layer cake needs to be implemented for 2-stroke and multi-portfolio.
11. Implementation for 2-stroke
12. Rules and algorithms for 2-stroke
13. Customer possibility to open exception cases and add comments
14. View historical notes
15. Decreasing or increasing trend detection
16. See individual trends of sensors in exception cases
17. Internal operational reports
18. Email tracking to customers
19. Mobile application to aid customer mobility (especially marine)
20. Pega documentation
21. Case manager application for wizards
22. Admin page for user management
23. Deployment manager
24. Pega platform upgrade documentation
25. High temperature difference over jackets for all engine types
26. A/B-bank engine average EGT temperatures
27. Fuel oil viscosity needs an ISO code
28. Differences in fuel modes
29. Common sensors linked together
30. Sensor failure indicator
31. Cylinder firing pressure deviation and averages need ISO codes
32. Update TE401 & TE401-1 ISO codes
33. Charge air pressure missing on some installations
34. UT93 engine load unit change (kw to %)
35. History tab for commenting on changes in uploads of tables
36. Option for expert if exception case should be sent or not
37. History comment preview to be enabled
38. Engine running check when data is received but under load limit
39. Ending contracts functionality
40. Pega user roles
41. Management of services for different installations
42. Manager option to transfer a whole installation to another expert
43. Error code handling

44. Exception case notification
45. Equipment health index
46. Installation health index
47. Add trends in exception case notification
48. Add comments on equipment level
49. Email successfully sent notification
50. Pega logs and notifications
51. Pega load filter metrics of running hours inside the load filter and in case of multi-fuel installations, running hours filtered by fuel mode

Appendix L. WOIS Application



Part of a WOIS application, here displaying the genset temperature specific data.

Appendix M. Quality of life improvements of the new Configurator

- Equipment configuration management. Configurations can be copied or created from predefined sets that are specific to the type of equipment to prevent incorrect duplication.
- Increased rigidity. The legacy tool would often time-out during operation which could lead to work being lost. The mapping process often requires the expert to use many tools and this could cause the CBM configurator to time-out. The new configurator facilitates the work by auto-saving.
- Introduction of new tools for enabling automatic parsing of the installation specifications, regardless of the data source (Chapter 6.1).
- ISO code suggestions. The software provides an automatic list of suggested mapping between physical and logical sensors that the user can approve or reject.
- List of unmapped sensors. The software can easily produce a report of unmapped sensors, a functionality that was missing before.
- The new configurator enables audit trails through version control and logging of events (see Appendix I).
- There is a formalized approval system with a lock-out to prevent several users from working on the same task. Previously there was no lock-out which meant in a worst-case scenario the data could become discombobulated.
- There is a larger breadth of cross-platform communication through APIs to help with data validation and uniformity. Installation master data can be synchronized with SAP (Chapter 6.1). Additionally, automated requests for change can be filed when disparity in data is detected while comparing with SAP or CRM. This means that data quality can be improved and consolidated across multiple platforms more easily.
- The Pega tool offers automatic detection of misconfigured sensors with a report being sent to the user so it can easily be remapped. This helps by expediting and assisting users with remapping when needed.
- ISO code normalization to harmonize equipment of the same kind despite regional or other differences.
- Logical grouping of ISO codes into a parent-child structure to help organize the data and align it with equipment architecture.
- Onboarding of new equipment types and data sources (WOIS, WISE, SWOIS, WDCU and others, see Chapter 7.5).
- Normalized data sources through standardized ISO lists, this ensures compatibility and a template for future installations (Chapter 6.6). The workflow benefits from this and potential variability between different users is decreased, or in the best case – removed.
- Computer assisted handling of big data to prevent human error.
- Increased error detection possibilities during commissioning with faster response time for correction with an immediate cost saving for Wärtsilä. New data validation possibilities will allow the user to detect errors in the configurations at an earlier stage. This will prevent extra work or sending out field service resources to correct some errors.

- The system allows the user to define common sensors such as ambient temperature, barometric pressure and so on. Thanks to this, common sensors do not have to be replicated as virtual sensors under each equipment.
- New option to add comments that are signed and timestamped to help memorize key information and leave directions to other users.
- Entire projects can be saved and exported to a single file.
- Possibility to undo actions, this was previously not possible.
- Improved error handling and visibility of transactions. Every stream needs to have an error log.
- Kafka handles streaming data (Chapter 6.3) and Timeseries API enables the use of high frequency data through InfluxDB (Chapter 6.8)
- New visualization options introduced by Trending tool and Expert UI (Chapter 6.8). Expert UI gives the reporters the liberty to modify the dynamic parts of the reports with enriched graphical overlays while retaining a harmonized graphical design. Expert UI also supports the generation of ad hoc reports for special circumstances such as an equipment investigation case. These can be saved and used for failure mode analysis or equipment optimization. Wärtsilä branding standard is upheld through the use of predefined report templates found in Expert UI. Trending tool allows the user to view custom sensor data in near real-time and supports the option of exporting data in a multitude of ways. This makes it very convenient for sharing data trends or creating custom reports.