CBM Condition Detection Algorithms W31

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BACHELOR'S THESIS

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Abstract

This thesis work was made for CBM, a group within Technical Services at Wärtsilä Finland and pertains to CBM´s core objective, namely monitoring engines condition.

The main purpose of this work was to build a health detection algorithm based platform for the Wärtsilä 31 diesel engine in Excel, the Excel platform would later be used in creating a platform for the monitoring system at CBM.

Information gathering is key when building health detection algorithms, the data have to be sufficient but more importantly, the data have to be accurate. A sensor availability list and dependencies matrix were then created in order to create equations that the algorithm uses. The algorithms are made so they choose equation combinations based on the engines configuration, it then renders calculated mean values based on the engines operational status during the time range as to when the data is being measured. If a measured value deviates from the calculated value to a certain limit, it will be marked as yellow or red depending on which limitation has been exceeded.

The result is an Excel platform that Wärtsilä personnel can use internally and it will also be used as a base to the platform that later will be created for CBM.

Language: English Key words: Condition based maintenance, Excel, Algorithms

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EXAMENSARBETE

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Titel: CBM konditionstillståndsalgoritmer W31

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Abstrakt

Detta examensarbete har gjorts för CBM, en underavdelning inom Technical Services vid Wärtsilä Finland Oy och koncentrerar sig på CBM:s huvuduppgift, att övervaka motorers kondition.

Huvudsyftet med det här examensarbetet var att bygga en plattform för Wärtsilä 31 dieselmotorn baserat på konditionstillståndsalgoritmer i Excel. Excel–plattformen skulle senare användas när en plattform för CBM:s övervakningssystem skapas.

Insamling av information är viktigt vid byggandet av konditionstillståndsalgoritmer. Informationen bör vara tillräcklig men ännu viktigare, informationen bör vara noggrann. En lista över sensortillgänglighet och en beroendematris gjordes för att kunna skapa ekvationer som användes av algoritmerna. Algoritmerna är gjorda så att de väljer ekvationskombinationer baserat på motorns konfiguration. De ger sedan ut kalkylerade medelvärden baserat på motorns driftdata under den tid då mätvärdena har tagits. Om ett uppmätt värde avviker från det kalkylerade värdet till en viss gräns så markeras värdet, endera som gult eller som rött beroende på vilken gräns som har överskridits.

Resultatet är en Excel–plattform som Wärtsiläs personal kan använda internt och den kommer även att användas som en grund för plattformen som kommer att skapas för CBM.

Språk: engelska Nyckelord: Tillståndsbaserat underhåll, Excel, Algoritmer

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Päivämäärä: 12.4.2017 Sivumäärä: 25

Tiivistelmä

Tämä opinnäytetyö on tehty Wärsilä Finland Oyj:n teknisen huollon CBM-osastolle ja sen toiminnan päätarkoitusta, moottorien kunnon valvontaa varten.

Opinnäytetyön päätavoitteena oli rakentaa Wärtsilä 31-dieselmoottorityypille Excel-alusta, joka perustuu kuntotila-algoritmeihin. Excel-alustaa tullaan käyttämään Wärtsilä 31-dieselmoottorityypin CBM-valvonnan suoritusarvorajojen perustana.

Suoritusarvodatan keruu on tärkeässä roolissa kuntotila-algoritmien luonnissa.
Datan määrän tulee olla riittävän laaja ja ennen kaikkea tarkka. Opinnäytetyössä tehtiin lista moottorissa olevista antureista ja riippuvuusmatriisi luodakseen yhtälöt algoritmeille. Algoritmit on luotu niin, että ne valitsevat yhtälökombinaatioita moottorin rakenteen perustella. Tällä saadaan aikaan jokaisesta moottorin anturilla mitattavasta suoritusarvosta mittausajakson keskiarvo.

Jos mitattu arvo poikkeaa ennaltatiedetyn keskiarvon sallitusta poikkeamasta (+/-), merkitään arvo keltaisella tai punaisella värikoodilla, riippuen poikkeaman suuruudesta. Opinnäytetyön lopputuloksena on syntynyt Excel-alusta, jota käyttämällä CBM-osasto luo raja-arvot valvottaville suoritusarvoille, kun Wärtsilän 31-moottorityyppi liitetään CBM-valvontajärjestelmään.

Kieli: englanti Avainsanat: kuntoon perustava huolto, Excel, Algoritmeja

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Foreword

As this thesis work culminates my studies here at Novia UAS I would like to show my gratitude to the people who have helped me on this journey, to my supervisors, Andreas Gammelgård at Novia and Jens Vägar at Wärtsilä. I would also like to show gratitude to the CBM team, to Mr. Jesper Engström at performance and to Mr. Fredrik Grönlund at the engine laboratory who all have been vital for the execution of this work.

Table of content

Abbreviations

CBM	Condition Based Maintenance
D	Diesel
SG	Spark-ignited Gas
DF	Dual Fuel
DMP	Dynamic Maintenance Planning
UNIC	Unified Controls
WOIS	Wärtsilä Operator´s Interface System
LNG	Liquefied Natural Gas
MDO	Marin Diesel Oil
HFO	Heavy Fuel Oil
IMO	International Maritime Organization
LP	Low-Pressure
HP	High-Pressure
CAC	Charge Air Cooler
HT	High Temperature
LT	Low Temperature
LVT	Linear Velocity Transducers
FAT	Factory Acceptance Test

1 Introduction

In a time of recession and when the oil price in 2009 was at the lowest it had been for over 5 years (Trading Economics, 2017), the marine industry had a challenging time ahead. From an environmental perspective, you could argue that it has been good. Because of the bad market situation, engine developers all over the world have had to come up with solutions that are more efficient, have lower fuel consumption, higher reliability and are more economically sound, this is where maintenance plays a big part.

This thesis work was commissioned by CBM (Condition Based Maintenance), a subdivision in Wärtsilä Finland. By collecting performance data, establishing parameters and constructing algorithms, this work will show the process in which an algorithmic platform is developed, a platform that analyses an engine´s health from a distance. This benefits both the company and the customer in regards to service, support and optimization of the engine.

After having been working at Wärtsilä´s engine laboratory in Vasa for two summers and one winter, I had procured a rather good knowledge of the Wärtsilä 31 marine diesel engine. My last summer practice I did in a Marine solutions subdivision called Auxiliary Systems, this gave me the chance to see another side of Wärtsilä and at the same time broaden my knowledge of the company and its products. Finally, I was given the chance of executing my thesis work.

1.1 Background

In 2016, production started on the W31D engine, this is a new engine with new technology and award winning efficiency. (Wärtsilä, W31 brochure, 2016)

1.2 Purpose

There are already several engine models that have CBM, every engine model is different in one way or another when you look at the design and sensor values, therefore the algorithms should be built to fit a specific engine. The purpose is to construct algorithms for the W31D engine, algorithms that will sort out the data from the engine sensors and based on cause and affect the algorithms will indicate if there are any faults or the beginning of a failure.

1.3 Delimitation

There are three types of the W31, the SG (Spark-ignited Gas) runs on gas, the DF (Dual Fuel) that is a dual fuel engine that can run on either gas or heavy- / light fuel oil and then there is the 31D (Diesel) that can run on heavy fuel oil or light fuel oil. The first engines to be produced for selling were W31D.s, as the task of constructing algorithms and all that pertains to it is rather time consuming we decided to limit this thesis work to this engine model.

1.4 Disposition

This thesis work consists of a theory part in which information pertaining to this work is relevant, after that comes a methodology part where the process and methods are described leading up to the end result of said work and finally a discussion about the work as a whole.

1.5 About the company

Wärtsilä Oyj build and deliver technologically advanced solutions for the marine and energy market, they are also a global leader in their field. Wärtsilä gives the customer better fuel economy and more environmental friendly solutions by concentrating on total efficiency and innovative technology.

In 2016, Wärtsilä had approximately 18 000 employees in over 200 different locations in 70 different countries and had a total net sale of EUR 4.8 billion. (Wärtsilä, about, 2017)

Marine Solutions

Marine Solutions is a division in Wärtsilä that provides high end marine solutions for the marine, oil and gas industry. The solutions are customer based and include products, systems and services. In 2016 Marine solutions had a net sale of EUR 1.7 billion. (Wärtsilä, about, 2017) (Wärtsilä, marine, 2017)

Energy Solutions

Energy solutions is another division in Wärtsilä that provides flexible power plants from 10 to over 600 MW and have delivered over 4700 plants to 170 different locations worldwide. They also deliver LNG terminals and distribution systems. Their net sale 2016 was EUR 1 billion. (Wärtsilä, about, 2017) (Wärtsilä, energy, 2017)

Services

Services is the third division in Wärtsilä, services give support and uphold service agreements to the customers. They strive to let the customer get the most out of an installation by preventing unexpected faults and optimizing performance, giving the installation a longer lifespan. In 2016 Services had a net sale of 2.2 billion. (Wärtsilä, about, 2017) (Wärtsilä, services, 2017)

1.5.1 CBM

CBM or Condition Based Maintenance is a subdivision within Wärtsilä Services, in short, they keep an eye on engines´ condition. This means that equipment can be optimized, scheduled and unscheduled maintenance can be reduced while at the same time availability, reliability and predictability increases. (Wärtsilä, CBM, 2016)

DMP (Dynamic Maintenance Planning), as CBM mostly monitors the engine and give feedback in the form of reports. DMP plans the maintenance with the information given from CBM and from on-site audits and inspections as well as from reports done by the operating crew.

CBM is a service offered to the customer by Wärtsilä, this service can be applied to any given installation. CBM is built up so that the engines sensors measure values that the engines control system, UNIC, collects and processes. WOIS collects the operating data processed by UNIC and sends said data wireless to Wärtsilä on a daily basis. The operational data is then stored in a database and processed by algorithms in an engine based evaluation tool. Engine experts analyze the data after the evaluation tool has processed it, based on the expert opinion, feedback and advice (if needed) are given back to the customer. See ***Figure 1*** *CBM way of working* for an overview.

The evaluation tool is engine based, which means that it is configured separately on each engine, below are the main data inputs needed.

- An engine´s configuration such as engine model, main type (D, DF or SG), turbocharger type and so on.
- Installation design such as static water pressure, lubrication oil system, water cooling system and so on.

- Liquid inputs meaning the quality of the engine´s liquids.
- Measured parameters meaning the values measured on the engine such as load, temperatures and other operational data.

The benefits of having CBM are many, for instance, a fuel consumption and emission reduction by 2 – 5%, unscheduled stops reduced by 60 – 90% and increasing total availability by 5 – 20%. This saves both time and money for the customer and keeps the engine running smoothly. (Wärtsilä, DMP & CBM, 2017)

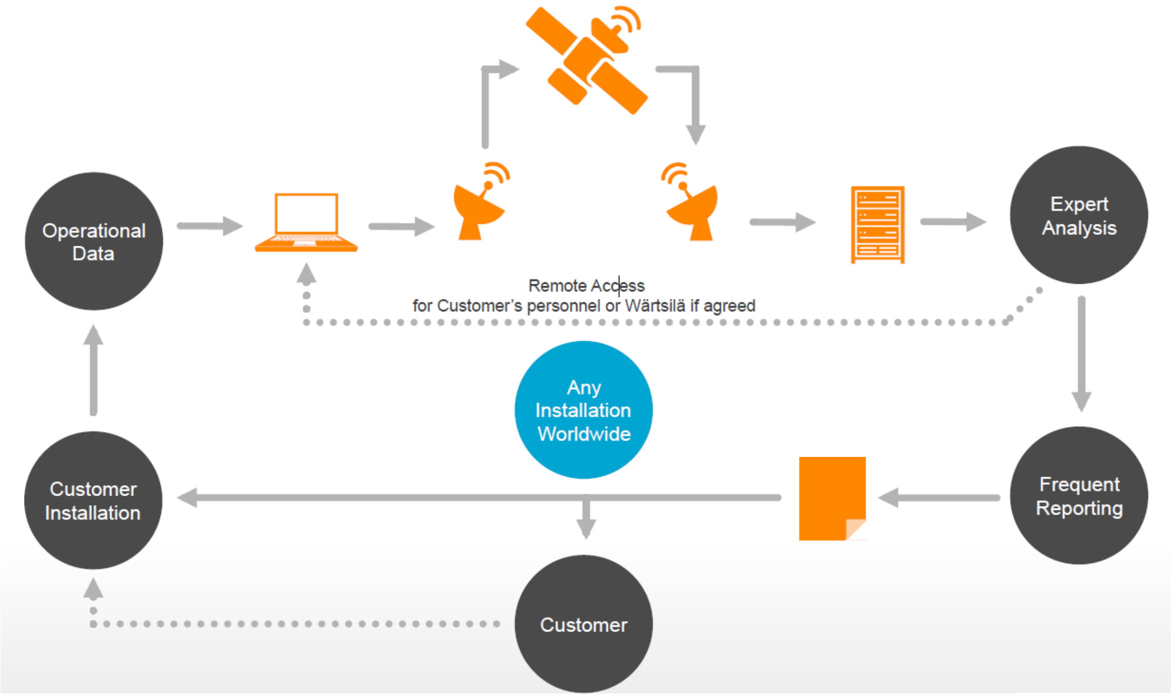


Figure 1 CBM way of working (Wärtsilä, DMP & CBM, 2017)

2 Theory

To get a better understanding of this work, this chapter will introduce the W31 engine and I will also go through some basics about the 4-stroke diesel engine as it pertains to what effects the sensors on the engine. In addition to that I will describe sensors relevant to this work and condition based maintenance.

2.1 4-stroke engine

A modern 4-stroke engine is comprised of several components, in this segment I will describe some of the main components, some basics in combustion, air flow and thermodynamics in engines. As this work revolves around the Wärtsilä 31 diesel engine, the following will relate to that.

2.1.1 Wärtsilä 31

The first W31 engine was installed at the testing facilities in Vaasa/ Finland in 2014, first out was the SG engine which runs on LNG (liquefied natural gas), then the diesel engine and later the DF engine was installed and was ready for testing.

The Wärtsilä 31 was in 2015 given the esteemed award of being the most efficient 4-stroke diesel engine in the world by the Guinness World Records.

The 31 is a medium bore, medium speed engine. It is divided up into 3 main categories, diesel, SG and DF. The difference being the fuels that they run on and the way they are configured based on said fuel. The diesel model can be operated on low sulfur fuels, MDO (Marine Diesel Oil) and HFO (Heavy Fuel Oil).

The diesel model is available in 8 to 16 cylinder configurations and a 20-cylinder model available for power plants. The power output ranges from 4.2 – 9.8 MW at 720 or 750 rpm with a cylinder power as high as 610 kW/cylinder. (Wärtsilä, W31 brochure, 2016)

Due to its low emissions, the Wärtsilä 31 meets IMO tier 2 and 3 (International Maritime Organization) regulations, IMO tier 3 can be achieved in gas mode or in diesel mode with SCR (Selective Catalytic Reduction) which reduces NO_2 (Nitrogen Oxide) by adding a urea solution to the exhaust gas. (Wärtsilä, Encyclopedia of Marine Technology, 2017)

Suitable for direct propulsion or diesel-electric as a main engine or as an auxiliary engine, it can be run on constant speed, by a propeller curve or with constant torque. This makes the 31 engines application range very broad, ranging from offshore to cruise and ferry and other marine segment, but also as a power plant installation. (Wärtsilä, W31 brochure, 2016)

What makes the Wärtsilä 31 engine the world’s most efficient 4-stroke diesel engine is a combination of new technology including a new turbocharger, stepless VIC (Variable Inlet valve Closing), newest UNIC engine control system and innovation such as the engines modular design.

The turbocharger is a second generation, two stage with a pressure ratio over 10 bar and an efficiency rating of 75%. Increased loading performance and load acceptance due to reduced inertia in the turbocharger.

S**tepless VIC** (Variable Inlet valve Closing) is a result of years of testing and validating, the first VIC, invented by Saku Niinikangas, was only on/off. Then, with the combined minds of Sören Höstman, Saku Niinikangas, johan Renvall and Magnus Sundsten, they were able to renew the VIC concept with the aid of the latest in solenoid technology, this gave them a fully variable valve closing function. The Wärtsilä 31 has the stepless VIC as a standard component.

UNIC is the engine control system that communicates with the engines´ sensors and base on given values from sensors and operator, adjusts the engines´ control parameters accordingly. Many of the control systems cable connections are doubled for redundancy reasons. (Wärtsilä, The new Wärtsilä 31 engine, 2015) Through the Modbus interface, communication is handled between the engines control system and the Wärtsilä operator´s interface system (WOIS). WOIS mostly monitors the engine. (Mandell, 2017)

The W31´s **modular design** makes it easier to carry out maintenance as the components for each cylinder are separate, from air intake to the cylinder head and exhaust as well as from the valve assembly to the camshaft and more. The modular design also makes it possible to convert between the three main types (D, DF and SG) and between different fuels without machining. It also prepares the engine for the future as the modular design makes it easier to upgrade the engine and therefore keep it up to date with coming regulations and demands. (Wärtsilä, The new Wärtsilä 31 engine, 2015)

2.1.2 Components

- **Engine block**, the engine block is the “body” of the engine, it is made of nodular cast iron and cast in one piece which makes it very durable against the forces that an engine produces. Inside the engine block resides air and water channels, also the upper crankshaft bearing housing and the camshaft bearing housing are incorporated. Due to the risk of oil mist igniting inside the crankcase, the block is fitted with explosion relief valves.

  The crankshaft is lubricated up through the supporting hydraulic jack, which are located under each crankshaft bearing cap and through the bearing cap itself. Depending on the application, a dry- or wet oil sump is mounted underneath the engine block.

- **Crankshaft**, the crankshaft is cast in one piece which makes it very resistant to fatigue. The crankshaft is fitted with counter weights, split camshaft gear wheel and pump drive arrangement. After being mounted the connecting rods are fitted. The connecting rods have wireless transfers of the big end bearings temperatures.

- **Cylinder liner**, the cylinder liner has a water jacket at its top collar which distributes water throughout the cooling bores in the liner. This makes it easier to regulate the fluctuating temperature that derives from the combustion chamber at different strokes and from the temperature raise due to friction between the piston and the liner. The liner is often designed with a conic shape so that it has a smaller diameter at the bottom and a lager at the top, because there are bigger temperature changes at the top of the liner.

- **Piston**, a piston is often made of aluminum in smaller engines, however, to get a more durable piston it is more likely made of a combination of steel and cast iron. In the W31 engine, the crown is made of steel and the skirt of nodular cast iron. Oil is used for cooling and lubricating the piston and is distributed by a jet nozzle which is mounted in the inner, lower section of the cylinder liner.

  The piston is injected with oil from underneath, the oil runs through channels in the piston and comes out through holes underneath the piston rings. Piston rings are used to seal the gap between the piston and the liner so that the pressure buildup in the combustion chamber does not leak past the piston, these rings are called compression rings. After the compression rings comes the oil scraper ring, its objective is to scrape oil of the cylinder liner wall. Besides preventing the compressed gas to trickle past the piston, the piston rings have another objective which is to lead heat from the piston to the liner.

- **Cylinder head**, on smaller engines the cylinder head covers all cylinders, but in larger engines the cylinder head is separate for each cylinder. Having separate cylinder heads, makes it easier when it comes to maintenance. The cylinder head is a sturdy boxlike construction that is fastened with 4 large pin bolts, it is made like this to withstand the enormous pressure build up in the combustion chamber. Most parts are replaceable in the cylinder head, the parts consist of inlet- and outlet valves, coil springs and valve seats. Then there are fuel injectors, charge air piping and exhaust manifolds among other parts that are assembled to the cylinder head to make it complete.

- **Camshaft and valves,** the camshaft is divided up in to separate pieces for each cylinder, this makes for easier maintenance rather than having to remove the whole camshaft. The valves are linked to the camshaft through a hydraulic system, at the camshaft end there are pistons that are fitted with rollers which roll against the cams, the piston moves parallel to the cam profile. The valves then move parallel to the piston via the hydraulic system. The valve timing for both inlet- and outlet valves can be altered to optimize emissions, fuel consumption and load. The camshaft is often driven by belt or chain on smaller engines or as in this case, by gear train. (Wärtsilä, product guide, 2016)

- **Turbo and charge air cooling,** a turbocharger, which comprises of an exhaust turbine and a compressor wheel fitted on the same axel, is often fitted to engines in order to increase the inlet air pressure. Increasing the air pressure is done by utilizing the heat energy in the exhaust gas that would normally just go to waste. The exhaust gas puts the turbine in motion which in turn rotates the compressor wheel. (Andersson, 2004, p. 91 – 93)

  The turbocharger in the Wärtsilä 31 is a 2 – stage type with a low – pressure (LP) stage and a high – pressure (HP) stage. By using a 2 – stage type, the charge air pressure can be raised even more by the second stage, it also gives a better efficiency even on lower loads. When exhaust gas is repelled out of the cylinder it flows through the HP turbine which in turn rotates the HP compressor, after the exhaust gas has passed through the HP it flows through the LP turbine which in turn rotates the LP compressor and then the exhaust gas flows out the exhaust gas outlet. The compressors suck in air through the air inlet, first through the LP compressor, then the HP compressor and finally to the air receiver and in to the cylinder. The LP compressor build up charge air pressure, it then cools down in the first 2 – stage charge air cooler (CAC), making it denser, then the HP compressor raise the pressure further and after that it´s cooled down again inside the second CAC and then onward to the charge air receiver. (Wärtsilä, product guide, 2016)

- **Fuel injection**¸ the fuel injection is of a common rail type. The system consists of one or more high pressure pumps depending on the cylinder configuration of the engine, these pumps build up a very high fuel oil pressure that is sent to a common pipe for each side of the engine, this pipe or common rail if you will, is connected to each fuel injector for each cylinder head. Safety valves are fitted to relieve pressure if needed. With the common rail system the engine gets a higher efficiency and runs smoother. (Simpson, 2007, p. 20 – 22) (Wärtsilä, product guide, 2016)

- **Lubrication system**, the content of the system varies depending on the engine, but you can say that smaller engines have all parts fitted on the engine and larger engines have several external components. On the Wärtsilä engine there is a pre-lube oil system besides the normal one. The normal system comprises of a lube oil pump, filters, lube oil cooler and safety valves. The pre-lube oil system is entirely comprised of external components. The lube oil system is one of the most important factors when it concerns the engines health and durability, the lubrication oils task is to clean the engine and cool certain components. The lube oil pump is fitted on the engine, from there the lube oil is divided up into the engine.

- **Cooling water system**, the main idea for a cooling system is to transport heat energy that we can´t use away from the engine to maintain a stable temperature in the engine. When air is compressed, friction and combustion occurs, heat raises drastically and if there were no cooling system, mechanical failure due to overheating would be unavoidable. (Simpson, 2007) In the Wärtsilä 31 engine, there are two circuits, a high temperature circuit (HT) and a low temperature circuit (LT), in normal conditions the LT circuit cools the lube oil cooler, the second stage of the first charge air cooler and the second charge air cooler. The HT circuit cools the engine jacket and the first stage of the first charge air cooler. The two circuits are closed circuits which are cooled externally in heat exchangers, the cooling fluid for the heat exchanger is usually derived from seawater and the engine cooling fluid is fresh water with an anti-corrosive agent added. (Andersson, 2004, p. 237 – 250) (Wärtsilä, product guide, 2016)

- **Exhaust system**, exhaust occurs when a fuel-air combination combusts in the cylinder’s combustion chamber, the heat energy and movement rotates the turbine wheels before exiting the system. The pipes are insulated with fire-retardant material to minimize heat transfer. (Wärtsilä, product guide, 2016)

2.1.3 Heat balance

Heat balance is a calculation of an engines output and losses in comparison to input, where fuel is the input energy and the output energy is the mechanical energy you can utilize. The losses are divided up into cooling, heat transference, exhaust and friction. For a diesel engine, the heat balance looks about the same irrespective of the engine specifics. (Andersson, 2004, p. 237)

2.1.4 Combustion process

In a 4-stroke diesel engine with a turbocharger, the process is as follows:

- Air is sucked in, compressed and cooled down through the turbochargers (compressor side) and charge air coolers.

- The piston moves downwards from top dead center creating an underpressure for the intake stroke, the inlet valve opens and the built-up charge air is sucked in to the cylinder.

- As the piston turns at bottom dead center and start moving upwards for its compression stroke, the inlet valve closes, pressure and temperature rises inside the combustion chamber due to the air being compressed.

- Just before reaching top dead center a fine vapor of fuel is injected and mixed with the air. The high pressure and temperature ignites the mixed gas right after the piston has turned at top dead center. Upon igniting, the pressure and temperature rises drastically in the combustion chamber forcing the piston downwards for its combustion stroke.

- The outlet valve opens just before the piston turns at bottom dead center. As the piston moves upwards again for its exhaust stroke, the exhaust gas is being pressed out of the cylinder. When the piston again reaches top dead center, the outlet closes and the process begins again with new charge air being sucked in, compressed, mixed with fuel, igniting and pressed out.

- The exhaust gas is pressed out through the turbocharger (turbine side) and onwards to the exhaust outlet. (Andersson, 2004, p. 6)

2.2 Sensors

The information about an engine can best be gathered by sensors, there are many kind of sensors depending on the environment of the operating location and what type of information it will collect. One should also keep in mind that many of these physical quantities affect each other as proven in several laws, the **combined gas law** is a combination of several laws which support this.

$$\frac{p_1V_1}{T_1} = \frac{p_2V_2}{T_2}$$

p = pressure
V = volume
T = temperature

Next I will describe sensors being used in this work.

Temperature sensors are often divided up into contact based and non-contact based sensor. Of the contact based sensors there are a few variations, **thermocouple** sensors that depend on thermal equilibrium and measures the difference in temperature with known reference points and material. The thermocouple sensors have a temperature range between -270 and up to +1800 ºC depending on the sensors material and are often used in different industries. The downsides to thermocouple sensors are their stability, accuracy and short life span. However, they are cheap, robust, easy to handle and have a fast response time.

Resistance thermometers use the resistance in a specific material to determine the temperature when the resistance depending on temperature for a specific material is known, when the temperature rises so does the resistance in said material. Resistance thermometers have a temperature range between -220 and up to +850 °C (+1000 over short periods of time) depending on sensor material. Downsides are the response time which is longer than with a thermocouple sensor, the cost as it is 5 – 10 times more expensive than a thermocouple and due to the fact that a current needs to flow through the material, a too high of a current could raise the temperature giving a false reading as a result, however, the resistance thermometer sensors are more accurate and have a longer life span.

Thermistors are functionally the same as resistance thermometer sensors, the main difference is the material as it is made of semi conductive material such as ceramics and polymers rather than pure metal. Thermistors are not as accurate as the two previous alternatives but much cheaper and have a temperature range from -50 and up to +600 °C.

The other type of temperature sensors is based on remote sensing, like **pyrometers**. Every material emits energy, this energy comes in the form of electromagnetic radiation. As the temperature rises, so does the radiation per unit area, so by measuring the radiation emitted the temperature can be determined. The downside is its inaccuracy and the upside is that it´s easily handled and fast when you need a temperature measured on the fly.

Other temperature sensor types are **bimetal sensors** and temperature sensitive color like **temperature tape.** (Grahm, et al., 2007, p. 269 – 313)

Pressure sensors are often used in engine technology.

Pressure per definition is a force affecting a surface area.

$$p = F/A$$

Where p is pressure, F is the applied force and A is the surface area on which the force is applied.

A pressure sensor which converts a physical pressure into an electrical signal are often made up of the following.

- A mechanical element which deforms when pressure is applied.
- A unit which converts the mechanical deformation into electrical impulses.
- A unit which transforms the electrical impulses into an adaptable signal.
- A mechanical casing.

There is a large variety of pressure sensors depending on the environment, what the measuring pressure range is, the accuracy, life span, response time and repeatability.

Membrane pressure sensors have a circular membrane on which the pressure is applied, a shaft or arm is fitted to the membrane and the movement of that shaft/arm is then converted into electrical impulses. They are often used when measuring low pressure (0 – 5kPa). Membrane pressure sensors are relatively affected by temperature.

Bellow pressure sensors are made up of a bellow and a spring element which returns the bellow to its original state when no pressure is applied. These types of sensors are divided up into sensors which are affected of an inner or outer force. The pressure range is 0 – 5MPa.

Aneroid pressure sensors are a special kind of membrane sensor which is used for very low pressures because of its sensitivity.

Bourdon-pipe pressure sensors are commonly used in industry, the pipe is deformed in its original state and when pressure is applied the pipe strive to straighten out itself. One end of the pipe is attached and the other end is free, the free ends movement when pressure is applied is proportional to the difference between the inner and outer pressure. A shaft or arm is fitted to the free end and that in turn is read and converted into electrical impulses. Bourdon-pipes have a pressure range from 0 and up to 200MPa depending on the number of twined rounds.

Semiconductive sensors and Piezoelectric sensors are very robust, can handle harsh environments and can be built in small sizes. They have a fast response time and due to their small size, they eliminate the risk of resonance. They have a pressure range from 0 and up to 70MPa. (Grahm, et al., 2007, p. 109 – 128)

Speed sensors measuring the speed is an important factor when it comes to industry and various processes. Speed can be measured in several different ways depending on the environment, what is being measured and what kind of speed measurement that is being taken. The methods involve speedometers, measuring revelations (rpm), flowmeters, measurement microphones and accelerometers (measuring vibration). This chapter will concentrate on the methods pertaining to the Wärtsilä 31 engine. Vibrations are usually measured in the testing stage and not as much when the engine has reached its customer.

Speed is defined as the time derivative of a position at a transfer, dx/dt where dx = transfer and dt = time interval.

Speed measurement is divided up into linear and angular velocity, the latter is easier to measure. In the Wärtsilä 31 engine, speed is measured at the turbocharger and the crankshaft, other speeds are measured by flowmeters and in the testing stage the valve movements are also measured.

Speed measurement depending on time and length¸ is in short, the time it takes for one point to move from A to B. This method is typically used at low and/or constant speeds where momentary speed is of now interest. Two sensors are placed with a known distance in between, as an object passes sensor one (start-sensor) and after a period of time passes the other sensor (stop-sensor), a mean time is given, the speed is then calculated based on this information. The sensors can be mechanical, optical, magnetic and inductive among others.

Inductive sensors or LVT.s = Linear Velocity Transducers, are used to measure periodic movement, an objects position and to regulate and determine speed. Because of its many good traits, it is a very common used sensor. The traits are:

- Contact free, no wear because of contact with material
- Environmental resistance, such as vibration, moist and many chemicals.
- Low maintenance
- Long life span
- High reliability and work frequency

An inductive sensor can be contact free and very resistant to powerful magnetic fields by using special filtering technique or by using high coercive material (ferromagnetic material) in the core of the oscillator coil.

Inductive (Magnetic) pulse sensors, are often used in different industry applications. Instead of using a light signal with a reflective point on a measured object as with the **optical pulse sensor**, the inductive pulse sensor use magnetic fields. With one common type, a toothed disc of ferromagnetic material is used, as the disc spins, the ferromagnetic material in the disc will affect the coils inductance. The coil, when introduced with a constant voltage, will produce current pulses with a repetition frequency that will be proportional to the rotational speed. Another type use permanent magnets on the measured object and a magnetic pick up coil, the coil feels each pulse as the measured object rotates and the magnets passes by. (Grahm, et al., 2007, p. 73 – 83)

2.3 Building algorithms

Before building of the algorithm in engine monitoring can begin, a few steps must be taken. First step is **sensor availability** which means collecting information of what´s being measured on the engine, the engines configuration must be taken into consideration as the measuring points can differ between engines. For instance, sensors measuring firing pressure are not installed as a standard, however, in some cases it can be recommended.

Next step is to comprise a **dependencies matrix**, this means determining what effects each value at each measuring point and putting them into an matrix for a better overview. For instance, the temperature of the big end bearing is effected by the engines load and lubrication oil pressure, this means that the dependencies for the big end bearing temperature are load and lubrication oil pressure.

The third step is to collect **operational data** to use in combination with the dependencies matrix, this meaning the engines operational data during normal operations. The best source would be calculated mean values for the engine, if that is not possible for some reason, then values given from testing facilities is the next best thing. In this step, it is important to verify that the data is reliable as the values collected here will be given as a reference in the algorithm.

After the data has been collected the next step begins, to produce **trends** and **equations** based on the operational data and the dependencies matrix. This can be done through calculations or by using a program like Excel, the latter is faster. In Excel it can be done by making a chart and adding a trendline with the equation as seen in ***Figure 2*** *Example of chart with trendline and equation (fictional data).*

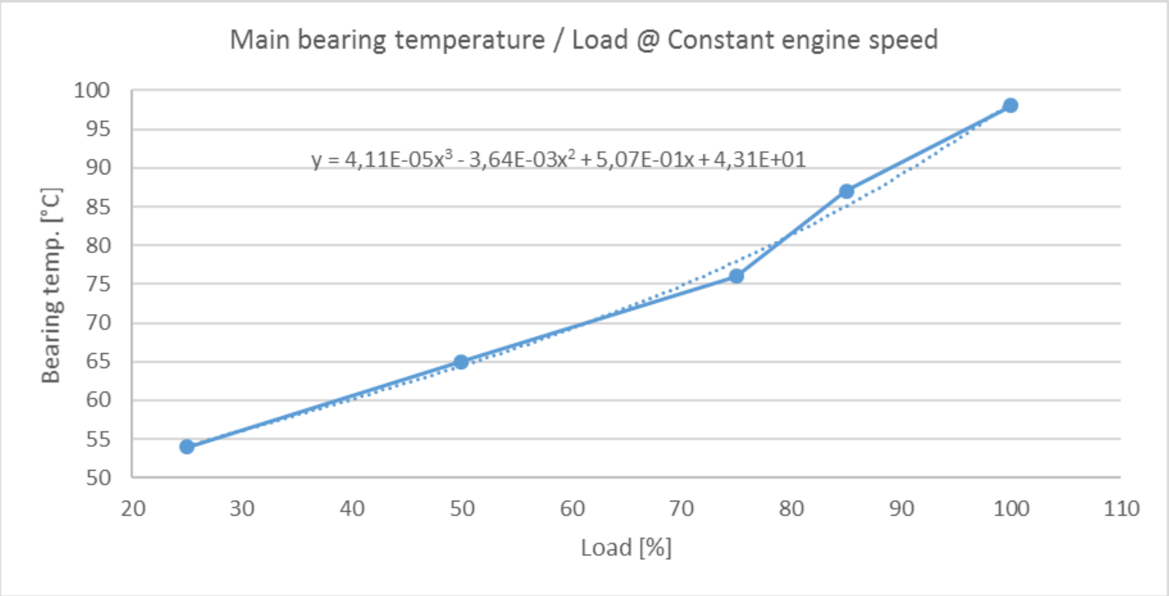
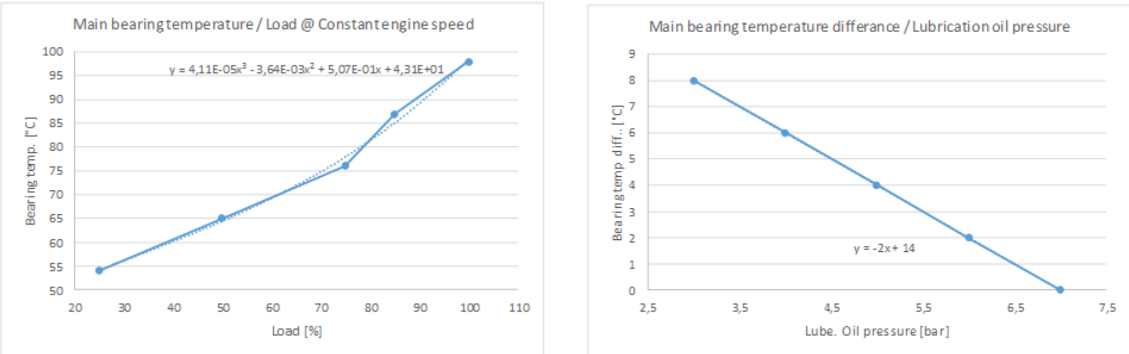


Figure 2 Example of chart with trendline and equation (fictional data)

In the final step the **algorithm** is built based on the engines specifications, dependencies matrix and the equations given from the operational data trends. As the dependencies in engine monitoring often are based on the engines load that can then be used as a baseline trend. If more than load effects the measure point, then these equations can be seen as variables of the baseline, as seen in ***Figure 3*** *Load seen as a base trendline and lubrication oil pressure seen as a variable (fictional data)* where load acts as the baseline and lubrication oil pressure acts as a variable which effects the end result.



Measuring point	Measured value		Equation
Load [%]	75		77,9890625
LO press [bar]	2,5		-9
Estimated value on bearing temperature			**68,9890625**

Measuring point	Measured value		Equation
Load [%]	50		64,4875
LO press [bar]	4		-6
Estimated value on bearing temperature			**58,4875**

0,0000411*Load^3 - 0,00364*Load^2 + 0,507*Load + 43,1 - (-2*LO press + 14)

Figure 3 Load seen as a base trendline and lubrication oil pressure seen as a variable (fictional data).

As an engine may have several different configurations, an algorithm is made to combine the right equations based on engine configuration. For instance, two turbochargers may have different speed curves, this would give them two different trendlines and equations. As an example, with an engine running with a 100% load at 750 rpm, turbocharger 1 gives out a rotational speed of 21000 rpm´s, whereas turbocharger 2 gives out a rotational speed of 23000 rpm´s.

After the algorithms have been created, they should be validated against a creditable source. Validation is done to ensure that the algorithms will render the correct value at any operational state.(Vägar, 2017)

2.4 Condition based maintenance

Condition based maintenance is often used in continuous running or automated processes where downtime because of maintenance is highly expensive or even a danger to life and/or environment. Examples of these are, oil rigs, power plants, ships, chemical industry and so on. The main reason for condition based maintenance is to prevent failure in a process before it causes any significant damage.

Whether to make a maintenance stop, just do a quick service or a small adjustment of a process is based on regular monitoring, manual inspection and measurement or continuous surveillance. There are three different kind of ways this can be done.

- By using ones sight, hearing, smell or perception of touch (Personal senses)
- By using a measuring method to monitor the wear regularly or continuously
- By doing a test run of the process and locate possible faults

The length of the maldevelopment time must also be taken into account as seen in *Figure **4** Examples of methods depending on the maldevelopment time.* , whether it is short or long determines if a scheduled inspection will suffice or if a more continuous surveillance is needed.

Example	Maldevelopment time	Method
Residual-current circuit breaker	< 1 s	Difficult to measure (aktiv safety system)
Low oil level indicator	< 14 days	Continuous surveillance
Alignment of engine shafts	< 6 months	Scheduled inspection
Corrosion	-15 years	General inspection

Figure 4 Examples of methods depending on the maldevelopment time. **(Nissen, et al., 2010, p. 109)**

A fixed sensor is recommended if the time between measurements is shorter than 2 weeks.

Visual based maintenance is used when measuring equipment is lacking, however, this method is not ideal for processes or machines like for instance fire ventilators or a windshield wiper motor where hidden wear and/or fault may occur. The same goes for components that are seldom in use like fire detectors and backup generators, these will often require a test start to see that everything is working as it should.

When foreseeing faults and/or wear in a process or a machine, there are many different methods in which that can be achieved. These methods are often based on 3 different properties.

- Electrical
- Mechanical
- Thermal

Electrical properties can for instance reveal faults in electrical motors, mechanical properties can be vibrations. Every engine has a unique set of vibrations, an engine that is vibrating at 4mm/s could be okay in every aspect whereas an engine vibrating at 3mm/s could have a serious fault although everything may seem fine to the naked eye. Thermal properties are often used as a mean to detect faults and/or wear in bearings but also in cooling water, charge air and exhaust gas. (Nissen, et al., 2010, pp. 22,23,109 – 115)

3 Methodology

This chapter will describe the methods used when executing this work, from my first meeting with my supervisors, the data collecting, the research and finally the construction stages of the platform.

3.1 Project start

At my first meeting with my supervisor from Wärtsilä and my supervisor from Novia, we discussed the intent of the project I was about to take on. After a brief introduction about CBM and its background we dug deeper into the specific task, what kind of knowledge I had from my previous work with the W31 engine, the delimitations of the work and how my work should be set up.

3.1.1 Previous knowledge

I had been working on the Wärtsilä 31 laboratory engine from May 2014 – August 2015, during this time I had required a good base knowledge of the engine. My work there began on the 31SG (LNG driven) model with some test running and some mechanical work. After a month the new 31D (diesel driven) model was about to be installed at the testing facilities in Vaasa. This was a very good educational skill for me as I got to be a part of the testing stages all the way from installment to the first startup and the first test run.

The first year on the diesel engine was comprised mostly of mechanical- and metal work, after the engine was positioned in its place the water-, oil-, fuel- and exhaust pipes as well as the working platform around the engine were constructed. Auxiliary systems were for the most part in place from previous engines, so only minor changes were required.

The first startup was a success and after an amount of running hours the engine was taken apart. Camshaft, cylinder head, connecting rods, pistons, water pumps among others were removed, disassembled and examined. Especially any potential wear on the bearings was of high interest. The water pumps were examined for cracks and tear, injectors were also examined. Everything that was examined was photographed and cataloged for further inspection. The remaining time I gathered test run information, analyzed it and converted it into more understandable information such as graphs, tables with explanatory text. In the summer of 2016 I had a position at Auxiliary Systems which is a subdivision of the main division, Marine Solutions. At Auxiliary Systems I got to familiarize myself with more of the auxiliary components that is needed at an engine installation.

In addition to my previous work at Wärtsilä I have also taken several courses at Novia UAS which further broadens my knowledge pertaining to this thesis work, courses that include automation, combustion engines, energy technology and maintenance among others.

3.1.2 New knowledge

For this specific task I had to obtain more information and educate myself even further, as previously said, I had worked on the test diesel engine and there obtained a network of people in different positions that were directly involved with the engine. Several of these persons as well as persons in the CBM group, the test run personnel and technical services personnel have been an invaluable asset to this project as they have a vast knowledge of the engine. Besides the internal information I also read up more on engine testing, diesel engines and sensors.

3.2 Sensor availability

The next stage in this project was to collect all information as to which sensors were available on the production engine. For this I contacted technical services that provided me with a device list containing all sensors, this was however not 100% accurate. When a new engine goes into production, the need for different values evolve as the engine get more running hours and thus the need for more or different sensors change, this goes beyond the testing period and into the field. I also got a sensor list from the laboratory engine, although I got a lot of information from the laboratory engine device list I could not use all of it, because the laboratory test engine has more sensors than a production engine. We decided that we would use the sensors that was available in the Modbus list on the 3 engines that had been delivered in November 2015, the platform will be updated as the sensor availability changes in the future.

3.3 Dependencies matrix

After the sensor availability list was finished a dependencies matrix had to be made, a dependencies matrix comprises of the sensors from the sensor availability list and the factors that affects the values from each sensor. As an example, a rise in combustion temperature could be a result of low charge air pressure, increased load, increased cooling water temperature or increased engine speed. Figuring out which factors affects the values was challenging. The factors had to be limited to those who have a direct and sufficient effect on the specific value. Without limitation the dependencies would spiral out of control, for example, low exhaust gas could be the result of low combustion temperature which could be the result of low cooling water temperature which in turn could be the result of low sea water temperature and so on. A meeting was held with a performance engineer from the W31D group and with his help and the help from the CBM group, the dependencies matrix could be finished.

3.4 Data input

When the dependencies matrix was finished, the data would be put in. First data had to be acquired and this was not all that easy. The platform that will come out of this project uses the engines mean values, if the values deviate there are two limitation zones that will activate if reached, this means that the mean values have to be accurate. When the engine is design and constructed, the mean values are also calculated, however, these values change over time as the engine is being tested and improved. The laboratory test engine may also have values that differ from the production engines values as it could have a different specification setup.

The most important data and the data that would be used in this project was from the factory acceptance tests (FAT) of the first 3 production engines. These engines have the same specification setup. After acquiring the needed data it was inserted into the dependencies matrix.

3.5 Building the algorithms

Before the algorithms were built, equations had to be created from the dependencies matrix and operational data that had been collected. By using Excel I was able to create chart curves and trendlines and then equations based on these. Depending on what effects each measuring point a combination of equations was made with a baseline trend and variables that would affect the end value from the baseline trend, this would give an estimated value as to what value said measuring point should be based on the engines current running data. If the measured value differs from the estimated value so much so that they exceed the risk limit, said value will be marked yellow or red depending on which limit that has been exceeded. The algorithms will say which equation combinations will be used based on the engines specifications. As an example, in *Figure 5 Algorithm structure (fictional data).*, there are two different types of turbochargers, depending which turbocharger is specified in the engine setup, the algorithm will choose which equation combination will be used.

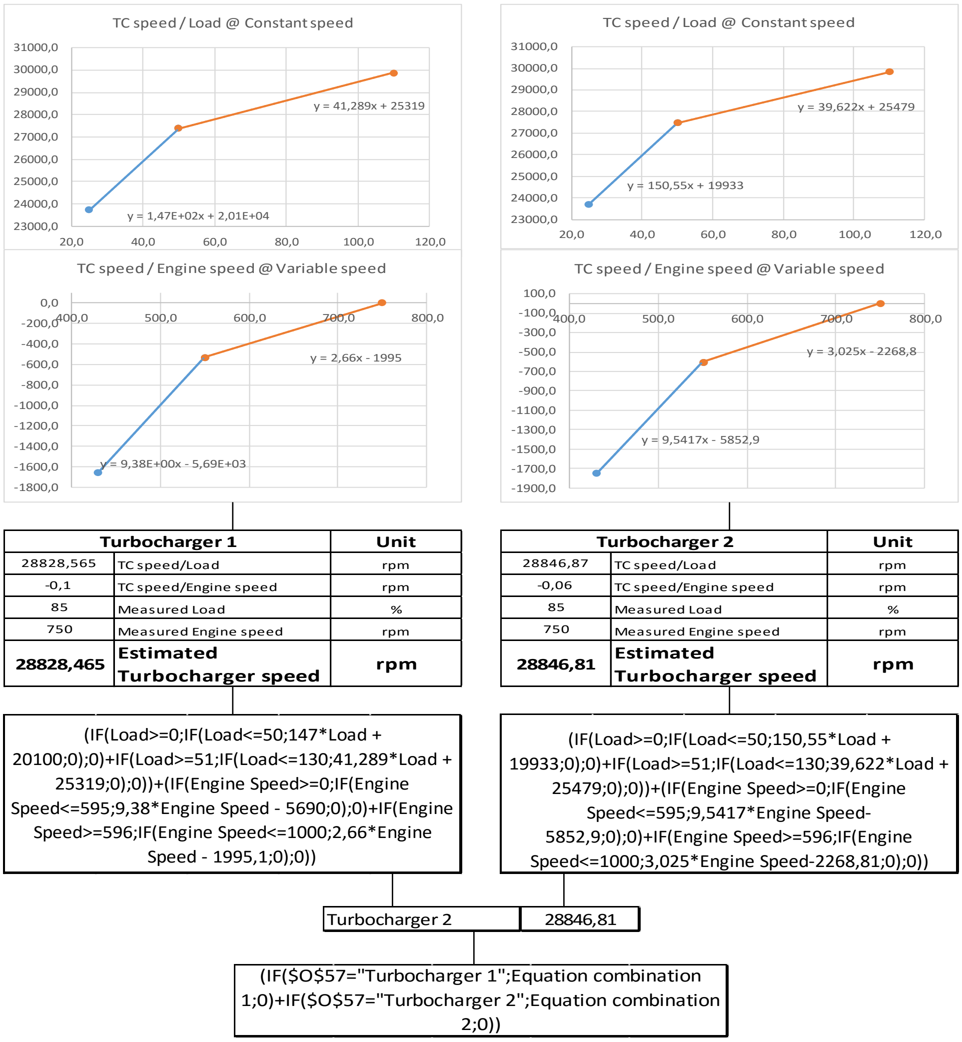


Figure 5 Algorithm structure (fictional data).

After the algorithms had been built, they were validated against the factory acceptance test. This was done in order to ensure that the algorithms will render the correct values throughout the engines total operating range.

4 Results

The purpose of this thesis work was to build algorithms for the Wärtsilä 31 diesel engine. In order to build the algorithms, several part goals had to be done.

- Sensor availability, this information was attained from technical services and from the first three engines that had undertaken the factory acceptance test (FAT), more precise, the engines Modbus list which contains an engines all measuring points, both digital and analog.

- The information for the engines operational values was gathered from Wärtsiläs factory acceptance test and some additional information was gathered from the engine laboratory facilities. Some data also had to be obtained from the engine performance team for the W31. All data however, only pertained to the W31 diesel with an 8 – cylinder V – configuration.

- Creating a dependencies matrix was done in cooperation with an engine performance engineer from the W31 engine performance team, with input from the engine laboratory in R&D (Research and Development) and with input from colleagues and my handler at CBM. This was done in Excel and shows what effects each measuring point on the engine.

- Creating equations, this was done in Excel based on the operational data and dependencies, the equations shows how much each dependency affects the value of the measuring point throughout the engines operational range.

- The creating of the algorithms were also done in Excel and was based on the equations given earlier in the work. The algorithms were then put into a working Excel platform. As operational data was only possible to be gathered from one model, the platform will have to be updated with other models as more data becomes available. By inputting operational data into the platform, algorithms will be able to see if there are any anomalies or if the engine is running at its full capacity. In case of an anomaly, one or more input values may exceed one out of four limitations per value where two are upper limits and two are lower limits. The first two limits are marked yellow and the next two limits are marked red, these limit values are based on the mean values of the engines operational data. The limitation values differ depending on the measuring point, as an example, if the high pressure turbocharger has an estimated mean value of 20000 rpm´s at 100% load and a measured value of 20016 rpm´s, and if the limitations where +/- 13% and +/- 30% as seen in *Figure **6** Example of turbocharger measuring point (fictional data).*, the measured turbocharger speed would be within the limits and therefore running as it should.

Measuring point	Measured value	Lower Values		Estimated value	Upper Values		Unit
HP TC speed	20016	14000	17000	20000	23000	26000	rpm

Figure 6 Example of turbocharger measuring point (fictional data).

5 Discussion

This thesis work have been both educational and interesting to do while at the same time it has been challenging, I have been able to implement my knowledge acquired both from my studies at Novia UAS and from my previous working experience at Wärtsilä, mostly so from my summer work at Wärtsiläs engine laboratory. Due to my already large contact network within the company and knowledge of the W31 engine, I was able to work rather self-sufficiently, this was one of the main reasons as to why I was given this work.

- **Obstacles**, there were some setbacks when information were gathered, because the information was so sensitive it had to be approved by several people before I could obtain it. Aside from the problem with the information gathering I would have wanted more time to have done a more accurate work, especially into what affects the measuring points and how other engine configurations would affect the values.

- **Improvements**, there should be more cooperation between departments within Wärtsilä when it comes to information as there were some resistance when I was gathering information for this work. Another suggestion to improvement would be to investigate the possibility of measuring the pressure difference before and after each charge air cooler, clogged charge air coolers causes a pressure drop as well as decreased cooling efficiency which leads to an increase in fuel consumption. A final suggestion would be aimed at the factory acceptance testing, the whole test lasts a few hours, however, the data that is stored is only a fraction of the total raw data and the rest is dumped. The suggestion here would be to investigate the possibility of storing all of the raw data without adding work or time to the testing procedure**.**

- **Future aspects**, I think that condition based maintenance will become more of a standard in the future, giving Wärtsilä more work in that field. The work I have done will also help make it easier to insert more engine configurations for the W31 engine line as more data becomes available, it will also work as a how-to for future engineers at CBM.

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