Master´s thesis

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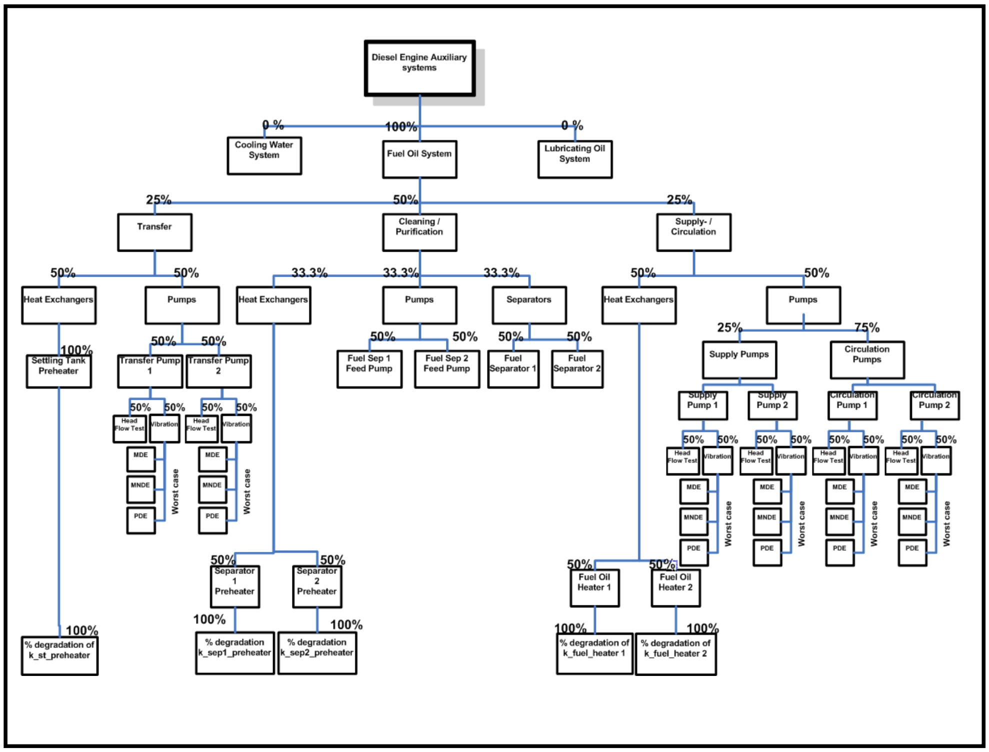
Technical Condition Indexes for Ship Engine Auxiliary Systems

Trondheim, 21 June , 2010



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Preface

This report is the result of my work in the course "TMR 4905 – Marine Systems, Master Thesis", which is the final project course producing 30 ECTS, and finishing 10th and last semester of my M.Sc. degree in Marine Technology at NTNU. The project is a natural continuation of the Specialization Project, which was concluded during the 9th semester.

Working with the Thesis has been a vast but highly educating task. Investigating the topic of condition monitoring for marine systems has proven to be challenging, as many developed methods of condition monitoring seems to be protected by patents and copyrights. Also the generic character of the study has added to the difficulty of finding representative information about the systems. Still I feel that the work has been concluded without major complications, I have been able to acquire great insight into the systems under study and current methods of performing condition monitoring of machinery systems in general, and I am proud of the result.

I would like to express my sincere gratitude towards those who have guided me during the course of work with the Thesis:

- Supervisor Prof. Magnus Rasmussen – for help throughout the entire process from planning the Specialization Project until completion og the Thesis
- M.Sc. Research Engineer Harald Rødseth of MARINTEK – for introduction and help with configuring the TeCoMan software.
- Sr. Research Engineer Christian Steinebach of MARINTEK– for assistance installing the TeCoMan software and instruction on how to use it.
- Eskil Kjemperud of DNV – for granting access to DNV Superintendents Manual Online.

Tyholt, June 21st 2010

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Summary

The topic of my individual Master Thesis study is the expansion of the Technical Condition Index (TCI) concept, developed at the Department of Marine Technology at NTNU, as to encompass the following Ship Engine Auxiliary Systems; Fuel Oil System, Lubricating Oil System and Cooling Water System.

The first chapter is a literature study on condition monitoring techniques, including an introduction on the role of TCI's and condition monitoring within a successful maintenance organization.

FMECA analysis concluded during the candidate's Specialization Project revealed three major common component groups subject to condition monitoring for the purpose of establishing TCI'; valves, pumps and heat exchangers. In order to reduce complexity and cost implications, TCI's and the condition monitoring techniques providing input data should be based on standardized methods, applicable to all components within one such major group.

For valves in the systems studied such standardized methods generally applicable to all valves could not be identified. The variety of valve types is vast, while common root-cause failure mechanisms are few, indicating that if valves truly are considered sufficiently critical to justify condition monitoring based on TCI's, methods must be developed individually each system to be monitored.

For pumps, TCI's are proposed to be based on a combination of vibration monitoring and process parameter analysis. Vibration monitoring should be based on measurement of vibration velocity, given in mm/s-RMS at bearings. ISO standards classification threshold values are proposed utilized in the transfer functions for calculating TCI's. TCI's based on process parameter analysis of pumps should utilize the Head – flow test at duty point. This method requires repeatable measurements flow rate and pressure difference over the pump.

TCI's for heat exchangers are proposed to be based exclusively on process parameter analysis, where the parameter to be monitored is the reduction in the overall heat transfer coefficient. The heat transfer coefficient is calculated from measurement of inlet and outlet temperature of both mediums flowing through the heat exchanger as well as mass flow rate and knowledge of the specific heat capacity of at least one of the two mediums.

Technical Condition Indexes proposed have been implemented into TeCoMan software for the Engine Fuel Oil System, and exemplified by calculation of aggregated higher level TCI's using fabricated data. Detailed description of the TeCoMan software and how to efficiently include a planned condition monitoring programme to calculate TCI's is included.

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Abbreviations

TCI	–	Technical Condition Indexes
FMECA	-	Failure Modes Effect and Criticality Analysis
TOCC	–	Technical Operation Competence Centre
CM	–	Condition Monitoring
VI	–	Visual Inspection
VA	–	Vibration analysis
FFA	–	Fast Fourier Analysis
PDF	–	Probability Density Function
API	–	American Petroleum Institute
ISO	–	International Standards Organization
TG	–	Thermography
IR	–	Infrared
UV	-	ultraviolet
TB	–	Tribology
AAS	-	Atomic Absorption Spectrometry
FT-IR	-	Infrared Fourier Transformation Spectrometry
AES	-	Atomic Emission Spectrometry
RDE	-	Rotating Disc Electrode
ICP	-	Inductive Coupled Plasma
DCP	-	Direct Current Plasma
XRF	-	X-ray Fluorescence
EDX	-	Energy Dispersive X-ray
DRF	–	Direct Reading Ferrography
DPI	-	Dye Penetrant Inspection
NDT	–	Non-destructive testing
UlS	–	Ultrasonic’s
SNR	-	Signal-to-Noise Ratio
AI	–	Artificial Intelligence
PPM	–	Parts Per Million

1 Introduction

The goal of this Master Thesis is to develop Technical Condition Indexes (TCI's) for Ship Auxiliary Systems:

- Engine Fuel Oil System
- Engine Cooling System
- Engine Lubricating System

As preparation for the Master Thesis, these three systems were investigated during the Specialization Project. The Specialization Project was focused at familiarization with the systems under study, and previous development of TCI's for Ship Main Engines, Auxiliary Engines and Tunnel Thrusters from the FLAGSHIP Project (2007-2009). Detail system descriptions of the systems under study were made, and a Failure Modes Effect and Criticality Analysis (FMECA) was concluded to assist the selection of components subject to development of TCI's.

The assignment text defines six tasks to be concluded for the successful development of TCI's for these systems:

"1. Conclude a literature study on the topic of Condition Monitoring. Emphasis should be on component types which were identified as especially important for the systems under consideration during the Specialization Project FMECA analysis, and at uncovering whether new CM methods have been developed recently which could/should be utilized in this TCI development.

2. Identify explicitly which components or sub-systems from each of the gross systems under consideration should be included in a condition monitoring program.

3. Inspection data could be additional information to establish a more reliable TCI for some of the systems components. The inspection program for these systems should be listed based on a ship owners' maintenance program. How such inspection data should be reported and included in the TCIs estimation should be proposed.

4. Develop proposals for TCIs for components and systems identified in 2, with corresponding measurements and condition monitoring methods.

5. Implement the TCI concept for one or more systems into the existing TeCoMan software, including aggregating diagram, equations and calculation of TCIs, etc.

6. Exemplify the concept for at least one of the system by TCI calculations and aggregation."

The tasks to be executed are defined rather specific in nature, and I plan to work with answering each task and presenting the results chronologically throughout this Master Thesis. Although the assignment text dictates the literature study to emphasize component types relevant to the systems in study, I would like to make this study a through investigation of all generic condition monitoring techniques.

Identifying components subject to the condition monitoring programme will be fully based on the FMECA analysis results from the previous project work, and I expect this to be the least time consuming task.

In order to propose how to include inspection data, I will first study the feasibility of organizing such data acquisition techniques into the current TCI concept. In addition I will try to investigate the standard reporting procedures of one or more ship owners to identify what amount of data are readily available from maintenance activities which has the potential of being utilized for TCI's. Otherwise I will not emphasize this task unless investigation of task four dictates such inspection data to be used extensively in order to establish reliable TCI's, as this will be the main effort.

Implementation of the proposed TCI concept into the TeCoMan software will be necessary in order to demonstrate that indices proposed produce valid and practicable TCI's in line with the TCI concept. As no explicit system is under study, data for the demonstration and exemplifications will have to be assumed based on literature.

During course of work with the thesis, I expect to educate myself in further detail on the specific machinery systems under study. Also I would like to create for myself a thorough understanding of the underlying principle technologies have been developed under the umbrella of condition monitoring, the nature of sensors and transducers utilized and the signal processing which is utilized in condition monitoring and more detailed failure diagnostics.

Sources of information on condition monitoring in general will be sought for in the library at the Department of Marine Technology, as well as taking use of all curriculum and knowledge acquired from previous courses. In addition of course the internet will serve as a source of information. The DNV Superintendents Manual Online was a great tool for assistance during the Specialization Project and will probably be consulted for guidance on the specifics of the systems under study.

MARINTEK staff working with the TeCoMan software will be consulted for assistance with the installation of TeCoMan and for instructions on how to use the software.

2 Literature Study on Condition Monitoring

Technical Condition Indexes (TCI's) are the topic of this Master Thesis; the concept was briefly explained in the Project Thesis (1) and will be elaborated in further detail in this and subsequent chapters. In order to highlight the scope of work to be concluded in my Thesis, I find it relevant first to explain some of the framework for any successful condition monitoring programme, and the role of TCI's linked to such programmes.

2.1 CM Position in Maintenance and Management

The term Condition Monitoring has several meanings within the realm of maintenance engineering and management. First of all it is vital to have an understanding of the maintenance functions. According to (2 p. 43) "the mission of the maintenance department in a world-class organization is to achieve and sustain the following:

- Optimum availability
- Optimum operating conditions
- Maximum utilization of maintenance resources
- Minimum spares inventory
- Ability to react quickly"

In order to ensure that all these functions are maintained, maintenance work needs to be planned, executed and evaluated. Efforts put into maintenance work will have several characters, ranging from routine work like tightening, cleaning and lubricating (TCL), to repairing equipment which fails suddenly and catastrophically. A classic illustration which describes the different efforts put into maintenance effectively is included below.

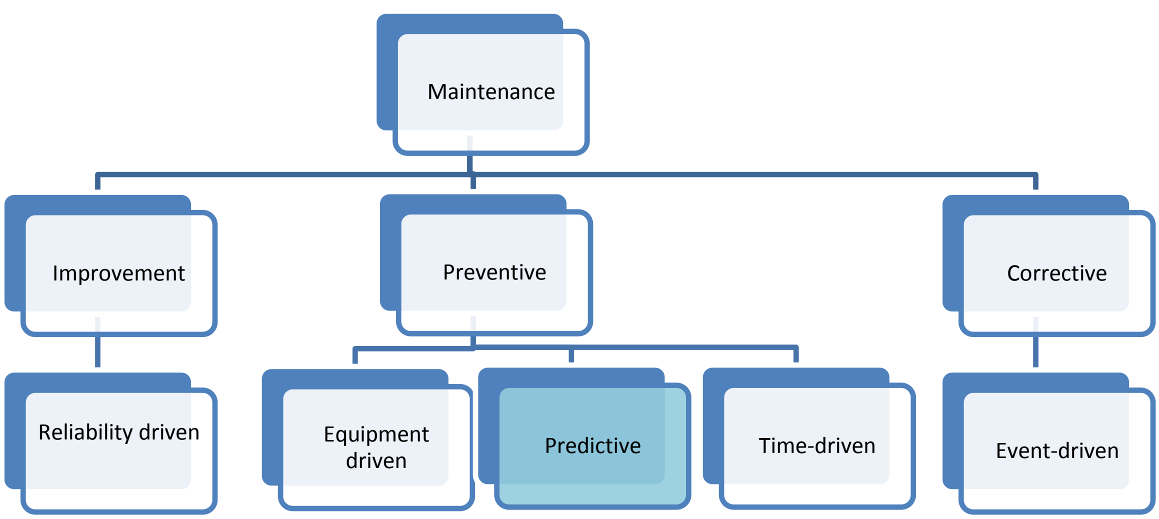

Figure 1: Structure of maintenance activities, Source: Adapted from (2 p. 46)

Maintenance improvement are efforts with the aim of reducing the need to perform maintenance work, and includes designing robust systems and components for minimum maintenance requirements, while at the same time optimizing maintainability, meaning the ability or ease of a component to be maintained. Maintenance improvement includes retrofitting and redesign of existing systems in order to improve these characteristics. Corrective maintenance is the reactive maintenance, repairs or replacement of components which have already failed. A maintenance philosophy based on “run-to-failure”-principles will be dominated by corrective maintenance efforts. Corrective maintenance will tend to produce high lead time to produce spare parts or replacements, which will reduce overall system availability. Also, running components to failure will often result in adverse conditions for other components in a system, reducing output quality and possibly damaging other system components.

Preventive maintenance denotes the activities performed with the aim of reducing unscheduled downtime of existing equipment, and could be broken down into three blocks. Often most of the preventive tasks will be time-based activities which are scheduled routine tasks; this is the baseline of preventive maintenance. Equipment driven tasks are done when it is obvious that the equipment is in need of service, based on observations of defects, either by humans or if machinery is equipped with a its own thresholds or scheduling of maintenance work.

Finally, we have the **predictive maintenance** efforts, which is the relevant realm of maintenance work for this Thesis. Predictive maintenance work is dictated by **condition monitoring** activities, which provide information on the actual operating condition of the system, through investigations such as statistical analysis and trending of key parameters.

Having identified CM as a prerequisite for performing predictive maintenance work, it should be obvious that CM could be used as a **maintenance management tool**, used for scheduling and prioritizing predictive maintenance actions. Too often it is forgotten however, that the application of having a CM programme has the potential of stretching much wider. According to (2 p. 61) the implementation of a CM programme is typically implemented in order to be utilized as a:

- Maintenance management tool
- Plant optimization tool
- Reliability improvement tool

The ability to of CM function as **a plant optimization tool** should be emphasized. Results from CM activities are well suited to establish best routines and practices for operation of systems. Most plants will during its lifetime operate under conditions deviating from the intended profile used as basis for dimensioning in the design phase. In such instances the information on the actual operating condition may help in establishing adapted production routines which takes these new conditions into account. Also, if CM is performed on a large range of similar plants or components operating under varying conditions, or from different equipment suppliers, data retrieved on the response of the components may prove a valuable base of information in order to make future business decisions. CM could also ease verification of compliance to contractual agreements with respect to technical performance of equipment purchased from vendors, ensuring that the desired product quality is received from such suppliers.

If properly utilized, CM will also function very well as a **reliability improvement tool**. If deviances from normal operation are detected in advance, minor adjustments or retro-fits may be performed in a timely manner, thus increasing reliability of components and systems. Specific data of physical properties like pressure and temperatures may also serve as an efficient tool in evaluating the design of components, comparing the real world with simulated or assumed values. Such information may prove vital in future design for optimum reliability and maintainability.

In a survey referred to by (2), 1500 companies which had implemented a CM programme reported the following arguments for choosing to implement such programme:

- Product quality 77%
- Asset protection 60%
- ISO certification 36%
- Management directives 31%
- Lower insurance rates 25%

As we can observe, many of these factors are not strictly maintenance issues. For example, the primary focus of those who reported "ISO certification" was compliance with ISO 9000 standards, which is not directly directed at maintenance, but rather of product quality. Compliance with this standard will typically be forced upon companies for commercial purposes, in effect customers request documentation stating their products are produced with a high degree of quality.

2.2 Structure of an Efficient CM Programme

As I understand it, the concept of TCI's could be seen as an explicit method of unifying, processing, analysing and aggregating data from the total Condition Monitoring (CM) activities undertaken on a number of individual technical plants which operate in relation to each other. This relation could be between components, between components and sub-system, between sub-systems and an entire producing facility (ship, offshore vessel or other technical plant) or between several individual producing facilities. TCI's are thus a tool enabling data to be processed to produce selected, relevant and simple information suitable for being communicated to relevant decision makers, when condition monitoring data are available.

Condition Monitoring (CM) encompasses a number of different methods and techniques, the common ground for these are that they provide information which can be used to make decisions in order to control and improve performance.

According to Alan Davies' Handbook of Condition Monitoring such "monitoring methods cover the following areas:

- Measuring the variations in, and or the absolute values of system output in terms of quality and quantity.

- Measuring the system's input/output relationship.
- Measuring and simultaneously comparing two output parameters with a standard set of operating conditions" (1 p. 20)

From these points it should be evident that measuring is the very essence of Condition Monitoring, and at present there is a vast variation of mechanical, optical, thermal and environmental transducers which provide measurements of an even greater number of physical properties. Properties provided by such **sensors** represent what we call **data**, as confirmed by (1 p. 36): "The output of a condition monitoring programme is data". In addition to information gathered from sensors, one may also take into account the subjective opinion given by a maintenance operator or equipment expert from operating or inspecting equipment and use this information as data as well. We may call such information **inspection data**. Care should be taken if planning to take use of such inspection data and one should strive to remove some of the subjective element of the assessment in order to make the information accurate and relevant. Standardizing the method of collecting and incorporating such data is thus an important issue, if inspection data is to be utilized. The complete set of activities undertaken to collect such hard data and inspection data, may be labelled as the "**data acquisition**" activities.

The data acquisition activities refers to data collected during operative CM activities, while in the initial phase planning a specific CM program, all relevant equipment data and documentation should be collected and structured into databases accessible for the CM system. At an initial point, such data should include component and system specification as well as any recorded performance testing from suppliers, sea trials or similar activities which could be used as a reference basis. We may label such information the **system data**. Such information is crucial in order to have control of the specific equipment installed at the plant under consideration, and for future failure diagnostics. The system data should preferably be continuously updated to include historical and current system condition.

For further assistance, the relevant **rule base**, which includes standards and regulations to which the plant or equipment should comply, is relevant information. Such information should be collected and incorporated into a similar database in the initial phase of establishing a CM-system. The level of detail and accessibility of the information should preferably be as extensive as possible, but due to the nature of such documentation being rather comprehensive, having all such data incorporated into a CM-system may prove practically impossible. However, current developments increasing focus on proper documentation, corporate governance and transparency in the industries, as well as technology advances in the IT-sector providing ever greater speeds and capacities for storing, sharing and accessing data should have potential to improve detail and accessibility of such information. If the actual rule base is not incorporated into the CM-system, reference to where it could be found should at least be stated. It is imperative that provisions are made to keep both equipment and system documentation and the rule base up to date, adjusting for equipment upgrades or regulatory changes.

Data alone represents very limited value unless organized, analysed and interpreted into useful information, and therefore these activities are an inherent part of CM. **Organizing data** should be an activity which in today's computerized world is pre-programmed process, which makes data collected from data acquisition activities readily organized and available for analysis throughout the CM-system.

Manual reporting of input and implementation outside a digital format must be regarded as obsolete, but limitation may exist with respect to capability of transferring data between marine installations operating globally at sea and CM facilities located on shore, or if data for CM is limited to make readings from gauges or sensors which are not digital in their nature.

Analysis and diagnostics are the activities where all the information collected is utilized in order to provide useful information to act upon. Analysis and diagnostics will in any circumstance involve input from experts. A trade-off will however exist between the level of detail which is put into the CM-system at an initial point, and the need to conclude analysis and diagnostics work on a continuous basis by experts. Analysis may be programmed to be executed automatically, and may be linked to diagnosis tools which incorporate the knowledge of diagnosis experts, without need to conclude manual analysis and/or diagnosing. The goal is of course for the automation of analysis and diagnostics to be as complete and cost efficient as possible, in order to reduce staff employed within this field, which is very costly. Analysis and diagnosing is a broad field encompassing numerous analytical task and logic reasoning, varying based on the condition monitoring method utilized.

It is important that results of diagnostics are communicated to all relevant parties, if not; the CM-programme will simply represent a huge investment in infrastructure, hardware and software, without making a difference in controlling and improving performance. The presentation of results from diagnosis through an efficient **user interface** is critical. The user interface should facilitate correct information to be distributed to relevant parties, enabling them to make correct decisions. Such information is typically alarms or notifications to operators of the technical plant; notifying them of deviances from optimum performance, probable causes of malfunction, and procedures to restore or adjust capabilities as appropriate.

I believe having computer software which include and combine all the above identified elements would provide a very powerful framework for utilizing CM activities actively in both plant operation and maintenance decisions. The idea is inspired by "Expert Systems" or "Knowledge Based Systems", as described and illustrated in unnumbered introductory chapter "The Role of Expert Systems In Condition Monitoring" written by Mr. Robert Milne as presented in (2). According to Wikipedia article (5); such expert systems are a subdivision within the field of Artificial Intelligence (AI). AI and expert systems and their application to condition monitoring was according to Christian Steinebach, Senior Research Engineer of MARINTEK, heavily discussed during the 1980's, but never took of within the industry. I would like to highlight that I do not mean that effective software for CM activities necessarily should be an expert system utilizing AI concepts, but I find the elements and interaction within an expert system is similar to those elements I consider relevant to for a CM programme, as depictured below.

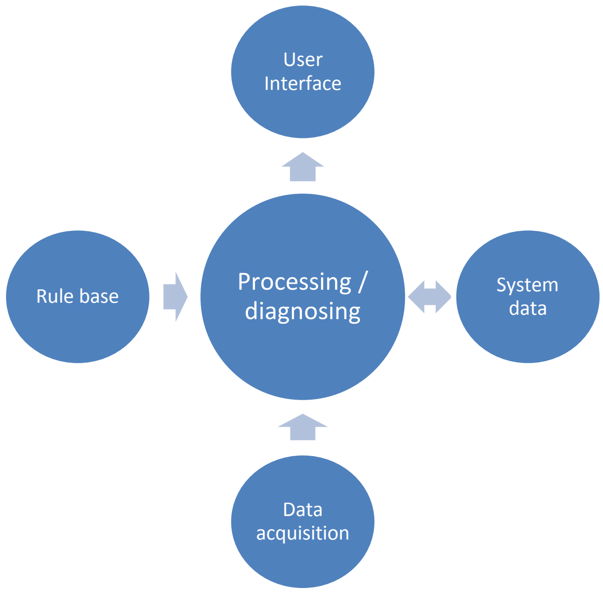

Figure 2: Elements of a complete CM programme software, Source: Authors own

The nature of the sensors providing data and the CM programme, and their interface with the CM programme, can be arranged in several ways, depending on sensor types. For very critical machinery, it may be applicable to install fixed sensors which monitor important parameters continuously and report them on-line at any time. Such systems are usually part of emergency shut down or machine control processes. Data for less critical machinery subject to condition monitoring will typically be monitored by portable measurement equipment, which may be shared for several components, thus reducing cost implications. Some portable equipment provides means of simple analysis, while for more advanced analysis; data will have to be loaded into a computer system for more thorough analysis. In any case, there will be a trade-off between high frequencies of data and analysis, which will provide more powerful failure prediction, and lower frequencies of reporting data which will be less costly. The frequencies of data acquisition and analysis should be related to how fast wear mechanisms will progress for different kinds of machinery, and the prospected savings from avoiding failure. Of course this also is true for the collection of inspection data, but in this case the workload possible for the crew must also be taken into consideration as their capabilities are limited.

2.3 Role of Flagship, TOCC and the TeCoMan Software

The introduction on the **Flagship** official webpage (6) reads:

"FLAGSHIP is a 42 month, part EU-funded project, focusing on improvement of safety, environmental friendliness and competitiveness of European maritime transport. The project will contribute to a further increase in the capacity and reliability of freight and passenger services and to a reduction of negative impact from accidents and emissions.

The emphasis of the project is on on-board systems and procedures, ship management systems on shore, impact of new technology on present ship-, owner- and operator organisations, effective and efficient communication interfaces and impact of standards and regulations".

The Flagship project partners list is included below in Table 1:

Project Co-Ordinator	ECSA European Community Shipowners' Associations
Project Partners	
Aker Yards SA	MJC2 Limited
Altair Special Maritime Enterprise	National Technical University of Athens
Autronica Fire and Security AS	Niederelbe Schiffahrtsgesellschaft mbH & Co. KG
BMT Group Ltd	Norwegian Shipowners' Association
Bureau Veritas	Norwegian University of Science and Technology
Cardiff University	Perseveranza SpA di Navigazione
Carnival plc	Port Authority of Valencia
China Shipping Agency SA	PORTLINE - Transportes Marítimos Internacionais, SA
Community of European Shipyards Associations	Regs4ships Ltd
CONS.A.R	RINA SPA
Danaos Shipping Co. Ltd	Rolls Royce Plc
EMEC European Marine Equipment Council	SAM Electronics GmbH
Germanischer Lloyd AG	Shipbuilders & Shiprepairers Association
Ingenieria de Sistemas para la Defensa de España S.A	Sirehna
Instituto Superior Tecnico	Spanish Depot Service, S.A.
Kongsberg Maritime	Superfast Ferries S.A.
Koninklijke Vereniging van Nederlandse Reders	Teekay Shipping
Kursiu Linija Ltd	Temis SA
Lodic AS	Trans-Base Soler, S.L.
Lyngsø Marine A/S	University of Strathclyde
MARINTEK	V. Ships
Meyer Werft	WEGEMT
Minoan Lines	Wärtsilä Finland Oy

Table 1: Flagship project partners: Source: (6)

As highlighted in red, the partnership list includes my university NTNU and the Norwegian Marine Technology Research Institute MARINTEK, which located and working together constitutes the Marine Technology Centre in Trondheim.

Within the umbrella of the Flagship project, the Technical Condition Index (TCI) methodology (as developed under previous "EUREKA Aging Management" project ('96-'99)) has been developed further under industry projects in Norway, most notably the Technical Operation Competence Centre (TOCC) to provide a "dimensionless measure of the condition, it could be for a Fleet, Vessel, System, or Component, taking into account the long-term degradation and the influences of operation and maintenance" (7 p. 3). For demonstration of the functionality of TCI's, the following systems were selected for demonstration:

- 2-stroke main engines
- 4-stroke auxiliary engines
- Tunnel thrusters

At **TOCC** the application for ship diesel main engine has been developed, tested and proven fit for its purpose. This has been achieved by establishing the theory and practices of collecting measurements from relevant components and applying the TCI concept to these data in computer software created, maintained and evaluated by TOCC.

TOCC Membership Organizations
DNV
MARINTEK
NTNU
LEIF HÖEGH & CO.
THE THORVALD KLAVENESS GRUOP
THE RESEARCH COUNCIL OF NORWAY

Table 2: TOCC membership organizations, Source: (8)

Data have been reported for selected ships in the fleet of the two ship owning companies being partners of TOCC, while the maintenance of the TOCC database has been facilitated by MARINTEK in Trondheim.

TeCoMan is the name of the software which has been developed to handle and analyse the extensive amount of data produced to utilize the TCI concept. The software is based on a Java platform, while imported and produce data are stored in databases. The software is intended to easily facilitate users to add and modify functionality, and thus being a general platform for any system which should be evaluated using the TCI concept. While TeCoMan is the intended platform for super users to set up, configure and update algorithms for the calculation and display of relevant information from the TCI system, another derivative computer application TeCoView has been developed to act as a live and accessible portal to display results via intranet or the internet to clients, without the possibility of manipulating the algorithms of calculation.

In previous chapter 2.2, I tried to define what I think are the inherent activities and ideal prerequisites necessary for an efficient condition monitoring programme, by investigating sources on the topic of condition monitoring and preventive maintenance. Remembering Figure 2 of section 2.2, I would like to compare the current use of TeCoMan software to the system I described as ideal.

- The practise in the TOCC demonstration project is that data acquisition is done manually, pdf input forms are filled out by crew on board once pr month and emailed to operators at TOCC, which convert the PDF to an .xml file on their computers and upload the .xml file into the system.
- Detail *equipment data* which I would include in an ideal system (e.g. serial numbers and documentation from suppliers) are not stored in the system.
- Neither relevant regulations nor standards used are displayed or incorporated in the software, only algorithms and parameters for the index calculations are specified. Having standards and regulations subject to compliance would probably enhance functionality.
- Otherwise TeCoMan is seemingly a principally functional platform for intended analysis.
- A user interface is developed through the TeCoView application. This prerequisite is thus met by the TOCC system.
- Historical system data of all the *monitored parameters* are stored in the databases. This is vital in order to learn from equipment failure statistics.

2.4 Condition Monitoring Techniques

This chapter will be focused at looking not into the TCI concept, but at methods of conducting Condition Monitoring, which is the underlying fundamental activity which must be present in order to utilize the TCI method. The intention is to create and describe a general understanding of the technologies available to produce CM data. That said, I would like to point out that I will focus my effort at understanding this topic in a marine perspective, sources of information will predominantly be those describing Condition Monitoring of Marine Systems, and with extra emphasis on those systems which are the scope of this Thesis.

2.4.1 Vibration Analysis (VA) Theory

Vibration analysis is according to (1 p. 39) "the dominant technique used for CM programmes. Consequently, since the greatest population of typical plant equipment is mechanical, this technique has the widest application and benefits in a total plant programme." Today the theory of this science, along with equipment and a number of different analysis methods are fully developed.

Vibration is usually defined simply as "The motion of a machine, or machine part, back and forth from its position of rest" (1 p. 269).

Vibrations are caused by an **exciting force**, which is **either changing in magnitude or direction**. However, the resulting vibration characteristic also depends on three other elements particular to the vibrating system:

- Mass
- Stiffness
- Damping characteristics

Any rotating mechanical machine will have an inherent level of vibration and noise, which is regarded as normal and acceptable, however deviations from this inherent vibration characteristic will usually stem from some mechanical defect or operating problem. Typically problems causing vibration changes can be related to some variation of the following phenomena's: imbalance, misalignment, loose parts, eccentricity or external forces. Different types of mechanical failures will manifest themselves in their unique way in terms of change of vibration characteristic. These are the facts which facilitate the use of CM and failure diagnostics based on data from vibration monitoring.

2.4.1.1 Characteristics, Measuring Parameters and Severity

The three descriptive characteristics defining any vibration are:

- Amplitude; represented by displacement, velocity or acceleration
- Frequency
- Phase

We may illustrate some of the theory in vibration by representing a vibration signal x as a standard sinusoidal signal. In this case represented by the equation $X(t) = A\sin(\omega t + \varphi)$, where

$A = \text{Amplitude}$

$\omega = \text{angular frequency (or speed)} = 2\pi f = \frac{2\pi}{T}, [rad/s]$

$\varphi = \text{phase angle, [rad]}$

f = frequency ,[Hz]

T=Period, [s]

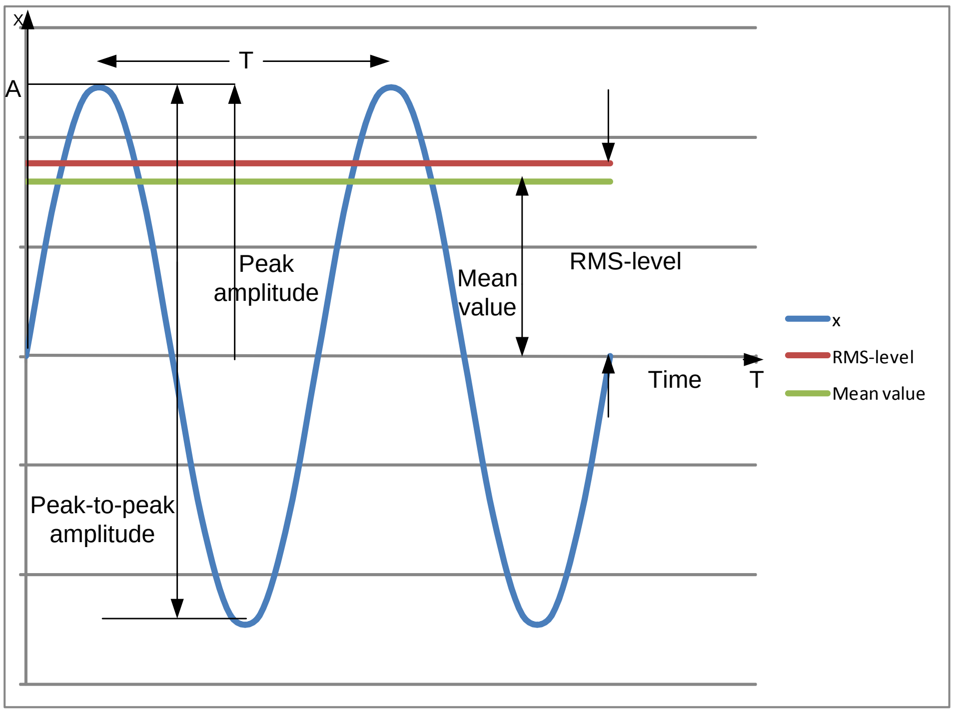

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Figure 3: Example of harmonic vibration signal showing some relevant characteristics

The mean and RMS values are defined by the following equations:

$Mean = \frac{1}{T}\int_0^T |X(t)| dt$, which for a simple harmonic signal reduces to:

$$\text{Mean} = \frac{2}{\pi} \text{ Peak amlitude} = 63.66\% \text{ of the Peak amplitude}.$$

$RMS = \sqrt{\frac{1}{T}\int_0^T X^2(t)dt}$, which similarly for a harmonic signal reduces to:

$$RMS = \frac{\pi}{2\sqrt{2}} Mean = \frac{1}{\sqrt{2}} Peak = \ 70.71\% \text{ of the Peak amplitude}$$

Equation 1: Equations for Mean and RMS values of a signal x

Frequency is the inverse of the Period, one period being the time to conclude one cycle of the vibration. The SI unit used for frequency is Hertz (HZ) and is this number of cycle's per second (CPS) [s^{-1}]. Very often the rotational speed of rotating machinery is given in terms of rounds/cycles per minute (RPM/CPM), and in some cases it is perhaps easier or more appropriate to use CPM when comparing vibration frequencies and rotational speed of the machine. The fundamental unit is undoubtedly Hz though, and the conversion is naturally done by the simple factor 60 [s/min].

Phase is "the angle between the instantaneous position of a vibrating part and a fixed reference position, or the fractional part of the vibration cycle through which the part has advanced relative to the fixed reference". If we are looking at two moving parts the definition of phase is "the fractional part of a cycle through which one part has advanced relative to the fractional part of the cycle through which the other part has advanced, expressed as an angular difference" (1 p. 276).

If displacement is the measured value, amplitude is usually stated in **microns**, 1 micron = 10^{-6} m, or thousands of millimetres (0,001mm), and presented as the "peak-to-peak" value giving distance between the two extreme limits of travel to either side of the reference rest position.

Velocity measurements usually record the very highest speed, usually given as "**millimetres per second peak**" [mm/s], but could also be represented as velocity RMS (Root Mean Square).

Acceleration denotes the rate of change in velocity, and is usually expressed in g's peak, where 1 g is the normal acceleration caused by gravity at the surface of the earth equal to 9.81 [m/s^2].

Displacement, velocity and acceleration are of course mathematically related through the relation that displacement or stretch is the integral of velocity with respect to time, and that velocity is the integral of the acceleration with respect to time, and combined or written into Newton's 2nd law they describe most motion physics.

$$Displacement\ \mathrm{s} = \int v \cdot dt,\ \mathrm{Velocity}\ v = \int a \cdot dt,\ \mathrm{Newtons\ 2nd:}\ a = \frac{Fres}{m}$$

As a result, velocity is always phase shifted 90 degrees (or π/2 rad) ahead of displacement, while acceleration is phase shifted another 90 degrees ahead of displacement. To illustrate this, along with the mathematical infliction of the phase angle ϕ, we may look at the equations and graphs below, showing indicatively the typical pattern for how displacement x(t), velocity v(t) and acceleration a(t) are related to each other for a simple harmonic sinusoidal vibration.

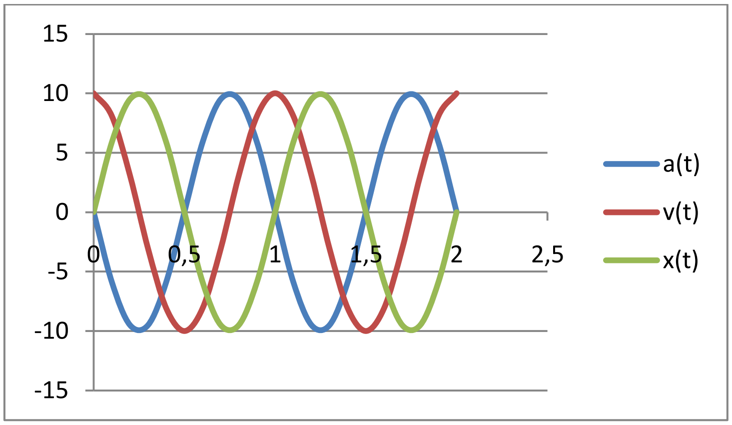


Figure 4: Displacement, velocity and acceleration for a simple harmonic sinusoidal vibration.

$x(t)=10\sin(2\pi t+0)$, $v(t)=10\sin(2\pi t+\frac{\pi}{2})$, $a(t)=10\sin(2\pi t+\pi)$

Equation 2: Example of mathematical representation of harmonic sinusoidal vibration signal as charted in above figure.

According to (1 pp. 277-278); "A measure of vibration velocity is a direct measure of vibration severity", and is the overall preferred amplitude indicator of machine health. Acceleration or displacement can also be helpful information, but can not be used without cross referencing with frequency, which is typically done in "severity charts". When measuring overall vibration levels, not knowing the frequencies, velocity is thus the only parameter which can be applied directly to scale severity.

General guidelines for vibration severity can among other places be found in ISO Standards, and were first defined in 1974 by ISO standard 2372. This standard also introduced velocity RMS as the standard unit of measurement as the best unit applicable for indicating vibration severity in most cases, due to the fact that RMS is basically a measure of average vibration amplitude as a function of time, and thus representing the damaging energy of the vibration (1 p. 288). According to (9 pp. 89-92), later ISO 3945:1997and ISO 10816-3:1998 standard provides guidelines for classification of severity for overall vibration of machines in general and for centrifugal pumps, respectively. ISO 3945 provides guidelines for vibrations in any direction, horizontal, vertical or axial, while ISO 10816-3 is based on radial vibrations of bearings or bearing housings, both measured in the broadband frequency range 10-1000 Hz.

There is however a weakness using RMS-values for some applications, such as gears and rolling element bearings, because vibration problems with such equipment will predominantly produce considerable, but very short duration pulses. Due to the short time, and nature of the RMS-value taking into account the time elapsed by a signal, the RMS-values of such vibrations become very low, although their spike amplitude may be damaging and reveal failure on the machinery. The solution for such appliances is of course to measure the peak, or peak-to-peak, amplitude of these short duration pulses, as described by (4 pp. 7.8 and 7.24-7.25) and (1 pp. 288-294).

To have a complete understanding og nomenclature used for significant frequency components of vibration signals I include the following definitions, as adopted from (1 pp. 285-286):

- Predominant frequency – frequency of vibration having the highest amplitude or magnitude

- Synchronous frequency – vibration frequency that occurs at 1 x RPM
- Sub synchronous frequency – vibration occurring at a frequency below 1 x RPM
- Fundamental frequency – the lowest frequency normally associated with a specific failure or cause.
- Harmonic Frequency – an exact, whole number multiple of a fundamental frequency.
- Order frequency – same as above
- Sub harmonic frequency – exact sub-multiple (1/2, 1/3, 1/4) of a fundamental frequency

2.4.1.2 Analysis Techniques

Analysis methods for analysing data collected from vibration monitoring activities are divided into three different domains; the time domain, the frequency domain and the quefrency domain, as illustrated in Figure 5 below.

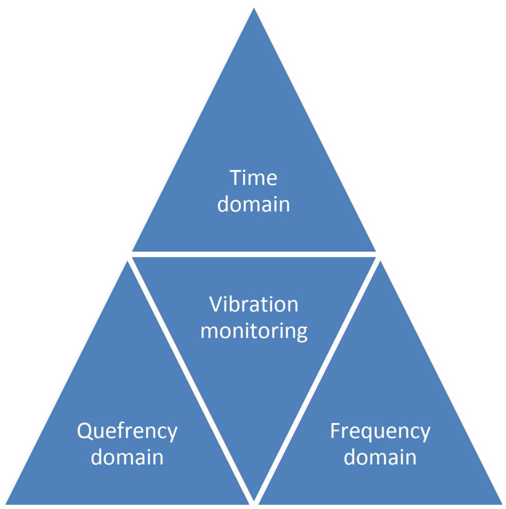


Figure 5: Domains of vibration monitoring techniques, as presented in page 306 in (1).

Time domain

The time domain is the simplest, most basic and intuitive realm of analysing vibration signals, as it is based on looking at the vibration signal the way we are used to see most signals represented, as some sort of magnitude plotted against time. Various techniques of highlighting characteristics, which are not readily observed at a first glance of a simple table or plot of such signals exist though, and could be organized as seen below.

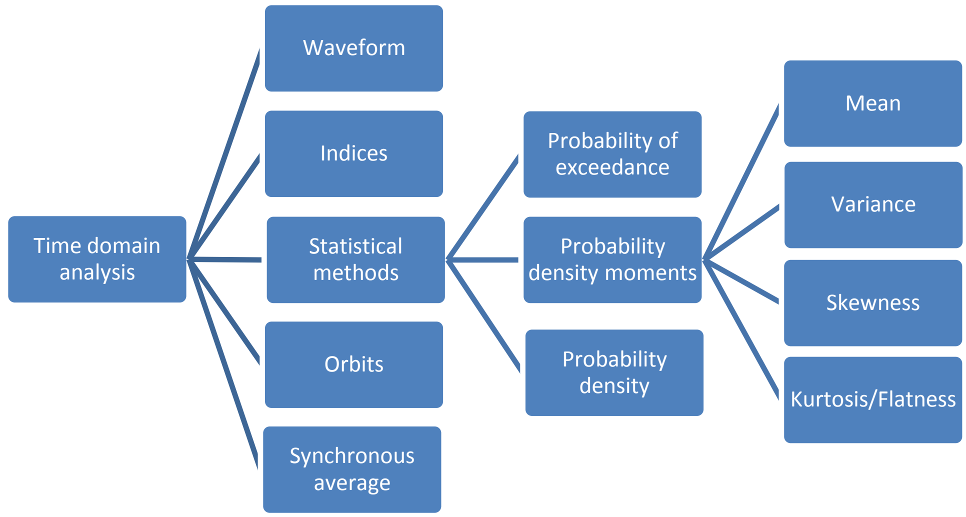


Figure 6: Time domain analysis techniques, as presented on page 307 in (1)

Waveform analysis is the basic time domain analysis method, displaying the time history of the signal on an oscilloscope or a computer analysis showing the equivalent representation, as exemplified in Figure 3 above. The application is basically to recognize periodicity or randomness of the signal, and the application is considered specifically useful in highlighting transient conditions or short impulses.

Indices include such quantities as peak level, RMS-level as well as their ratio, the Crest factor, and the Kurtosis factor. Peak and RMS-levels have been discussed above, and we remember that general severity is best characterized by velocity RMS-level. The ratio between these two values have been named Crest factor $C_f = \frac{A_{peak}}{A_{rms}}$, and has been proposed as a trending parameter which could be used for detecting incipient failure in rolling element bearings as this will resulting in an increase in the crest factor. However, the application of the Crest factor is disputed by (1), at least unless continuously or at least frequently checked, as progressed failure usually results in an increased RMS-value, the parameter will only have a short duration increase during incipient failure, before it will decrease to values not significantly different from baseline references.

Synchronous averaging is done by averaging the time signal over a larger number of cycles at the running speed of the machinery. The method is mostly used for diagnosing gears, as background noise and periodic events are removed.

Lissagous figures are produced by showing time waveforms collected from two sensors being 90˚ phase shifted in relation to each other, where the time base is substituted with the signal from one of the two sensors. If one does this on signals from two sensors measuring shaft relative displacement, the resulting diagram is depicting the **shaft orbit**. Shaft orbit is used to indicate such failures as misalignment, bent shafts, journal or sliding bearing wear, instability in hydrodynamic bearings and rub between rotor and housing. Displacement probes could be of magnetic spool type, or eddy current transducers.

Statistical methods comprise plotting probability density, probability of exceedance or investigating the moments of the probability density function (PDF). "The probability density is the probability of finding instantaneous values within a certain amplitude interval, divided by the size of the interval" (1 p. 309), and will have a certain characteristic for any vibration signal. For condition monitoring purposes it is necessary to produce a reference curve for comparison with monitored values. This type of analysis could be used for high-speed rolling element bearings. The probability density is expressed logarithmically, and plotted against a normalized axis of amplitude. Failures will result in a change in waveform relative to the reference probability density function, and the logarithmic scaling helps alter the shape of the PDF. For trending purposes, three-dimensional cascading or "waterfall" plots can be a useful tool in order to help illustrate the developing alteration in the PDF as a function of time.

Probability of exceedance is another statistical analysis method, and is basically the integral of the probability density function, depicting the probability that the instantaneous vibration amplitude is exceeding any particular amplitude. This method is similarly used to detect bearing failure.

Finally, when investigating time domain signals through use of statistical methods there are the investigation of moments of the PDF curve. A PDF curve as a stochastic variable could be described by a series of single-number indices or factors. The first moment is the mean value, and the second is the variance. Central moments of order n of a stochastic variable x are defined by the equation:

$$\overline{\mu}_x^{(n)} = \int_{-\infty}^{\infty} (x-\mu_x) f_X(x) dx$$

Equation 3: Central moments of order n, as defined in page 2.27 in (5)

The skewness coefficient, saying something about the position of the peak value relative to median value is defined by:

$$\text{Skewness coefficient: } \gamma_1 = \frac{\overline{\mu}_x^{(3)}}{(\overline{\mu}_x^{(2)})^{\frac{3}{2}}} = \frac{\overline{\mu}_x^{(3)}}{\sigma_x^{3}}$$

Equation 4: Skewness coefficient, from page 2.27 in (5)

While the 4th order coefficient is defined as the:

$$\text{Flatness coefficient, Kurtosis factor: } \gamma_2 = K_f = \frac{\overline{\mu}_x^{(4)}}{(\overline{\mu}_x^{(2)})^{\frac{4}{2}}} = \frac{\overline{\mu}_x^{(4)}}{\sigma_x^{4}}$$

Equation 5: Flatness, or Kurtosis coefficient, as found on page 2.28 in (5)

Or general for coefficients of order above 2: $\gamma_n = \frac{\overline{\mu}_x^{(2+n)}}{(\overline{\mu}_x^{(2)})^{\frac{2+n}{2}}} = \frac{\overline{\mu}_x^{(2+n)}}{\sigma_x^{\ n}}$

Equation 6: General higher order moment coefficient, authors own.

For moments of higher order and odd values of n, the coefficient is close to zero, while even values of n relate to description of shorter and shorter impulsive behaviours of the signal. The Kurtosis coefficient has been proposed as a trending parameter for detecting failures in rolling element bearings, being a compromise between high-frequency impulse-sensitivity and insensitive lower moments. However, similar to the Crest factor, the Kurtosis parameter used for trending "could not be relied on as a trending parameter for the purposes of prognosticating bearing condition". Based on the fact that tests have shown that the ability to predict failure from Kurtosis or Crest-factor trending are quite similar, the much cheaper Crest factor meters can be used for monitoring of rolling element bearings.

Frequency domain

The frequency domain analysis techniques, as recognized by (1), and their relation to each other can be illustrated as seen below in Figure 7.

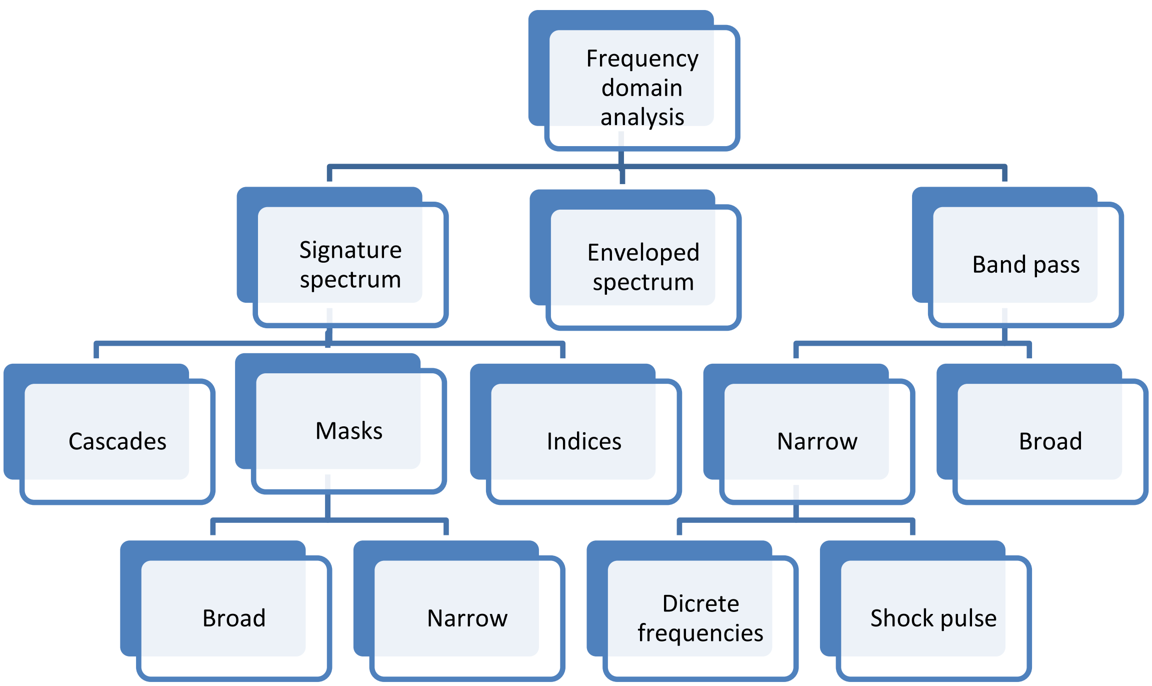


Figure 7: Frequency domain analysis techniques, as presented on page 314 in (1)

Previously, deriving the frequency domain signal was done by utilizing analogue filter sets which were tuned to provide information only from frequency bands of interest. Today, however, digital (real-time) Fast Fourier Analysis (FFA) is the modern method of doing this. Since the local environment and the history of assembly and installation will inflict the vibration response, one should obtain signature spectrum from trial condition as reference. This is especially true for marine applications, where the foundation and the background vibration from the structure to which the machine is mounted may play a role as well.

Spectral comparison is perhaps the most basic form of analysing in the frequency domain. Vibration level is plotted against frequency, and compared to the baseline spectrum collected at sea-trials or similar reference measurement. This is a simple two-dimensional plot, and increases in general or distinct frequencies will probably indicate a fault or wear condition. Today's equipment for spectral comparison is based on "portable microprocessor instrumentation which has both memory and intelligence" according to (1 p. 315). Similar to what was described for time domain analysis, frequency domain spectra collected at different point in time may be plotted in three-dimensional cascade plots, where the development of deviances can be illustrated better.

In (1), the use of cascade plots are said to be applicable for plotting displacement or acceleration levels, however it is indicated that the broad frequency response and large harmonic content usually provided by acceleration transducers may result in signals which simply contain too much information to provide useful cascading plots. Nothing is said of plotting velocity levels, but I assume this is possible as well.

Indices may be useful to reduce the amount of information, and according to (1 p. 316) "the amount of information present in a cascade plot can be reduced if each spectral change that occurred is expressed by a single number". It is said that indices based on such spectral frequencies have proven much more sensitive than similar time domain indices, as described above, in detecting failure in rolling element and journal bearings and gears. The proposed and exemplified index parameter in (1) is the Matched Filter RMS:

$$Mf_{RMS} = 10\log\left((\frac{1}{N}) \left(\sum_{i=1}^{N} (\frac{F_i}{F_{iref}})^2 \right) \right), [dB]$$

where:

$\mathrm{F}_i =$ amplitude of the ith point in the frequency spectrum

$F_{iref} =$ amplitude of the ith point in the baseline spectrum

$N =$ number of points in the frequency spectrum

Figure 8: Matched Filter RMS index definition, as from page 323 in (1).

Applying **spectral masks** is another method of evaluating the spectral change. This is done by defining allowable tolerance limits outside the reference spectrum. If the measured signal is within the mask, then the situation is deemed ok. Masks could be broad or narrow, depending on the anticipated speed variation, as this has to be compensated for. Masks could be either constant percentages in regions, or more complex functions where relative mask width varies with varying frequency, depending on notion of critical frequency regions on the machinery. Expertise on the equipment and its vibration response throughout the frequency spectrum is necessary to create mask widths which balance the need to avoid spurious alerts or shut-downs with the need to have early fault detection.

Enveloped, or demodulated, spectrum analysis is done by first applying a high-pass filtering stage, removing low-frequency components in the spectrum, which will often dominate in magnitude. Next, the signal is rectified, and a signature spectrum is derived in same manner as usual by a real-time FFA or computer processing of the data. If computer analysis is used to create the spectrum, then an extra low-pass filtering is included. The reason for this extra filter is that it will avoid aliasing of the signal, which means an incorrect reconstruction of a sampled signal due too low sampling frequency, relative to the highest frequency carried by the signal, according to the Nyquist-Shannon Sampling Theorem (12). Enveloped spectrum analysis is said by (1) to have proven useful detecting damage in complex machinery, but failure in high-speed rolling element bearings with a progressed failure mode may not be detectable, because the high-frequency impulses from such failure is usually not within the data collected from transducer commonly used for such bearings. None the less, the applicability of enveloped spectral analysis is for relatively short duration pulses, given that the frequencies of such pulses in fact are picked up by the transducer utilized.

Pass band analysis means monitoring only a band of frequencies, broad or narrow, in which defect frequencies of components are anticipated to dominate, or change significantly upon failure. A narrow-pass band monitoring is often referred to as discrete frequency monitoring. The weakness with such monitoring is of course all the frequency which one omits in the analysis. I would say that such analysis should not be an overall condition monitoring method, but a more specified failure diagnosis supplementary check if condition monitoring not including frequency spectral analysis has been done, and one knows anticipated frequencies for different typical failure modes.

The **shock pulse method** is a specialized application of characteristic frequency monitoring, and utilizes the fact that high-speed rolling element bearing failure produces energy omitted at frequencies in the ultrasonic frequency range. Basically, the trick is to use a transducer which is tuned to pick up these high frequencies, and then analyse the signal using similar methods as described above, for instance spectral analysis.

Quefrency domain analysis

"Quefrency is the abscissa for the cepstrum which is defined as the spectrum of the logarithm of the power spectrum" according to (1 p. 318), the derivation of the cepstrum is not a trivial matter, and is predominantly used for gearbox vibrations. Since my systems to my notion does not include gearboxes, I will not go further into this particular domain of vibration analysis, other than to acknowledge its position as a useful, though fairly complicated, analysis technique used on gears.

2.4.1.3 Vibration Sensors

As identified in above chapter 2.4.1.1, there are basically three different amplitudes which are measured in order to evaluate vibrations for CM appliances; displacement, velocity and acceleration. In this chapter I would like to present the fundamentals of different vibration sensors, their working method and basic design, and their limitations as presented in (2 pp. 152-159).

Displacement (or proximity) probes are predominantly used to ascertain relative displacement of shafts, expressed as microns peak-to-peak. The probes are non-contact devices, either based on capacitive or eddy current principles. An eddy current probe will consist of a pick-up coil which will introduce a magnetic field around it. The interaction of the nearby shaft on the magnetic field induced by the coil will be detectable, either in a secondary pick-up coil or as deviations from the forced current in the primary coil, thus utilizing the eddy current principle to ascertain the gap between the sensor and the shaft. Capacitive probes will instead utilize the change in an electric field introduced, as opposed to a magnetic field. Generally, capacitive probes will have higher resolution, while eddy current probes tend to perform better in dirty or hostile environments (13). Relevant standards for proximity measurement are API 6710 and ISO 7919 (14).

Probes must be mounted on a rigid and stationary structure close to the shaft, in order to provide valid and repeatable data. The working frequency range is usually 10-1000 Hz (2 p. 153). As we remember, two such sensors mounted with 90˚ angle between them will produce information which will provide sufficient information to depict the shaft orbit. The major limitation to the use of displacement sensors is the cost of installation, which for a fixed sensor is reported by (2 p. 154) to be approximately 1000 USD pr installation.

Below is an illustration of such displacement sensor and subsequent signal processing equipment:

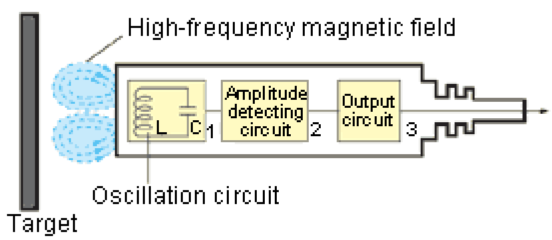


Figure 9: Principle illustration of an eddy current proximity probe, Source: (14)

Velocity transducers are electromechanical sensors used to measure housing/casing or relative vibration, which consist of three key components; a permanent magnet, a coiled wire and a spring supported mass. The coiled wire is fixed to the spring supported mass, which will be forced by vibrations to move through the magnetic field, thus inducing a current. The velocity of the current will depend on the vibration speed, and thus the principle is viable in order to measure vibration velocity.

Velocity transducers will typically have similar frequency range as displacement probes (10-1000 Hz); however, their major limitation is sensitivity to thermal or mechanical damage. Velocity transducers must therefore be subject to frequent calibration in order to produce valid and repeatable data (2 p. 154).

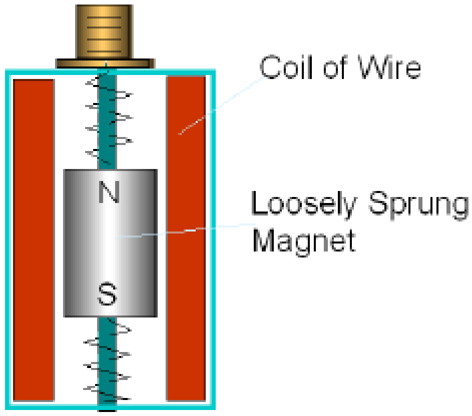


Figure 10: Principal drawing of velocity transducer, Source: (14)

Today, velocity sensors have to a large degree been replaced with accelerometers equipped with electronic integrators. In effect, most accelerometers may display both acceleration and velocity readings.

Accelerometers are the most popular type of vibration sensor for casing/housing measurements. Most common accelerometers use piezoelectric crystals or films to convert mechanical energy into electric signals in piezoelectric accelerometers. A piezoelectric material is a material which demonstrates the ability to generate an electric field or potential, in response to applied mechanical strain. A piezoelectric accelerometer consists of a seismic mass preloaded onto a section made from piezoelectric crystals or a piezoelectric ceramic, accompanied by wiring to measure the voltage over the piezoelectric material, all suspended within a casing. As the mass is accelerated by the vibration, the applied force of the mass onto the piezoelectric layer will vary proportional to the acceleration following Newton's 2.nd law, which in turn will result in a voltage potential over the piezoelectric element which is the measured signal. Piezoelectric ceramics provide greater sensitivity and are cheaper to produce than piezoelectric crystal accelerometers; however their sensitivity will decay with time, thus reducing their longevity (17).

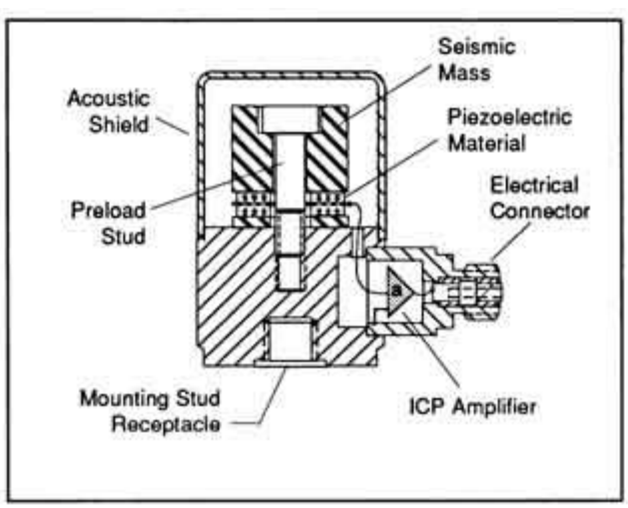


Figure 11: Schematic representation of piezoelectric accelerometer, Source: (14)

Effective range of general-purpose accelerometers is typically 1-10000 Hz, while the same principle is utilized for Ultrasonic range measurements up to frequencies of 100 kHz or more. As previously stated, the usual representation value from most accelerometers is in terms of the gravitational constant $g=9,81m/s^2$.

Accelerometers usually do not bring forth the need for frequent recalibration. Although the piezoelectric materials are prone to thermal damage, the exposure is limited at least for transducers not mounted in a fixed position, as data acquisition can be performed within less than a minute (2 p. 155).

Piezoresistive accelerometers are similar to piezoelectric, but the piezoeffect of the material used in these sensors is that their electrical *resistance* will change if mechanical strain is applied. Piezoresistive accelerometers are preferred in applications where shock impacts are expected (19). Other principles in addition to piezoelectric and piezoresistive accelerometer types are available, a full list of technologies used for accelerometers, as presented in (14) is given below, however piezoelectric or –resistive technologies dominate the current market.

- Capacitive
- Piezoelectric
- Piezoresistive
- Hall effect
- Magneto-resistive
- Heat transfer
- MEMS (MicroElectroMechanical Systems)
- Future nano technological advances NEMS (NanoElectroMechanical Systems)

Especially the last two types, MEMS and NEMS represent very interesting recent developments which may evolve further to dominate the future market of accelerometers. MEMS accelerometers are already implemented in numerous consumer applications, such as airbag sensors in automotive industry and within consumer electronics included in such items as Nintendo Wii, Iphone, various HTC phones and Canon Ixus digital photo cameras (15). The potential of MEMS and NEMS is vast, although at present rather expensive in development cost, they may in the future lead to significantly smaller and cheaper sensor equipment.

According to (14), usual specification of accelerometers includes such variables as:

- Dynamic range – maximum/minimum amplitude which can be measured, given in g's.
- Sensitivity – Scale factor in terms of output signal change per input, given in mV/g's.
- Frequency response – frequency range given in Hz where the sensor will produce correct value.
- Sensitive axis – sensors range from being of single-axis to tri-axial.
- Size and mass – for sensitive systems, the size and mass of the accelerometer may inflict on quality of measurement.

2.4.1.4 Applicability

VA is typically applicable for rotating machinery, such as pumps, compressors, centrifuges and electric motors amongst others, which all are machines we recognize from the systems under study in this Thesis. Also taking into account that VA is dominant technique for most CM-programmes, and has the widest applicability; it is therefore very likely that vibration monitoring will be a vital element of the CM-programme for these systems.

A diagram of typical failures on different types of rotating machinery can be seen in Figure 12.

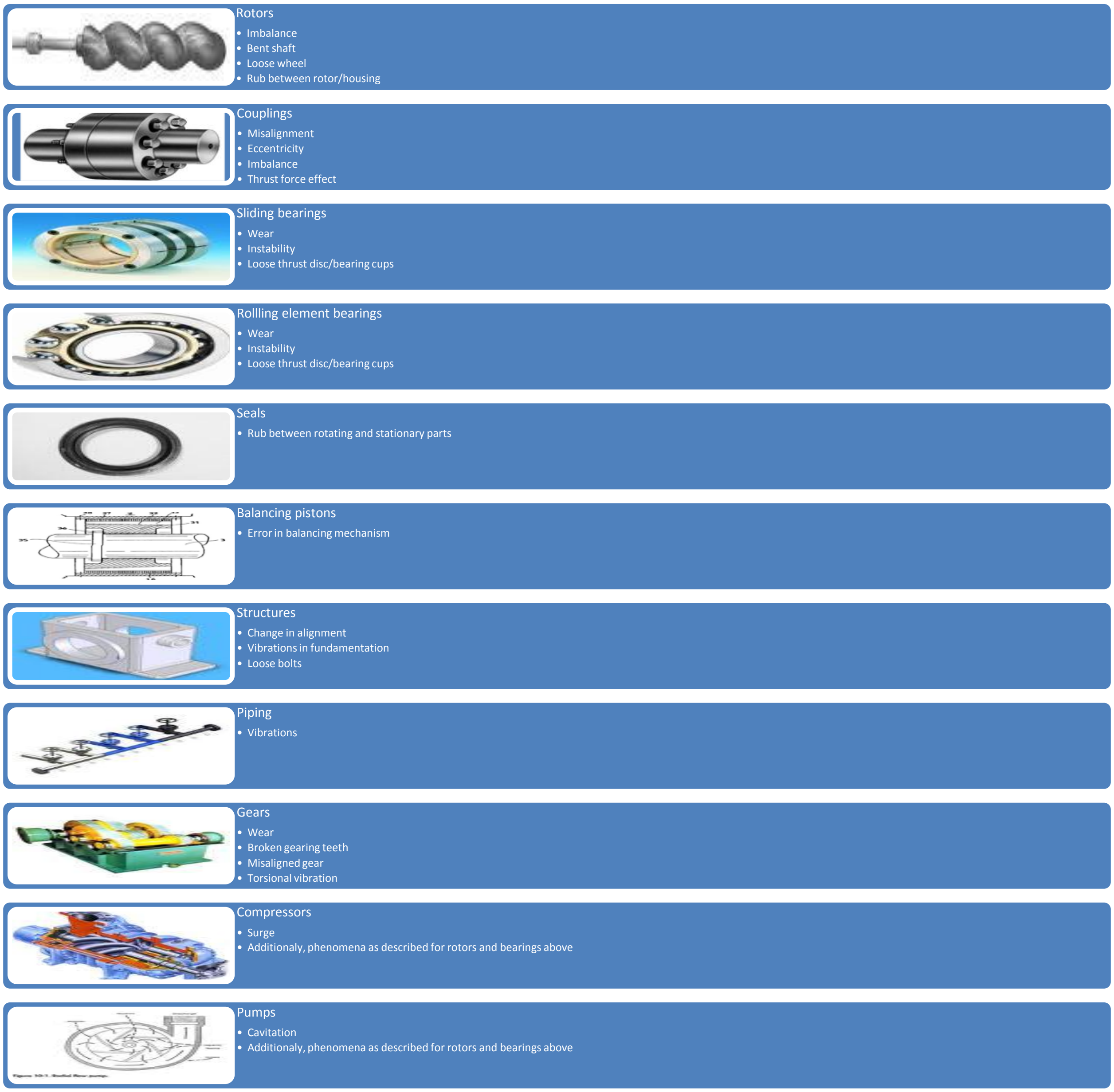


Figure 12: Typical failure on rotating and adjacent equipment, Source: (4 p. 7.18)

0 shows typical vibration characteristics for different types of failure, combined with relevant measurement method to discover these failures. The diagram sums up a lot of what we have learnt from this chapter on VA in condition monitoring.

We have learnt that generally, condition monitoring with the aim of indicating overall vibration severity in most machinery should be concluded by measuring velocity-RMS value, and compare this value with relevant severity charts, which are given in standards. For rolling element bearings, which will produce very high frequency pulses, there are problems with using this method. First, regular transducers may not be tuned to pick up signals in this frequency range. Secondly, the increase in RMS value due to a short duration vibration signal is often insignificant relative to the lower frequencies whose contributing energy is much greater in most cases. Therefore, rolling element bearings must either be monitored continuously or very frequently using Crest-factor or Kurtosis coefficient trending, which are methods sensitive to show incipient failure in such bearings. Alternatively, and probably more effectively, such bearings should be monitored using the spike energy, or shock pulse, method. This method involves using a transducer tuned to pick up high-frequency vibrations in the ultrasonic region, and in stead of using RMS values the peak amplitude is preferred as an indicator.

The equipment needed for most vibration monitoring activities is off-the-shelf and readily available, usually portable for operators to use on several machines on board. Some have integrated analysers, while others may store data which needs transferring into a computer with software for further post-processing. I assume that the cost of equipping a ship with analysing equipment for operators to use on board will not impose a vast economical burden, relative to other maintenance and monitoring equipment in total. However, the time available for operators to actually conclude measurement and analysing activities may be an issue. If this is the case, it would be natural to look to mount fixed vibration sensors to machines of interest, and have automated feed of signals to the CM-system, to reduce time consumption for the crew. This would likely impose significantly larger investments in equipment. As no emphasis is put on the economical implication of the CM-programme in the assignment text of this Thesis, I will not conclude analysis of equipment cost.

2.4.2 Ultrasonic's (UlS)

Ultrasonic's utilizes the same principles as those used for VA, however for higher frequencies. "Frequencies capable of being heard by humans are called audio or sonic. The range is typically considered to be between 20 Hz and 20 000 Hz" (22). The word ultrasonic means "beyond sonic", beyond having reference to frequency. Ultrasonic's is therefore the investigation of signals having frequencies above that of the audible range of frequencies. Some inconsistency was found as for the exact definition of the interval from different sources: 20-100 kHz proposed in (1 p. 51), 25-100 kHz in (8 p. 13 and 29) 30-100 kHz according to (11 p. 111), I will assume 20-100 kHz as the representative interval.

There are two principle types of ultrasonic equipment: those observing airborne ultrasonic's and those observing structural borne ultrasonic's. Furthermore, ultrasonic methods are mainly utilized in three applications in a predictive maintenance perspective (9 p. 256):

- Airborne noise analysis
- Leak detection
- Materials testing

Airborne noise analysis is used to verify that ambient noise levels are within rules of occupational health and safety regulations, as specified by governing authorities relevant to the industries. This has little or no application for CM activities. However, both airborne and structural ultrasonic detectors can be used for leak detection, as turbulent flow will produce high-frequency noise, ideal for detecting leaks in valves, steam traps, piping and other process equipment. Airborne detectors can be operated in scanning mode, or contact mode. In scanning mode, they will simply monitor the ultrasonic frequency range of the air in its surroundings and this mode is typically used for gas leak detection. Operated in contact mode, a contacting rod will be placed at a surface, while airborne ultrasonic activity transmitted by the surface from the *other* side can be observed.

Structural borne ultrasonic's could be used in somewhat different applications. One is the monitoring of structural integrity by measuring acoustic emission in materials from propagating cracks. This method involves a very high number of transducers as signals at these high frequencies will usually be damped very rapidly, and thus proximity of transducers are important. Structural borne ultrasonic's has also been proposed as an alternative to VA for some appliances, like bearing monitoring. Sources investigated have been deviating with respect to whether such use of ultrasonic's is a viable in CM.

In (1 p. 52) it is stated that "…the only reliable method of determining the condition of specific machine component including bearings, is vibration analysis. The use of ultrasonic's to monitor condition is thus not recommended". Furthermore, this view is supported by the following consideration: "...ultrasonic's should be limited to detection of abnormally high ambient noise levels and leaks. Attempting to replace vibration monitoring with ultrasonic's simply will not work", as stated in (11 p. 111).

On the contrary, in one source (8) which is looking more detailed at structure borne ultrasonic and acoustic emission than at CM in general, several advantages of structure borne UlS over vibration monitoring are presented. First of all, high frequency measurement (UlS) offers "improved resolution in the time domain" (8 pp. 60-61), although most energy is released at lower frequencies (typically those covered by VA transducers). As a result of this, UlS monitoring must be more sensitive with high gain and low noise, thus resulting in the need to operate in a narrow band of frequencies compared to VA. The fact that most energy released from failure processes are at lower frequencies than those monitored by UlS is however compensated for as " at high frequencies it is virtually always the case that the background noise signals are very much lower" (8 p. 61), thus resulting in a net increase in Signal-to-Noise Ratio (SNR). The point made in chapter 3.5 of (8), comparing structure borne UlS to VA, is that VA is a very powerful tool for diagnosis, but typically in need of analysis in the frequency domain, which represents a complicated signal processing and analysis method. Since UlS has such improved resolution in the time-domain, which is a simpler analysis, "it seems likely that the near term trend for rotating machinery will be increasingly for AE techniques to provide the 'front-line' of instrumented CM. In this role it can quickly categorize machinery as 'OK' or 'Suspect' and provide easily interpreted trend plots indicating the rate of degradation…In particular, as knowledge spreads of the true capabilities of AE, the present situation where unnecessarily complex, costly and slow vibration based instruments are used as front-line CM instruments, must surely change".

Ultrasonic's is also one of the primary Non-Destructive material testing (NDT) procedures. In materials testing using ultrasonic's, even higher frequencies are utilized, typically in the range between 250 kHz –

250 MHz (9 p. 257). Ultrasonic's used in materials testing can be used to monitor corrosion through thickness measurements, and to locate cracks or erroneous welds.

2.4.2.1 Applicability

Sources investigated have been deviating with respect to the applicability of ultrasonic's, especially compared to, or used for applications which usually have been monitored by VA. It seems as if developed ultrasonic methods are typically protected by patents or trademarks, which make it hard to assess their correctness as limited information of the signal processing and trending methods is available. Since sources have been found to be deviating with respect to applicability of such monitoring, I will be most cautious with utilizing such methods for the CM programme to be developed.

The applicability of airborne ultrasound used for noise monitoring is of little importance for CM activities.

2.4.3 Thermal Monitoring Theory - Thermography (TG)

"Thermal monitoring determines the temperature of a surface or substance, by direct contact or remotely" (7 p. 8). Thermal monitoring would therefore include such monitoring as using a thermometer to measure temperature of a surface or fluid, which is not to be considered a unique branch within condition monitoring techniques. It is important to remember that temperature energy may be transmitted in three essentially different ways:

- Conduction – direct transfer through matter
- Convection – indirect heat transfer through circulating liquid or gas medium
- Radiation – direct heat transfer across space, not demanding any medium

Thermal monitoring as a technique within the context of condition monitoring is done through devices which are non-contact, meaning they only take into account radiation information in order to ascertain the temperature of a surface, unlike thermometers which need to be placed in contact or proximity with the surface or medium whose temperature we would like to measure.

The fact that all objects at a temperature above absolute zero will emit radiation energy is utilized in infrared thermal monitoring. This electromagnetic thermal radiation is located in the infrared (IR), visible light and ultraviolet (UV) regions of the electromagnetic spectrum (7 p. 20).

Radiation region	Wavelength [µm]	Frequency [THz]
Infrared	100-0,8	3,0-375 THz
Visible	0,8-0,4	375-750 THz
Ultraviolet	0,4-0,1	750-3000

Table 3: Electromagnetic wave categories where thermal radiation is present.

We recognize the thermal radiation in the visible region from watching glowing coal or wood from a bonfire or the frying pan glowing red if we forget to turn of the stove in our kitchen, while most of the thermal radiation is invisible to us humans. Thermal monitoring equipment detects radiation within the infrared region, typically in the wavelength range 0,9-14 µm (25). As we will see, the intensity of the radiation is a function of the surface temperature of the object, and from the measurement of this energy the surface temperature can be deduced.

A black-body is a term for an ideal object with regards to temperature measurement by means of thermography, which is characterized "as an object that absorbs all the radiation that approaches it at any wavelength", while at the same time "…being equally capable of emitting radiation" (7 p. 22).

Three well known formulas describe the radiation from black-body radiation from an object;

- **Planck's radiation law** describing, at any wavelength, the spectral radiance, or energy per unit time per unit surface area per unit solid angle per unit wavelength radiated by the body as function of temperature of the black body.

$$I'(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda kT}} - 1}$$

I' = spectral radiance, $[J \cdot s^{-1} \cdot m^{-2} \cdot sr^{-1} \cdot Hz^{-1}]$, λ = wavelength, [m], T = temperature of black body [K], h = Planck constant = $6{,}6 \times 10^{-34}$ [J·s]

c = velocity of light = 3×10^{8} [m/s], e = base of natural logarithm = 2.718..[-], k = Boltzmann constant = 1.38×10^{23} [J / K]

- **Wien's displacement law**, which is the result of differentiating Planck's radiation law with respect to λ, yielding:

$$\lambda_{\max} = \frac{C}{T}$$

Equation 7: Wien's displacement law (7 p. 25)

where $\lambda_{\max}$ = wavelength at which maximum intensity of radiation occurs [m],

T = temperature of body, and C = Wien's displacement constant = 2.89×10^{-3} [m·K].

Wien's displacement law describes how the colour of a radiating object is depending on temperature of the object, as the perception of colour will relate to the wavelength at which radiating intensity is the highest. The intensity as function of wavelength is illustrated in Figure 13 below.

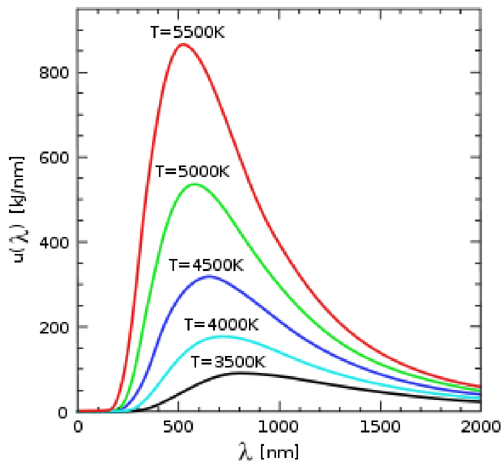


Figure 13: Black body thermal emission intensity as a function of wavelength for various temperatures, Source: (26)

- **Stefan-Boltzmann formula**, which is the result of integrating Planck's radiation law from λ=0 to λ=∞, to find the total radiant energy (black-body irradiance or emissive power) of a black body pr unit time:

$$E = \sigma T^4$$

$$E = \text{total radiated energy from black-body } [\mathrm{W \cdot m^{-2}}]$$

$$\sigma = \text{ Stefan-Boltzmann constant} = 5.6696 \times 10^{-8} [\mathrm{W \cdot m^{-2}} \cdot K^{-4}]$$

$$T = \text{temperature of object}$$

Equation 8: Stefan-Boltzmann formula, Source (7 p. 25)

This is the actual equation which most radiation thermometers are based upon, but the fact that most objects are not black-body objects has a complicating influence. The thermal radiation observed from an object may arise not only from energy emitted by the object, but also radiation reflected and/or transmitted by the object, which are not indicative of the objects itself, but rather of incident thermal energy from the environment surrounding the object, as illustrated in Figure 14.

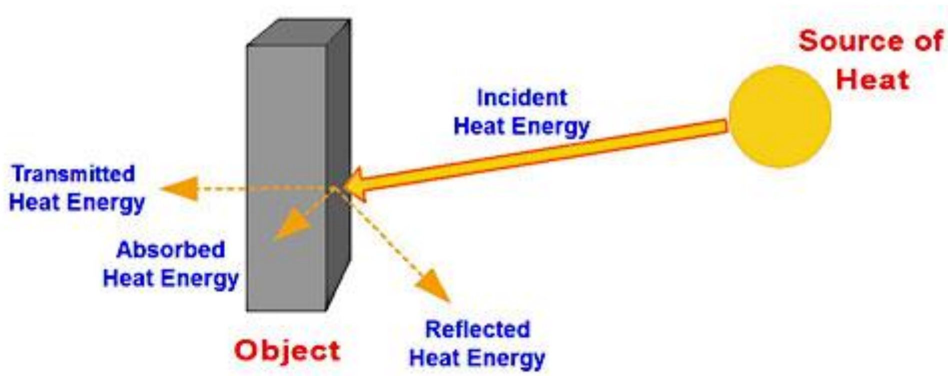


Figure 14: Incident thermal radiation on object, Source: (9).

These factors are dealt with in **Kirchoff's law of thermal radiation**, stating that absorption, reflectance and transmittance must always sum up to unity at any wavelength:

Equation 9: Kirchoff's law of thermal radiation (7 p. 26)

$$\alpha_\lambda + \rho_\lambda + \tau_\lambda = 1$$

$\alpha_\lambda =$ spectral absorption [-], fraction of incident radiation absorbed by object

$\rho_\lambda =$ spectral reflectance [-], fraction of incident radiation reflected by object

$\tau_\lambda =$ spectral transmittance [-], fraction of incident radiation transmitte by object

Notice should be taken that according to the definition of a black-body, absorption is equal to emittance. Introducing for any object the emissivity (or spectral emittance), ε, describing the fraction of radiant emittance at wavelength λ of a black-body (bb) produced by an object (o) at a specific temperature:

$$\varepsilon_\lambda = \frac{E_{\lambda o}}{E_{\lambda bb}},$$

we arrive at the expression of the Stefan-Boltzmann formula of radiation from practical bodies:

$$E(\lambda, T) = \varepsilon(\lambda)\sigma T^4$$

Equation 10: Stefan-Boltzmann formula for general radiating body

Radiation from objects can be divided into three categories, depending on the nature of their emissivity. Emissivity for a *black-body* is of course equal to unity, while most bodies observed in CM appliances will be so-called *grey-bodies*, where the emissivity is a constant, less than unity, independent on wavelength $\varepsilon(\lambda) = \varepsilon = a$. The third category consists of *selective radiating bodies*, where emissivity varies with wavelength (7 p. 27). To utilize thermography to accurately assess temperature, one must therefore know the emissivity of the material being scanned. In addition to material, variations in coating or paint, surface condition and several other variables may inflict the emissivity (11 p. 173).

In addition to uncertainty related to emissivity of objects subject to thermography, there are environmental factors which need to be taken into account. Carbon dioxide and water content in air absorbs radiation strongly in the wavelength regions 4,2-4,4 µm and 2,6-2,9 µm, respectively, thus these regions should be avoided (7 p. 29), if not, calibration of equipment taking into account humidity and concentration of CO2 in the local environment.

There are basically three different non-contact thermal monitoring instruments:

- Infrared thermometer – provides measurement of actual temperature at a small point
- Line scanner – provides lines of comparative radiation
- Infrared thermal imaging – creates a picture of temperature, not only a single point

Infrared thermometers are useful in making detail measurements of hot spots on specific machine details. One application of infrared thermometers within condition monitoring is used in conjunction with vibration monitoring to take temperature readings of critical spots, typically bearing caps. Other applications are electrical motor windings and piping, according to (1 p. 42) . Line scanners are used for "temperature processes at speed, e.g. steel strip or kiln temperatures" (7 p. 9). According to (1 p. 42), the application of line scanners is limited within condition monitoring. Thermal imaging, better known as thermography, "is a way of redefining the appearance of an object (system or components) in terms of temperature" (7 p. 10). Basically, we can produce and store a picture of a component or complete machinery, showing the surface temperature at all locations within the picture. This is of course useful wherever increased friction forces from machinery damage will manifest in exposed surfaces with increased temperature, or where an insulating wall is damaged giving leakage. Perhaps the most important application of thermal imaging is within detecting faulty electrical equipment, where bad electrical wiring will result in larger resistance and therefore produce hot surfaces. Therefore the largest consumer of thermal imaging services is the power generation and distribution industry, where thermal imaging cameras are flown by helicopters to inspect power lines (1 p. 88).

Relevant standards providing guidelines for the use of thermography in CM activities are:

- ISO 18434-1, Condition monitoring and diagnostics of machines - Thermography - Part 1: General procedures
- ISO 18436-7, Condition monitoring and diagnostics of machines - Requirements for qualification and assessment of personnel - Part 7: Thermography" (25)

2.4.3.1 Applicability

From the sources investigated on the topic of thermography, the following applications for CM purposes have been mentioned:

- Electrical machines – poor insulation will result in increased resistance and thus overheating of electrical wiring.
- Faulty bearings – as inadequate lubrication, misalignment, misuse or normal wear are some of the problems which can cause bearing overheating and failure.
- Other rotating equipment such as gears, shafts, couplings, V-belts, pulleys, chain drive systems, conveyors' air compressors, vacuum pumps and clutches are amongst the common components to fail due to overheating.
- Refractory and insulation materials in "ovens, furnaces, dryers, kilns, boilers, ladles, hot storage tanks and insulated pipes." (24 p. 93)
- Valves – controlling heat loss in valves for steam systems.

Methods of utilizing indexing based on thermographic measurements have not been located in the sources investigated. This may be based on the stated fact that "in most applications, infrared thermography is used to pinpoint a problem area while other inspection techniques such as vibrational analysis are used to find the cause of the problem" (1 p. 94).

2.4.4 Tribology (TB)

"Tribology is the general term referring to the design and operating dynamics of the bearing, lubrication and rotor support structure of machinery (1 p. 43)". Lubricating oil analysis and wear particle collection are the two main tribological techniques which are used within predictive maintenance.

Lubricating oil analysis determines the condition of lubricating oil used in machinery. This is done by sampling and analysing the oil which is circulating in the machinery. Although lube oil analysis determines the condition of the lubricating oil it self, "it is not a tool for determining the operating condition of machinery or detecting potential failure modes" (11 p. 108). The applications for lube oil analysis are rather quality checking the lubricants and optimizing intervals between oil changes, thus reducing operating cost of the plant. In light of this, I believe the application of lubricating oil analysis is limited with respect to this Thesis.

2.4.4.1 Wear Particle Analysis

Wear particle analysis is a technique where the solids which are found in samples of collected oil or lubricating oil are investigated. In opposition to oil analysis which determines the condition of the oil it self, wear particle analysis can "provide significant information about the condition of the machine" (1 p. 46). Parameters such as shape, composition, size and quantity of particles in the oil are studied and determined through wear particle analysis.

There are basically two main analysing methods within wear particle analysis; spectrographic and ferrographic analysis.

In spectrographic analysis, several filters are used to separate solids by size, and this method is normally limited to detect contaminants with a maximum size of 10 microns (11 p. 109). The purpose of spectrographic analysis is to determine the concentration of the different elements present in the oil as wear particles. Typically the result is presented as parts per million (PPM), based on weight, for different elements, such as iron, copper, zinc, tin and others, and could be compared to reference concentrations measured at new-condition. Notion of the chemical composition of the wear particles is a powerful diagnosis tool, as chemical composition of components may be recognized, and thus the origin of wear particles may be determined. There are several types of spectrometric analysis, which differ to some extent in their principle mechanism utilized, and in analysing apparatus.

Atomic Absorption technologies:

Atomic Absorption Spectrometry (AAS) is a method which utilizes the principle that free atoms of different elements will absorb a set of given quant's of energy, in effect light at specific wavelengths, according to their orbital electron distribution. The sample is diluted and atomized in either an acetylene burner or a high temperature inert-gas environment, while a photon detector will measure the absorption of the free atoms of light which is directed at the sample. The technique will provide information about both particle concentration and chemical composition. Particle size cannot exceed 1µm.

Infrared Fourier Transformation (FT-IR) Spectrometry is used for oil analysis only, and uses infrared spectroanalysis to measure the amount of molecular compounds in an oil sample. The output is based on Fourier transformation of infrared absorbance versus wavelength, presented as cascade plots.

Atomic Emission Technologies

Atomic Emission Spectrometry (AES) is a method working on very similar principles as the AAS method, however instead of measuring absorption, one measures emission from excited atoms. The excitation of atoms is done by adding thermal energy, rather than directing (white) light at the specimen, thus the emission observed from the atoms are at wavelengths characteristic for the atom orbital distribution. Thermal energy quant's will initially be absorbed by the atom similar to what is observed when using AAS, but as we know, the excited atom will be in an instable state, and the energy quant will be emitted after very short time while leaving the atom at the initial stable state. Particle size is limited to a maximum of 5 µm; along with AAS this method is slow but accurate.

The **Rotating Disc Electrode (RDE)** method has evolved from AES. The specimen is lifted from a sampling cup by a rotating graphite electrode, then atoms are excited by a high-temperature discharging arc. Emitted wavelengths are detected by directing the radiation from the specimen through prisms onto photon detectors. The method is relatively quicker to perform than the above mentioned methods, because samples need no preparation before analysis. Size is limited to max. 8 µm. The principle is illustrated in Figure 15 below.

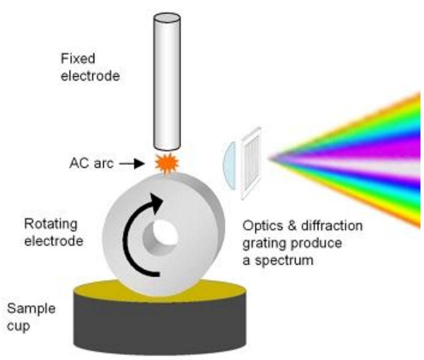


Figure 15: Rotating Disc Electrode illustration, source (14)

Inductive Coupled Plasma (ICP) is another method based on atomic emission. An electrically conducting gas is ionized and made into a high-temperature plasma source, by transferring power from a strong radio frequency source. The sample is introduced to the high temperature plasma torch by means of a nebulizer, spraying the sample oil into the plasma area. The technique is quite fast and has a large dynamic range, sensitive to both wear debris and additives in the oil. Maximum particle size is 5 µm.

Direct Current Plasma (DCP) has a significantly lower plasma temperature, but is otherwise very similar to ICP. The plasma generation is done using two graphite anodes and a tungsten cathode in stead of inductive heating of a gas. Cost of analysis is lower, has the same size-restriction on particles, but not equally large dynamical range.

Fluorescence Technologies:

X-ray Fluorescence (XRF) is an analysis method which can be utilized for liquid or solid samples taken from the oil, independent of size and without destroying the sample. Fluorescence is similar to atomic emission, in that an atom will absorb one amount of energy producing an instable exited state, then return to a more stable state while emitting energy. In atomic absorption the energy absorbed and emitted is equal, while in cases of fluorescence, the energy (i.e. wavelength of the radiation) is different from the absorbed energy. X-rays are radiated onto the sample to produce fluorescence, and elements are detected by the intensity of emitted radiation.

Energy Dispersive X-ray Analysis (EDX) is used on dry samples containing solids only. The sample is covered in a conductive coating and using a scanning electron microscope, the electron beam of the microscope is directed onto the sample, resulting in fluorescence, equally capable of detection as in the previous method. The method is fairly slow, but applicable for any particle size.

Description of all above spectrometric methods have been based on the more thorough descriptions found in (3 pp. 397-401).

Ferrographic analysis utilises a magnet to separate particles. Particles from non-ferrous materials such as e.g. copper and aluminium will thus not be detected by this analysis technique. An advantage over spectrography of normal ferrographic equipment is that their measurements can detect particles in the range of ca 1-100 microns, and thus they incorporate more of the larger debris which may result from wear.

According to (4), most ferrographic equipment is based on a two-stage analysis. The first is a Direct Reading Ferrography (DRF) device, which provides a quantitative analysis of wear particle size distribution. A strong magnet separates particles by size, and the density of particles of different size are measured by obscuration of beams of light directed through the particles. According to the same source, particle size is divided in two: large particles (>5 µm) and small particles (1-2 µm). As wear particles from normal wear predominantly produce small wear particles, while more severe wear will normally produce larger wear particles, the distribution of particle size taken from the DRF may be used to indicate severe and abnormal wear. The severity of wear index is based on this fact. If D_L denotes the concentration of large particles, and D_S denotes the concentration of small particles then (D_L+D_S) is proportional to the total sum of wear particles, while (D_L-D_S) is a measure of severity of the wear mechanism observed. The product of these two measures is called the severity of wear index (I_S):

$$I_S = (D_L + D_S)(D_L - D_S) = D_L{}^2 - D_S{}^2$$

Equation 11: Severity of wear Index, Source: (4 p. 8.10)

The second analysis stage of a ferrograph is qualitative in nature. The analyser consists of a pump delivering precise flow of oil onto specially treated glass surface, mounted at a given inclination relative to the horizontal plane, and equipped with a magnet. The oil sample is diluted and offset on the top of the glass surface, and will be affected by forces from both gravity and the magnet, and their distance covered down on the surface until at rest will be inversely related to the size of the particles. Large particles will almost instantly stop and fall to rest on top of the ferrogram, while the smallest (submicrosopic) particles will be offset at the bottom of the ferrogram.

"Wear particle analysis is an excellent failure analysis tool and can be used to understand the root-cause of catastrophic failures (11 p. 109)". From sources investigated on wear particle analysis ((1) and (11)), it is evident that lubricating oil analysis can be used for condition monitoring purposes. However, tribology in general is stated to have some disadvantageous limitations when it comes to cost of equipment, difficulty of collecting correct and relevant samples, along with the demand for very high level of expertise needed from the people responsible for interpreting data into useful information.

The conclusion drawn by Mr. Davies in (1 p. 467) is therefore that "…the methods of wear debris analysis should be seen as a complementary to the other techniques involved in condition monitoring". My interpretation of this fact, relevant to this thesis, is that wear debris analysis is not the best indicator for general degradation of machinery, but perhaps more typically called for when other CM activities are indicating deviances from normal operation. For the purpose of producing indices describing the general degradation of equipment, I therefore assume that utilizing wear debris analysis data alone will not be sufficient for any component or machinery system; however some indices could require input from several CM technology types, where wear debris analysis could be one out of several technologies utilized.

2.4.5 Visual Inspection (VI)

"Visual inspection is probably the simplest and most cost-effective method of condition monitoring", according to (1 p. 57). In its most basic form, visual inspection is done by the bare and un-aided human eye, and is thus a highly subjective method. However, the term visual inspection for CM appliances seems to have evolved into incorporating many aids which have been developed to aid the human eye in sensing changes in behaviour of a machinery or system. Typically, maintenance personnel will for one not only use their sight in inspecting equipment, they will in fact use all their human body senses: sight, smell, sound, taste and touch. Also, different kinds of practical and scientific aids to extend the reach of the human senses seem to have been encompassed into the definition of visual inspection, thus labelling these activities "visual inspection" in fact seems not very descriptive. The common feature of activities mentioned under the topic visual inspection in literature, are rather that these are activities which require a human operator to perform them. Categorizing them as "human intervention inspection techniques" or something similar would probably have been more precise.

Basic aids for visual inspection would encompass such equipment as lamps or mirrors to access inaccessible spaces, while many of the complex methods mentioned for other CM techniques in chapters above are classified as visual inspection methods as long as they are used by an operator as opposed to being mounted at a fixed place and operated automatically. This is typically because many of these methods were developed as an aid for operators in their inspections, while the principle later has been developed further and automated, either to reduce cost or because of the possibility of more objective evaluation if analytic interpretation of data is utilized, as opposed to the subjective opinion of an operator.

Simple aids include such equipment as:

- Borescope – optical rigid tube with eyepiece on one end and lens on the other for visual inspection in inaccessible areas, but accessible in a straight line (15).
- Fibrescope – flexible borescope with bundle of optical fibres dividing the image into pixels, used for inaccessible areas around corners and bends. Less accurate image than rigid borescope. Both borescopes and fibrescopes may be equipped with magnifiers, lighting possibilities and photo/video equipment (15).
- Stroboscopes – lamp producing a light flickering at adjustable rate. Helpful to make rotating equipment appear stationary, used to detect vibrations, imbalance or gaps (1 p. 58).
- Dye Penetrant Inspection (DPI) – used for detecting surface cracks. 1. The surface is cleaned and penetrant added, 2. excess penetrant is removed, 3. a developer is added to draw the penetrant out of the crack to make it visible, 4. inspection using white light or ultraviolet depending on fluorescence or visibility of the penetrant to identify cracks, before 5 the surface is cleaned after inspection procedure is finished (30).
- Magnetic flux leakage – method used for detection of corrosion, pitting or cracks, predominantly used for pipelines and storage tanks. The metal is magnetized by a strong magnet and a magnetic field detector is able to identify areas of abnormalities by the fact that the magnetic fields will "leak" out at these areas resulting in a weaker magnetic field (17).
- Eddy current testing – used for detection of both surface and sub-surface cracks in electrically conductive materials only. The principle is based on the fact that a circular coil with an alternating current will induce a variable magnetic field around it. The variable magnetic field will induce so-called eddy currents in the specimen. The eddy currents will change in case of varying electrical conductivity or magnetic permeability in the specimen, and these changes are identified either by a secondary search-coil or by measuring variations in the current in the primary excitation coil (32) .
- Corrosometer - low-cost electrical potentiometer used to detect corrosion. Detection level claimed to be in the range of 1 micron (1 p. 59).
- Visual temperature measurement - conducted by use of thermographic paints, crayons or tapes (1 p. 59).

More sophisticated aids presented as visual inspections methods in (1) are such methods as:

- Thermography
- Radiography, by X-ray or gamma-ray inspection
- Laser systems (for accurate distance and angle measurements)
- Imaging (humans have low memory for exact colours)
- Microscopes
- MRI Magnetic resonance imaging (very expensive)
- Ultrasonic's

Thermography and ultrasonic's have been investigated in other chapters, while radiographic examination was mentioned as one of the methods within tribological wear particle analysis, however, radiography could be used to produce images, e.g. of welds, in addition to be used for spectrometric analysis. Radiographic imaging is for probably most known for its application within medicine, to produce images of fractured bones or dental damage. Laser equipment could be used for precise geometrical survey of machine parts, because it can very accurately measure distance and angle. The equipment is portable, but expensive and demands a trained operator to use it. In automated visual inspection appliances, several techniques of imaging have been developed. One which may be very useful is colour imaging, because the human perception of colour is very objective, it is helpful to make judgement on the basis of analysing images rather than to rely on the human interpretation of the observed colour. Microscopes are of course a well-known tool to aid visual inspection, when information of materials down to a micro-level is needed. MRI-technology is a very expensive analysis method, and applicability for industrial purposes seems limited today, according to (1 p. 74).

2.4.6 Process Dynamics Parameter Analysis

Process dynamic parameter analysis, unlike other CM methods explained above, is not directed at detecting root-cause problems using explicit scientific methods, but rather at monitoring the calculated efficiency with which a system or component is observed to be performing its function. Such analysis could be vital to flag key parameters inflicting especially plant economy which are not normal, indicating that problems not detected by other CM methods are present.

For the purpose of this thesis, taking into account the FMECA analysis from the Project Thesis, the thermodynamical efficiency of heat exchangers and the efficiency of the numerous pumps and perhaps filters found to be critical could be monitored effectively using this concept. Review of the theory of process parameter analysis applicable to such component types are done in this chapter.

2.4.6.1 Thermodynamical Process Parameter Analysis for Heat Exchangers

In Appendix C, a fault tree describing typical failure causes for heat exchangers as presented by (9) can be inspected. Reduced heat transfer capability, typically a result of clogging, air entrapment or reduced foreign objects into heat exchangers, is one of the two main adverse effects which may lead to inadequate performance of heat exchangers. The other as we can see is leakage from material defects. Heat exchangers are however usually equipped with control systems, using by-passing or restricting flow principles, to ensure correct temperature on the target flow. Thus, heat exchangers may be operating with severe inefficiencies without it showing on the temperature of the target outflow. In effect, we have to monitor the thermal efficiency of the heat exchanger in order to uncover such problems. This can be done relatively easy by means of process parameter analysis, given that we have sufficient and calibrated measurements of the correct parameters.

The parameter best describing the change in heat transfer efficiency is the heat transfer coefficient, defined by:

$$k = \frac{\dot{Q}}{A\Delta T_m}[KW/m^2K]$$

Equation 12: Heat transfer coefficient k, Source: (4)

$\dot{Q}$ = heat input or heat lost [J]

A = heat transfer surface area, [m^2]

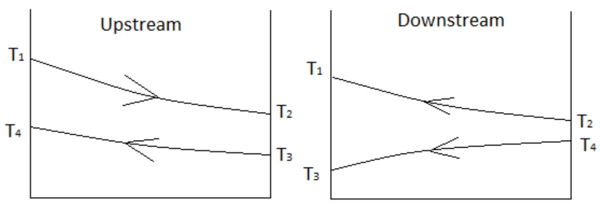
ΔT_m = mean temperature difference, [K]

For unified parallel flow directions, either upstream or downstream, the logarithmic temperature difference is utilized. In case of other types of geometry it may be more applicable to use the arithmetic temperature difference, depending on the specific flow geometry. The formulas for these two temperature differences are given as follows:

$$\Delta T_{\log} = \frac{\theta_1 - \theta_2}{\ln \frac{\theta_1}{\theta_2}} \text{ logarithmically, or } \Delta T_{artm} = \frac{T_1 + T_2}{2} - \frac{T_3 + T_4}{2}, \text{ arithmetically}$$

Equation 13: Logarithmic and arithmetic temperature differences for heat exchangers, Source: (4)

Below Figure 16 gives an illustration of the correct temperature locations for upstream and downstream configuration of heat exchangers.



$$\theta_1 = T_1 - T_4 \qquad \theta_1 = T_1 - T_3$$
$$\theta_2 = T_2 - T_3 \qquad \theta_2 = T_2 - T_4$$

Figure 16: Temperature locations for formula of temperature difference in heat exchangers, Source: (10)

The condition parameter to be monitored for heat exchangers, as proposed by (10) is:

$$\text{Cond.}parameter_{heatex} = \frac{k_{ref} - k_{meas}}{k_{ref}}$$

Equation 14: TCI parameter for heat exchangers, source (4)

where k_{ref} is the measured reference value, while k_{meas} is the measured value.

In effect, the surface area is a constant, and the absolute value is of little interest since the condition parameter is a relative comparison, and it could be set to equal to any constant. If the surface area or the heat exchange coefficient of new condition is given in documentation, the correct value of A should be used to provide the correct heat transfer coefficient.

The heat added to (or withdrawn from) mediums must be known or calculated from the temperature change in either medium, or as a mean of the two, by the formula:

$$\dot{Q} = \dot{m} \cdot c_p \cdot \Delta T,$$

Equation 15: Heat input or loss Q from temperature difference, Source: (4)

Where $\dot{m}$ is the mass flow of the medium [kg/s], c_p is mean specific heat capacity at constant pressure, and ΔT is the temperature difference of the medium. For comparison at equal flow rates, this index can be used without corrections. Therefore, measurements must either be taken at similar flow rates or corrections must be made.

In order to perform condition monitoring activities on heat exchangers we therefore have to measure:

- T1, T2, T3, T4 - Temperature of both mediums entering and exiting the heat exchanger
- $\dot{m}$ - mass flow of at least one of the two mediums, preferably both

In addition, we need to know the specific heat capacity c_p of at least one, preferably both of the mediums.

2.4.6.2 Process Parameter Analysis of Pumps

A number of root-cause failures of pumps may be detected by vibration monitoring, however the efficiency of a pump may also provide vital indications of deviations from ideal operating conditions for pumps. Specific pump internal wear mechanisms such as corrosion, erosion, fouling and worn seals may inflict pumps negatively (9 p. 6.33), without it necessarily being detected by vibration monitoring equipment. This is where the importance of process parameter analysis comes into play.

Process parameter analysis of pumps could be performed in several ways, according to (9) using such methods as:

- Pump efficiency, by head-flow-power measurement
- Full head-flow testing
- Simplified head-flow test at duty point
- Shut-off Head method

The most extensive method is done by monitoring the pump efficiency, through head-flow-power measurements, as pump efficiency is given by the formula:

$$\eta_P = \frac{Q \rho g H}{P}$$

Equation 16: Pump efficiency formula; Source (32 p. 47)

where;

Q=flow [m^3/s]
ρ=density [kg/m^3]
g=grav.const. [m/s^2]
H=Head [m]
P=Power[W]

Monitoring and trending the efficiency is the most complete and best indicator of pump performance. Complete Head-Flow-Power test are usually part of standard acceptance testing of new equipment, where η_{Pref} -diagrams are established, while rarely needed for monitoring (32 p. 56) as less requiring methods may also provide useful information on pump internal conditions.

Head-Flow testing is a simpler method where power consumption is removed from the consideration. In a full head-flow test the complete datum curve for a pump may be established. The pump is set to manual control and throttled by the discharge valve to obtain a full series of readings/measurements of pressure difference (Head) vs. flow rate of the pump. Comparisons of head flow curves of worn pumps to new condition will demonstrate a lowering of the head-flow curve. For equal flow rate, the worn pump will produce smaller differential pressure, whereas for equal head the flow rate will be reduced if worn.

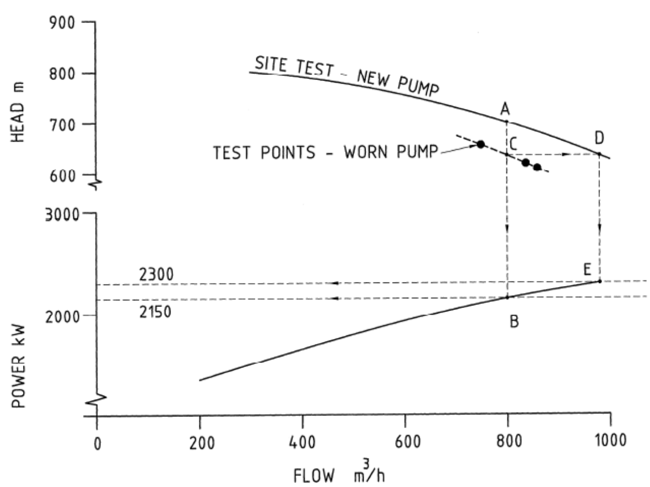


Figure 17: Illustration of head flow characteristic of worn pump vs. new pump, Source: (33)

Using a full head flow comparison for condition monitoring purposes has two adverse consequences. If the pumps are part of a continuous running process system, the system most likely will have to be shut down, as output from the pump is varied during the test. Also, the method is said to be unpopular with operators who had to work the discharge valve (32 p. 57), as this for several pumps is time-consuming and very un-inspiring work.

Head Flow test at duty point is *considered to be the most useful condition monitoring method*, because it will detect both internal deterioration and change in system resistance (33). Such testing is done by comparing differential pressure over the pump with the reference differential pressure at equal flow at the duty point, i.e. at a constant pump speed. A reference head-flow curve is established using similar procedures as for a complete head flow test, however not in the full operating range of the pump, but limited to 10-15 points within an area close to the normal operating condition of the pump. Future registrations of head and flow at the same pump speed as the established reference curve are sufficient to perform CM. For the measured flow rate, the ratio of differential pressure measured to reference differential pressure is used as an indicator. In order to perform such monitoring it is needed to measure:

- Flow rate, either mass flow [kg/s] or volumetric flow [L/h], [m^3/h] or similar
- Differential pressure over the pump [kPa]

If such sensors are permanently fitted, or flanges to mount gauges or sensors during operation of the pumps, then the pumps may be monitored without being taken out of service and with minimum work for operators.

Care should be taken, however, to ensure that establishing the flow rate is done in a correct manner. If the measured value is the volumetric flow, than differences in density due to changing mediums, or temperature differences (affecting density) may have to be taken into consideration. With reference to systems under study in this Thesis, this is of course an issue especially within the fuel system, as fuels will vary in chemical composition and thus vary in density.

Shut-off head method (or dead-head) measurement is yet another technique for pump monitoring, where the discharge valve of the pump is closed during the test, allowing zero flow from the pump. Suction and discharge pressures along with temperature are registered and compared to reference testing. This method has severe limitations; for obvious reasons the test will require shut down of adjacent process systems, but also some high-energy pumps cannot be tolerated to operate at zero flow. More importantly, the test does not reveal the condition of the system (32 p. 60). Therefore, I find that the shut-off head method is not worthy of further investigation in this study, as applicability as a general CM indicator seems limited.

3 Identification of Components Subject to Condition Monitoring

For the purpose of this chapter, it is especially important for the reader to be well acquainted with the prior Project Thesis (19) concluded as a preparation study for this Thesis, where detailed system descriptions, brake-down of systems into sub-systems and criticality analysis were made. I assume the reader has access and knowledge of the content of this document.

The FMECA results from chapter 4.8 in (19) will provide the basis for the selection of components which are to be subject of CM. The result of the FMECA was a list of component criticality for all components sub-system by sub-system, for all eight defined sub-systems in study for this Thesis. The comprehensiveness of the CM will have implications both economically, and with respect to the impact the program will have for crewmembers on board who will have to perform tasks induced by the CM programme. With respect to number of components to be monitored, agreement was made with the Supervisor that 2-4 components per sub-system should be a reasonable estimate for the comprehensiveness of the CM programme.

Since the criticality of the components have been thoroughly investigated in the FMECA analysis, and is the best criterion by which to prioritize the activities and resources spent on CM, I do not feel the need to make this decision process very comprehensible. The process of making the selection will thus be based on investigating the results from the FMECA analysis, and making selection of components which I believe will be sufficient to monitor.

The proposed list of components to be monitored is seen below in Table 4:

System	Sub-system	Component Name	No. of comp.	Sys. Importance	Agg Criticality
Fuel Oil	Transfer	Settling Tank Pre-heater	1	0,5	5
		Feed Pumps	2	0,5	3
		Settling Tank Heating	1	0,5	3
	Purification	Control Valve Sep. Water Outlet	2	1	18
		Regulating Valve Sep. oil outlet	2	1	18
		Heater	2	1	14,5
		Inlet Control Valve	2	1	14
		Separator	2	1	13
		Feed Pump	2	1	11,5
	Circulation	Supply Pressure Control Valve	1	2	26
		Fuel Oil Heaters	2	2	20
		Circulation Pumps	2	2	18
		Fuel Selection Changeo. Valve	1	2	14
		Flow Transmitter Bypass Valve	1	2	12
		Supply Pumps	2	2	12
Lubricating Oil	Circulation	Piston Lube Oil Cooler*	1	1,5	33
		3-way flow split valve	1	1,5	25,5
		Lube Oil Pumps	2	1,5	16,5
		Other Lube Oil Cooler*	1	1,5	16,5
	Cleaning	Control Valve Separated Water Outlet	1	1	21
		Regulating Valve Separator Oil Outlet	1	1	20
		Inlet Control Valve	1	1	17
		Separator	1	1	17
Cooling Water	Seawater	Inlet Control Valve	2	1	16
		Filters	2	1	23
		Central Coolers*	2	1	11
		Central Cooler Selection Valve	2	1	10
		Seawater Pump Selection Valve	2	1	8
		Seawater Pumps	2	1	6
	Freshwater	3-way Pneumatic Reg. Valve	1	1	11
		Freshwater Pumps	2	1	8
	Jacket	3-way Regulating Valve	1	1	11
		Jacket Water Cooler*	1	1	11
		Jacket Water Pump Selection Valves	2	1	10
		Jacket Water Cooling Pumps	2	1	9
All systems in total		35 component types	55	individual components	

Table 4: Components subject to CM, note that component criticality is not directly comparable between systems.

*Component is part of more than one individual sub-system.

This selection has in all essence been done by collecting the 2-4 most critical components for each sub-system, although a few notable exceptions have been made:

- Scavenge air cooler from the Central Cooling Freshwater system is not included, because it is considered to be part of the engine. Also this item is included in the TCI concept applied to Main Engines in previous Flagship and TeCoMan work (7).
- For the Fuel Oil Purification System, I felt that it was logic to extend the amount of components to six, to include feed pumps and the main component itself, the separator.

- In the Fuel Oil Circulation System, the list was similarly extended to six components to include the supply pumps, as I believe these are relevant for CM. As Flow Transmitter Bypass Valve showed higher criticality than the pumps, this item was also included.
- Similar to the two elements above, the number of components monitored for the Seawater Cooling system was extended to include the seawater pumps and their selection valves. The low criticality of these pumps seems unlikely, because without a functioning seawater pumping capacity, the entire cooling system will cease to function.

As for the number of components included for the cooling water system, I chose to include only the pumps dimensioned for operation at sea, as this system both with respect to freshwater and seawater pumps are provided with 2x100% capacity plus an extra pump intended for operation in port. Of course, any pump could be utilized in any mode, and this is probably the reason why the pumps show their surprisingly low level of criticality in the FMECA analysis. I believe the most important thing, especially with regards to economy, is that the larger pumps used for operation at sea are condition monitored.

I find that the amount of components subject to CM is vast by this selection, but I have problems reducing it. The criticality assessment of the different components produced in the Project Thesis was in-depth in terms of methodology, but the frequencies of failure which were used were rather rough, and therefore I do not like the thought of keeping central components out of the scope of CM. Another important element, which I have limited knowledge on, is what kind of minimum maintenance and/or test regime these components are subject to by default through existing procedures. A more practically experienced analyst would probably be able to take such concerns into consideration in order to make a more sound judgement.

For the purpose of planning CM activities, I find it relevant to organize the components subject to CM by component type, rather than by system as done above. This rather large amount of components to monitor will require standardized procedures based on component type rather than individual CM methods for each component. Below Table 5 shows the largest category of components, the valves.

Component type	Component name	System	Sub-system	No. of Comp.
Valves	Control Sep. Water Out	Fuel	Purification	2
	Regulating Sep Oil Out	Fuel	Purification	2
	Inlet Control Valve	Fuel	Purification	2
	Supply Pressure Control	Fuel	Circulation	1
	Fuel Selection Changeover	Fuel	Circulation	1
	Flow Transmitter Bypass	Fuel	Circulation	1
	3-way Flow Split	Lubricating	Circulation	1
	Control Sep. Water Out	Lubricating	Cleaning	1
	Regulating Sep Oil Out	Lubricating	Cleaning	1
	Inlet Control Valve	Lubricating	Cleaning	1
	Inlet Control Valve	Cooling	Seawater	2
	Central Cooler Selection	Cooling	Seawater	2
	Seawater Pump Selection	Cooling	Seawater	2
	3-way Pneumatic Regulating	Cooling	Freshwater	1
	3-way Regulating	Cooling	Jacket	1
	Jacket Water Pump Selection	Cooling	Jacket	2
Total Valves	16	types	individuals:	23

Table 5: Valves to be condition monitored

The second largest category of components is the pumps, summarized below in Table 6.

Component type	Component name	System	Sub-system	No. of Comp.
Pumps	Fuel Transfer Feed Pumps	Fuel	Transfer	2
	Separator Feed Pumps	Fuel	Purification	2
	Supply Pumps	Fuel	Circulation	2
	Circulation (Booster) Pumps	Fuel	Circulation	2
	Lube Oil Pumps	Lubricating	Circulation	2
	Seawater Pumps	Cooling	Seawater	2
	Freshwater Pumps	Cooling	Freshwater	2
	Jacket Water Cooling	Cooling	Jacket	2
Total Pumps		8 types	individuals:	16

Table 6: Pumps to be condition monitored

The third and last main group of components which will be subject of condition monitoring are the heat exchangers, as seen below.

Component type	Component name	System	Sub-system	No. of Comp.
Heat exchangers	Settling Tank Preheater	Fuel	Transfer	1
	Separator Pre-heater	Fuel	Purification	2
	Fuel Oil Heaters	Fuel	Circulation	2
	Piston Lube Oil Cooler	Cooling&Lubricating	Freshwater/Circulation	1
	Other Lube Oil Cooler	Cooling&Lubricating	Freshwater/Circulation	1
	Central Cooler	Cooling	Seawater/Freshwater	2
	Jacket Water Cooler	Cooling	Jacket/Freshwater	1
Total Heat exchangers		7 types	individuals:	10

Table 7: Heat exchangers to be condition monitored

In addition to these three major units there are four other components to be condition monitored:

Component type	Component name	System	Sub-system	No. of Comp.
Separator	Fuel Oil Separators	Fuel	Purification	2
Separator	Lubricating Oil Separator	Lubricating	Cleaning	1
Filters	Seawater Intake Filters	Cooling	Seawater	2
Heating Coil	Settling Tank Heating	Fuel	Transfer/Purification	1
Total Other		4 types	individuals:	6

Table 8: Other components to be condition monitored

Fuel oil and Lubricating oil separators should in all essence be considered as identical component types and condition monitoring activities for these two components should be identical. Condition Monitoring of the settling tank heating coil was proven vital in the FMECA analysis; it seems unlikely however to condition monitor only one single heating coil when we know that also bunker tanks are equipped with such equipment. Similar holds for the filters. In addition to being paralleled, I've since work with the Project Thesis FMECA found out that most seawater intake filters today are automatic back flush filters where pressure drop over the filters are monitored and clogging is prevented by applying a high pressure flow in opposite of the normal direction. Since the "other components" category in light of the above seems much less important than the three major component groups, emphasis will be put into developing TCI's for these three component groups.

4 Collecting and Incorporating Inspections Data into TCI's

In the current practice within the TOCC pilot programs utilizing TeCoMan with the TCI concept, all data acquisition is reported to TOCC from the ship on a monthly basis. The process is not automated as it depends on operators to fill in designated forms provided by TOCC. The forms, however, are computerized as they consist of pdf documents where tables containing the designated parameters to be monitored are filled in on a computer by operators on board. When the form is completed, it is emailed as a .pdf file to TOCC, where it is converted to a .xml file (which is the input file format which TeCoMan requires) by a TOCC employee and uploaded to the TOCC database.

To my knowledge, all data reported to TeCoMan are thus inspection data in the sense that no data is transmitted directly from sensors on board into the TeCoMan system, but has been referenced by an operator on board who may have read it from data collectors, gauges or other instruments on board.

From what I understand, most shipowner's ship management and maintenance programs include monthly reports of data considered to be relevant to manage consumption of consumables and forecast maintenance needs. From one shipowner I have received what they call an "Engine Report" which includes the data which is monthly reported from the ship to the shore-based organization. The document is included in 0 , but has been made anonymous by request from the company. From inspecting this report, we can observe that large amounts of data relevant to engine performance including fuel and lubricating oil properties are already reported within a ship owning company which does not utilize the TeCoMan TCI system. According to the technical employee who presented me with this information, most of these values were readily available from instruments on board, and many of the important variables are checked much more frequently by crew, without being reported.

From this observation I draw the conclusion that collecting data from technical systems relevant for vital machinery on a monthly basis is a common practice, undertaken by most ship owning companies, and probably this is also the reason why reporting to TeCoMan currently is done on a monthly basis; for convenience. If the systems studied in this Thesis should be included in similar pilot program to prove the validity of methods used, I would suggest reporting be done similar to the current reporting scheme within TeCoMan, simply by adding the desired measurements and variables relevant for these systems into current TeCoMan reporting forms.

I have not been granted access to the software to produce such TeCoMan registration forms, and in agreement with the Supervisor, producing such forms for the proposed CM programme is not considered within the scope of work in this Thesis.

As a comment, however, I would like to point out that if the TCI concept should be applied to numerous other systems, not only machinery systems but generally all relevant ship systems, then the data acquisition process must be automated to a greater extent. Otherwise, the amount of labour placed at the crew of the ships will not be sustainable. Being no computer engineer, exactly how this process could be automated is not a question I know the answer to. However, as illustrated in chapter 2.2, I believe integrating information from the ship system databases into TeCoMan should be possible, allowing TeCoMan to access relevant information already recorded by ship systems without the need to input these manually into a form and emailing it to TOCC. If export of measurements already recorded and available in the ship system were automatically exported to TeCoMan, then the only attention the crew would need to have of CM activities would be the collection of true inspection data. By true inspection data I mean data collected where the human element cannot be replaced. This is the case where data are not logged electronically, typically readings of analogue gauges or similar, or where CM is performed by assessing the objective observations made by a human operator inspecting a component.

5 Condition Monitoring Programme

This chapter will be concentrated at describing the proposed CM programme for the systems studied during Project and Master Thesis. As indicated in chapter 0, I intend to group similar components together and select methods which are generically applicable to all components within each such component category. Standardizing the procedures is critical in order to reduce complexity of the CM efforts and investments. Standardizing CM methods will ease performance comparisons, reduce the need to educate operators to perform CM related tasks, reduce investments in sensor equipment and implementation into TeCoMan or similar applications will be simplified.

Defining the CM program implicates for each component type the evaluation of such items as:

- Selection of relevant CM technologies for component groups
- Description of parameter to be used as TCI
- Measurement procedures and equipment required

5.1 Valves

5.1.1 Condition Monitoring Technology Selection

The component group which includes the largest number of units are the valves, totalling at 16 types comprising 23 individual valves. Due to the large number of units found to be critical and thus selected for CM, one would expect it to be important to find efficient methods of performing CM for this group. Yet I have significant problems finding out how, or in fact even whether or not, to perform CM on the valves, mainly for two reasons:

- During my literature study on CM technologies, very few of the investigated sources have described applicable methods of performing CM on valves.

- Also, the nature of this Thesis complicates the matter, since the intention is to develop TCI's for generic systems, meaning that I am not looking at one real life existing system, but at a general system. Detail data of the equipment to be monitored is thus not available. Valves come in a great number of configurations and designs, and from the sources investigated in the Project thesis (1) where I tried to define the typical generic systems, valves were either not described in detail or they were simply said to vary in configuration within a number of options.

Due to these facts, I find myself insecure of whether or not the conclusion drawn in chapter 0 to perform condition monitoring of valves on these system was correct. If TCI's are to be established, they need to rely on collection of repeatable data which are relevant for predicting the development of typical root-cause failure mechanisms.

Most valves defined as candidates for CM in chapter 0 are regulating or control valves. According to (2 p. 249), control valves have limited common failure modes, however it is indicated that most failures relate to leakage or problems with the actuator mechanisms. Actuators vary in operating principle between mainly pneumatic, hydraulic or electrical actuators in addition to manually operated control valves. With such variation in actuators, it is difficult to identify a general methodology which would apply to all actuator types. The integrity of valves with respect to leakage is documented through pressure testing at manufacturer or client final acceptance tests upon delivery. However, I have not been able to find that such test can be proven viable as a condition monitoring method. This is probably due to the fact that such test would demand the valve to be taken out of service, either dismounted and put into a testing environment or that the local environment at one or both sides of the valve would be pressurized.

If TCI's should be created for valves, the parameters will probably have to be tailor made for different valve types, but typically would have to rely inspection or non-destructive test methods which would involve such elements as:

- Taking the pump out of service
- Function testing of the actuator mechanism
- Pressure testing for leak detection
- Inspecting material wear on internal components

Having discussed the difficulty of performing CM on valves with the Supervisor, my view that this is not an easy task to be done cost effectively was too a large degree confirmed. We agreed that TCI's for valves, if applicable, would have to rely on inspection data, which will require valves to be taken out of operation. Taking into consideration the number of valves to be monitored for the mere 3 systems in study in this Thesis, I highly doubt such CM procedures will prove beneficial. Therefore, I have decided not to recommend involving valves into the TCI parameter monitoring of the systems in study.

5.2 Pumps

5.2.1 Condition Monitoring Technology Selection

In chapter 0 it was identified in total eight pump types, all paralleled, thus resulting in totally 16 pumps to be condition monitored. To my knowledge, all pumps within the three systems studied are typically of centrifugal fixed speed type, and therefore quite similar in working principle. The main differences between the pumps are the mediums they are used to pump, and their physical size and capacities.

Pumps are rotating machinery, and from investigations made in chapter 2.4.1 they are obvious candidates for vibration monitoring. Of the methods investigated during the literature study on vibration monitoring, ISO standards were found to be applicable to classify general vibration severity specific to centrifugal pumps, and I believe TCI parameters should be based on the methodology and threshold values presented in such standards. The standards presents threshold values for vibration measured on bearings or bearing housings, presented in velocity-RMS value, where machines are classified by their foundation, either rigid or flexible, and power range. Vibration severity monitoring should be able to indicate such machine train failures as imbalance, misalignment, bent shafts or loose bolts according to 0, and I propose this method is included in the CM programme for all pumps.

Although such vibration severity is measured on the bearings, detection of damage to rolling element bearings themselves are generally not detected by such low-frequency vibration measurement using RMS values, as rolling element bearing failures will produce shock-like high frequency vibrations. Detection of rolling element bearing degrading using trending of parameters like the Crest-factor or

Kurtosis factors have been mentioned, but necessitates continuous or at least very frequent monitoring, as they only will provide a short increase during incipient failure. Due to the current nature of the reporting scheme within TeCoMan based on monthly reports, such methods would probably provide limited value, and I will not recommend Crest-factor or Kurtosis-factor trending used as TCI parameter within the current TOCC reporting scheme.

Alternatively, TCI's for prediction of bearing failure could be based on higher frequency range structure borne ultrasonic techniques, as indicated in chapter 2.4.2. Remembering the contents of this chapter, however, developing TCI's based on this technology is problematic for two reasons:

- The use of ultrasonic's as an alternative to vibration monitoring is disputed by several sources investigated.
- The technologies developed seem to vary in signal processing method, each technique being protected by trademarks, which makes complicated to ascertain the exact analysis method utilized.

Therefore, I propose to limit the CM activities undertaken on pump bearings to vibration monitoring, where guidelines and threshold values are given in ISO-standards, which assures that the technology is proven.

In addition to the such vibration monitoring, aimed at identifying machine train problems related to the pump, the process parameter analysis method described in chapter 2.4.6.2 is chosen as basis for pump TCI's. This method of CM of pumps will verify that the efficiency of the internals of the pump is maintained.

Technologies selected to make basis for TCI's for pumps are therefore:

- Vibration monitoring, based on ISO 103945, ISO 10816-3 or similar methods
- Process parameter analysis, based on Head-flow test at duty point

5.2.2 TCI Parameter for Pump Vibration Monitoring

For the vibration monitoring of pumps, applicable ISO standards are chosen as basis for TCI calculation. ISO 3945 provides threshold values for measured RMS-value of vibration velocity for general machines, while ISO standard 10816-3 is dedicated for centrifugal pumps. Vibration severity classifications based on ISO 2945 is included in Appendix A. Assuming pumps are single speed, the TCI parameter for each bearing will simply be the measured vibration velocity RMS value. The threshold values from standards will therefore be utilized in the transfer function in TeCoMan, which relates parameters to TCI's, rather than to calculate the parameter itself. The severity threshold values are applicable to all bearings or bearing housings associated with the pump.

5.2.3 Measurements for Pump Vibration Monitoring

A pump drive train will typically include bearings on each end of the electric motor, plus two bearings, one located where the shaft enters the pump unit, and another bearing position in between the aforementioned bearing and the rotor. For most cases I believe that on the pump side, only the bearing located at the end is accessible for measurements. Thus, for the standard pump, there will be three bearings to be measured.

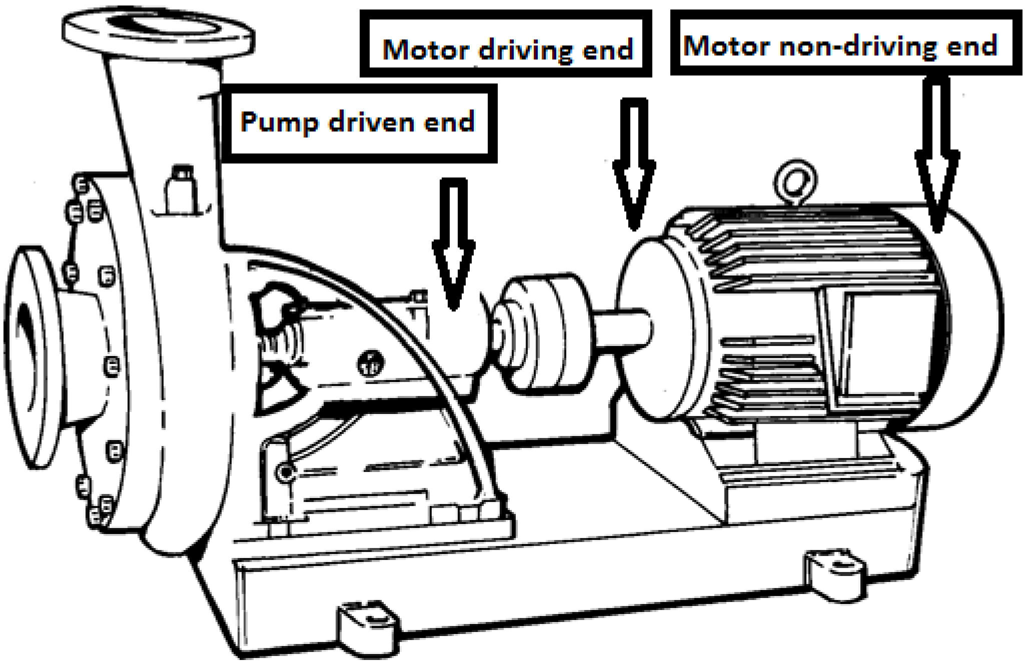


Figure 18: Centrifugal pump vibration measurement locations, Source: Authors own

The sensor to be used must be capable of recording vibration velocity in the 10-1000 Hz frequency range and displaying the mm/s-RMS value. In practice, most piezo-electric accelerometers for the intended frequency range equipped with an integrator will be able to display this value, and could be utilized. For such monthly sampling as required for the application in this study, the only reasonable solution is to use a single portable transducer for all measurements. According to (2 p. 348), handheld transducers, or even magnetically fixed ones should be avoided at all times. The best solution ensuring measurements are repeatable is to install quick-connection mounts at each measurement point.

5.2.4 TCI Parameter for Pump Process Parameter Analysis

The proposed TCI parameter for the head flow test at duty point is the percentage drop in pump head (differential pressure over the pump) at volumetric flow through the pump relevant to the reference condition:

$$TCIparam\_headflow_{pump}(\Delta p_{meas}, \dot{v}flow_{meas}) = 100 \times \frac{\Delta p_{meas} - \Delta p_{ref}(\dot{v}flow_{meas})}{\Delta p_{ref}(\dot{v}flow_{meas})} \text{ [\%]}, where:$$

Δp_{meas} = measured differential pressure over pump [kPa]

$\dot{v}flow_{meas}$ = measured volumetric flow through the pump [L/h]

$\Delta p_{ref}(\dot{v}flow_{meas})$ = value of reference differential pressure over pump at measured flow rate

Equation 17: TCI parameter for head flow test at duty point for pumps.

In order to calculate $\Delta p_{ref}(\dot{v}flow_{meas})$ the reference head – flow curve as function of the volume flow must be established during reference testing. Assuming any head flow curve could be described by a 2nd degree polynomial, regression analysis must be performed on data collected during such reference testing to establish the reference constants (a, b and c) for this polynomial:

$$\Delta p_{ref}(\dot{v}flow_{ref}) = a \times \dot{v}flow_{ref}^{\,2} + b \times \dot{v}flow_{ref} + c$$

Equation 18: Reference head-flow polynomial

Effectively, the complete representation of the TCI parameter formula is therefore:

$$TCIparam\_headflow_{pump}(\Delta p_{meas}, \dot{v}flow_{meas}, a, b, c) = 100 \times \frac{\Delta p_{meas} - (a \times \dot{v}flow_{meas}^{\,2} + b \times \dot{v}flow_{meas} + c)}{a \times \dot{v}flow_{meas}^{\,2} + b \times \dot{v}flow_{meas} + c} \text{ [\%]}$$

Equation 19: Complete TCI parameter formula

Where constants a, b and c are established based on regression analysis of Equation 18 using reference data. The constants represent input parameters for the TCI, while Δp_{meas} and $\dot{v}flow_{meas}$ are input variables.

5.2.5 Measurements for Pump Process Parameter Analysis

As indicated above, the pressure difference Δp [kPa] over the pump and the accompanying flow $\dot{v}flow$ [L/s] through the pump are the measurements which are necessary in order to calculate the TCI parameter. Regression analysis to find parameters a, b and c to be included are based on measurements of these same two variables. If the pump is not equipped with a reliable mass flow or volume flow measurement, one proven method of providing this information is by mounting either an orifice plate or a venturi, and calculating the mass flow by formula provided in ISO 5167, as described further in Appendix E. According to (9 p. 38), pressure readings can be facilitated by mounting tapping's for pressure gauges at both pump suction and discharge flanges, if electronic transducers have not already been mounted. NB! Attention must be kept at whether suction pressure is negative (below atmospheric) or not at the pressure reading on the suction side of the pump!

5.3 Heat Exchangers

5.3.1 Condition Monitoring Technology selection

Heat exchangers are a major component group, as I have identified seven different heat exchanger types to be monitored, totalling at 10 heat exchangers for the three systems studied. Remembering the fault tree in Appendix C, the desire is to monitor the heat exchanger in order to detect development of any of the two failure major failure modes:

- Fouling resulting in reduced heat transfer
- Material defect resulting in leaks

Process parameter analysis, by calculating the overall heat transfer coefficient, as presented in chapter 2.4.6.1, is ideal to monitor the overall efficiency of a heat exchanger. Therefore, I will apply this method to the heat exchangers.

Leakage in a heat exchanger will typically be due to corrosion. If the heat exchanger is leaking, this is failure will probably materialize in obvious adverse conditions; an external leak will show spillage from the heat exchanger, while internal leaks will affect the heat transfer coefficient as well as mixing the mediums. Therefore, I believe that detection of a leakage situation itself should not be the intention of CM of the heat exchanger. CM methods relating to leaks, if applied, should be aimed at uncovering the root-cause of material defects, which in most cases would be corrosion. However, performing trending of the corrosion situation in a heat exchanger is a complex matter. Both galvanic corrosion and corrosion due to turbulence flow would typically develop in a local area of the heat exchanger which is not easily identified, as a heat exchanger is designed to provide a maximum heat exchange area in the smallest volume possible. In order to predict with some certainty the integrity of materials in a heat exchanger, it would be necessary to perform inspection or thickness measurements of the entire surface of the essential tubes, which would necessitate the system to be taken out of operation for a considerable period of time. I believe such actions would be much to elaborate just in order to establish an indicator of condition, and therefore I will limit CM of heat exchangers to encompass process parameter analysis for detection of reduced heat transfer coefficient.

5.3.2 TCI Parameter for Heat Exchanger Process Parameter Analysis

The proposed condition parameter using process parameter analysis for heat exchangers to indicate overall heat exchanger degradation is the drop in heat transfer coefficient compared to the reference value in new condition, as presented previously in Equation 14 chapter 2.4.6.1:

$$\text{Cond.}parameter_{heatex} = \frac{k_{ref} - k_{meas}}{k_{ref}}$$

For simplicity and to more intuitively relate to a range from 0-100, which is the range of TCI's, I would like to modify the parameter slightly from the "relative degradation" above, into "percentage drop" TCI parameter by multiplying the expression by -100:

$$\mathrm{TCI}parameter_{heatex} = -100 \times \frac{k_{meas} - k_{ref}}{k_{ref}} = 100 \times \frac{k_{ref} - k_{meas}}{k_{ref}}$$

Equation 20: Heat exchanger TCI parameter

Since a number of heat exchangers are to be monitored, establishing a TeCoMan user function which takes in the relevant static parameters along with measurement variables to produce this condition indicator will be useful. This will be described further in chapter 0.

5.3.3 Measurements for Heat Exchanger Process Parameter Analysis

From the equations in 2.4.6.1, it is obvious that we need to monitor the four different temperatures going into and out of the heat exchanger. In addition we need to know the mass flow of one of the mediums. Since the target flow in a heat exchanger may be temperature regulated by by-passing some of the flow, it is important to measure the local temperature at the inlet and outlet flow of the heat exchanger, thus measuring the temperature *fluid which actually travels through it*, and not the bulk temperature or mass flow which partially may by-pass the heat exchanger.

The reference value has to be calculated based on similar measurements according to the formula and preferably knowledge of the heat transfer area. If heat transfer area is not known, it is adequate to calculate reference heat transfer coefficient using an arbitrary constant for the area, as long as the same constant set as the parameter for heat transfer area.

5.4 Other Components

As indicated in chapter 3, the main focus of the development of the CM programme and TCI's was at the aforementioned three component groups. Seawater inlet filters of recent date have in (34) been found to typically be automatic back flush filters which in effect already are equipped with sensors which indicate when filters are clogged and in need of being flushed. Therefore I consider development of TCI's for these not important.

The settling tank heating is one out of numerous tank heating coils, as all heavy fuels have to be continuously heated to prevent them from solidifying within tanks. Heating coil systems may be based on electricity, thermal oil, hot water or steam. Therefore there is no obvious and readily available method of performing general condition monitoring of such equipment, but it would have to be assessed individually with the system at hand.

Separators are rotating machinery, and therefore candidates for vibration monitoring. A separator is in fact quite similar to a pump when looking at the machine train configuration. The shaft rotating in the separator is driven by an electric motor, and with or without gears, it has to be supported by a bearing in the bottom section of the separator. I assume similar vibration monitoring as utilized for pumps can be applied to separators. This will include measurement of vibration levels at the motor driving end, motor non driving end and on the driven end of the separator. The TCI parameter is the measured vibration velocity (mm/s-RMS), and the thresholds for general machinery vibrations given in ISO 3945 are assumed to be applicable to be utilized in the TCI transfer function.

6 Implementation into TeCoMan

6.1 Software Overview

The TeCoMan software is best described by investigating the main platform window where icons to open subsequent task dedicated windows are shown. In order to give the reader a short overview below Figure 19 is included, showing a print screen illustration where the main platform window and perhaps the most frequently used menu window, the explorer window, are open. The print screen has been manipulated with numbers below icons of some important sub-menus.

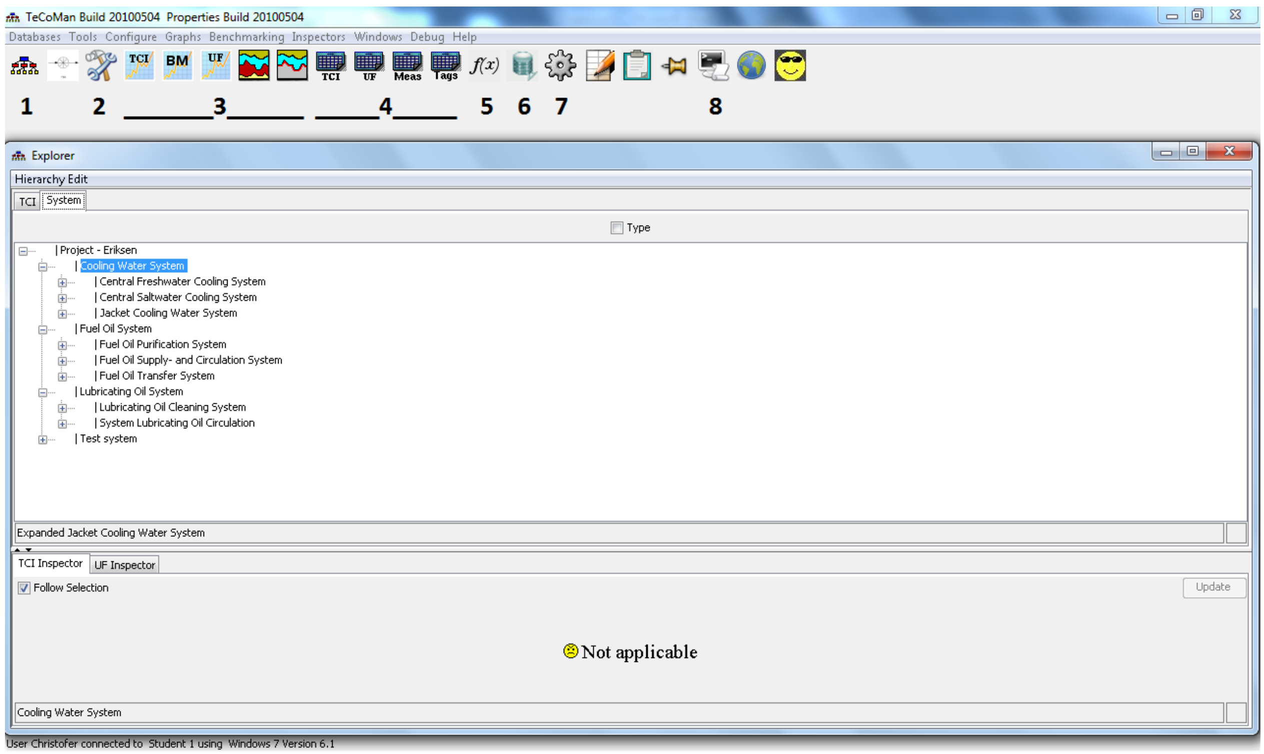


Figure 19: Overview of TeCoMan program window, including the higher level system hierarchy.

The main window is seen as the top section of Figure 19: Overview of TeCoMan program window, including the higher level system hierarchy.. The most important windows have been numbered, and a short description of the functionality of these tools according to numbering from Figure 19 is given below:

1. **Explorer Window** – This window is used to define and navigate within the hierarchies which are included in the current database. The *system hierarchy* is the basic hierarchy, and this hierarchy category is created by default, and is intended for depicting the system under consideration. The system hierarchy is developed by adding nodes, either aggregation nodes or measurement nodes. Measurement nodes are at the bottom of the hierarchy, while all higher level parent nodes are aggregation nodes. A number of additional *measurement hierarchies*, may be defined using the explorer window. Measurement hierarchies are developed by adding the desired nodes from the system hierarchy.

2. **Node Properties Window** – The node properties menu is used for investigating and configuring each specific node. The menu is applied to nodes within both the system hierarchy and the measurement hierarchies. In the system hierarchy, the node property menu is used to select appropriate user function at each measurement node at the bottom of the hierarchy. A user function is a mathematical formula which calculates the node measurement parameter from input variables and parameters. In the measurement hierarchy, the menu is utilized for both measurement nodes and aggregation nodes. At aggregation nodes, the menu is used to configure the aggregation at the current node from child nodes, while at measurement nodes in the measurement hierarchies; the menu is used to specify the transfer function to be utilized to relate the measurement parameter to TCI values.
3. **Graphic Tool Windows** – These 5 windows are not used for configuring TeCoMan, but to exploit and analyse historic developments derived from collected data. From left to right in numbered 3 in Figure 19, here is a short description of each graphic tool:
    - **TCI Graphs** – displays TCI graphs for the current navigated node in the explorer window.
    - **Benchmark Chart** –can be used to benchmark (compare) TCI or user function value of current navigated node in the explorer window against another chosen parameter.
    - **Input Data** – This tool is used to display the value of navigated measurement node within a measurement hierarchy. The tool shows a graph of the historical development of the raw values of the user function applied to the measurement node.
    - **Relative Contribution** – This tool is applicable only to aggregation nodes within a measurement hierarchy. It will display the relative contribution to reduction in TCI value at the node from nodes at one lower level in the hierarchy. If data is recorded for a long period of time, this could be a very powerful management tool to identify improvement potential and plan future replacements or system upgrades.
    - **Absolute Contribution** – this window is similar to the above, only the absolute contribution instead of relative contribution is displayed.
4. **Inspector Tool Windows** – These four windows are helpful to inspect values in a table format. There are four different inspector tools, each whose function and application is described below:
    - **TCI Inspector** - The TCI inspector is applicable to any node within a measurement hierarchy, and will display historical TCI values on the navigated node in a table format. This could be useful in order to inspect or export data from TeCoMan at a table format.
    - **User Function Inspector** – This is similar to the input data graphic tool, only in a table format rather than a graphic chart.
    - **Measurement Inspector** – The measurement inspector is a general tool, not taking in regard which hierarchy or node is currently navigated in the explorer window. It could be used to inspect all the basic measurement variables in a table format by tag name. The tool includes a search function, and for the chosen tag name, it will display the historical values registered.
    - **Tag inspector** – Similar to the measurement inspector, this is a general tool, applicable at any time when connected to a database. The tool is used to inspect tags registered within the database, and is searchable.

5. **Function Editor Window** – The function editor is used to define and configure user functions. User functions are applicable to measurement nodes within the system hierarchy only. A measurement node will always be represented by a user function value. A user function is a definition of the measurement node value, as a mathematical function of a set of input variables and parameters. Input variables are individual measurement values which are named by unique tags, while user function input parameters basically are constants for the mathematical function.
6. **Data Source Configuration Window** – This tool is used to configure the sources where input data are stored. Data sources range from simple text files, via designated TOCC mail import files to entire databases.
7. **Aggregation Tool Window** – this tool is utilized at any navigated node level within a measurement hierarchy. The tool will calculate historical and aggregated TCI values from a start date set by the operator in the window until the current date. In effect, the aggregation tool is used to update calculated data displayed in TeCoMan after updating input data.
8. **Report Setup Window** – As the name indicates, this window is used to configure the production and export of reports with results from TeCoMan.

In my opinion, these are the most basic and important features of the software, and predominantly those which I have been configuring and inspecting during my work with TeCoMan.

6.2 Configuring TeCoMan for a CM programme

In this chapter I will try to describe the basic procedure for configuring TeCoMan for a CM programme application. I will try to describe in chronologic order what I believe is an efficient approach, exemplified by the implementation of the CM programme defined in chapter 0.

6.2.1 System hierarchy

The first objective is to define and develop a complete system hierarchy. This hierarchy is the base hierarchy which is intended to depict the system down to measurement node level. Any subsequent measurement hierarchies, where aggregations of TCI's are to be performed, must import selected elements from the system hierarchy.

The system hierarchy may take different forms for any given system to be implemented, based on the philosophy and the detail level chosen by the analyst, and there may be no saying which hierarchy is correct for any system. The system hierarchy should however reflect the natural dependency between systems, functions and hardware (components) subject to evaluation.

The three systems studied in this Thesis are the Fuel Oil System, the Lubricating Oil System and the Cooling Water System. During the FMECA analysis from the Project Thesis (1) these three systems were found to consist of in total eight sub-systems, and in the hierarchy established for the FMECA analysis, where all system components were to be investigated, the hierarchical structure was divided into the following categories as illustrated below:

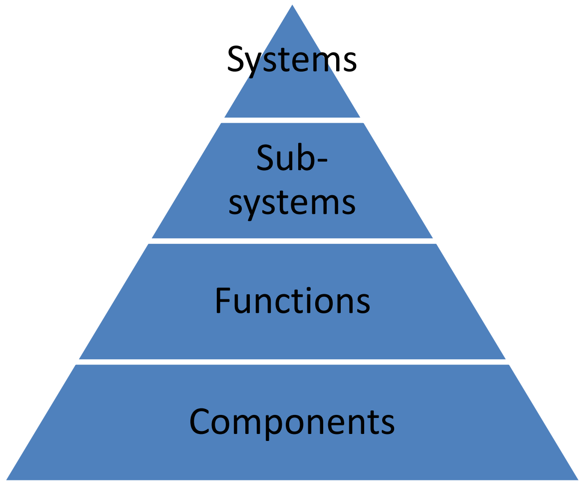


Figure 20: Systems breakdown from FMECA analysis in Project Thesis

For the system hierarchy within TeCoMan where condition monitoring activities define the system hierarchy, I find it better to remove functions as a hierarchical level, and rather group similar component types together. This better reflects the choice made in chapter 0, where condition monitoring activities for equal components types are standardized. For the system hierarchy in TeCoMan I propose that below individual machines (or components) the next hierarchical level to be the CM method or principle utilized, and below that any individual measurements. Thus resulting in a hierarchical breakdown like indicated in Figure 21 below:

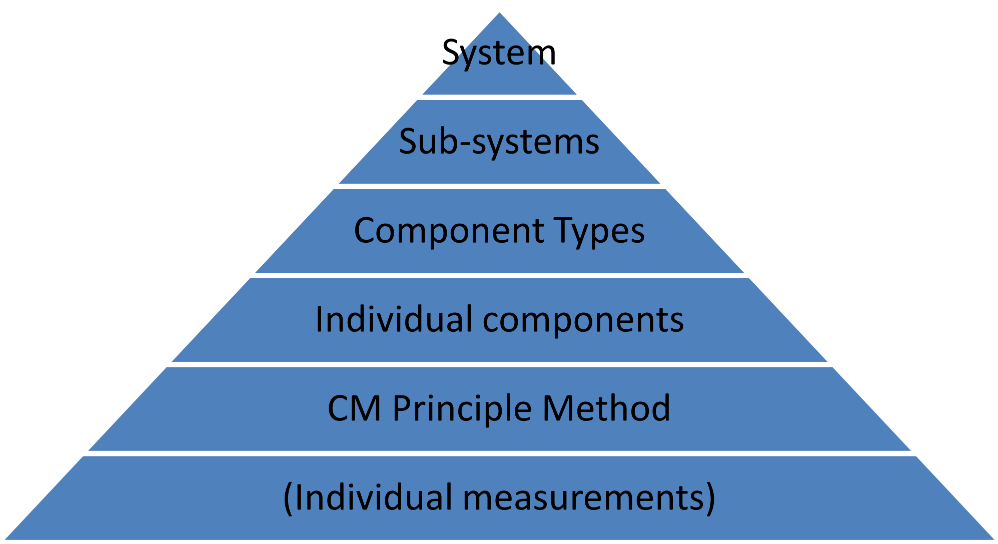


Figure 21: Proposed TeCoMan system hierarchy breakdown for systems subject to CM

Brackets have been added for the individual measurements because where a user function is used, such as typically would be the case for Process Parameter Analysis, all individual measurements will be directly included into the one user function being the measurement node.

The complete system hierarchy for all three systems in study was imported into TeCoMan down to component level. However, only the fuel oil system was developed further in full detail down to measurement level. Appendix F gives an overview of the system hierarchy structure as well as showing the entire fuel oil sub-system hierarchies, as implemented and shown in the TeCoMan Explorer view.

6.2.2 User Functions

Next, the user functions included in TeCoMan should be investigated. When a user function has been created, it can be used several times for several different components or measurements. If user functions already included in TeCoMan are found sufficient to calculate the proposed theoretical condition parameters applicable to CM program to be implemented, no action is needed. If additional user functions are required, these should be added to the TeCoMan user function library through the Function Editor.

For my proposed Process Parameter Analysis methods for pumps and heat exchangers, no applicable user function was included in TeCoMan.

6.2.2.1 Pump Process Parameter Analysis User Function

A user function was created in order to calculate the TCI parameter proposed for pumps, given in Equation 19. As required by the formula, the user function takes in parameters representing the constants describing a 2nd degree polynomial for the pump head as function if the mass flow. Measured pump head and mass flow are the input variables into the user function as shown below:

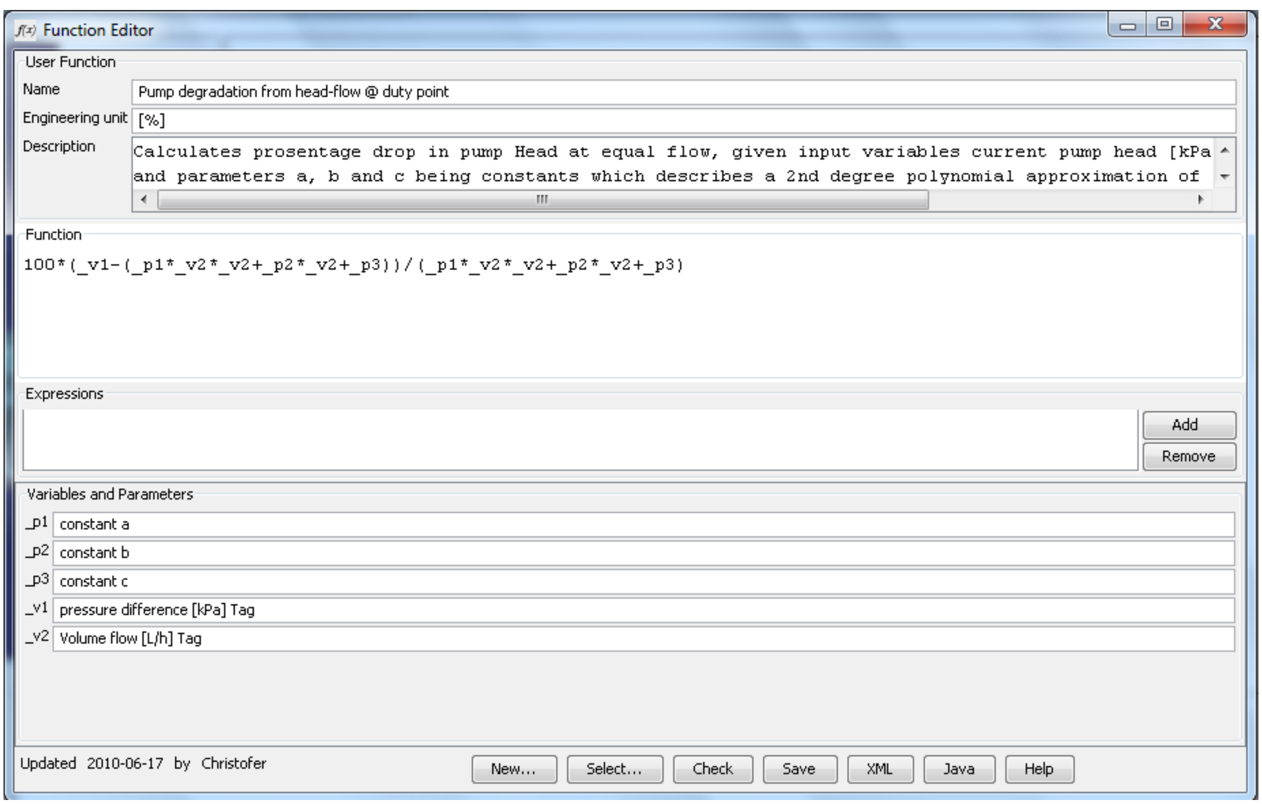


Figure 22: User function for pump degradation from heat-flow testing at duty point

6.2.2.2 Heat Exchanger Process Parameter Analysis User Function

For calculating the TCI parameter for heat exchangers proposed in chapter 5.3.2 described by

$$\text{TCI}parameter_{heatex} = -100 \times \frac{k_{meas} - k_{ref}}{k_{ref}} = 100 \times \frac{k_{ref} - k_{meas}}{k_{ref}}$$

Equation 20, with contents further elaborated in Equation 12 and Equation 13, I created a user function. The user function calculates the proposed parameter for a heat exchanger with logarithmic temperature difference as applicable to a heat exchanger with counter flow using measured mass flow and specific heat capacity of the medium whose temperature is increased through the heat exchanger, along with input temperature measurements denoted by the same temperature numbering as presented for such counter flow heat exchangers in Figure 16, chapter 2.4.6.2.

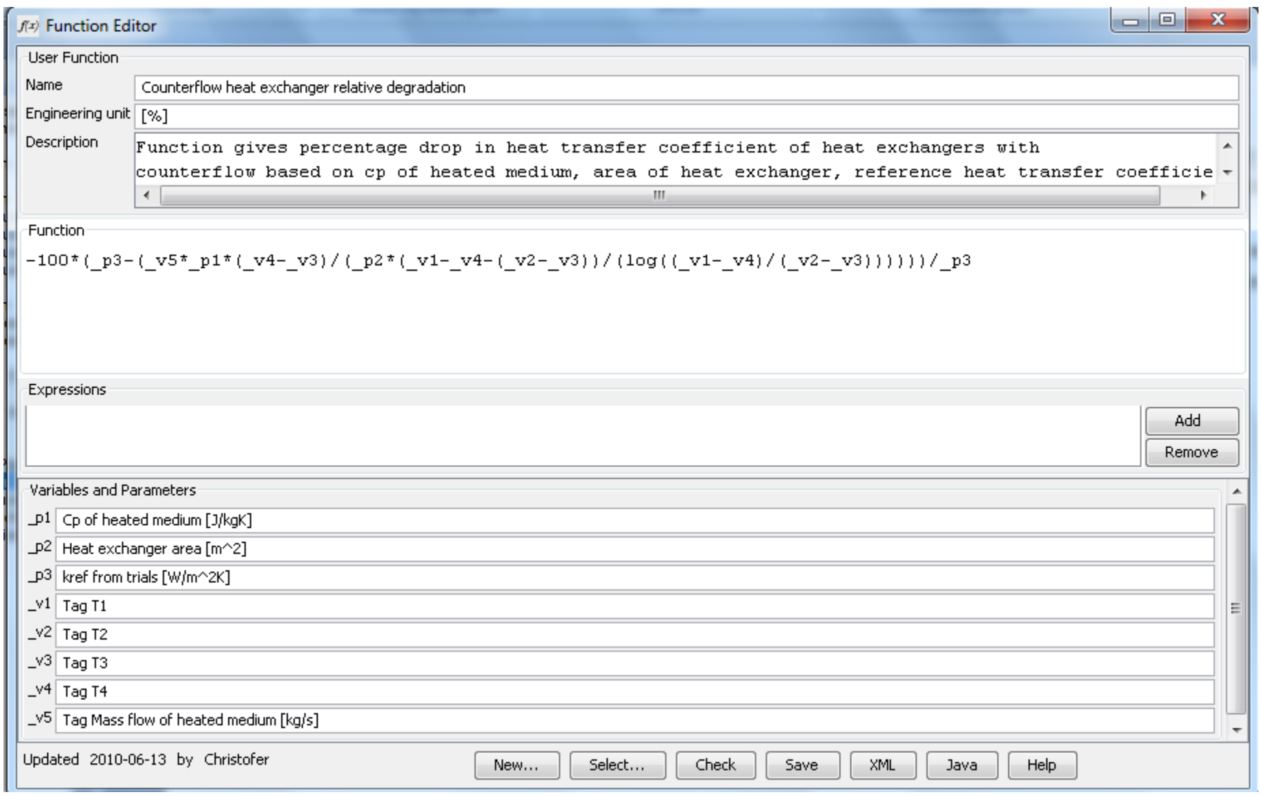


Figure 23: User function for TCI parameter for heat exchangers with counterflow measuring Cp and mass flow of the heated medium

Similar user functions could be added for downstream flow directions, and/or taking in either mass flow and specific heat capacity of the medium which is cooled in the heat exchanger, or possibly using the mean value of the heat lost/absorbed by the two mediums.

6.2.3 Data Import Configuration

The next step is to configure the data sources to identify where files or databases containing measurement data are kept. For the application of this Thesis, no measurement data were available, as the study is theoretic in nature and not applicable to a specific ship or ship system. Therefore, in order to exemplify the functionality of the implemented measurement hierarchy and user functions, data were fabricated. The text file import module was chosen, where file location and structure of the text file is defined, the text file import module is shown in Figure 24:

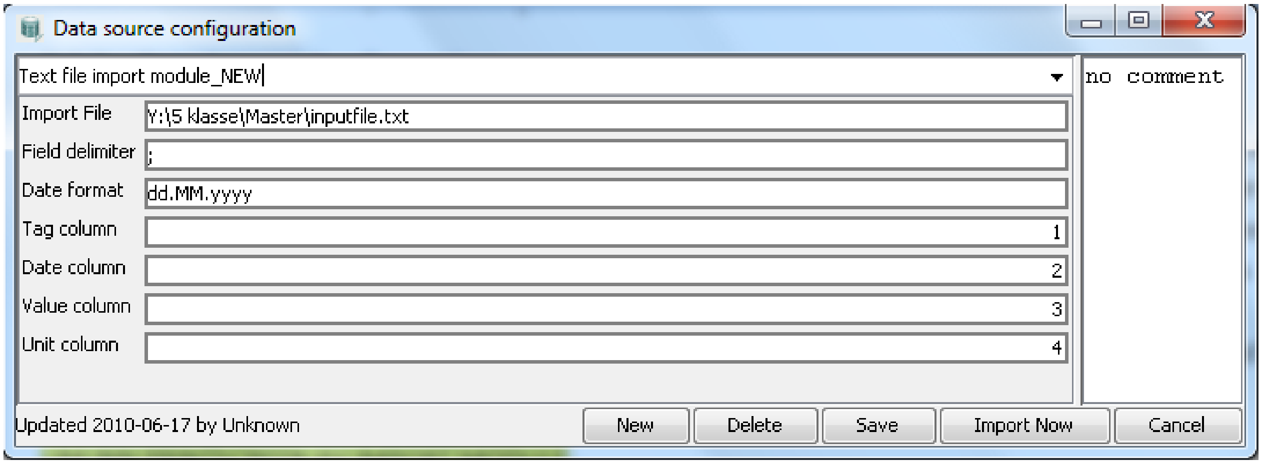


Figure 24: Print screen showing TeCoMan Data source configuration, text file import module.

Measurement data were fabricated in a simple .txt file using standard Microsoft Notepad software, where measurement data were defined by text strings containing tag name, date, value and unit as specified in the text file import module shown above, and each text line will therefore look like this:

tagname;dd.MM.yyyy;value;unit;

The full input file can be found in Appendix G.

6.2.4 Measurement Hierarchy Configuration

In order to utilize the TeCoMan software and TCI principle the desired measurement hierarchies must be established. This is done within the explorer window. Numerous measurement hierarchies can be created based on one system hierarchy, this could be useful if TCI's should be used to quantify the performance of a technical system with respect to different objectives. According to (34) such objectives could typically be:

- Technical degradation
- Efficiency
- Productiveness
- Losses
- Waste
- Uptime

For the purpose of this Thesis, in agreement with the Supervisor, it was decided only to include only one measurement category, which is intended to reflect the technical degradation. This measurement category was called TCI and established as the only measurement hierarchy.

Aggregation of TCI's are defined in the measurement hierarchy. First, relevant nodes from the system hierarchy are imported. At measurement nodes, the transfer function relating user function parameters to TCI values must be established. In addition, the status indication traffic lights can be configured for TCI values at turnover from green to yellow, and from yellow to red may be defined. These were set at TCI = 90 and TCI = 80 respectively for all applications in this Thesis. Finally, comments can be defined to provide additional information to the values. Comments are text messages displayed based on TCI or user function values, and could be relating to diagnostic help messages, maintenance instructions or similar. At aggregation nodes, the aggregation of child nodes is defined. Aggregation may be based on such functions as mean value, worst case, weighted sum and several others. In addition, status traffic lights and comments must be defined also at aggregation node level.

The structure of the measurement hierarchy can be inspected in Appendix H.

Further discussion of aggregation functions and weighting is done in chapter 0.

6.2.5 Aggregation

If all the above steps have been executed and data have been recorded, the basic steps which needs configuration in order to start exploiting the TeCoMan software have been finished. In order to calculate TCI's the final step is to utilize the Aggregation Tool. If done on the top level aggregation node at a measurement hierarchy, then the full set of TCI's for this hierarchy from the bottom measurement nodes to the top node will be calculated. When this is done, the graphic and measurement tools will display correct historical values at all node levels from the desired start date of aggregation, and in the measurement hierarchies the status traffic lights will display the current status, based on the latest recorded data.

6.2.6 Reports

When aggregation of latest data set has been concluded, the possibility of communicating the current system status outside TeCoMan is present. Client users of the TOCC system will be able to view the status indication, graph and inspector tools through their TeCoView application. For communicating information on the current and historical system status to parties without access to TeCoMan or TeCoView, the reporting tool should be utilized. This tool can be used to generate reports configured in TeCoMan. Reports may be printed, emailed or automatically sent to other databases as applicable.

The report tool was not investigated in detail or configured within my work with TeCoMan.

7 Exemplification of TCI Calculations and Aggregation 5

Task 6 in the assignment text specifies that exemplification of the TCI calculations and aggregation for at least one system must be demonstrated. The Fuel Oil System has been selected for this purpose, and this chapter will demonstrate the full TCI calculations and aggregation for this system, as executed in TeCoMan.

In order to perform calculations of TCI's the following items must be in defined in detail:

- Reference data, necessary for input into user functions or transfer functions
- Measurement data, as input to user functions
- User functions
- Transfer functions
- Aggregation functions and settings

The user functions applicable to the TCI's proposed for my system have been described in detail in chapter 6.2.2; however I needed to fabricate plausible reference and measurement data in order to perform calculation of TCI's.

7.1 Reference and Measurement Data Fabrication

In order to fabricate a set of plausible reference and measurement data, I chose to set up an excel sheet where I made assumptions for capacities of the Fuel Oil System, based on formulas and typical values stated in literature. From (35) I found that the maximum fuel oil consumption is the dimensioning factor for the fuel oil system, taking into account the most viscous fuel to be burnt. Furthermore, the fuel oil purification system should be capable of handling the maximum daily fuel consumption within 20-22 hours. Transfer pump system is said to be dimensioned with capability of emptying one bunker tank and filling another within "reasonable time" (35). I assume twelve hours is reasonable time. With such dimensioning criterions in mind, I started by defining the basis for the Fuel Oil System, assuming the following:

Fuel Oil System Specification	Symbol	Value	Unit	Comment
Engine Power	P	10000	kW	Assumed value
Specific fuel consumption	SFOC	0,18	kg/kWh	Assumed, typical value
Fuel Spec	Fuel	RMH45	-	Assumed fuel
Viscosity of fuel	v_f	45	cSt	Source: (36 p. p 510)
Temperature for above viscosity	-	100	degC	Source: (36 p. p 510)
Fuel Density (at 15 deg C)	$\rho_f^{15\ degC}$	991	kg/m^3	Source: (36 p. p 510)
Fuel cons at full power	mfuel	0,50	kg/s	Calculated: mfuel = P * SFOC / 3600
Fuel consumption pr day	Cons	43,2	ton	Calculated: Cons = P * SFOC *24 /1000
Range at full speed	Range	30	days	Assumed approximately one month
Bunker tanks capacity	Mtank	1296	ton	Calculated from above consumption and range
Number bunker tanks	n	4	-	Assumed

Table 9: Fuel Oil System Specification

In (36), practical thresholds values for kinematic viscosity of fuels for pumping, separation and fuel injection and atomizing are given:

Viscosity Thresholds	Symbol	Value	Unit	Comment
Pumping	$\nu_f^{pump} \leq$	500	cSt	Source: Diesel Engines Volume 3: Combustion p 513
Separating in centrifuge	$\nu_f^{sep} \leq$	40	cSt	Source: Diesel Engines Volume 3: Combustion p 513
Fuel injection and atomizing	$\nu_f^{injct} \leq$	15	cSt	Source: Diesel Engines Volume 3: Combustion p 513

Equation 21: Viscosity thresholds for various applications, Source: (36 p. 513)

These values can be utilized to identify temperatures at important locations in the Fuel Oil System, as temperature (θ) and kinematic viscosity (ν_f) are related in through the formula:

$$\log\log(\nu_f^{\theta} + 0{,}85) = p + m\log(\theta + 273{,}15)$$

Equation 22: Fuel temperature - viscosity relation, Source: (36 p. 513)

where m is nearly constant at m =3,32, while p is fuel dependent (36 p. 513). Using the known viscosity of the specified RMH fuel I found p = 8,759. Using this information I could now calculate threshold temperatures for pumping, separating and injecting the fuels:

Calculated Temperatures	Symbol	Value	Unit	Comment
Temperature for pumping viscosity	$T_f^{pump} \geq$	49,2	degC	I assume 50 for simplicity
Temperature for separation viscosity	$T_f^{sep} \geq$	103,5	degC	Theoretic value, I assume 98 from (36 p. 527)
Temperature for injection viscosity	$T_f^{injct} \geq$	138,4	degC	I assume 140 for simplicity

Equation 23: Calculated threshold fuel temperatures for pumping, separating and injection.

In the comment field I chose some simplified temperatures which I will assume to be the intended system temperatures at bunker tanks, separator inlets, and fuel oil final heater outlet, respectively. Also, I assumed for the settling tank an intended temperature of 80 degrees, and for the mixing tank 130 degrees. The complete set of intended temperatures at locations interesting with respect to the CM programme will therefore be:

Assumed intended temperatures in system	Temp [deg C]	Unit
T fuel transfer feed pump	50	degC
T fuel settling tank preheater in	50	degC
T fuel settling tank preheater out	80	degC
T fuel separator feed pump	80	degC
T fuel Separator preheater in	80	degC
T fuel Separator preheater out	98	degC
T fuel circ supply pump	98	degC
T fuel circ booster pump	130	degC
T fuel circ fuel oil heater in	130	degC
T fuel circ fuel oil heater out	140	degC

Table 10: Chosen reference fuel temperature at points of interest for CM

In order to have a complete specification of the fuel at all locations, density and specific heat capacity of the fuel oil at these temperatures were calculated, as these properties will be input for the various user functions. Density was calculated by formula:

$$\rho_f{}^{\theta} = \rho_f{}^{15} - 0,68(\theta - 15)$$

Equation 24: Fuel density ρ as function of temperature θ, Source: (36 p. 512)

Specific heat capacities at relevant locations were calculated from:

$$Cp_f{}^{\theta} = \frac{1}{\sqrt{d}}(0,402 + 0,00081 \cdot \theta)[kcal / kg \cdot K]$$

Equation 25: Specific heat capacity of fuel oil as function of temp. (θ) and specific gravity at 15 deg C (d), Source: (37)

Tables showing these calculated values are included below, specific heat capacities were converted to unit J/kg K by factor 1 kcal = 4186.8 J, as the aware reader will identify:

Densities	Density [kg/m^3]	Unit
ρ fuel transfer feed pump	967,2	kg/m^3
ρ fuel settling tank preheater in	967,2	kg/m^3
ρ fuel settling tank preheater out	946,8	kg/m^3
ρ fuel separator feed pump	946,8	kg/m^3
ρ fuel Separator preheater in	946,8	kg/m^3
ρ fuel Separator preheater out	934,6	kg/m^3
ρ fuel circ supply pump	934,6	kg/m^3
ρ fuel circ booster pump	912,8	kg/m^3
ρ fuel circ fuel oil heater in	912,8	kg/m^3
ρ fuel circ fuel oil heater out	906,0	kg/m^3

Calculated Fuel Specific Heat values	Temp, [degC]	$Cp_{fuel}^{(Temp)}$ [J/kgK
Specific heat at bunker tanks	50	1852,96
Average spes. heat in settling tank preheater	65	1903,84
Specific heat at settling tank	80	1954,72
Average spes. heat in separator preheaters	89	1985,25
Specific heat at day tank and supply pumps	98	2015,77
Specific heat at mixing tank	130	2124,31
Average specific heat in fuel oil heaters	135	2141,27
average specific heat of fuel at T = 140 deg C	140	2158,23

Table 11: Fuel Oil density and specific heat capacity at locations of interest

Having established this set of fuel properties, I made excel sheets for all components to be condition monitored where I established plausible reference and measurement data through iteration. As these calculations and tables are extensive, they have been placed in the appendices.

All calculations and measurement data for head – flow testing pumps can be found in Appendix I.

Similar calculations and measurement data for heat exchangers are included in Appendix J.

Complete vibration data for all components subject to such monitoring are given in Appendix K.

Notice should be taken that in order to demonstrate the aggregation and functionality of the TeCoMan software, for all paralleled components to be monitored data for component numbered “1” were set according to tables in the aforementioned appendices, while for components numbered “2”, data for all dates were set equal to the those of component 1 at date 01.02.2010. All data for this date should produce TCI=100.

7.2 Transfer Functions

Transfer functions were defined in the measurement hierarchy at lowest node level for all user functions. In order to reduce time consumption, all transfer functions for similar TCI parameters were chosen equal. Since user function values for head flow testing of pumps and heat exchangers are both %

decrease relevant to reference conditions, transfer functions were made equal for both these user functions.

7.2.1 Head –Flow Test and Heat Exchanger Degradation Transfer Functions

Transfer functions defined for both these user functions were configured using a six point saddle curve transfer function, using identical values for all items. The user function parameters both express % degradation relative to the reference condition.

Decision was made to keep the transfer function simple. In the region of the user function degradation between -20% and 0, a 1:1 translation of user function value to TCI reduction was desired. The point of total degradation (TCI = 0) was chosen to translate to a - 50 % user function value. In principle, there is no reason why measurements should produce positive values, i.e. improved condition from reference measurements. A margin of 2 % increase of user function value was however allowed to translate to TCI = 100, followed by a linear drop to TCI = 0 for positive 20 %. This should produce a low TCI indicating that measurements are probably erroneous. The desired translation was produced by inserting values shown in Figure 25 below.

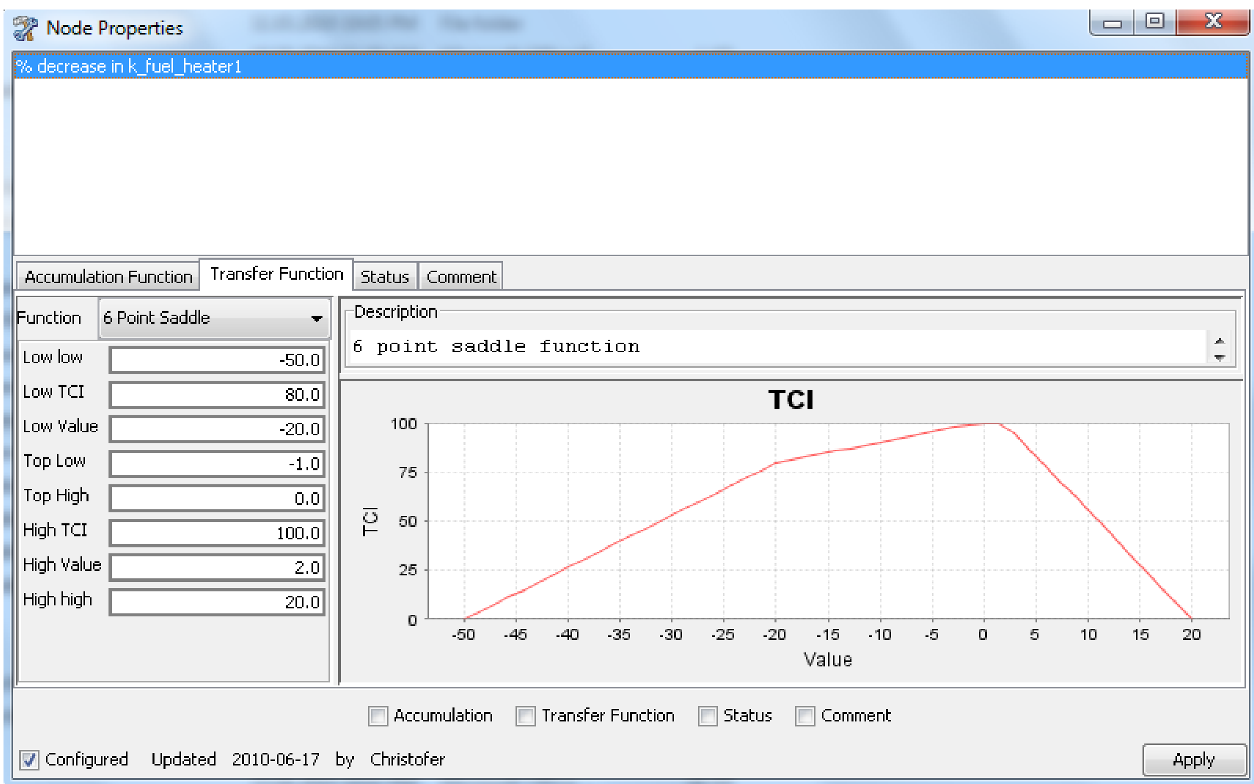


Figure 25: Transfer function for pump head - flow test and heat exchanger degradation

With "Top-low" at -10, this means that any pump or heat exchanger with less than 1% decrease in their parameter will have a TCI = 100, and that the translation is not exactly 1:1 in the user function interval 0 – (-20).

7.2.2 Vibration Monitoring Transfer Function

For vibration monitoring, the simple user function "pass through" was utilized, which means that the user function value is equal to the measurement value. The intention was to incorporate threshold values for vibrations according to ISO standards within the transfer function directly, as described in 5.2.2. As the threshold values are classified by machine size and rigidity of mounting, the calculated indicated pump power from Appendix I are helpful. All pumps have an indicated power of less than 15 kW, which means all pumps are within machinery "Type 1 - Small machines" in the vibration severity chart of ISO 39545 which can be found in Appendix A. All small machines with vibration velocity in mm/s-RMS less than 0,71 are placed in Category A "Good to excellent". I assume all vibration levels less than 0,71 therefore should produce TCI = 100. Vibration levels above 1.8 are classified as "Not Satisfactory". As the TCI classification in TOCC applications as defined in (7 p. 28) has been based on categorizing TCI's below 80 as the red "alarm condition", which I interpret similar to "not satisfactory", I assume values above 1.8 to translate to TCI's less than 80. I therefore utilized the linear conversion transfer function, defining these two data points only:

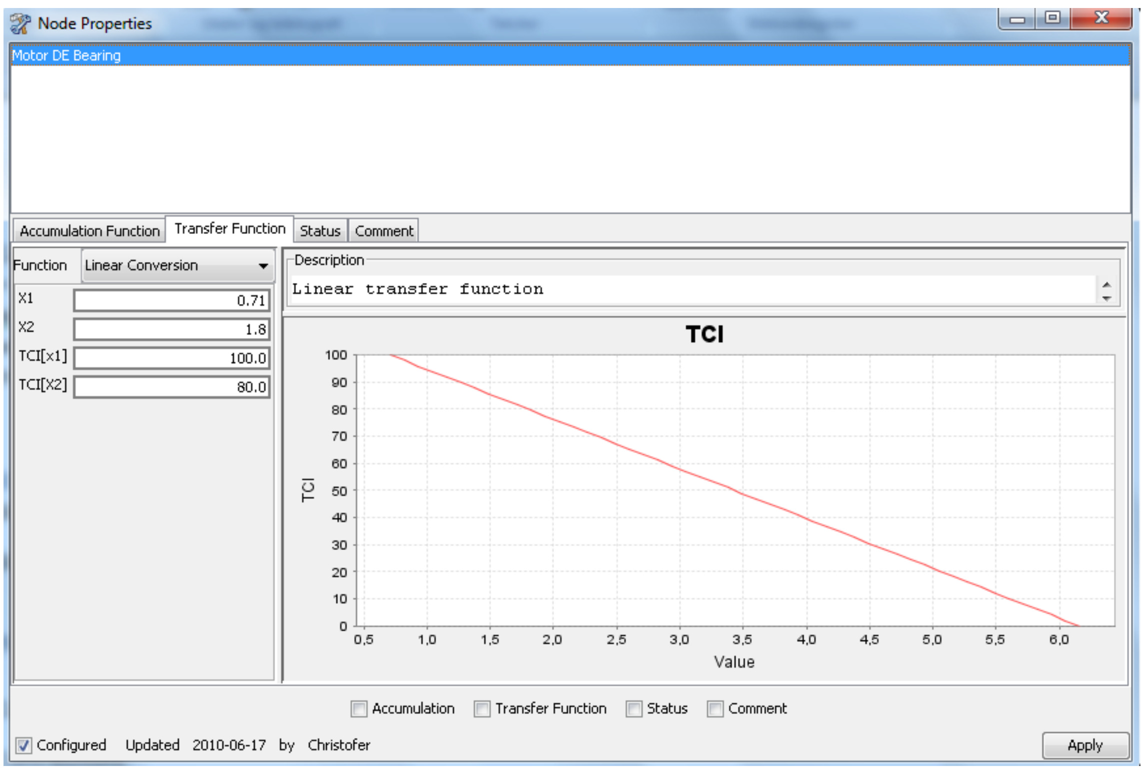


Figure 26: Transfer function definition for vibration monitoring user functions

7.3 Aggregation Functions and Weighting

The structure of aggregation within the measurement hierarchy was briefly mentioned in chapter 6.2.4 and can be seen in Appendix H. The aggregation function chosen, however, is not evident from the structure.

7.3.1 Aggregation Function Selection

Aggregation functions are defined at all aggregation nodes within the measurement hierarchy. A number of aggregation functions are available within TeCoMan, but comment fields describing their working principle were not filled out. Therefore I was limited to choose from the aggregation functions whose name could not be mistaken. These are “mean”, “weighted sum” and “worst case”. Weighted sum was chosen for all aggregation nodes except for vibration monitoring nodes. As it seems likely that bearing vibration and the accompanying damaging energy at one bearing will produce increased vibration levels and distribute increased damaging loads at other bearings connected to the same machinery, the bearing worst off for each machine train was considered the best indicator. Therefore, the worst case aggregation function was considered applicable to vibration aggregation nodes.

7.3.2 Aggregation Function Weighting

Not much time was attributed to propose “correct” or documented weighting within aggregation functions. Since only the fuel oil system was fully implemented into TeCoMan, weighting between fuel oil system, lubricating oil system and fuel oil system was not considered an issue and therefore weight of lubricating oil system and cooling water system was set to 0.

Weighting should be based on either expert judgement or complete FMECA utilizing detail historical data. I only have the FMECA analysis from the Project Thesis (1) to rely on in this respect, and although considered detailed in method, the data input to the FMECA was not detailed. Therefore I feel reluctant to propose weighting to be based on the “aggregated component criticality” and “sub-system importance” values proposed in the Project thesis.

Therefore, I used evenly distributed weighting at all aggregation nodes except for at two locations were I felt the assumptions and results from the FMECA analysis in (1) indicate that weight should not be distributed equally:

At Fuel Oil System aggregation node, the following weighting between the three sub-systems was chosen

- Fuel Oil Supply and Circulation system was attributed 50 % weight
- Fuel Oil Transfer and Fuel Oil Purification was both attributed 25% weight

This is based on the fact that failure in the fuel oil supply and circulation system will result in need of shutting down the engine in relatively short time, typically a matter of seconds or hours. If the fuel oil transfer system should shut down, however, the engine may still run for quite some time on fuel already contained within the settling tank and the day tank, with greater probability of being able to reach the closest safe haven or navigate out of harms way in tight spots like harbours or canals.

For similar reasons, at the “pumps” aggregation node within the fuel oil supply and circulation sub-system, the fuel oil circulation pumps were given 75 % weight, while supply pumps were given 25%, as failure in the fuel oil circulation pumps will result in engine shut-down within a matter of seconds.

An illustration of the complete aggregation diagram, illustrating the aggregation function and weighting can be seen in Figure 27 on the next page.

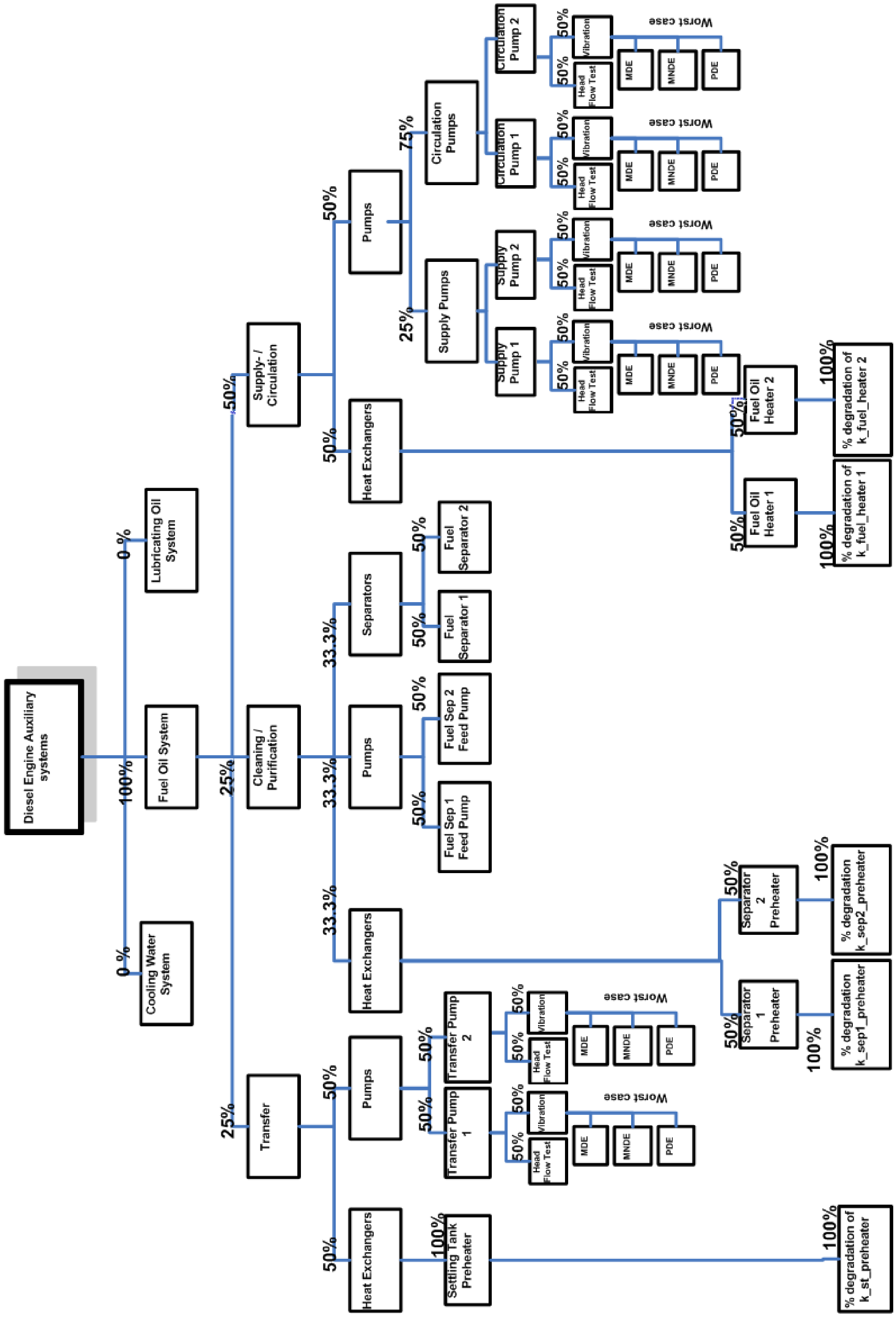


Figure 27: Aggregation Diagram for TCI's

7.4 Demonstration of Results in TeCoMan

Using the reference and measurement data, transfer functions and aggregation as defined in above chapters, the TeCoMan Aggregation Tool was used to update the TCI values to display current status.

In order to verify that calculations of TCI's were similar to the intended values, a comparison between values calculated in Excel and the values displayed in TeCoMan was performed for date 01.05.2010. Below table shows the user function and TCI values for all user functions at bottom level in the Fuel Oil System as calculated using the Excel spreadsheet and values collected by inspecting these nodes after having ran aggregation in TeCoMan.

User function	Excel UF	Excel TCI	TeCoMan UF	TeCoMan TCI
% deg k_st_preheater	-13,591	86,409	-13,593	86,740
Head Flow Test TP1	-3,411	96,589	-3,410	97,460
Worst vib Transfer Pump1	0,890	96,697	0,889	96,700
Head Flow Test TP2	-0,039	100,000	-0,437	100,000
Worst vib Transfer Pump2	0,520	100,000	0,519	100,000
% deg k_sep1_preheater	-16,640	83,360	-16,641	83,540
% deg k_sep2_preheater	0,001	100,001	0,001	100,000
Head Flow Test Sep FP1	-1,535	98,465	-1,600	100,000
Worst vib Sep Fp1	0,580	100,000	0,579	100,000
Head Flow Test Sep FP2	0,005	100,000	0,041	100,000
Worst vib Sep Fp2	0,620	100,000	0,620	100,000
Worst vib Sep 1	3,690	45,321	3,690	45,320
Worst vib Sep 2	0,490	100,000	0,490	100,000
% deg k_fuel_heater1	-0,925	100,000	-0,923	100,000
% deg k_fuel_heater2	0,001	100,000	0,002	100,000
Head Flow Test Supply P1	-0,267	100,000	-0,267	100,000
Worst vib Supply P1	0,440	100,000	0,439	100,000
Head Flow Test Supply P2	-0,600	100,000	-0,599	100,000
Worst vib Supply P2	0,520	100,000	0,519	100,000
Head Flow Test Circ P1	-6,752	93,248	-6,751	93,950
Worst vib Circ P1	1,150	91,927	1,149	91,930
Head Flow Test Circ P2	0,035	100,000	0,003	100,000
Worst vib Circ P2	0,650	100,000	0,649	100,000

Table 12: Comparison of values from Excel sheet and TeCoMan for user function and TCI values.

As we can see, most values are practically identical. This should verify that the implementation into TeCoMan has been correct. For some reason I cannot understand, some of the worst case vibration user functions show a value which is 0,001 less than the value of the input file, which is a bit strange, since these user function values should be simply "pass through" values displaying the same value as the input file dictates for that tag. Of course these rounded values for vibration data does not provide any difference in TCI since the deviation was much less than the 1% needed to get a TCI value less than 100.

The largest differences between the excel and the TCI values are most likely from the fact that the transfer functions for heat exchangers and pump head flow testing does not give an exact 1:1 relation between % change in user function value and TCI value, as the "top-low" value was set at -1%. However, I believe the comparison confirms that the input into TeCoMan has been correct, and that the CM methods defined in chapter 5, are possible to utilize within the TeCoMan software.

In addition to looking at user function values and transfer functions at bottom level, I calculated the TCI value at the top node of the fuel oil system in excel using the defined aggregation, using weighting as specified in Figure 27, for values at the same date. The value calculated in excel was 94,393, while the value displayed in TeCoMan was 94,53; nearly identical values.

In addition to these checks verifying the TCI calculations are plausible using the latest values dated 01.05.2010, we may look at the historical development of TCI at the any of the pumps, like for instance the pumps. Both vibration and head flow test data were meant to simulate a gradual decrease in condition from good at the first date (01.02.2010) to an unacceptable level in the third month (01.04.2010), followed by a repair or similar action, which would restore the system to normal conditions. This description is clearly recognizable looking at the absolute contribution to TCI reduction at the aggregation node of the two supply pumps:

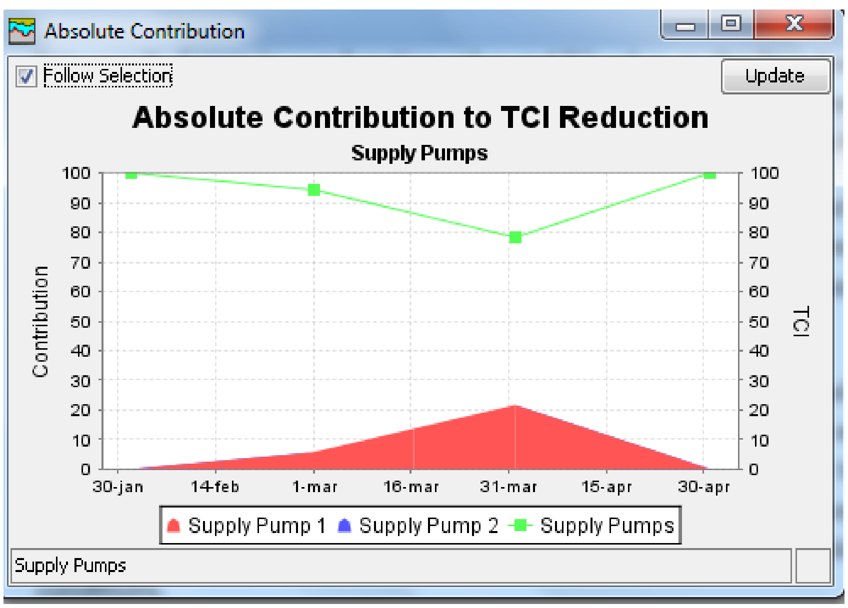


Figure 28: Absolute contribution to reduction of TCI for Supply Pumps.

Knowing also that the data for all components numbered "2" were not varied between dates, it should be obvious from Figure 28 that TCI's displays correct historical contribution to reduction in TCI's given the data input.

As the data inserted into TeCoMan have been randomly fabricated, I see no reason to present the results from TeCoMan in further detail, but an image showing how the explorer window will look when fully configured with status indicator lights after aggregation of data:

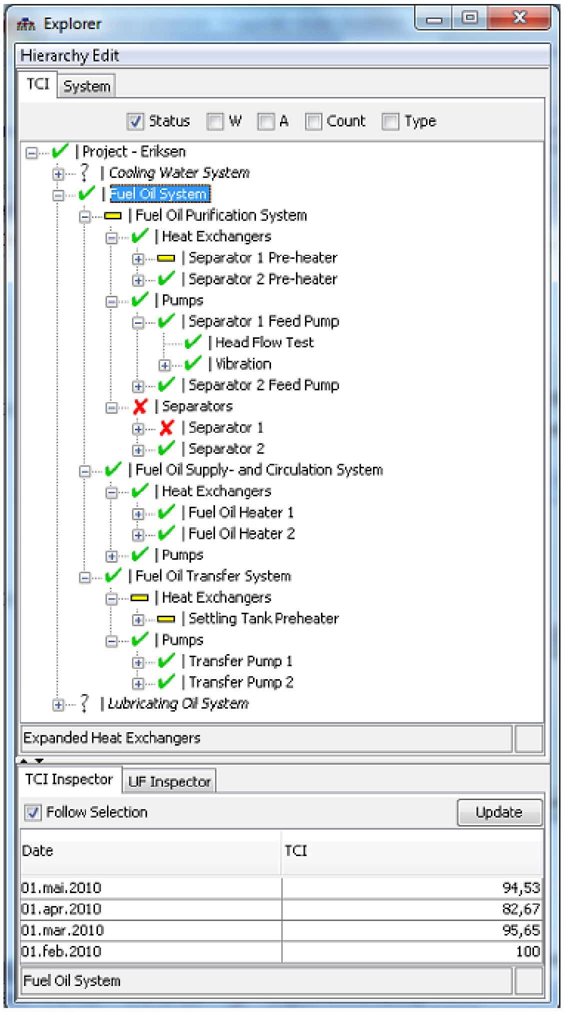


Figure 29: Print screen showing traffic indicator lights denoting TCI status after aggregation.

The indicator lights will serve to help operators or analysts to easily identify where TCI's show significant reduction, and navigating down to identify the root component(s) who contribute to the reduced value

8 Conclusions and Further Work

Technical Condition Indexes must be based on reliable and repeatable data collected through condition monitoring activities. Ideally, the condition monitoring techniques utilized should be aimed at revealing typical root-cause failure mechanisms of machinery considered critical for safe, efficient and profitable operation. Condition monitoring techniques includes such methods as vibration monitoring, ultrasonic monitoring, thermography, tribological wear particle analysis, visual inspection and process parameter analysis, and literature study describing theory of such elementary condition monitoring disciplines has been concluded.

All data currently reported within the ongoing TOCC demonstration projects utilizing the TCI concept for TeCoMan are inspection data in the sense that they are not reported automatically, but involve human intervention. For TCI's established in this Thesis, all inputs requested are hard measurable data. The human subjective opinion used as input for TCI's is not considered to ensure reliable and repeatable data.

For the Ship Engine Auxiliary Systems "Engine Fuel Oil System", "Engine Cooling System" and "Engine Lubricating Oil System" studied, FMECA analysis concluded during the candidate's Specialization Project revealed three major common component groups subject to condition monitoring for the purpose of establishing TCI's:

- 16 valve types, in total 23 individuals
- 8 sets of pumps, in total 16
- 7 Heat exchangers, in total 10 individual units

In order to reduce complexity and cost implications, TCI's and the condition monitoring techniques providing input data for similar components should be based on standardized methods, applicable to all components within one such major group.

For valves in the systems studied such standardized methods generally applicable to all valves could not be identified. The variety of valve types is vast, while common root-cause failure mechanisms are few, indicating that if valves truly are considered sufficiently critical to justify condition monitoring based on TCI's, methods must be developed individually for the actual system studied.

For pumps, TCI's are proposed to be based on a combination of vibration monitoring and process parameter analysis. Vibration monitoring should be based on measurement of the most powerful indicator of the damaging energy of vibrations at machine train bearing locations; the vibration velocity given in mm/s-RMS. ISO standards give classification threshold values for such measured vibrations based on machine type, rigidity of foundations and power. Such classification threshold values should be utilized in the transfer functions for calculating TCI's. TCI's based on process parameter analysis of pumps are proposed to utilize the Head – flow test at duty point method. This method requires repeatable measurements of pressure difference over the pump, as well as flow rate, either expressed by volumetric or mass flow rate.

TCI's for heat exchangers are proposed to be based exclusively on process parameter analysis, where the parameter to be monitored is the reduction in the overall heat transfer coefficient. The heat transfer coefficient is calculated from measurement of inlet and outlet temperature of both mediums flowing through the heat exchanger as well as mass flow rate and knowledge of the specific heat capacity of at least one of the two mediums.

For separators, TCI's based on similar measurements and principles as utilized for vibration monitoring of pumps are assumed to be applicable.

Technical Condition Indexes proposed have been implemented into the TeCoMan software for the Engine Fuel Oil System, and exemplification of the functionality of TCI's using fabricated data for an assumed typical system has been performed, verifying that the proposed TCI's could very well be calculated within this software environment. Detail description of the TeCoMan software and how to configure this software to calculate TCI's for a proposed condition monitoring programme has been made. The description could be used as a contribution to the software instruction manual for new users of the program.

For further work with the development of TCI's for the systems studied, the most important aspect would be to investigate whether condition monitoring of valves are justified by their criticality. This should be done by analysing the presumed total costs and benefits of necessary activities to perform condition monitoring of valves.

TCI's implemented for the three systems in TeCoMan are not complete. Measurement hierarchies of sub-systems Engine Lubricating System and Engine cooling Water System aggregation were not fully implemented into TeCoMan, as time did not allow for this.

Finally, weighting factors used in the aggregation functions for different systems, sub-systems and components has only been done for the Engine Fuel Oil System. Factors have predominantly been based on the FMECA analysis from the Specialization Project, where sources of reliable input failure data were not located. Expert judgement based on experience with the systems or FMECA using reliable failure data are necessary in order to assume sound weighting of the contributors to TCI's.

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Appendices

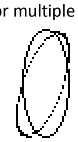
Appendix A. ISO 3945 Severity Classification

Vibration Velocity (bearing, maximum H, A and V directions) mm/s-RMS	Small machines up to 15kW	Medium Machines < 75 kW and to 300kW on special foundations	Large Machines 'Rigid' foundations (resonance above service speed)	Large machines 'Flexible' foundations (resonance below service speed)	Reciprocating machines, rigid in direction of measurement	Recoprocating machines, flexible in direction of measurement
	Type 1	**Type 2**	**Type 3**	**Type 4**	**Type 5**	**Type 6**
0,71						
1,12						
1,8			Category A: Good to excellent			
2,8						
4,5			Category B: Satisfactory			
7,1						
11,2			Category C: Not satisfactory			
18						
28			Category D: Unacceptable			
45						
71						

Table 13: ISO 3945 General Machine Vibration Severity Classification, Source: (9 p. 90)

Chart applies to machines with rotational speeds between 600 and 1200 RPM's.

Appendix B. Vibration Failure Characteristics in Rotating Machinery

Failure/Cause	Measuring Method	Total level	Frequency components (n = RPM)	Orbit (shaft vibration)	Phase	Other information
Imbalance • Misalignment • Growth, wear on rotor • Damaged rotor • Displaced parts on rotor	Bearing housing or shaft vibration	Severe increase ↑	1 x n radial	Circular o	90˚ between x and y probe	
Bent shaft • Cooled of too fast during shut down • Over-heated bearing or similar	Bearing housing or shaft vibration	Severe increase ↑	1 x n radial	Circular o	90˚ between x and y probe	NB! Shaft vibration will give readings also at low RPMs.
Misalignment • Erroneous mounting/ overhaul • Uneven heating of machinery • Forces from adjacent piping • Weak foundations, sliding, sagging	Bearing housing or shaft vibrations	Moderate increase ↑	1 x n 2 x n (3 x n) (4 x n) Radial and axial	Flat or figure 8-looking orbit 	Random angle between x- and y-probe. Approx. 180˚ phase angle between adjacent bearings.	
Rotor/Housing Rub • Bent axel • Touching seals • Axial displacement • Foreign objects • Inaccurate mounting	Bearing housing or shaft vibrations	No severe increase (could in some cases even decrease)	Sub-harmonical (n/2, n/3..) If heavy rubbing; also higher order harmonics, occasionally also a coherent increase in the frequency spectrum.	Extra loops in orbit;  or multiple orbits; 		
Wear Sliding bearings • Normal, from high hour count • Insufficient lubrication • Debris in lubricating oil • Electrostatic erosion (steam turbines) Overload	Shaft vibration	Increase ↑	Usually 1 x n	Unstable orbit 		• Usually increase in bearing temp and/or lub. Oil temp • Axial displacement if thrust bearing
Loose bolts	Bearing housing vibration	Increase ↑	Usually 1 x n, but often higher order harmonics as well			
Cavitation in pump • Insufficient suction pressure • Air in flow	Bearing housing vibration	No significant increase	Increase in higher frequency components			Noise (crackling sound from pump)
Damaged rolling element bearing • Fatigue • Insufficient lubrication • Overload, misalignment etc.	Bearing housing vibration	No significant increase	Some resonance frequencies in the housing in range 500Hz up to 10-30 kHz Frequencies of rolling elements may be recognize-able			Alternative equipment exists: Spike energy method should be used for such equipment.
Damaged gears • Pitting	Bearing housing vibration	No significant	Frequency of contacting teeth and			

• Fatigue		increase	higher orders of it.			

Table 14: Vibration characteristics for failure in rotating machinery, Source: adapted from (4 pp. 7.19-7.20)

Appendix C. Failure Causes of Heat Exchangers

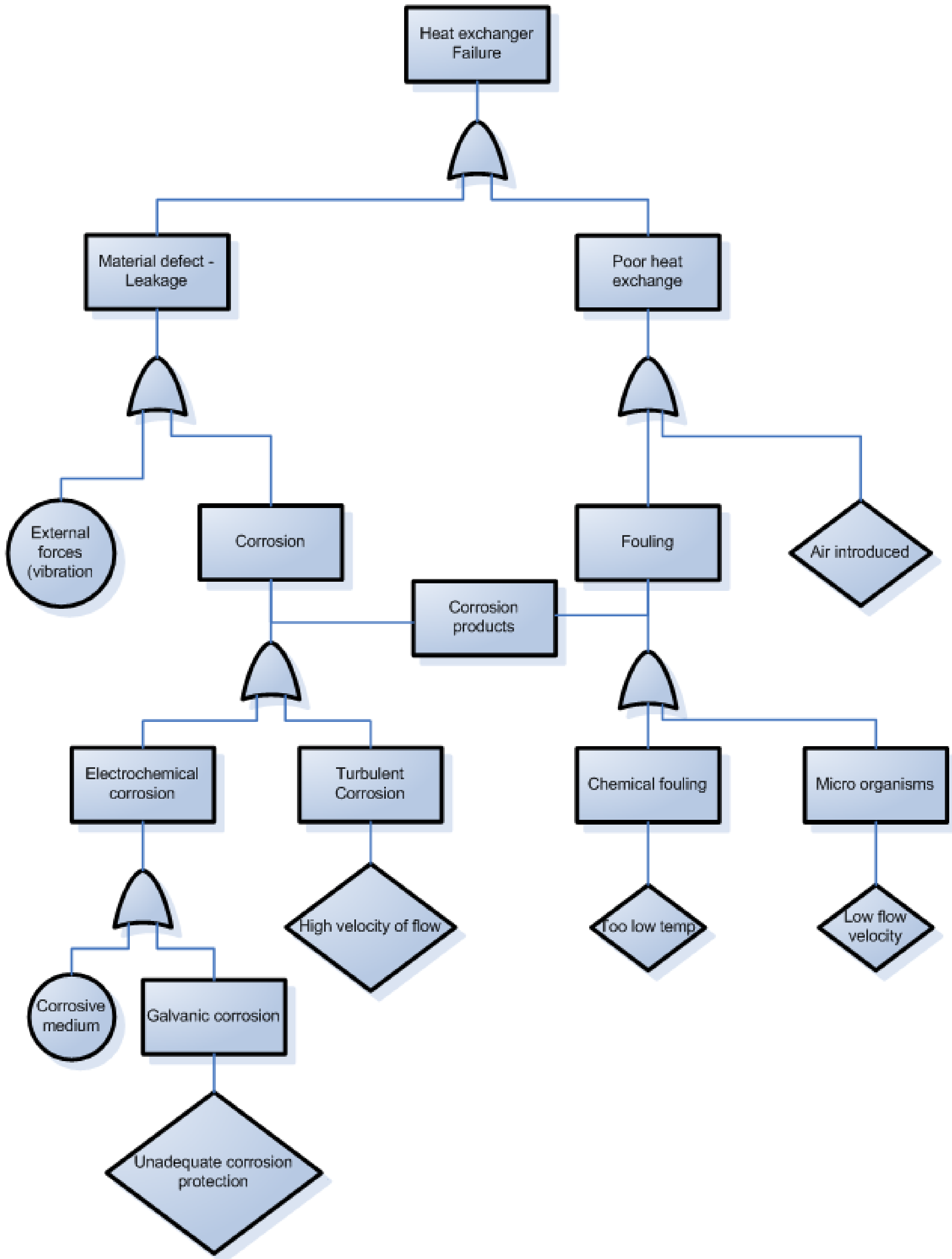


Figure 30: Fault Tree showing common failure causes of heat exchangers, Source: (10)

Appendix D. Shipowner Engine Report

Engine Report

Place	Month	Date
At Sea	December	31/12/2009

Summary

Page 1 of 6 - Summary

FUEL AND DIESEL STOCK	End of last month	Cons this month	End of this month	Corrections	RECEIVED ON BOARD Date	Qty (t)
Fuel Oil	403.00	310.20	1243.50	0.00	20/12/2009	1150.70
Diesel Oil	45.50	19.60	25.90	0.00		0.00
Diesel Oil - Low Sulphur	26.40	77.50	103.90	0.00	19/12/2009	155.00
Low Sulphur IFO	323.00	123.00	200.00	0.00		0.00

Comments to corrections:

FUEL AND DIESEL CONSUMPTION

	Hrs	Days	Fuel oil (t)	Diesel Oil D.O (t)	Diesel Oil L.S (t)*3	L.S. I.F.O. (t)	Fuel oil (t/d)	Diesel Oil D.O (t/d)	Diesel Oil L.S (t/d)	L.S. I.F.O. (t/d)
Main engine (1*)	359.00	15.0	310.20	0.00	0.00	123.00	20.74	0.00	0.00	8.22
AUX. engine	1281.00	53.4	0.00	19.50	65.00	0.00	0.00	0.37	1.22	0.00
Boiler (2*)			0.00	0.10	12.50	0.00	0.00	0.00	0.00	0.00

LUB. OIL STOCK	Stock (Ltr) end of last month	Stock (Ltr) end of this month	Corrections	Purchased (Ltr)	Consumption (Ltr)
M.E. Cylinder oil	11320	27270	0	20086	4136
M.E. System oil	20000	30202	0	10202	0
A.E. System oil	6580	11050	0	6090	1620
Stern tube (5*)	0	0	0	0	0
Hydraulic oil	2043	3979	0	2080	144
Sundry	1509	3087	0	1632	54
Total	41452	75588	0	40090	5954
Grease - KG	356	432	0	108	32

Comments to corrections:

LUB. OIL CONSUMPTION	MAIN ENGINE Cyl.oil	MAIN ENGINE Sys.oil	AUX.ENG Sys.oil
Kgs	3909	0	1477
Kgs/day	261.29	0.00	27.68

LUB. OIL CONS. EACH ENGINE	Ltr/month	Ltr/Day
Aux. Eng No.1	1110	37.31
Aux. Eng No.2	465	24.42
Aux. Eng No.3	45	9.82
Aux. Eng No.4	0	

The total consumption is based on data recorded at page 2. Stock at end of month is calculated accordingly. If actual sounding of stock at end of month differ, then correct 'stock end of last month' according to correct soundings.

Consumption

Get daily consumptions

Page 2 of 6 - Consumption

Day	CONSUPTION TONN												CONS. LTR. / DAY					
	MAIN ENGINE				AUX. ENGINE				BOILER / INC				MAIN ENGINE		AUX. ENGINE			
	Fuel oil	Diesel oil		L.S I.F.O	Fuel oil	Diesel oil		L.S I.F.O	Fuel oil	Diesel oil		L.S I.F.O	Cyl. oil	System oil	Lub. oil			
		D.O	L.S			D.O	L.S			D.O	L.S				No.1	No.2	No.3	No.4
1	29.00	0.00	0.00	0.00	0.00	2.50	0.00	0.00	0.00	0.00	0.00	0.00	270.00	0.00	25.00	45.00	0.00	
2	26.00	0.00	0.00	0.00	0.00	2.70	0.00	0.00	0.00	0.00	0.00	0.00	270.00	0.00	45.00	25.00	0.00	
3	26.00	0.00	0.00	0.00	0.00	2.50	0.00	0.00	0.00	0.00	0.00	0.00	270.00	0.00	50.00	0.00	0.00	
4	34.00	0.00	0.00	0.00	0.00	2.70	0.00	0.00	0.00	0.00	0.00	0.00	280.00	0.00	45.00	25.00	0.00	
5	32.60	0.00	0.00	0.00	0.00	2.50	0.00	0.00	0.00	0.00	0.00	0.00	280.00	0.00	45.00	0.00	0.00	
6	27.40	0.00	0.00	0.00	0.00	2.10	0.60	0.00	0.00	0.10	0.20	0.00	260.00	0.00	50.00	25.00	0.00	
7	0.00	0.00	0.00	0.00	0.00	0.00	2.80	0.00	0.00	0.00	0.60	0.00	0.00	0.00	50.00	0.00	0.00	
8	0.00	0.00	0.00	0.00	0.00	0.00	2.80	0.00	0.00	0.00	0.60	0.00	0.00	0.00	25.00	25.00	0.00	
9	19.00	0.00	0.00	0.00	0.00	1.20	1.50	0.00	0.00	0.00	0.20	0.00	140.00	0.00	25.00	0.00	0.00	
10	35.00	0.00	0.00	0.00	0.00	2.50	0.00	0.00	0.00	0.00	0.00	0.00	280.00	0.00	0.00	0.00	0.00	
11	30.50	0.00	0.00	0.00	0.00	0.80	1.80	0.00	0.00	0.00	0.30	0.00	270.00	0.00	30.00	0.00	0.00	
12	2.50	0.00	0.00	0.00	0.00	0.00	3.00	0.00	0.00	0.00	0.60	0.00	30.00	0.00	60.00	0.00	0.00	
13	0.00	0.00	0.00	0.00	0.00	0.00	3.00	0.00	0.00	0.00	0.60	0.00	0.00	0.00	20.00	25.00	0.00	
14	10.50	0.00	0.00	0.00	0.00	0.00	2.40	0.00	0.00	0.00	0.30	0.00	100.00	0.00	35.00	0.00	0.00	
15	0.00	0.00	0.00	30.70	0.00	0.00	2.40	0.00	0.00	0.00	0.00	0.00	270.00	0.00	45.00	0.00	0.00	
16	0.00	0.00	0.00	20.10	0.00	0.00	2.60	0.00	0.00	0.00	0.40	0.00	200.00	0.00	35.00	25.00	0.00	
17	0.00	0.00	0.00	4.70	0.00	0.00	3.00	0.00	0.00	0.00	0.60	0.00	100.00	0.00	35.00	25.00	0.00	
18	0.00	0.00	0.00	0.00	0.00	0.00	3.00	0.00	0.00	0.00	0.60	0.00	0.00	0.00	50.00	25.00	0.00	
19	0.00	0.00	0.00	0.00	0.00	0.00	2.50	0.00	0.00	0.00	0.60	0.00	0.00	0.00	40.00	0.00	20.00	
20	0.00	0.00	0.00	0.00	0.00	0.00	2.80	0.00	0.00	0.00	0.80	0.00	0.00	0.00	0.00	0.00	0.00	
21	0.00	0.00	0.00	0.00	0.00	0.00	2.80	0.00	0.00	0.00	0.80	0.00	0.00	0.00	50.00	20.00	25.00	
22	0.00	0.00	0.00	1.50	0.00	0.00	2.80	0.00	0.00	0.00	0.80	0.00	0.00	0.00	35.00	35.00	0.00	
23	0.00	0.00	0.00	5.90	0.00	0.00	2.90	0.00	0.00	0.00	0.60	0.00	136.00	0.00	50.00	20.00	0.00	
24	0.00	0.00	0.00	26.00	0.00	0.00	3.00	0.00	0.00	0.00	0.00	0.00	280.00	0.00	40.00	40.00	0.00	
25	0.00	0.00	0.00	34.10	0.00	0.00	3.00	0.00	0.00	0.00	0.00	0.00	300.00	0.00	40.00	20.00	0.00	
26	24.70	0.00	0.00	0.00	0.00	0.00	3.00	0.00	0.00	0.00	0.30	0.00	260.00	0.00	25.00	20.00	0.00	
27	0.00	0.00	0.00	0.00	0.00	0.00	2.80	0.00	0.00	0.00	0.80	0.00	0.00	0.00	25.00	20.00	0.00	
28	0.00	0.00	0.00	0.00	0.00	0.00	2.50	0.00	0.00	0.00	0.80	0.00	0.00	0.00	20.00	10.00	0.00	
29	0.00	0.00	0.00	0.00	0.00	0.00	2.70	0.00	0.00	0.00	0.80	0.00	0.00	0.00	40.00	0.00	0.00	
30	0.00	0.00	0.00	0.00	0.00	0.00	2.70	0.00	0.00	0.00	0.80	0.00	0.00	0.00	40.00	20.00	0.00	
31	13.00	0.00	0.00	0.00	0.00	0.00	2.60	0.00	0.00	0.00	0.40	0.00	140.00	0.00	35.00	15.00	0.00	
Σ	*310.2*	*0.0*	*0.0*	*123.0*	*0.0*	*19.5*	*65.0*	*0.0*	*0.0*	*0.1*	*12.5*	*0.0*	*4136.0*	*0.0*	*1110.0*	*465.0*	*45.0*	*0.0*

	Cyl. oil	System oil	No.1	No.2	No.3	No.4
Sum Kg	*3908.5*	*0.0*	*1012.3*	*424.1*	*41.0*	*0.0*
Default value spec. gravity (cyl. oil and system oil)	0.945	0.899	0.912	0.912	0.912	0.912

High Lub.oil consumption to be commented on / system oil that has been changed (Reason / Quantity) & leaks in sterntube to be commented on:

Sulphur content

Page 3 of 6 - Sulphur content

Day	Fuel Oil	Low sulphur fuel oil	Diesel oil	Low sulphur Diesel oil
1	3.1	1.14	0.4	0.07
2	3.1	1.14	0.4	0.07
3	3.1	1.14	0.4	0.07
4	3.1	1.14	0.4	0.07
5	3.1	1.14	0.4	0.07
6	3.1	1.14	0.4	0.07
7	3.1	1.14	0.4	0.07
8	3.1	1.14	0.4	0.07
9	3.1	1.14	0.4	0.07
10	3.1	1.14	0.4	0.07
11	3.1	1.14	0.4	0.07
12	3.1	1.14	0.4	0.07
13	3.1	1.14	0.4	0.07
14	3.1	1.14	0.4	0.07
15	3.1	1.14	0.4	0.07
16	3.1	1.14	0.4	0.07
17	3.1	1.14	0.4	0.07
18	3.1	1.14	0.4	0.07
19	3.1	1.14	0.4	0.087
20	3.1	1.14	0.4	0.087
21	2.8	1.14	0.4	0.087
22	2.8	1.14	0.4	0.087
23	2.8	1.14	0.4	0.087
24	2.8	1.14	0.4	0.09
25	1.57	1.14	0.4	0.09
26	2.8	1.14	0.4	0.09
27	2.8	1.14	0.4	0.087
28	2.8	1.14	0.4	0.087
29	2.8	1.14	0.4	0.087
30	2.8	1.14	0.4	0.087
31	2.8	1.14	0.4	0.087

Main Engine

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Date	25/12/2009	S/Water temp	14 °C	Eng. room temperature	30 °C
Cyl. diam.	0.66	Stroke	1.4	Mech.effic. (From test)	0.89

M.E. RPM	Forw. Turbo RPM	Aft. Turbo RPM	F.O.cons Ltr/Hr *	F.O. cons. GR./BHP HR.	F.O. visc. Bef. eng	F.O. temp. Bef. eng.	F.O. dens. at 15°C	LCV (MJ)
108.0	12100	12100	1536.0	172	15.00 C.St	120 °C	0.988	40.72

	Fresh Water out °C	Piston out °C	Exh. temp °C	P Max Bar	P comp Bar	P ind Bar	Pump index	VIT index	IHP
Cyl. No. 1	74	62	400	112	71	11.80	7	3.0	1383
Cyl. No. 2	71	61	360	108	72	10.80	7	3.0	1266
Cyl. No. 3	75	64	420	113	76	11.50	7	3.0	1348
Cyl. No. 4	76	68	420	111	75	11.20	7	3.0	1313
Cyl. No. 5	75	63	380	117	75	12.00	7	3.0	1407
Cyl. No. 6	75	64	400	125	80	13.10	7	3.0	1536
Cyl. No. 7	75	70	390	113	75	11.00	7	3.0	1289

TEMPERATURE	
Lub oil purifier A.E. inlet	°C
Lub oil purifier M.E. inlet	75 °C
Lub oil M.E. inlet	40 °C
Fuel oil purifier inlet	98 °C
Stern tube bearing (Forw./Aft.)	44 °C °C
Inner shaft bearing	42 °C
Thrust bearing	44 °C
Air receiver	34 °C
Air cooler forw. S.W. In	14 °C
Air cooler forw. S.W. Out	30 °C
Exh. before turbo ch.. Forw.	410 °C
Exh. after turbo ch. Forw.	310 °C
Exh. before turbo ch. Aft.	370 °C
Exh. after turbo ch. aft.	310 °C
M.E. High temp. cooling F.W. inlet	65 °C
Piston cooling inlet	53 °C

PRESSURE		
Lub. oil M.E. inlet	2.40	BAR
F.O. inlet	5.00	BAR
Scavenging air	1.20	BAR
Pressure drop air cooler Forw.	75	MMWC
Pressure drop air cooler Aft.	101	MMWC
Pressure drop air filter Forw.		MMWC
Pressure drop air filter Aft.		MMWC
Exh. pressure manifold		BAR
M.E. high temp. F.W. inlet	4	BAR
Exh. gas back pressure between TC and economiser	11	MMWC
GENERAL		
Calculated IHP	9542	
Calculated BHP(*)	8492	
Draft Forw.	5.30 m	
Draft Aft.	7.05 m	
Propeller pitch	4.04 m	

* BHP are calculated automatically based on indicated mean pressure or entered manually based on RPM and pump index calculations.

GENERAL	
Log speed	12.6
Wind direction (1 - 8)	2
Wind force	Moderate breeze (11 -16 knots)
Sea direction (1 - 8)	4
Sea waves	Moderate 1.25 to 2.5 m
Slip	10.86
Calculated HFO consumption in tonn/day, adjusted for 14 knots and 10 mtr draft	59.38

NOTE: Lub. oil purifiers, maintain 90°C, steady temperature and about 25% of max flow capasity. Fuel oil purifiers maintain 98°c of steady temperature. Back pressures to be measured by water u-tube with one end opened. F.O. cons. to be measured from flowmeter during a period of minimum 30 minutes. If LCV not known, 42,7 MJ to be used as default.

V = LOG SPEED, TROUGH WATER (NOT GPS), N=RPM p = PROPELLER PITCH AT 0,7R (METR)

Aux. Engines

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Date	25/12/2009	Eng. Room temperature	30.0 °C	S/Water Temperature	14.0 °C
F.W pressure inlet	2.2 BAR	F.O. temperature	°C	F.O. pressure	1.5 BAR

DATA TO BE RECORDED AT A LOAD BETWEEN 70 AND 80 PCT

AUX. ENGINE NO. 1

	P max bar	P comp bar	Exh. temp °C	Fuel index
Cyl. No. 1	73	33	310.0	20.0
Cyl. No. 2	72	34	350.0	21.0
Cyl. No. 3	76	35	320.0	22.0
Cyl. No. 4	78	34	350.0	21.0
Cyl. No. 5	67	32	320.0	21.0
Cyl. No. 6	79	35	320.0	20.0
Cyl. No. 7				
Cyl. No. 8				
Average	74	34	328.3	

Load KW	460
Percentage of full load	71 %
Scav. press. after air cooler	0.80 BAR
Lub. oil pressure in	3.80 BAR
Lub. oil temperature in	45.0 °C
F.W. temperature out	57.0 °C
F.W. temperature in	54.0 °C

Remarks

AUX. ENGINE NO. 2

	P max bar	P comp bar	Exh. temp °C	Fuel index
Cyl. No. 1	73	33	300	20
Cyl. No. 2	75	35	310	20
Cyl. No. 3	78	34	340	21
Cyl. No. 4	68	37	360	21
Cyl. No. 5	75	31	330	21
Cyl. No. 6	70	32	330	20
Cyl. No. 7				
Cyl. No. 8				
Average	73	34	328.3	

Load KW	460	
Percentage of full load	71	%
Scav. press. after air cooler	0.70	BAR
Lub. oil pressure in	3.60	BAR
Lub. oil temprature in	40.0	°C
F.W. temperature out	55.0	°C
F.W. temperature in	50.0	°C

Remarks

AUX. ENGINE NO. 3

	P max bar	P comp bar	Exh. temp °C	Fuel index
Cyl. No. 1	68	34	340	20
Cyl. No. 2	70	33	370	22
Cyl. No. 3	71	33	360	20
Cyl. No. 4	74	32	330	20
Cyl. No. 5	70	33	330	20
Cyl. No. 6	72	33	330	20
Cyl. No. 7				
Cyl. No. 8				
Average	71	33	343.3	

Load KW	460	
Percentage of full load	71	%
Scav. press. after air cooler	0.55	BAR
Lub. oil pressure in	3.70	BAR
Lub. oil temperature in	40.0	°C
F.W. temperature out	55.0	°C
F.W. temperature in	50.0	°C

Remarks

AUX. ENGINE NO. 4

	P max bar	P comp bar	Exh. temp °C	Fuel index
Cyl. No. 1				
Cyl. No. 2				
Cyl. No. 3				
Cyl. No. 4				
Cyl. No. 5				
Cyl. No. 6				
Cyl. No. 7				
Cyl. No. 8				
Average	0.00	0.00	0.00	

Load KW		
Percentage of full load		%
Scav. press. after air cooler		BAR
Lub. oil pressure in		BAR
Lub. oil temperature in		°C
F.W. temperature out		°C
F.W. temperature in		°C

Remarks

Running Hours

Page 6 of 6 - Running Hours

Main Engine Running Hours / Maintenance

Cyl. No.	Liner total hours	Hours until next overhaul: Cylinder unit	Exhaust valve	Fuel pump	Fuel valves
1	52882	7989	1246	1075	7783
2	10123	7154	299	1075	7849
3	6821	7200	299	1075	1222
4	39180	4781	1246	1075	7989
5	14283	4781	2067	1074	6148
6	9277	6703	2696	1075	6132
7	24720	6148	2132	1075	6132

Main Engine Total Running Hours

Last month total	This month	Total hours
141334	359	141693

TURBO CHARGER

TC ME Last Cleaned (Dry & Water)

HOURS SINCE LAST CLEANED

HOURS UNTIL NEXT T/C OVERHAUL	
TC Fwd, until next overhaul.	5675
TC Aft, until next overhaul.	5675

	Exh. side
Fwd.	12
Aft.	12

RUNNING HOURS AUX. ENGINE

				Hours until next overhaul				
	Last month total	This month	Total	Major overhaul	T/C overhaul	Cyl. head overhaul	Fuel valve overhaul	Air cool overhaul
Aux eng No. 1	124762	714	125476	-361	7944	-426	744	2944
Aux eng No. 2	131385	457	131842	7990	5298	2990	1980	2990
Aux eng No. 3	133607	110	133717	1729	355	1728	1445	2922
Aux eng No. 4	0	0	0					
Total this month		1281						

MARPOL ITEMS	
Quantity of sludge burned in incinerator or boiler this month, Ltr.	0 Ltr.
Quantity of sludge evaporated this month, Ltr.	1600 Ltr.
Quantity of sludge delivered ashore this month, Ltr.	44000 Ltr.
Quantity of bilge water discharged through OWS this month, Ltr.	11800 Ltr.
Quantity of bilge water evaporated this month, Ltr.	0 Ltr.
Quantity of bilge water delivered ashore this month, Ltr.	5000 Ltr.
Sludge ROB at end of month, Ltr.	10140 Ltr.
Bilge water ROB at end of month, Ltr.	6900 Ltr.

FW. GENERATION / EXH. BOILER	
Fw. production (T/D)	19.00
When was exh. boiler last w.w	15/11/2009

STORAGE (TOTAL TANK) CAPACITY	
Bilge water	Sludge
32300	131200

REMARKS TO FIGURE IN THIS REPORT

1. The Mechanical Efficiency for calculating the BHP of ME if taken as 0.915 as per mail from WAR, the BHP is working out to be 8731 and F.O. consumption works out 167 gms/BHP/hr2. Hours until next overhaul of Exhaust valves are actually of scavenge valves. No exhaust valves on this ME.

Copy of main engine indication cards or printout of MIP-calculator always to be sent office.

x

Appendix E. Mass flow measurements by use of orifice plate or a venturi

Mass flow measurements can be done by installing an orifice plate or a venturi into the flow. Guidelines for how to conduct such flow measurements are governed by ISO 5167, which includes a formula for calculating the mass flow, given in Equation 26 below. Figure 31 shows the principle of an orifice plate, while Figure 31 shows similar venturi installation. The principle is basically the same.

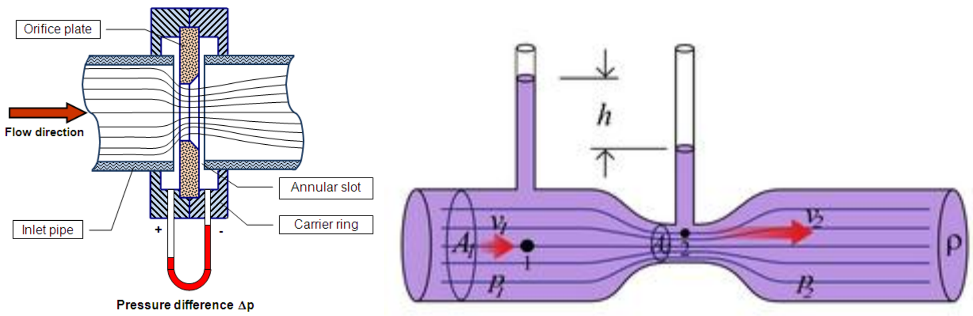

Figure 31: Illustration of Orifice plate and Venturi, Source: Wikipedia

The formula is on Bernoulli, and calculated the

$$q_m = CE\varepsilon \frac{\pi}{4} d^2 \sqrt{2\Delta p \rho_1}$$

Equation 26: ISO 5167 Mass flow calculation formula: Source (32)

Symbol	Description	Unit	Comment
q_m	Mass flow	kg/s	Desired quantity to calculate by the formula
E	Velocity of Approach Factor	-	Calculated from formula : $E = \frac{1}{\sqrt{(1-\beta^4)}}$
β	Diameter ratio, throat to upstream	-	d/D, where D is the diameter of the pipe upstream of the flow element, while d is the diameter of the restricted flow
ε	Expansion factor	-	unity for liquids
d	diameter of throat, at temperature condition in service	m	
Δp	pressure difference over flow element	Pa	
ρ_1	density of fluid at upstream tapping	kg/m3	

Table 15: Description of parameters in ISO 5167 mass flow formula, Source: (32)

Appendix F. System Hierarchies

All systems were defined down to component level in TeCoMan. First, system hierarchy top structure, showing the three main systems and sub-systems:

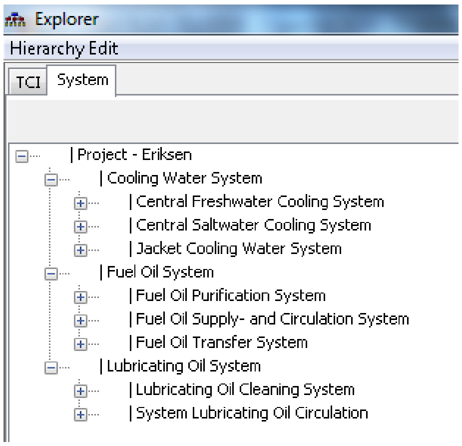

Figure 32: Print screen showing top level system hierarchy.

Fuel Oil System was developed in detail down to measurement node level. Due to screen limits, "vibration" CM aggregation node are not expanded fully except in the Fuel Oil Transfer System, however structure is similar for all pumps and separators.

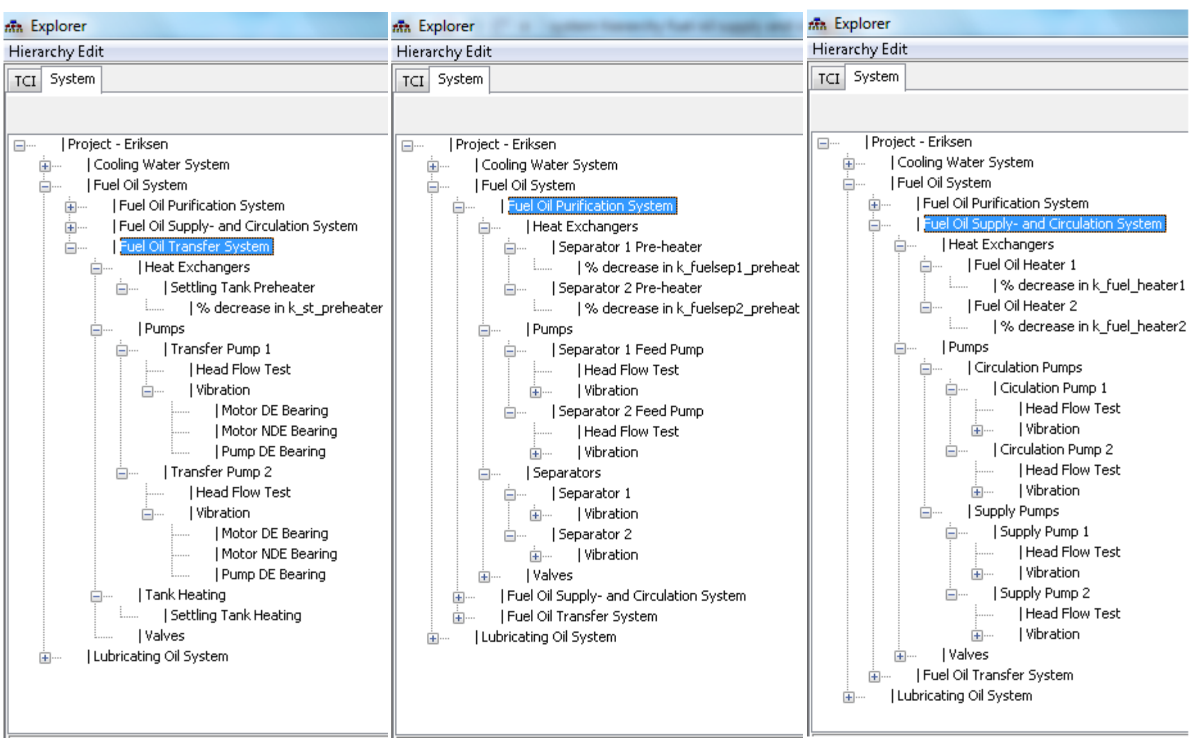

Figure 33: Print screen showing expanded system hierarchies for Fuel Oil Transfer, Fuel Oil Purification and Fuel Oil Supply- and Circulation Sub-systems.

Appendix G. Input Data File

The full input.txt file, containing all fabricated measurement data used to calculate TCI's and demonstrate the functionality of TeCoMan is included below.

```
vflow_fuel_tfp_1;01.02.2010;97500;L/h;
vflow_fuel_tfp_1;01.03.2010;100000;L/h;
vflow_fuel_tfp_1;01.04.2010;101500;L/h;
vflow_fuel_tfp_1;01.05.2010;103000;L/h;
dp_fuel_tfp_1;01.02.2010;142.3;kPa;
dp_fuel_tfp_1;01.03.2010;140.0;kPa;
dp_fuel_tfp_1;01.04.2010;120.5;kPa;
dp_fuel_tfp_1;01.05.2010;138.5;kPa;
vibv_fuel_tfp_1_mde;01.02.2010;0.45;mm/s-RMS;
vibv_fuel_tfp_1_mde;01.03.2010;1.75;mm/s-RMS;
vibv_fuel_tfp_1_mde;01.04.2010;3.40;mm/s-RMS;
vibv_fuel_tfp_1_mde;01.05.2010;0.89;mm/s-RMS;
vibv_fuel_tfp_1_mnde;01.02.2010;0.52;mm/s-RMS;
vibv_fuel_tfp_1_mnde;01.03.2010;1.89;mm/s-RMS;
vibv_fuel_tfp_1_mnde;01.04.2010;4.06;mm/s-RMS;
vibv_fuel_tfp_1_mnde;01.05.2010;0.67;mm/s-RMS;
vibv_fuel_tfp_1_pde;01.02.2010;0.36;mm/s-RMS;
vibv_fuel_tfp_1_pde;01.02.2010;1.13;mm/s-RMS;
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vflow_fuel_tfp_2;01.04.2010;97500;L/h;
vflow_fuel_tfp_2;01.05.2010;97500;L/h;
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vibv_fuel_tfp_2_mde;01.04.2010;0.45;mm/s-RMS;
vibv_fuel_tfp_2_mde;01.05.2010;0.45;mm/s-RMS;
vibv_fuel_tfp_2_mnde;01.02.2010;0.52;mm/s-RMS;
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vibv_fuel_tfp_2_mnde;01.04.2010;0.52;mm/s-RMS;
vibv_fuel_tfp_2_mnde;01.05.2010;0.52;mm/s-RMS;
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vflow_fuel_sp_2;01.04.2010;2150;L/h;
vflow_fuel_sp_2;01.05.2010;2150;L/h;
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dp_fuel_sp_2;01.03.2010;1852;L/h;
dp_fuel_sp_2;01.04.2010;1852;L/h;
dp_fuel_sp_2;01.05.2010;1852;L/h;
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vibv_fuel_sp_2_mde;01.03.2010;0.24;mm/s-RMS;
vibv_fuel_sp_2_mde;01.04.2010;0.24;mm/s-RMS;
vibv_fuel_sp_2_mde;01.05.2010;0.24;mm/s-RMS;
vibv_fuel_sp_2_mnde;01.02.2010;0.32;mm/s-RMS;
vibv_fuel_sp_2_mnde;01.03.2010;0.32;mm/s-RMS;
vibv_fuel_sp_2_mnde;01.04.2010;0.32;mm/s-RMS;
vibv_fuel_sp_2_mnde;01.05.2010;0.32;mm/s-RMS;
vibv_fuel_sp_2_pde;01.02.2010;0.52;mm/s-RMS;
vibv_fuel_sp_2_pde;01.03.2010;0.52;mm/s-RMS;
vibv_fuel_sp_2_pde;01.04.2010;0.52;mm/s-RMS;
vibv_fuel_sp_2_pde;01.05.2010;0.52;mm/s-RMS;

vflow_fuel_circp_1;01.02.2010;5600;L/h;
vflow_fuel_circp_1;01.03.2010;5900;L/h;
vflow_fuel_circp_1;01.04.2010;5950;L/h;
vflow_fuel_circp_1;01.05.2010;6200;L/h;
dp_fuel_circp_1;01.02.2010;465;L/h;
dp_fuel_circp_1;01.03.2010;450;L/h;
dp_fuel_circp_1;01.04.2010;440;L/h;
dp_fuel_circp_1;01.05.2010;405;L/h;
vibv_fuel_circp_1_mde;01.02.2010;0.65;mm/s-RMS;
vibv_fuel_circp_1_mde;01.03.2010;0.67;mm/s-RMS;
vibv_fuel_circp_1_mde;01.04.2010;0.71;mm/s-RMS;
vibv_fuel_circp_1_mde;01.05.2010;0.89;mm/s-RMS;
vibv_fuel_circp_1_mnde;01.02.2010;0.63;mm/s-RMS;
vibv_fuel_circp_1_mnde;01.03.2010;0.68;mm/s-RMS;
vibv_fuel_circp_1_mnde;01.04.2010;0.69;mm/s-RMS;
vibv_fuel_circp_1_mnde;01.05.2010;1.15;mm/s-RMS;
vibv_fuel_circp_1_pde;01.02.2010;0.55;mm/s-RMS;
vibv_fuel_circp_1_pde;01.03.2010;1.59;mm/s-RMS;
vibv_fuel_circp_1_pde;01.04.2010;15.5;mm/s-RMS;
vibv_fuel_circp_1_pde;01.05.2010;0.55;mm/s-RMS;

vflow_fuel_circp_2;01.02.2010;5600;L/h;
vflow_fuel_circp_2;01.03.2010;5600;L/h;
vflow_fuel_circp_2;01.04.2010;5600;L/h;
vflow_fuel_circp_2;01.05.2010;5600;L/h;
dp_fuel_circp_2;01.02.2010;465;L/h;
```

dp_fuel_circp_2;01.03.2010;465;L/h;
dp_fuel_circp_2;01.04.2010;465;L/h;
dp_fuel_circp_2;01.05.2010;465;L/h;
vibv_fuel_circp_2_mde;01.02.2010;0.65;mm/s-RMS;
vibv_fuel_circp_2_mde;01.03.2010;0.65;mm/s-RMS;
vibv_fuel_circp_2_mde;01.04.2010;0.65;mm/s-RMS;
vibv_fuel_circp_2_mde;01.05.2010;0.65;mm/s-RMS;
vibv_fuel_circp_2_mnde;01.02.2010;0.63;mm/s-RMS;
vibv_fuel_circp_2_mnde;01.03.2010;0.63;mm/s-RMS;
vibv_fuel_circp_2_mnde;01.04.2010;0.63;mm/s-RMS;
vibv_fuel_circp_2_mnde;01.05.2010;0.63;mm/s-RMS;
vibv_fuel_circp_2_pde;01.02.2010;0.55;mm/s-RMS;
vibv_fuel_circp_2_pde;01.03.2010;0.55;mm/s-RMS;
vibv_fuel_circp_2_pde;01.04.2010;0.55;mm/s-RMS;
vibv_fuel_circp_2_pde;01.05.2010;0.55;mm/s-RMS;

mflow_fuel_stpreheat;01.02.2010;27.2;kg/s;
mflow_fuel_stpreheat;01.03.2010;27.2;kg/s;
mflow_fuel_stpreheat;01.04.2010;27.1;kg/s;
mflow_fuel_stpreheat;01.05.2010;26.5;kg/s;
t1_medium_fuel_stpreheat_in;01.02.2010;105.0;degC;
t1_medium_fuel_stpreheat_in;01.03.2010;105.5;degC;
t1_medium_fuel_stpreheat_in;01.04.2010;106.0;degC;
t1_medium_fuel_stpreheat_in;01.05.2010;106.3;degC;
t2_medium_fuel_stpreheat_out;01.02.2010;90.0;degC;
t2_medium_fuel_stpreheat_out;01.03.2010;90.5;degC;
t2_medium_fuel_stpreheat_out;01.04.2010;90.3;degC;
t2_medium_fuel_stpreheat_out;01.05.2010;90.8;degC;
t3_fuel_stpreheat_in;01.02.2010;50.0;degC;
t3_fuel_stpreheat_in;01.03.2010;50.8;degC;
t3_fuel_stpreheat_in;01.04.2010;51.0;degC;
t3_fuel_stpreheat_in;01.05.2010;51.5;degC;
t4_fuel_stpreheat_out;01.02.2010;80.0;degC;
t4_fuel_stpreheat_out;01.03.2010;80.0;degC;
t4_fuel_stpreheat_out;01.04.2010;80.0;degC;
t4_fuel_stpreheat_out;01.05.2010;79.0;degC;

mflow_fuel_sep1preheat;01.02.2010;0.60;kg/s;
mflow_fuel_sep1preheat;01.03.2010;0.59;kg/s;
mflow_fuel_sep1preheat;01.04.2010;0.57;kg/s;
mflow_fuel_sep1preheat;01.05.2010;0.58;kg/s;
t1_medium_fuel_sep1preheat_in;01.02.2010;119.9;degC;
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t1_medium_fuel_sep1preheat_in;01.04.2010;122.8;degC;
t1_medium_fuel_sep1preheat_in;01.05.2010;123.1;degC;
t2_medium_fuel_sep1preheat_out;01.02.2010;105.1;degC;
t2_medium_fuel_sep1preheat_out;01.03.2010;105.6;degC;
t2_medium_fuel_sep1preheat_out;01.04.2010;105.0;degC;
t2_medium_fuel_sep1preheat_out;01.05.2010;105.1;degC;
t3_fuel_sep1preheat_in;01.02.2010;80.0;degC;
t3_fuel_sep1preheat_in;01.03.2010;81.6;degC;
t3_fuel_sep1preheat_in;01.04.2010;81.4;degC;
t3_fuel_sep1preheat_in;01.05.2010;81.5;degC;
t4_fuel_sep1preheat_out;01.02.2010;98.0;degC;
t4_fuel_sep1preheat_out;01.03.2010;98.0;degC;
t4_fuel_sep1preheat_out;01.04.2010;97.8;degC;
t4_fuel_sep1preheat_out;01.05.2010;97.7;degC;

mflow_fuel_sep2preheat;01.02.2010;0.60;kg/s;
mflow_fuel_sep2preheat;01.03.2010;0.60;kg/s;
mflow_fuel_sep2preheat;01.04.2010;0.60;kg/s;
mflow_fuel_sep2preheat;01.05.2010;0.60;kg/s;
t1_medium_fuel_sep2preheat_in;01.02.2010;119.9;degC;
t1_medium_fuel_sep2preheat_in;01.03.2010;119.9;degC;
t1_medium_fuel_sep2preheat_in;01.04.2010;119.9;degC;
t1_medium_fuel_sep2preheat_in;01.05.2010;119.9;degC;
t2_medium_fuel_sep2preheat_out;01.02.2010;105.1;degC;
t2_medium_fuel_sep2preheat_out;01.03.2010;105.1;degC;
t2_medium_fuel_sep2preheat_out;01.04.2010;105.1;degC;
t2_medium_fuel_sep2preheat_out;01.05.2010;105.1;degC;
t3_fuel_sep2preheat_in;01.02.2010;80.0;degC;
t3_fuel_sep2preheat_in;01.03.2010;80.0;degC;
t3_fuel_sep2preheat_in;01.04.2010;80.0;degC;
t3_fuel_sep2preheat_in;01.05.2010;80.0;degC;
t4_fuel_sep2preheat_out;01.02.2010;98.0;degC;
t4_fuel_sep2preheat_out;01.03.2010;98.0;degC;
t4_fuel_sep2preheat_out;01.04.2010;98.0;degC;
t4_fuel_sep2preheat_out;01.05.2010;98.0;degC;

mflow_fuel_heater_1;01.02.2010;1.50;kg/s;
mflow_fuel_heater_1;01.03.2010;1.45;kg/s;
mflow_fuel_heater_1;01.04.2010;1.45;kg/s;
mflow_fuel_heater_1;01.05.2010;1.50;kg/s;
t1_medium_fuel_heater_1_in;01.02.2010;160.0;degC;
t1_medium_fuel_heater_1_in;01.03.2010;161.5;degC;
t1_medium_fuel_heater_1_in;01.04.2010;160.2;degC;
t1_medium_fuel_heater_1_in;01.05.2010;160.6;degC;
t2_medium_fuel_heater_1_out;01.02.2010;145.0;degC;
t2_medium_fuel_heater_1_out;01.03.2010;145.1;degC;
t2_medium_fuel_heater_1_out;01.04.2010;145.0;degC;
t2_medium_fuel_heater_1_out;01.05.2010;145.2;degC;
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t3_fuel_heater_1_in;01.04.2010;130.0;degC;
t3_fuel_heater_1_in;01.05.2010;130.0;degC;
t4_fuel_heater_1_out;01.02.2010;140.0;degC;
t4_fuel_heater_1_out;01.03.2010;140.0;degC;
t4_fuel_heater_1_out;01.04.2010;139.0;degC;
t4_fuel_heater_1_out;01.05.2010;140.1;degC;

mflow_fuel_heater_2;01.02.2010;1.50;kg/s;
mflow_fuel_heater_2;01.03.2010;1.50;kg/s;
mflow_fuel_heater_2;01.04.2010;1.50;kg/s;
mflow_fuel_heater_2;01.05.2010;1.50;kg/s;
t1_medium_fuel_heater_2_in;01.02.2010;160.0;degC;
t1_medium_fuel_heater_2_in;01.03.2010;160.0;degC;
t1_medium_fuel_heater_2_in;01.04.2010;160.0;degC;
t1_medium_fuel_heater_2_in;01.05.2010;160.0;degC;
t2_medium_fuel_heater_2_out;01.02.2010;145.0;degC;
t2_medium_fuel_heater_2_out;01.03.2010;145.0;degC;
t2_medium_fuel_heater_2_out;01.04.2010;145.0;degC;
t2_medium_fuel_heater_2_out;01.05.2010;145.0;degC;
t3_fuel_heater_2_in;01.02.2010;130.0;degC;
t3_fuel_heater_2_in;01.03.2010;130.0;degC;
t3_fuel_heater_2_in;01.04.2010;130.0;degC;
t3_fuel_heater_2_in;01.05.2010;130.0;degC;
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t4_fuel_heater_2_out;01.03.2010;140.0;degC;
t4_fuel_heater_2_out;01.04.2010;140.0;degC;
t4_fuel_heater_2_out;01.05.2010;140.0;degC;

vibv_fuel_sep_1_mde;01.02.2010;0.21;mm/s-RMS;
vibv_fuel_sep_1_mde;01.03.2010;0.99;mm/s-RMS;
vibv_fuel_sep_1_mde;01.04.2010;1.04;mm/s-RMS;
vibv_fuel_sep_1_mde;01.05.2010;1.77;mm/s-RMS;
vibv_fuel_sep_1_mnde;01.02.2010;0.35;mm/s-RMS;
vibv_fuel_sep_1_mnde;01.03.2010;1.27;mm/s-RMS;
vibv_fuel_sep_1_mnde;01.04.2010;2.46;mm/s-RMS;
vibv_fuel_sep_1_mnde;01.05.2010;3.69;mm/s-RMS;
vibv_fuel_sep_1_sde;01.02.2010;0.49;mm/s-RMS;
vibv_fuel_sep_1_sde;01.03.2010;1.94;mm/s-RMS;
vibv_fuel_sep_1_sde;01.04.2010;14.35;mm/s-RMS;
vibv_fuel_sep_1_sde;01.05.2010;0.25;mm/s-RMS;

vibv_fuel_sep_2_mde;01.02.2010;0.21;mm/s-RMS;
vibv_fuel_sep_2_mde;01.03.2010;0.21;mm/s-RMS;
vibv_fuel_sep_2_mde;01.04.2010;0.21;mm/s-RMS;
vibv_fuel_sep_2_mde;01.05.2010;0.21;mm/s-RMS;
vibv_fuel_sep_2_mnde;01.02.2010;0.35;mm/s-RMS;
vibv_fuel_sep_2_mnde;01.03.2010;0.35;mm/s-RMS;
vibv_fuel_sep_2_mnde;01.04.2010;0.35;mm/s-RMS;
vibv_fuel_sep_2_mnde;01.05.2010;0.35;mm/s-RMS;
vibv_fuel_sep_2_sde;01.02.2010;0.49;mm/s-RMS;
vibv_fuel_sep_2_sde;01.03.2010;0.49;mm/s-RMS;
vibv_fuel_sep_2_sde;01.04.2010;0.49;mm/s-RMS;
vibv_fuel_sep_2_sde;01.05.2010;0.49;mm/s-RMS;

Appendix H. Measurement hierarchy

Top level measurement hierarchy is identical to system hierarchy, while for the fuel oil sub-systems the measurement hierarchies are shown below:

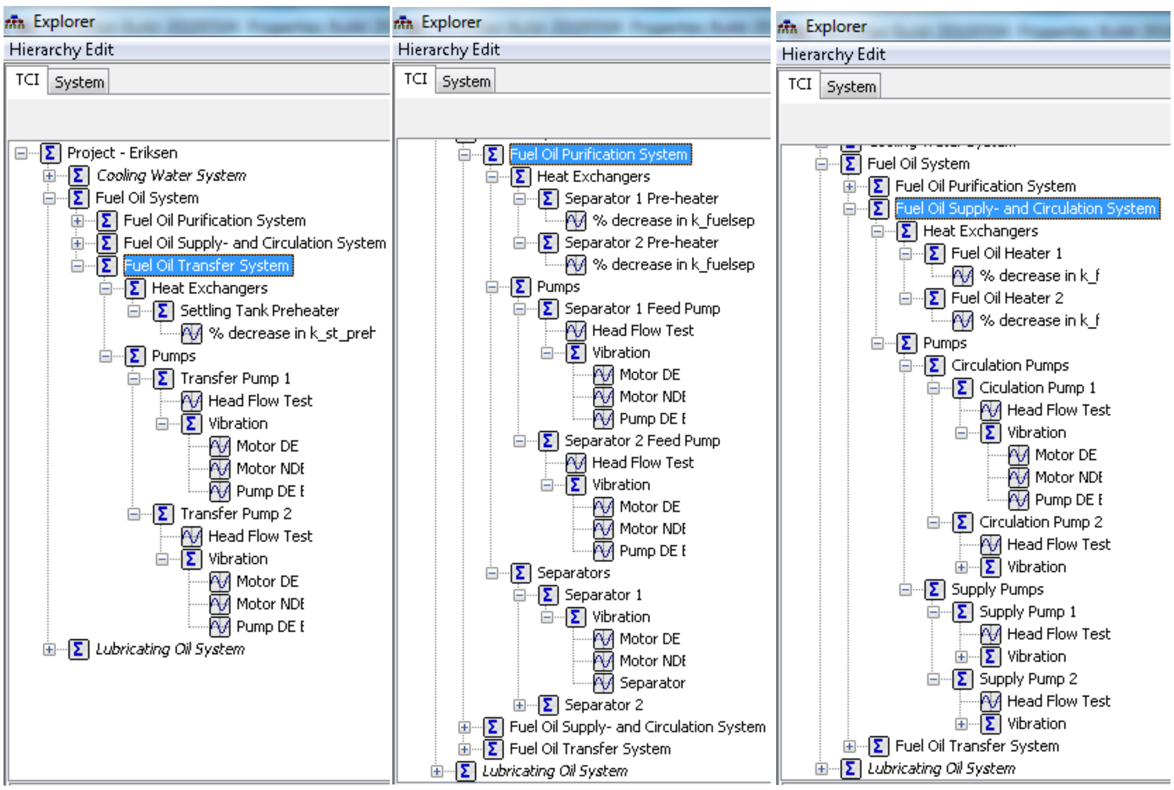

Figure 34: Print screens showing fuel oil sub-systems measurement hierarchies.

The $\sum$ symbol, of course, depicts aggregation nodes, while graph symbol depicts measurement nodes. Not all vibration aggregation nodes have been expanded fully, however these are equal for all pumps and separators, all with three bearings measurement points mde, mnde and pde (or for separators sde).

Appendix I. Calculations of Reference and Measurement Data: Pumps

General formulas used:

$$Vflow = \frac{mflow(kg/s) \cdot 3600}{\rho_f{}^{\theta}(kg/m^3)}(m^3/h)$$

$$Vflow = 1000\frac{mflow(kg/s) \cdot 3600}{\rho_f{}^{\theta}(kg/m^3)}(L/h)$$

$$Power = \frac{vflow(m^3/s) \cdot Head(kPa)}{\eta}(kW)$$

$$Head(kPa) = \frac{Head(m) \cdot g(m/s^2) \cdot \rho_f{}^{\theta}(kg/m^3)}{1000}$$

Fuel Oil Transfer Pump

For the transfer pumps, the criterion saying emptying and filling one bunker tank within reasonable time, assumed to be 12 hours, was used to find a value of the typical mass flow for the pump. Necessary pump head of such pumps will be dominated by the pressure vessel head necessary to pump fluid into a nearly full tank. I assume a total pump head of 15 m is typical.

Parameter	Unit	Value	Comment
Mass flow	27,0	kg/s	Assume for trimming purposes moving contents of one complete bunker tank within 12 hours
Volumetric flow	100,5	m^3/h	
Pump Head at flow	139,3	kPa	Calculated assuming typical pump head for such pumps is 15 m
Power	6,5	kW	Assuming pump efficiency η =0,6

Table 16: Fuel Oil Transfer Pump flow, head and indicated power

Rounding off the values slightly, I assumed the following reference condition test data and values at test dates to be used for demonstration of TCI's in TeCoMan:

Parameters	Symbol	Unit	Reference	1.2.2010	1.3.2010	1.4.2010	1.5.2010
p1	a	-	-3,96E-09				
p2	b	-	0				
p3	c	-	180				
v1	dp	kPa	140	142,3	140	120	137,5
v2	vflow	L/h	100500	97500	100000	101500	103000
TCI user function value		%	0,0	0,0	-0,3	-13,8	-0,4

Table 17: Reference and test data for fuel oil transfer pumps

With the constants defined in Table 17 above, the test points can be plotted against the Head – flow curve to demonstrate how test points are positioned relative to the reference curve:

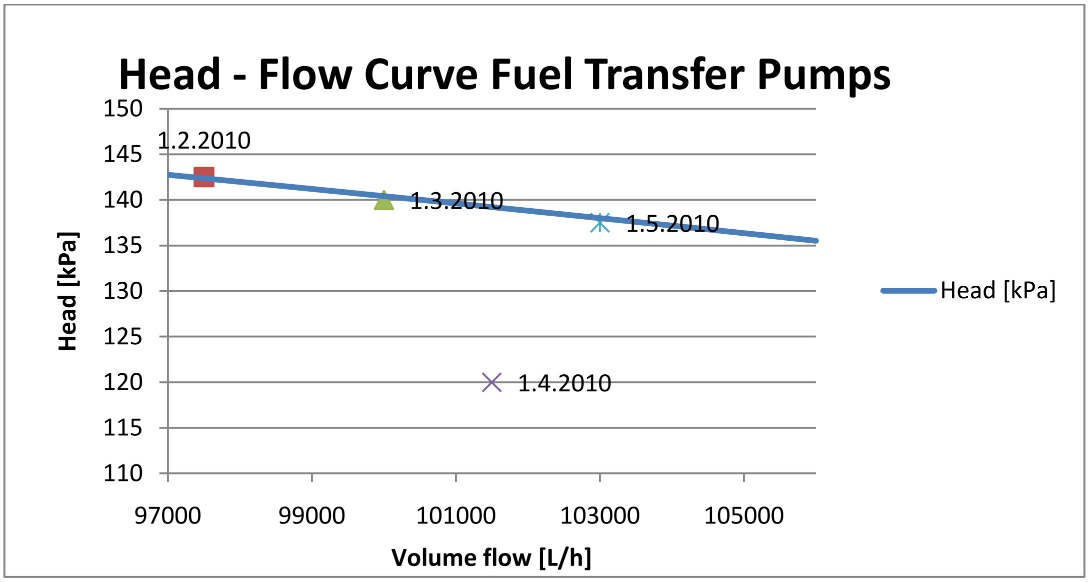

Figure 35: Head-flow curve and test points for fuel oil transfer pump

Fuel Oil Separator Feed Pump

For the fuel oil feed pump, it was assumed to typically handle 1,2 times the maximum continuous fuel consumption, as separation should have some overcapacity. For the pump head, a value of 450 kPa was simply assumed.

Parameter	Unit	Value	Comment
Mass flow		0,6kg/s	Assume 1,2 times maximum fuel consumption
Volumetric flow		2281,4L/h	Multiplied above by 3600 and divided by density
Pump Head at given flow		450kPa	Assumed value
Indicated Power		0,5kW	Assuming pump efficiency η =0,6

Table 18: Head, flow and indicated power for fuel oil separator feed pump

Reference and measurement data were proposed through iteration in the spreadsheet and chosen:

Parameters	Symbol	Unit	Reference	1.2.2010	1.3.2010	1.4.2010	1.5.2010
p1	a	-	-0,00002835				
p2	b	-	0				
p3	c	-	600				
v1	dp	kPa	450	475	455	405	430
v2	vflow	L/h	2300	2100	2200	2300	2400
TCI User function value		%	0,0	0,0	-1,7	-10,0	-1,5

Table 19: Reference and measurement data for fuel oil separator feed pump

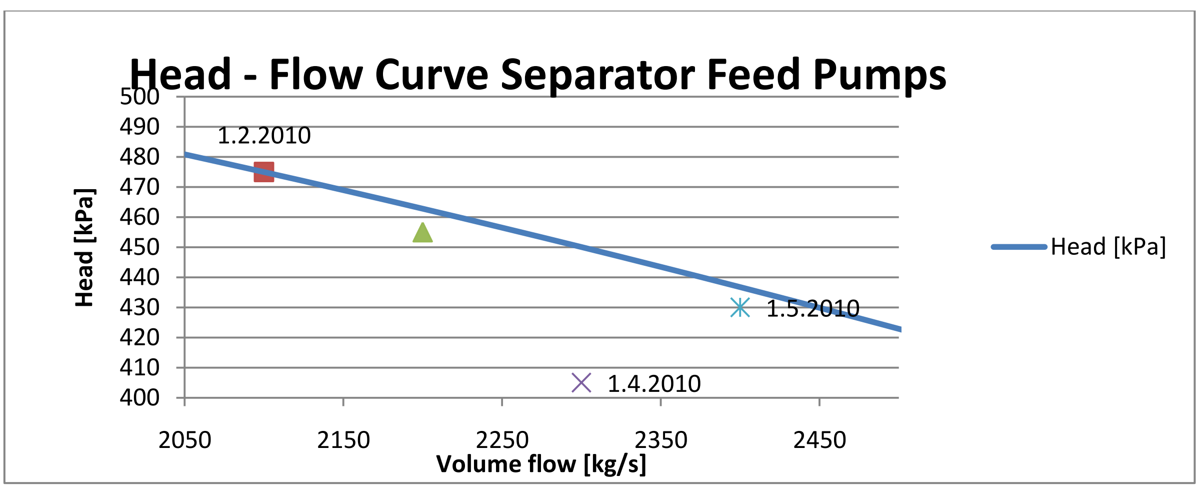

Figure 36: Head - flow curve and measurement data for fuel oil separator feed pump

Fuel Oil Supply Pumps

For the fuel oil supply pumps, the mass flow was once again assumed to have a 20% overcapacity with respect to the maximum fuel flow. The pump head was assumed to be 1,5 times the pressure vessel head between the day tank (approximately 1 atmosphere) and the mixing tank assumed to have a pressure of 12 bars. In fact the pressure vessel head would then be 11 bars or conversely produce a pump head of 1650 kPa, however I forgot the day tank 1 atmosphere pressure and used 12 bars giving a value of 1800 kPa.

Parameter	Unit	Value	Comment
Mass flow		0,6kg/s	Assume 1,2 times maximum fuel consumption
Volumetric flow		2311,2L/h	Multiplied above by 3600 and divided by density
Pump Head at flow		1800kPa	Assumed 1,5 times pressure vessel head at mixing tank
Indicated Power		1,9kW	Assuming pump efficiency η =0,6

Table 20: Head, flow and indicated power for fuel oil supply pumps

Reference and measurement values were chosen:

Parameters	Symbol	Unit	Reference	1.2.2010	1.3.2010	1.4.2010	1.5.2010
p1	a	-	-0,0000945				
p2	b	-	0				
p3	c	-	2300				
v1	dp	kPa	1800	1852	1800	1650	1760
v2	vflow	L/h	2300	2150	2200	2300	2380
TCI user function value		%	0,0	-0,6	-2,3	-8,3	-0,3

Table 21: Reference and measurement values for fuel oil supply pump

The Head – Flow curve and test points from these data is shown below.

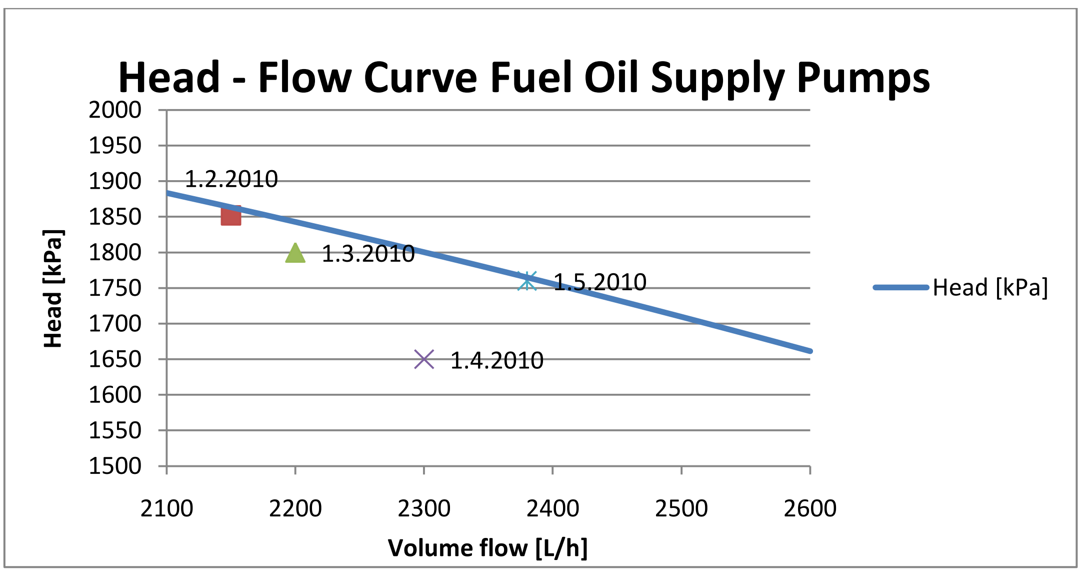

Figure 37: Head - Flow curve and measurement points for fuel oil supply pump

Fuel Oil Circulation Pumps

For the mass flow of the circulation pumps, according to (35 p. 82) there must be an overcapacity in flow rate relative to the maximum fuel consumption of the engine of about 3. For the pump head, it was assumed that pump head is approximately 1,5 times the pressure vessel head. Assuming 12 bars at the mixing tank and according to (38) a typical 15 bars pressure available at the high pressure fuel injection pumps, the pressure vessel head is 3 bars.

Parameter	Unit	Valuee	Comment
Mass flow	1,5	kg/s	Assume 3 times maximum fuel consumption (35)
Volumetric flow	5915,9	L/h	Multiplied above by 3600 and divided by density
Pump Head at given flow	450	kPa	Assume typical pump head is 1,5 times the pressure vessel head
Indicated Power	1,2	kW	Assuming pump efficiency η =0,6

Table 22: Head, flow and indicated power for fuel oil circulation pump

Rounding off the flow rate slightly and otherwise iterating within the sheet I chose the following reference and measurement values:

Parameters	Symbol	Unit	Reference	1.2.2010	1.3.2010	1.4.2010	1.5.2010
p1	a	-	-0,00000431				
p2	b	-	0				
p3	c	-	600				
v1	dp	kPa	450	465	450	440	405
v2	vflow	L/h	5900	5600	5900	5950	6200
TCI user function value		%	0,0	0,0	0,0	-1,7	-6,8

Table 23: Reference and measurement data for fuel oil circulation pump

From these data we obtain the following head – flow curve and data points:

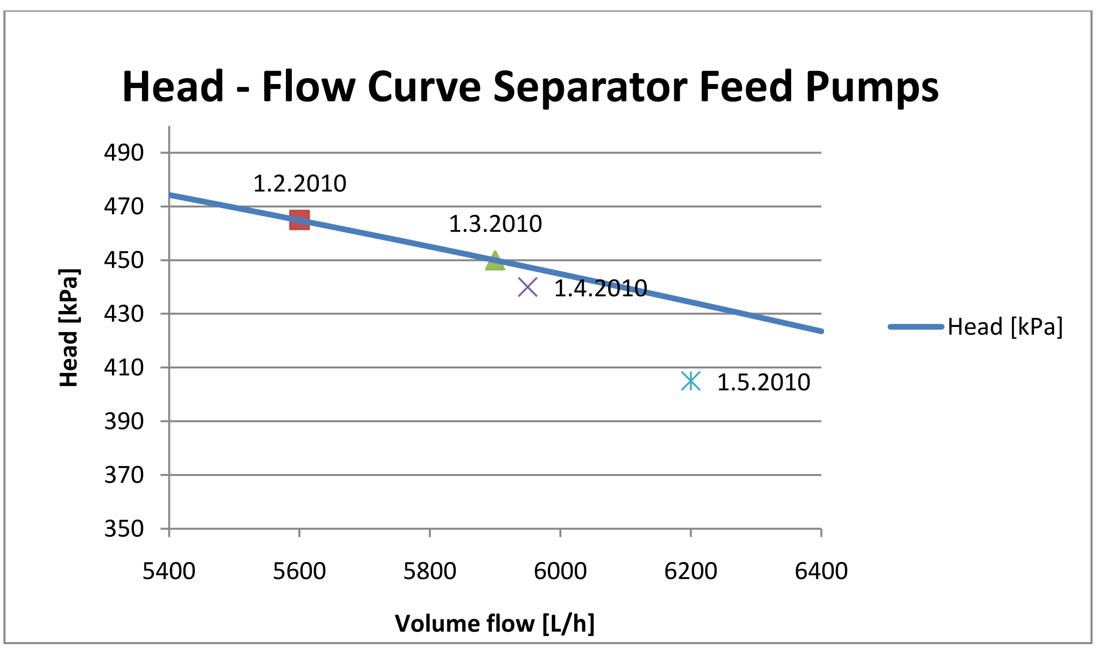

Figure 38: Head - Flow curve and measurement points for fuel oil circulation pump

Appendix J. Reference and Measurement Data: Heat Exchangers

Settling Tank Preheater

For the settling tank preheater, mass flow was chosen equal to the fuel transfer feed pumps. Temperatures of the fuel oil at reference were taken from calculated intended design temperature. All other data were chosen arbitrarily or through iteration to reflect plausible values.

Parameters	Name	Unit	Reference	01.02.2010	01.03.2010	01.04.2010	01.05.2010
p1	cp medium	j/kgK	1903,8	1903,8	1903,8	1903,8	1903,8
p2	A	m^2	25	25	25	25	25
p3	kref	W/m^2K	1950	1950	1950	1950	1950
v1	T1	deg C	105,0	105,0	105,5	106,0	106,3
v2	T2	deg C	90,0	90,0	90,5	90,3	90,8
v3	T3	deg C	50,0	50,0	50,8	51,0	51,5
v4	T4	deg C	80,0	80,0	80,0	80,0	79,0
v5	mflow medium	kg/s	27,20	27,20	27,20	27,10	26,50
	TCI user function value	%	-0,1	-0,1	-3,3	-4,7	-13,6
	kmeas	W/m^2K	1947,1	1947,1	1885,5	1859,0	1685,0

Table 24: Reference and measurement data for settling tank preheater

Separator Preheaters

For the separator preheater, mass flow was chosen equal to the maximum continuous fuel consumption of the engine. It would perhaps be more likely that mass flow was set equal to that of fuel separator feed pumps. However if temperature control is done by by-passing the heaters, the flow through the preheaters may likely be somewhat smaller than for the pump. For demonstrating the concept of TCI's this is unimportant. Temperatures of the fuel oil at reference were taken from calculated intended design temperatures. All other data were chosen arbitrarily or through iteration to reflect plausible values. These data were implemented for separator preheater 1 in TeCoMan, while all measurements for preheater 2 for all dates were set equal to measurements dated 01.02.2010 below.

Parameters	Name	Unit	Reference	01.02.2010	01.03.2010	01.04.2010	01.05.2010
p1	cp medium	j/kgK	1985,2	1985,2	1985,2	1985,2	1985,2
p2	A	m^2	0,5	0,5	0,5	0,5	0,5
p3	kref	W/m^2K	1827,5	1827,5	1827,5	1827,5	1827,5
v1	T1	deg C	120,0	119,9	120,3	122,8	123,1
v2	T2	deg C	105,0	105,1	105,6	105,0	105,1
v3	T3	deg C	80,0	80,0	81,6	81,4	81,5
v4	T4	deg C	98,0	98,0	98,0	97,8	97,7
v5	mflow medium	kg/s	0,60	0,60	0,59	0,57	0,58
	TCI user function value	%	0,0	0,0	-9,1	-16,4	-16,6
	kmeas	W/m^2K	1827,2	1827,6	1660,3	1527,8	1523,4

Table 25: Reference and measurement data for separator preheater

Fuel Oil Heaters

For the fuel oil heaters, mass flow was set equal to that of fuel oil circulation pumps, 3 times maximum fuel consumption. Temperatures of the fuel oil at reference were taken from calculated intended design temperatures. All other data were chosen arbitrarily or through iteration to reflect plausible values. These data were implemented for fuel oil heater 1 in TeCoMan, while measurements for fuel oil heater 2 for all dates were set equal to measurements dated 01.02.2010 below.

Parameters	Name	Unit	Reference	01.02.2010	01.03.2010	01.04.2010	01.05.2010
p1	cp of selected medium	j/kgK	2141,3	2141,3	2141,3	2141,3	2141,3
p2	A	m^2	1	1	1	1	1
p3	kref	W/m^2K	1848	1848	1848	1848	1848
v1	T1	deg C	160,0	160,0	161,5	160,2	160,6
v2	T2	deg C	145,0	145,0	145,1	145,0	145,2
v3	T3	deg C	130,0	130,0	129,8	130,0	130,0
v4	T4	deg C	140,0	140,0	140,0	139,0	140,1
v5	mflow selected medium	kg/s	1,50	1,50	1,45	1,45	1,50
	TCI user function value	%	0,0	0,0	-6,0	-15,6	-0,9
	kmeas	W/m^2K	1848,0	1848,0	1737,7	1559,2	1830,9

Table 26: Reference and measurement data for fuel oil heater

Appendix K. Vibration data

Table shows data for all bearing position of all components subject to vibration monitoring. Unit of all values are mm/s-RMS vibration velocity. The last subscript of each string denotes the bearing location, mde is motor driving end, mnde is motor non-driving end, pde is pump driven end and sde is separator driven end. All data was fabricated arbitrarily within a range of plausible threshold values according to ISO 3945.

Fuel Oil Transfer pump 1	01.02.2010	01.03.2010	01.04.2010	01.05.2010
vibv_fuel_tfp_1_mde	0,45	1,75	3,40	0,89
vibv_fuel_tfp_1_mnde	0,52	1,89	4,06	0,67
vibv_fuel_tfp_1_pde	0,36	1,13	3,04	0,55
Fuel Oil Transfer pump 2				
vibv_fuel_tfp_2_mde	0,45	0,45	0,45	0,45
vibv_fuel_tfp_2_mnde	0,52	0,52	0,52	0,52
vibv_fuel_tfp_2_pde	0,36	0,36	0,36	0,36
Fuel Separator 1 Feed Pump				
vibv_fuel_sep1fp_mde	0,62	1,28	4,45	0,58
vibv_fuel_sep1fp_mnde	0,55	1,33	4,01	0,49
vibv_fuel_sep1fp_pde	0,42	1,45	3,88	0,47
Fuel Separator 2 Feed Pump				
vibv_fuel_sep2fp_mde	0,62	0,62	0,62	0,62
vibv_fuel_sep2fp_mnde	0,55	0,55	0,55	0,55
vibv_fuel_sep2fp_pde	0,42	0,42	0,42	0,42
Fuel Oil Supply Pump 1				
vibv_fuel_sp_1_mde	0,24	1,13	2,18	0,21
vibv_fuel_sp_1_mnde	0,32	1,4	1,89	0,35
vibv_fuel_sp_1_pde	0,52	1,87	5,02	0,44
Fuel Oil Supply Pump 2				
vibv_fuel_sp_2_mde	0,24	0,24	0,24	0,24
vibv_fuel_sp_2_mnde	0,32	0,32	0,32	0,32
vibv_fuel_sp_2_pde	0,52	0,52	0,52	0,52
Fuel Oil Circulation Pump 1				
vibv_fuel_circp_1_mde	0,65	0,67	0,71	0,89
vibv_fuel_circp_1_mnde	0,63	0,68	0,69	1,15
vibv_fuel_circp_1_pde	0,55	1,59	15,5	0,55
Fuel Oil Circulation Pump 2				
vibv_fuel_circp_1_mde	0,65	0,65	0,65	0,65
vibv_fuel_circp_1_mnde	0,63	0,63	0,63	0,63
vibv_fuel_circp_1_pde	0,55	0,55	0,55	0,55
Fuel Oil Separator 1				
vibv_fuel_sep_1_mde	0,21	0,99	1,04	1,77
vibv_fuel_sep_1_mnde	0,35	1,27	2,46	3,69
vibv_fuel_sep_1_sde	0,49	1,94	14,35	0,25
Fuel Oil Separator 2				
vibv_fuel_sep_2_mde	0,21	0,21	0,21	0,21
vibv_fuel_sep_2_mnde	0,35	0,35	0,35	0,35
vibv_fuel_sep_2_sde	0,49	0,49	0,49	0,49

Table 27: Vibration measurement data for all components subject to vibration monitoring.

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