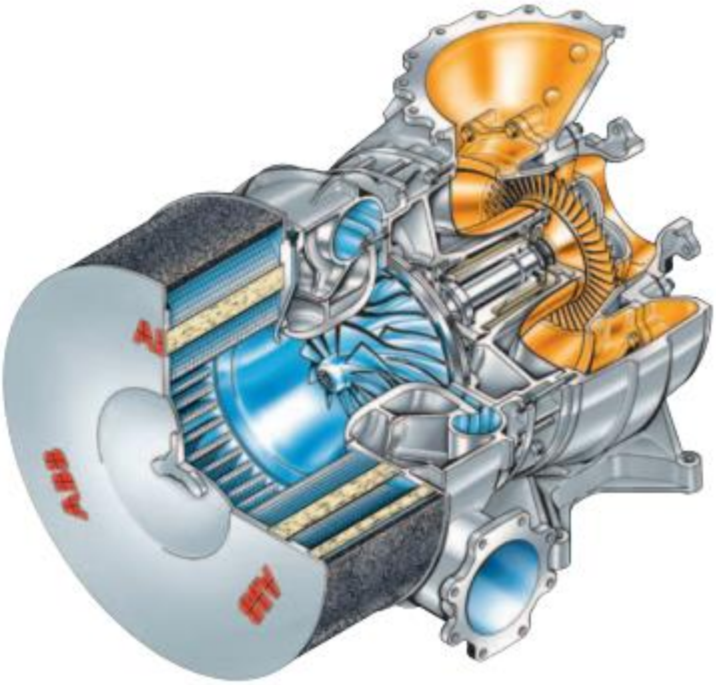

FUEL SAVINGS THROUGH NEW TURBOCHARGERS?

Will the fuel savings be worth the cost?

Dies A.W. Franse

CU12197V8-2021
HZ – University of Applied Sciences
Year: 2022-2023
Teacher: A. de Groot
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Source cover picture: (ABB, 2022)

Foreword

Firstly, I would like to thank Holland America Line for giving me the opportunity to conduct this research on board the m/s Oosterdam. Secondly I want to thank the engineers of the Oosterdam who helped me whenever they could by providing relevant information. Thirdly, I would like to thank Erich Strassle for providing the information about the cost of the project. Lastly, I would like to thank Arie de Groot, as he was a huge asset by coaching me with his enthusiasm and knowledge.

Dies Franse, 15/03/2023

Abstract

As fuel is expensive and profit must be maximized, it is wise for the maritime industry to invest in fuel saving applications. One of the possibilities is to replace old turbochargers by new fuel saving ones on the already installed engines, recommended by Wärtsilä. Although the potential fuel savings claimed by Wärtsilä, only two out of five engines on board the m/s Oosterdam have received the upgrade. This raised the question if it is really that profitable to install the new turbochargers and thus the importance of this research was born.

The research-question was: *"How much profit can be made within five years through saving fuel after installing new turbos on the diesel engines of the M/S Oosterdam?"*, accompanied by three sub-questions. The first: *"What is the difference between the real Specific Fuel Oil Consumption of the engines with the new turbos compared to the ones with the old turbos?"* Second: *"At which load are the most running hours made?"* and the third: After which period of time will the return on investment be made?

A quantitative research which assesses the SFOC of the engines which currently have the old and the ones with the new turbochargers has been conducted. Through this, the running hours per load and fuel prices, the potential profit for the next five years could be calculated. For the 12-cylinder engine it is commendable to perform the upgrade, but the 16-cylinder had little to no savings according to the data collected in this research.

Index

1. Introduction

There are five *Diesel Generators* (DG's) on board the Oosterdam. Three of them are Sulzer 16ZA40S and the other two are Sulzer 12ZA40S. DG 1, 3 and 4 are the same type of engine, namely the 16ZA40S, this is a 16-cylinder V-engine made by Sulzer and the default turbocharger was the ABB VTR-454. DG 4 has gotten the ABB TPL73-A32 turbocharger upgrade. DG 1 and 3 still have the default turbocharger. DG 2 and 5 are both the 12ZA40S, this is a 12-cylinder V-engine and they came with the default ABB VTR-354 turbocharger. DG 5 now has the ABB TPL69-A32 upgrade.

DG 1, 2, 4 and 5 all have scrubbers, so they can use *High Sulphur Heavy Fuel Oil* (HSHFO) and still be compliant with environmental regulations (International Maritime Organization, 2022). DG 3 does not have a scrubber and at the Oosterdam, only HSHFO and *Marine Gas Oil* (MGO) are being used. This results in DG 3 always having to run on MGO. As HSHFO and MGO have different calorific values and this is an important factor in the *Specific Fuel Oil Consumption* (SFOC) calculations (Wärtsilä, 2017).

1.1. Motive

"The Wärtsilä Performance upgrade for ZA40S engines offers an upgrade from a VTR to TPL turbocharger combined with engine tuning. According to results obtained on a laboratory engine at 85% load, the solution reduces SFOC by a minimum of 1.5 g/kWh and exhaust gas temperatures by approximately 30°C when comparing a new VTR with a new TPL turbocharger. When comparing an older VTR with a new TPL, fuel savings may be even higher." (Wärtsilä, 2019)

Wärtsilä says an upgrade for the diesel engines of the *Motor Ship (M/S)* Oosterdam will be worth it because of the potential fuel savings which would be a minimum of 1,5 g/kWh. The upgrade has been done to two of the five diesel generators, the other three still have the old turbochargers. In this research, data has been collected in order to find out if the replacement of the turbochargers is really worth the cost, considering the age of the ship.

1.2. Objective

The objective was to write an advisory report for the Holland America Line on whether it is profitable to install new turbos, through the execution of a quantitative research. This research has been conducted during the period of 16/9/2022 until 11/1/2023 on board of the Oosterdam.

1.3. Research question

The research-question is: *"How much profit can be made within five years through saving fuel after installing new turbos on the diesel engines of the M/S Oosterdam?"*

This question has been answered through first answering the three sub-questions listed below.

Sub-questions:

1. What is the difference between the real Specific Fuel Oil Consumption of the engines with the new turbos compared to the ones with the old turbos?
2. At which load are the most running hours made?
3. After which period of time will the return on investment be made?

1.4. Research scope and relevance

The research was focused on VTR-type and TPL-type turbochargers mounted on the diesel engines on board the M/S Oosterdam. The research has been scoped down into the topic of SFOC. Possible savings on maintenance will be excluded from the research. Technical design aspects and possible flaws of the ABB on-board computer and SFOC-calculator and wear on the engine and turbocharger parts have been excluded. As a result of this research, a recommendation could be given about upgrading the three remaining engines by replacing the old turbochargers for the new ones.

1.5. Reading guide

In chapter two Theoretical framework, the theoretical and scientifical base of the research can be found. It contains the results of a similar research done by Wärtsilä, a description of the turbochargers, a definition of SFOC and what could cause changes in SFOC. It also contains information about the different types of fuel used for marine purposes. Furthermore, it describes how long ships are usually in Holland America's service. Then, the concepts and definitions and conceptual framework can be found.

In chapter three, the method which has been used to answer the research-question and sub-questions can be found as well as the study population and sample. Then, information about the research tools and data entry can be found.

In chapter four the research results of the sub-questions are displayed in graphs. These graphs will give a clear overview of the results.

In chapter five, the conclusions and recommendations are discussed. These include the conclusions of the research and sub-questions. The recommendations given to Holland America concerning a future upgrade can also be found in this chapter and recommendations for further research.

Chapter six is the last chapter and this contains the *Discussion*. The discussion contains all the flaws of this research. Then, the literature used to give the research a scientific basis can be found.

Lastly, the appendixes relevant to this research are added. These include raw measuring data, graphs, T-tests and the turbocharger upgrade cost.

2. Theoretical framework

The theoretical background and source of information for the research which is to be conducted.

2.1. Wärtsilä

Wärtsilä has done a research regarding the fuel savings the changing of a VTR-type turbocharger for a TPL-type would bring. This research has been done on other vessels with the same type of engines, namely the Sulzer 16ZA40S and 12ZA40S. They found that all engines which got an upgrade, had a better fuel economy afterwards. The 12-cylinders had the biggest differences in SFOC. The 12ZA40S engines got the TPL69-A32 and the 16ZA40S got the TPL73-A32. The results can be seen in Figure 1.

Table 1

DG type	Old turbocharger type	New turbocharger type	SFOC results [g/kWh]
16ZA40S	VTR454	TPL73-A32	-1,4
16ZA40S	VTR454	TPL73-A32	-2,7
16ZA40S	VTR454	TPL73-A32	-3,2
16ZA40S	VTR454	TPL73-A32	-3,7
16ZA40S	VTR454	TPL73-A32	-4,1
12ZA40S	VTR354	TPL69-A32	-6,7
12ZA40S	VTR354	TPL69-A32	-7,7

Figure 1: Differences in SFOC
Source: (Wärtsilä, 2019)

Overall, Wärtsilä claims a SFOC-reduction of at least 1,5 g/kWh for the 16ZA40S and 3,0 g/kWh for the 12ZA40S. The highest savings are achieved between 75%-85% (Wärtsilä, 2019).

Apart from the fuel savings, Wärtsilä also claims reduced maintenance cost of €13.100 per year due to greater simplicity of installing spare parts. There is also a lower thermal load as the exhaust gas temperatures of the engines with the TPL-type turbochargers are reduced by 40°C. This results in a longer lifespan of certain parts of the engine and turbocharger (Wärtsilä, 2019).

2.2. Turbochargers

Turbocharging is a method that is aimed at achieving maximum mechanical efficiency and fuel-economy. The principle objective of turbo charging is to increase the power output per volume and cost of engine. A turbocharger increases the mass of air in the cylinder and consequently allows more fuels to be burnt, improves the volumetric efficiency of the engine and simultaneously improves engine efficiency (Gupta & Narayan, 2015). In order for the turbocharger to function correctly, the ambient air must be >25°C (Sulzer, 1999).

2.2.1. ABB VTR type

The VTR-type turbocharger, as displayed in Figure 2, consists of two machines: a compressor and a turbine. The numbers and names of the components can be found in Figure 2 and Figure 4 (ABB, 2016).

The exhaust gasses of the diesel engine flow through the gas inlet casing and the nozzle ring. The exhaust gasses exit through the gas outlet casing. On their way out, they pass the turbine and the turbine uses the energy contained in the exhaust gas to drive the compressor wheel. The compressor wheel draws in fresh air and compresses it (ABB, 2016).

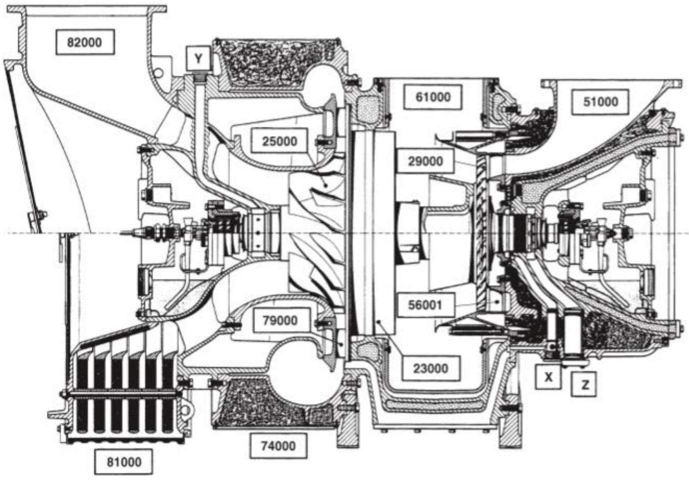

Figure 2: ABB VTR-type turbocharger
Source: (ABB, 2016)

The air needed for operation of the engine passes through the suction branch or the silencer into the compressor wheel. After that, it passes through the diffuser and leaves the turbocharger through the air outlet housing, into the cylinders of the engine (ABB, 2016).

The air is separated from the gas by the partition wall. Sealing air from the compressor is led into the labyrinth seal of the turbine through the channel. The seal prevents exhaust gasses from flowing into the compensation channel and bearing space. The compressor side and turbine side channels provide pressure compensation in the bearing spaces. It also prevents oil loss (ABB, 2016).

The rotor runs in elastically mounted rolling contact bearings which are accessible at either end. Each bearing point is lubricated through its own lubrication device. The bearing space covers have openings for filling up, as well as draining the oil. Two sight glasses in each cover, allow inspection of the bearing space and oil level (ABB, 2016).

The VTR454 and VTR354 have the same working principle (ABB , 2016).

2.2.2. ABB TPL-A32 type

The TPL-A32, as displayed in Figure 3, has two main components which are the turbine and the compressor. These are mounted on a common shaft. The exhaust gasses form the diesel engine enter the turbocharger through the gas inlet casing and nozzle ring, pass by the turbine wheel and exit through the gas outlet casing (ABB, 2017).

The turbine wheel starts spinning due to the energy it absorbs from the exhaust gasses and due to the common shaft, the compressor wheel also starts spinning. The compressor then sucks in the fresh air through the filter silencer to the compressor wheel. The compressor wheel compresses the fresh air and through the diffuser and the compressor casing, it gets forced into the engine's cylinders (ABB, 2017).

The rotor runs in two radial plain bearings. One of them is in the bearing bush and the other one is in the thrust bearing.

Table 2

Part number	Part name
51000	Gas inlet casing
56001	Nozzle ring
29000	Turbine
25000	Compressor wheel
61000	Gas outlet casing
82000	Suction branch
81000	Silencer
74000	Air outlet casing
23000	Partition wall
X	The channel to labyrinth seal
Z	Compensation channel
Y	Compressor side channels

Figure 4: Part numbers and names

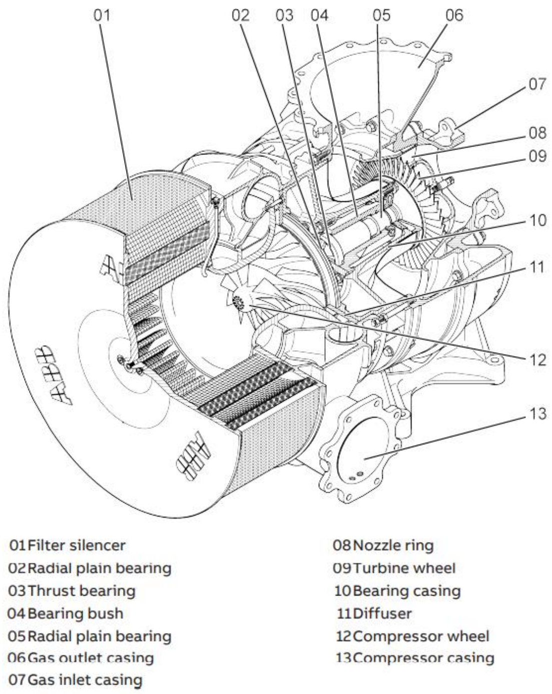

Figure 3: ABB TPL-A32 type turbocharger
Source: (ABB, 2017)

The TPL69-A32 and TPL73-A32 have the same working principle (ABB, 2017).

2.3. SFOC

Specific Fuel Oil Consumption (SFOC) describes how much fuel is needed to produce one *kilo Watt hour* (kWh) and is depending on the actual power (Lundh, Garcia-Gabin, Tervo, & Lindkvist, 2016). SFOC can differ between similar engines, as dirty intake air filters, turbocharger partly blocked or dirty nozzle ring, partly blocked charged air coolers, worn injection pump elements, and worn injection nozzles can increase the SFOC. (Lundh, Garcia-Gabin, Tervo, & Lindkvist, 2016). Maintaining the engines in a proper manner can help prevent the increase of 2% in SFOC between service intervals (MAN, 2013). Accelleron, previously called ABB, claims: *"An engine's performance is also* *affected by wear of the fuel spray system, intake air & exhaust valves and piston rings, due to the fact that peak and compression pressures are not optimal anymore."* (Brand, 2023). Variations between SFOC between complete overhauls can reach up to 6% (Wärtsilä, 2015).

SFOC can be calculated with the formula (de Koster, 2015):

$$b_e = \frac{1}{\eta_{tot} * H_0} = Specific\ Fuel\ Oil\ Consumption\ [\frac{kg}{kJ}]$$

Or:

$$b_e = \frac{3600}{\eta_{tot} * H_0} = Specific\ Fuel\ Oil\ Consumption\ [\frac{kg}{kWh}]$$

And:

$$b_e \left[\frac{kg}{kJ}\right] = \frac{b_e[\frac{g}{kWh}]}{3.6}$$

With:

$$\eta_{tot} = \left(\frac{P_e}{P_{th}} = \frac{P_e}{\dot{m}_b * H_0}\right) = \left(\frac{\frac{P_e}{P_e}}{\frac{\dot{m}_b}{P_e}} = \frac{1}{b_e * H_0}\right) = Total\ Efficiency\ of\ the\ Engine\ [\%]$$

And:

$$H_0 = Calorific\ Value\ [\frac{kJ}{kg}]$$

$$P_e = Effective\ Power\ [W]$$

$$P_{th} = Theoretical\ power\ [W]$$

$\dot{m}_b = Mass\ of\ Fuel\ Flow\ [\frac{ks}{s}]$ and $\dot{m}_b = b_e \left[\frac{kg}{kJ}\right] * P_e$ and $\dot{m}_b \left[\frac{kg}{s}\right] = \left(\frac{b_e\left[\frac{g}{kWh}\right]}{3.6} * 10^{-6}\right) * P_e\ [kW]$

Different types and qualities of fuel also have an impact on the SFOC values. Fuel water content, low fuel heat value, fuel Sulphur content, fuel ash content are all quality-concerning factors which affect the SFOC (Lundh, Garcia-Gabin, Tervo, & Lindkvist, 2016).

2.3.1. Deviating SFOC

SFOC variations are also caused by sudden load changes, such as those due to a vessel manoeuvring through a *shallow waterway*, *restricted waterway* or a *confined waterway* (Judge & Waters, 2005).

In a restricted waterway, more sinkage occurs due to decrease in pressure. The decrease in pressure is caused by the increased flow around the hull. The increase in sinkage leads to a greater surface area. The greater water velocities and pressure differences lead to greater waves and thus more drag. More drag means more power and thus more fuel is needed to reach the same speed as in comparison to when the vessel is in deep waters (Judge & Waters, 2005).

Manoeuvring in shallow waters leads to steeper waves due to the keel being closer to the bottom than in deep water. These steeper waves will also result in more resistance on the ship and thus a higher SFOC (Judge & Waters, 2005).

The constant change in load will result in a fluctuating SFOC-value. As the engines have to use more power to get to a certain amount of rpm, than they would need to maintain a steady amount of rpm. This will result in a higher SFOC-value at a certain load than it would be at a steady amount of rpm, while on the same load. If the power demand decreases, the SFOC-values will be lower, as the engines need to produce less power, so less fuel is burnt (Sulzer, 1999).

This knowledge can be used to determine whether a measurement can or cannot be used to get an accurate picture of the average SFOC of the DG's.

2.4. Different Fuels

There are two main types of fuel suitable for marine use. The first type is *Residual Marine* (RM) fuel and the second type is *Distillate Marine* (DM) fuel (Vedachalam, Baquerizo, & Dalai, 2022).

2.4.1. Residue Marine Fuels

RM fuels are made of the heavy residue which remains after the refining of crude oil. These fuels can be divided into *High Sulphur Heavy Fuel Oil* (HSHFO), *Very-Low Sulphur Fuel Oil* (VLSFO), *Ultra-Low Sulphur Fuel Oil* (ULSFO). As the names suggest, there is a difference in sulphur content between these fuels. HSHFO has a sulphur content of >0,5%, VLSFO of <0,5% and ULSFO has a sulphur content of <0,1%. These fuels have a viscosity ranging from 8 centistokes (cSt) to 700 cSt at 50°C (Vedachalam, Baquerizo, & Dalai, 2022).

Intermediate Fuel Oil (IFO) 380 and 180 are both in the HSHFO category. The 380 and 180 stand for the amount of centistokes. (Notteboom & Vernimmen, 2009). The global average price for one metric tonne lies at US $534.50, as can be seen in Figure 5 . The calorific value lies at 40.000 kJ/kg (Wild, 2005). The density at 15°C of HSHFO lies at 900 kg/m^3 (OECD, 2022).

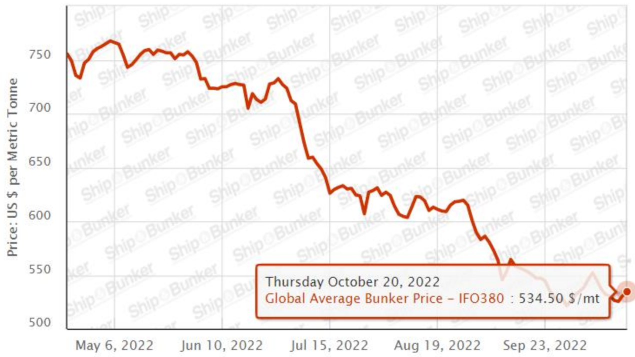

Figure 5: IFO380 prices
Source: (Ship & Bunker, 2022)

2.4.2. Distillate Marine Fuels

DM fuels are cleaner and contain less sulphur. The viscosity reaches from 1.4 cSt to 6 cSt at 40°C. A DM-type fuel called *Marine Gas Oil* (MGO) which consists of only distillate, has a viscosity of 1.4 cSt at 40°C. *Marine Diesel Oil* (MDO) is a DM fuel, but other than distillate it also contains a small portion of *Heavy Fuel Oil* (HFO) (Vedachalam, Baquerizo, & Dalai, 2022). The calorific value lies at 42.700 kJ/kg for both MGO and MDO (Wild, 2005). The density at 15°C typically lies at 860 kg/m^3 (Anish, 2020).

The price for one metric tonne of MGO lies at US $1217.50, as can be seen in Figure 6.

Figure 6: MGO prices
Source: (Ship & Bunker, 2022)

2.5. Future fuel prices

It is expected for the bunker fuel prices to have a *Compound Annual Growth Rate* (CAGR) of 15.9% until 2028 (Market Data Forecast, 2022). This means, the value of bunker fuels will increase through the years and the prices with it (Anson, Fabozzi, & Jones, 2010). Extra oil demand is a major factor as in why the bunker prices are increasing, so says a research conducted by *Steve Christy* (Christy, 2022). The bunker price forecast can be found in Table 3

Figure 7.

Table 3

Year	**MGO [$/mt]**	**IFO380 [$/mt]**
2022	1217	534
2023	1411	619
2024	1635	717
2025	1894	831
2026	2196	963
2027	2545	1116
2028	-	1293

Figure 7: fuel prices
Source: (Ship & Bunker, 2022)

2.6. Age of M/S Oosterdam

The M/S Oosterdam was built in 2002 and came into service for the Holland America Line (HAL) in 2003 (Marine Traffic, 2010). Other ships in service of the HAL are put out of service after 21 years on average, as seen in Figure 8.

Table 4

Name of ship	Year in service	Year out of service	Years of service
Westerdam	1988	2002	14
Prinsendam	2002	2019	17
Amsterdam	2000	2020	20
Ryndam	1994	2015	21
Rotterdam	1984	2005	21
Statendam	1993	2015	22
Rotterdam	1997	2020	23
Veendam	1996	2020	24
Maasdam	1993	2020	27
		Average	21
		Most common	21

Figure 8: Average years of service
Source: (Wikipedia, 2022)

2.7. Concepts and Definitions

Table 5

CONCEPT	DEFINITION
STAFF CHIEF ENGINEER	Staff Chief Engineer of the Oosterdam
CHIEF ENGINEER	Chief Engineer of the Oosterdam
G/KWH	Grams per kilo Watt hour
FUEL SAVINGS	The difference in SFOC values
RETURN OF INVESTMENT	The time it takes to earn back an investment
OLD TURBOS	ABB VTR-type turbochargers
NEW TURBOS	ABB TPL-type turbochargers
LOAD	Percentage of kilo Watts of the maximum continuous rating of the engine
SHIPS OF HOLLAND AMERICA LINE	All ships that have been in service of the Holland America Line after 1984
ENGINEERS	Engineers of the Oosterdam
THEORETICAL POWER	The power which comes out of the fuel by burning it e.g. effective power + waste heat
EFFECTIVE POWER	The power that is used for effective purposes
MGO	Marine Gas Oil
HFO	Heavy Fuel Oil
SFOC	Specific Fuel Oil Consumption
PRICE	Fuel prices
MCR	The maximum continuous rating is the maximum power output for the for the engine running continuously under safe conditions (Gautam, 2017)
SHALLOW WATERWAY	An area of water with unlimited lateral extent and boundaries in the vertical direction close enough that the resistance for a given speed is greater than in deep water (Judge & Waters, 2005).
RESTRICTED WATERWAY	Either deep or shallow water with lateral boundaries close enough to the ship to increase its resistance for a given speed (Judge & Waters, 2005).
CONFINED WATERWAY	A waterway which is both restricted and shallow at the same time (Judge & Waters, 2005).
OVERNIGHT	When the Oosterdam stays in the same port during at least two days and one night.
SURGING	A stall in the turbocharger which results in the complete disruption of airflow through the turbocharger.

Figure 9: Terms and definitions

2.8. Conceptual framework

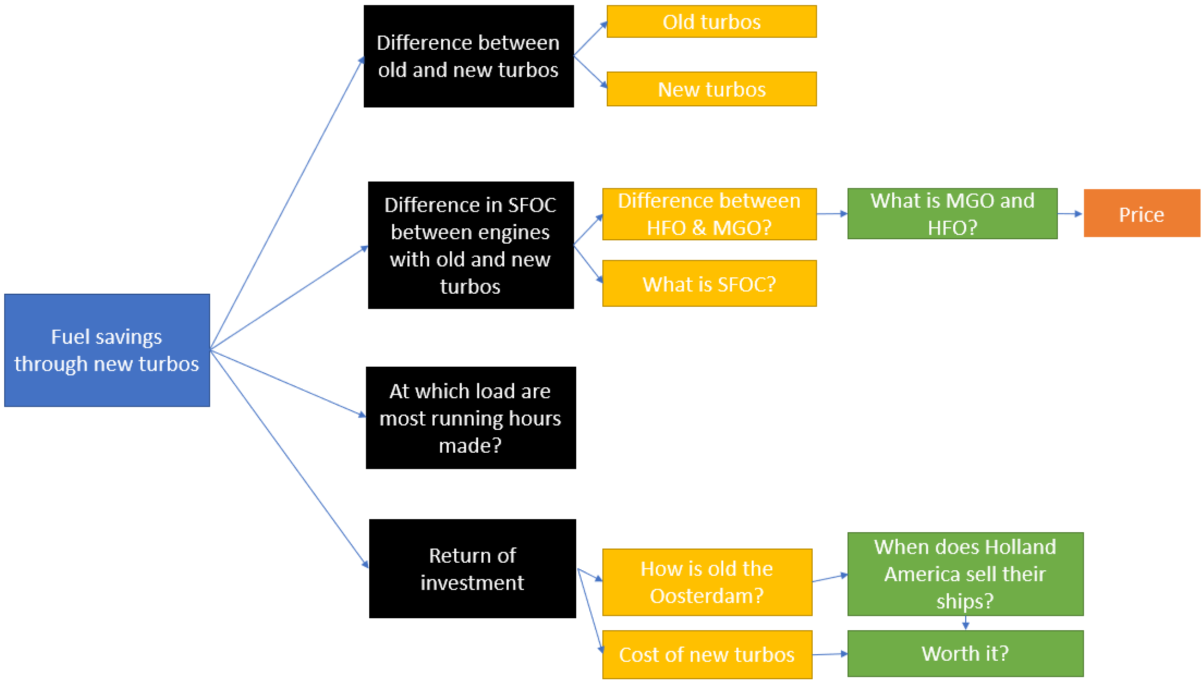

Figure 10: Conceptual framework

3. Method

To answer the research question and its sub-questions, data had to be collected and analysed. In this chapter, the data collection analysation methods which have been used in this research, will be discussed.

3.1. Data collection method

In this part it will be clarified which method of data collection is used to answer the sub-questions and the reasons why.

3.1.1. Method sub-question 1: What is the difference between the SFOC of the engines with the new turbos compared to the ones with the old turbos?

This sub-question has been answered through an observation of the SFOC values of the engines when they are using MGO as well as HFO, displayed in the on-board ABB computer. This is a quantitative research method and this method was chosen, as there was a lot of data taken on multiple occasions. After filtering out the faulty measurements, this method gave a trustworthy picture of the SFOC at certain loads.

The data was gathered in a longitudinal research to get a good and trustworthy picture of the SFOC in different situations. Data taken with engines running on IFO380 (HFO) have not been compared with data taken while the engines are running on MGO. Instead, the data was compared separately per kind of fuel. This was done to prevent any speculation on whether the difference in SFOC was due to the different kind of fuel or not. The external factors of whether the ship is manoeuvring, at sea or in port were also taken into consideration when comparing the data.

3.1.2. Method sub-question 2: At which load are the most running hours made?

This sub-question has been answered through an observation of the load of the diesel engines. The ABB-computer records the load percentage of the engines 24 hours per day and can display it in a graph. This is a quantitative research method, because there is much data to be analysed.

This will also be a longitudinal research, as the results from multiple weeks will give a more precise picture of in which load the engines are running for a certain amount of hours.

3.1.3. Method sub-question 3: After which period of time will the return on investment be made?

For this sub-question, a price indication was requested from Wärtsilä. This is a quantitative research method and this method was chosen, because it will be able to give the figures for the unit and install costs.

The information needed has been gathered through a cross-sectional research, as the quotation is provided once.

After the quotation has been received, the price of the upgrade was known and in combination with the difference in SFOC and for how long the engines are in a specific load, the return of investment will be calculated.

The fuel prices from 2023 until 2028 have been calculated with the forecasted CAGR of 15,9%. This results in the figures as displayed in Figure 7. These figures have been used to calculate the ROI and how much profit will be made in five years.

3.2. Study population and sample

The study population of this research was turbochargers in general. The sample was the VTR-type and TPL-type turbochargers installed on the diesel engines on board the m/s Oosterdam. The sample is select, because there was no real choice in turbochargers for this research.

The research has been conducted on board the Oosterdam and both the old and the new turbochargers were in operating conditions. This means all the variables could be gathered to make a comparison.

3.3. Research tool

In this part, the variables of the research tool which have been measured for sub-question 1 and 2 will be given. The ethical aspects regarding the quotation used to give an answer to sub-question 3, will also be discussed.

3.3.1. Wärtsilä SFOC-calculator

To get the SFOC and load of the engines, the on board Wärtsilä SFOC-calculator has been used. The SFOC is displayed in g/kWh and the load is displayed in a percentage of the MCR as well as in kilo Watts.

The Wärtsilä SFOC-calculator uses the fuel calorific value, *Low Temperature* (LT) cooling water temperature, ambient air temperature and barometric pressure to calculate the SFOC (Wärtsilä, 2017). Because of this, the ambient temperature, LT cooling water temperature and the barometric pressure will be noted. This is done to declare why some values might deviate from the others.

The SFOC-calculator uses the density, volume and temperature of the fuel to convert volume to mass (Wärtsilä, 2017).

3.3.2. Running hours per load

To get the load percentages and for how long the engines ran in this load, the load graphs generated by the SFOC calculator, displayed on the on board ABB-computer have been used. The load percentage was displayed on the Y-axis and the time was displayed on the X-axis. The graphs were generated for each engine individually.

3.3.3. Quotation

Wärtsilä is the company that came up with the idea and performed the upgrade. *Erich Strassle* has been contacted to give the quotation of the upgrade. He is the *Manager of Fuel Conservation* active at Wärtsilä. To calculate the return on investment, the costs of the project were needed.

The method *Theoretical Sampling* has been used. *"In theoretical sampling it is not about the sheer number of people that get interviewed, but the quality of the information that person has"* (Crang & Cook, 2007). Because of Mr. Strassle's function, he had access to the financial information regarding the project. The quotation is displayed in Appendix 13: *Turbocharger cost*.

Erich Strassle has given permission to mention his name and function in the research.

3.4. Data entry

The hypothesis was that there is much profit to be made in five years, as a research from Wärtsilä suggests. They say the ROI can be made in 2,4 years and the rest will be profit (Wärtsilä, 2019). The way this hypothesis has been tested was by taking SFOC measurements of the engines with the old turbochargers and compare them which the measurements taken on the engines with the new turbochargers. The graphs which have been made, have been made using *Microsoft Excel.*

3.4.1. Difference in SFOC

The measurements are gathered in a range of 45-85 percent of the MCR, as the engines are mostly ran in this range. The measurements have been noted as described in Figure 11. This was done to make the data entry more doable.

For all engines, data has been gathered at multiple loads and every engine has gotten its own two SFOC-graphs. One for MGO and one for HFO. The SFOC-graphs have 'load' or 'power' in kW on the x-axis and SFOC in g/kWh on the y-axis. Through this method, it was easy to spot any strongly deviating SFOC-values and to consider leaving them out or not.

Table 6

Measured value [%]	Noted value [%]
43, 44, 45, 46	45
47, 48, 49, 50, 51, 52	50
53, 54, 55, 56	55
57, 58, 59, 60, 61, 62	60
63, 64, 65, 66	65
67, 68, 69, 70, 71, 72	70
73, 74, 75, 76	75
77, 78, 79, 80, 81, 82	80
83, 84, 85, 86	85

Figure 11: Noted values SFOC

As most useful values have been gathered around the same load, bar graphs have been made per load percentage, per kind of engine. This gave a clear view of the overlap in values or savings when comparing the engines with the VTR to the ones with the TPL turbocharger.

There are 3 different PMS-modes, namely port, sea and manoeuvring mode. These modes represent the situations the vessel is in, so in sea mode the vessel is in open waters, port mode means the vessel is in port and manoeuvring mode means the vessel is manoeuvring.

A visual representation of the data entry tool can be found in Appendix 1: MGO Raw Data SFOC and Appendix 6: HFO Raw Data SFOC.

To validate the results are not based on coincidence, the *T-test* was used to calculate the difference in SFOC with a probability of coincidence of <1%. To perform a T-test, all values at the same load percentage are taken and then, the T-test in *Microsoft Excel* is used. This was done per kind of engine per kind of fuel. With the engines running on MGO, this was done at 75% for DG 1, 3 and 4 and at 80% for DG 2 and 5. With the engines on HFO, this was done at 75% for DG 1 and 4 and at 80% for DG 1, 2, 4 and 5.

The SFOC-reduction has also been validated by comparing them to the results Wärtsilä got out of their research, stated in paragraph *2.1: Wärtsilä*, Figure 1.

The SFOC-values during manoeuvring and rough seas can deviate from the average and thus be not representative. The SFOC-values that differ too much, have not been taken into the calculation of the average SFOC. These values can be found in Figure 12.

Table 7

DG	Load [%]	Load [kW]	SFOC [g/kWh]	Engine room temperature [°C]	Air pressure [Bar]	PMS mode	LT in [°C]	LT out [°C]	Reason
5	60	5418	155,1	25,4	0,999	Manoeuvring	30	33	Manoeuvring
1	65	7315	225	26,1	0,999	Manoeuvring	30	33	Manoeuvring
2	65	5524	227	26,1	0,998	Manoeuvring	30	33	Manoeuvring
2	70	5800	198	32	0,998	Manoeuvring	30	33	Manoeuvring
2	70	6000	200,6	32,3	1,023	Manoeuvring	31	35	Manoeuvring
2	70	6000	201,6	35,1	1,019	Manoeuvring	30	34	Manoeuvring

Figure 12: Left out data

3.4.2. Running hours per load

The load percentage and for how long the engine keeps running at this load, have been documented in an excel sheet. The running hours per day have been noted and the running hours of all engines will be added up. Then, the running hours per load are divided by the total amount of running hours. The running hours per load are also divided by the total amount of hours in the days the running hours are documented, to get an accurate picture of how long the DG's are actually running.

The engines' running hours also were looked at separately, so the running hours for the engines which still have to be upgraded could be determined. A visual representation of the data entry tool can be found in Appendix 11: Raw Data Running Hours and Appendix 12: Running hours per load.

The data was collected between the period of 06/11/2022 and 06/01/2023. In this period there were a lot of seadays as well as port days and overnights. This is representable for the normal sailing habits, and this is why it could be said that these sailing habits are generalizable for the rest of the 5-year period.

The measurements have been taken as in Figure 13. This is done to make sure the data entry is more doable.

Table 8

Measured value [%]	Noted value [%]
0, 1, 2	0
3, 4, 5, 6	5
7, 8, 9, 10, 11, 12	10
13, 14, 15, 16	15
17, 18, 19, 20, 21, 22	20
23, 24, 25, 26	25
27, 28, 29, 30, 31, 32	30
33, 34, 35, 36	35
37, 38, 39, 40, 41, 42	40
43, 44, 45, 46	45
47, 48, 49, 50, 51, 52	50
53, 54, 55, 56	55
57, 58, 59, 60, 61, 62	60
63, 64, 65, 66	65
67, 68, 69, 70, 71, 72	70
73, 74, 75, 76	75
77, 78, 79, 80, 81, 82	80
83, 84, 85, 86	85
87, 88, 89, 90, 91, 92	90
93, 94, 95, 96	95
97, 98, 99, 100	100

Figure 13: Noted values load

3.4.3. ROI

To answer sub-question 3, the data from sub-question 1 and 2 were used.

According to the data collected, the difference in SFOC of the 16ZA40S was negligible, so the calculations only have been made for the 12ZA40S. For the 12ZA40S there were not enough data below or above 80%. Wärtsilä says most savings will be achieved between 75% and 85%, so the same savings have been used in this range (Wärtsilä, 2019). Below this range, no savings have been assumed, because the savings could be higher or lower than the assumed values. In addition, calculated guess could be made.

To calculate the ROI, the investment cost in dollars was needed. The upgrade for the 12-cylinder engine was done at the cost of €622.000,00. Converted to dollars at the time of the upgrade which was in 2019 at $1,12 to €1,00 this would be $698.537,10. This price has been used to calculate the ROI.

These SFOC-savings which have been determined, have been used for the further equations. The SFOC or b_e, on the SFOC calculator is given in g/kWh. To get to the mass flow of fuel, it first had to be converted to kg/kJ. This was done by using the formula:

$$b_e\left[\frac{kg}{kJ}\right] = \frac{b_e[\frac{g}{kWh}]}{3.6}$$

And so, the mass flow of fuel could be calculated.

$$\dot{m}_b\left[\frac{kg}{s}\right] = \left(\frac{b_e\left[\frac{g}{kWh}\right]}{3.6} * 10^{-6}\right) * P_e\ [kW]$$

After it had been determined for how many hours per day the engines usually stay in a certain load, the average fuel-savings per day per engine per kind of fuel could be calculated. According the following formula:

$$\dot{m}_{b\ per\ day}\ [\frac{tonnes}{day}] = (((\dot{m}_{b\ 1} * \%\ of\ hours\ in\ day\ running\ with\ specific\ SFOC) + (\dot{m}_{b\ 2} * \%\ of\ hours\ in\ day\ running\ with\ specific\ SFOC) + (\dot{m}_{b_n} * \%\ of\ hours\ in\ day\ running\ with\ specific\ SFOC) + \ ...) * 3600)/1000$$

The savings have been calculated separately for every year, taking inflation into account. The fuel prices given in Table 3

Figure 7 have been used to calculate the savings per year. The formula is:

$$Savings\ in\ dollars\ per\ year_n = \dot{m}_b\left[\frac{tonnes}{day}\right] * 365 * Fuel\ price\ per\ tonne\ in\ year_n$$

This has been calculated for 2023 until 2027. The savings per year have been added up and a total was displayed in a table in Excel for each year so a clear overview would show in which year the ROI would be made. In the year of the ROI, the savings in US Dollars per day have been calculated and what was left after the full years will be divided by the savings per day. Like so:

$$Days\ left\ in\ year\ of\ ROI = \frac{\$698.537{,}10 - Savings\ in\ dollars\ per\ year_1 - Savings\ in\ dollars\ per\ year_{...}}{Savings\ per\ day\ in\ year\ of\ ROI}$$

This has been added up to the full years until ROI and through this method, the ROI has been calculated.

3.5. Method answering research question

To answer the research question, the data from sub-question 1 and 2 were used.

According to the data collected, the difference in SFOC of the 16ZA40S was negligible, so the calculations only have been made for the 12ZA40S. For the 12ZA40S there were not enough data below or above 80%. Wärtsilä says most savings will be achieved between 75% and 85%, so the same savings have been used in this range (Wärtsilä, 2019). Below this range, no savings have been assumed, because this could give an unrealistic figure for the fuel savings.

To calculate the profit, the investment cost in dollars was needed. The upgrade for the 12-cylinder engine was done at the cost of €622.000,00. Converted to dollars at the time of the upgrade which was in 2019 at $1,12 to €1,00 this would be $698.537,10. This price has been used to calculate the profit.

These SFOC-savings which have been determined, have been used for the further equations. The SFOC or b_e, on the SFOC calculator is given in g/kWh. To get to the mass flow of fuel, it first had to be converted to kg/kJ. This was done by using the formula:

$$b_e\left[\frac{kg}{kJ}\right] = \frac{b_e[\frac{g}{kWh}]}{3.6}$$

And so, the mass flow of fuel could be calculated.

$$\dot{m}_b\left[\frac{kg}{s}\right] = \left(\frac{b_e\left[\frac{g}{kWh}\right]}{3.6} * 10^{-6}\right) * P_e\ [kW]$$

After it had been determined for how many hours per day the engines usually stay in a certain load, the average fuel-savings per day per engine per kind of fuel could be calculated. According the following formula:

$$\dot{m}_{b\ per\ day}\left[\frac{tonnes}{day}\right] = (((\dot{m}_{b\,1} * \%\ of\ hours\ in\ day\ running\ with\ specific\ SFOC) + (\dot{m}_{b_2} * \%\ of\ hours\ in\ day\ running\ with\ specific\ SFOC) + (\dot{m}_{b_n} * \%\ of\ hours\ in\ day\ running\ with\ specific\ SFOC) + \ ...) * 3600)/1000$$

The savings have been calculated separately for every year, taking inflation into account. The fuel prices given in Table 3

Figure 7 have been used to calculate the savings per year. The formula is:

$$Savings\ in\ dollars\ per\ year_n = \dot{m}_b\left[\frac{tonnes}{day}\right] * 365 * Fuel\ price\ per\ tonne\ in\ year_n$$

The savings in dollars have been calculated for each year from 2023 to 2027. After adding up the savings in each year and subtracting the investment cost, the profit after five years could be calculated. This was done using the formula:

$$Profit\ after\ 5\ years = (Savings\ in\ dollars\ per\ year_{2023} + Savings\ in\ dollars\ per\ year_{2024} + Savings\ in\ dollars\ per\ year_{2025} + Savings\ in\ dollars\ per\ year_{2026} + Savings\ in\ dollars\ per\ year_{2027}) - \$698.537{,}10$$

4. Results

The raw data of results for sub-question 1 can be found in *Appendix 1: MGO Raw Data SFOC* and *Appendix 6: HFO Raw Data SFOC.* The raw data for sub-question 2 can be found in *Appendix 11: Raw Data Running Hours.*

4.1. Difference in SFOC

According to the data retrieved in this research, there is little difference in SFOC for the 16ZA40S. There was a great overlap in measuring results, this can be seen in Figure 14 with DG 1 in blue and DG 4 in orange. According to the T-test, this results in that the savings are <0,1 g/kWh if the probability of coincidence must be ≤1%.

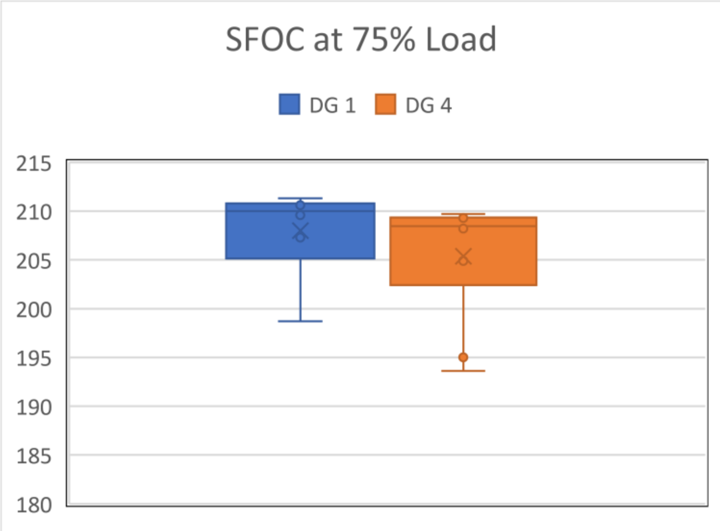

Figure 14: DG 1 and DG 4 on HFO

Further information on the results for the 16ZA40S can be found in *Appendix 4: MGO T-test and box-and-whisker graph 75%*, *Appendix 9: HFO T-test and box-and-whisker graph 75%* and *Appendix 10: HFO T-test and box-and-whisker graph 80%.*

4.1.1. 12ZA40S MGO

As can be seen in Figure 15 with DG 2 in black and DG 5 in green, there is a clear difference in SFOC with DG 2 and DG 5 running on MGO. According to the T-test, the difference in SFOC for the 12ZA40S is 3,5 g/kWh. The probability of coincidence is 1%.

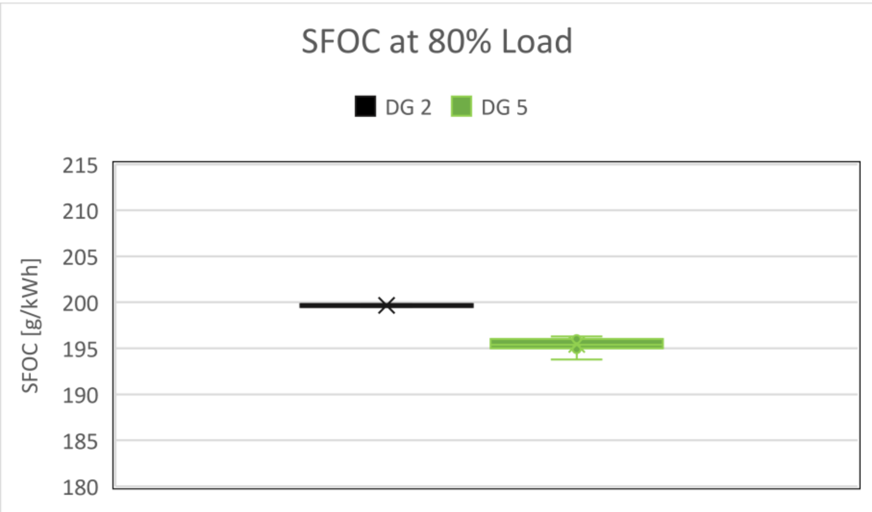

Figure 15: DG 2 and DG 5 on MGO

Further information on the results for the 12ZA40S running on MGO at 80% can be found in *Appendix 5: MGO T-test and box-and-whisker graph 80%.*

4.1.2. 12ZA40S HFO

As displayed in Figure 16 with DG 2 in black and DG 5 in green, there is a clear difference in SFOC between DG 2 and DG 5, while running on HFO. As result of performing the T-test, the mean difference turned out to be 3 g/kWh, with a probability of coincidence of 1%.

For further visualization of the results, *Appendix 10: HFO T-test and box-and-whisker graph 80%* can be consulted.

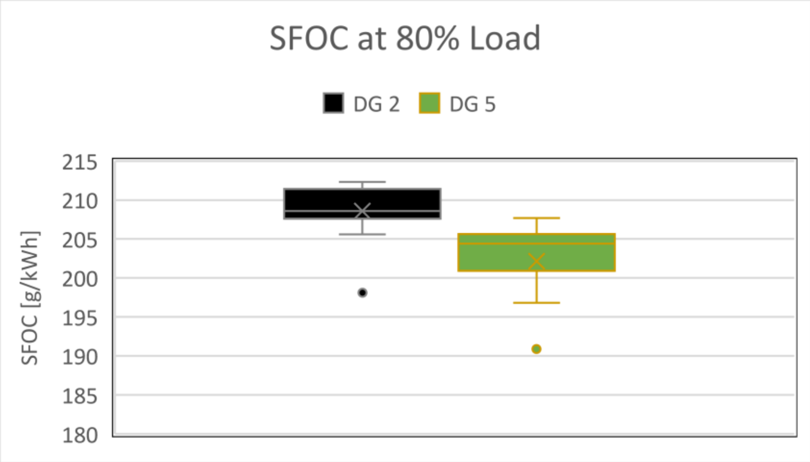

Figure 16: DG 2 and DG 5 running on HFO

4.2. Running hours per load

All raw data for this sub-question can be found in *Appendix 11: Raw Data Running Hours*.

The results for sub-question 2 are displayed in Figure 17. What can be seen in the graph, is what load the engines are running in and what percentage of the day they stay in this load. The spike at 0% can be explained by the fact that all engines are not always running.

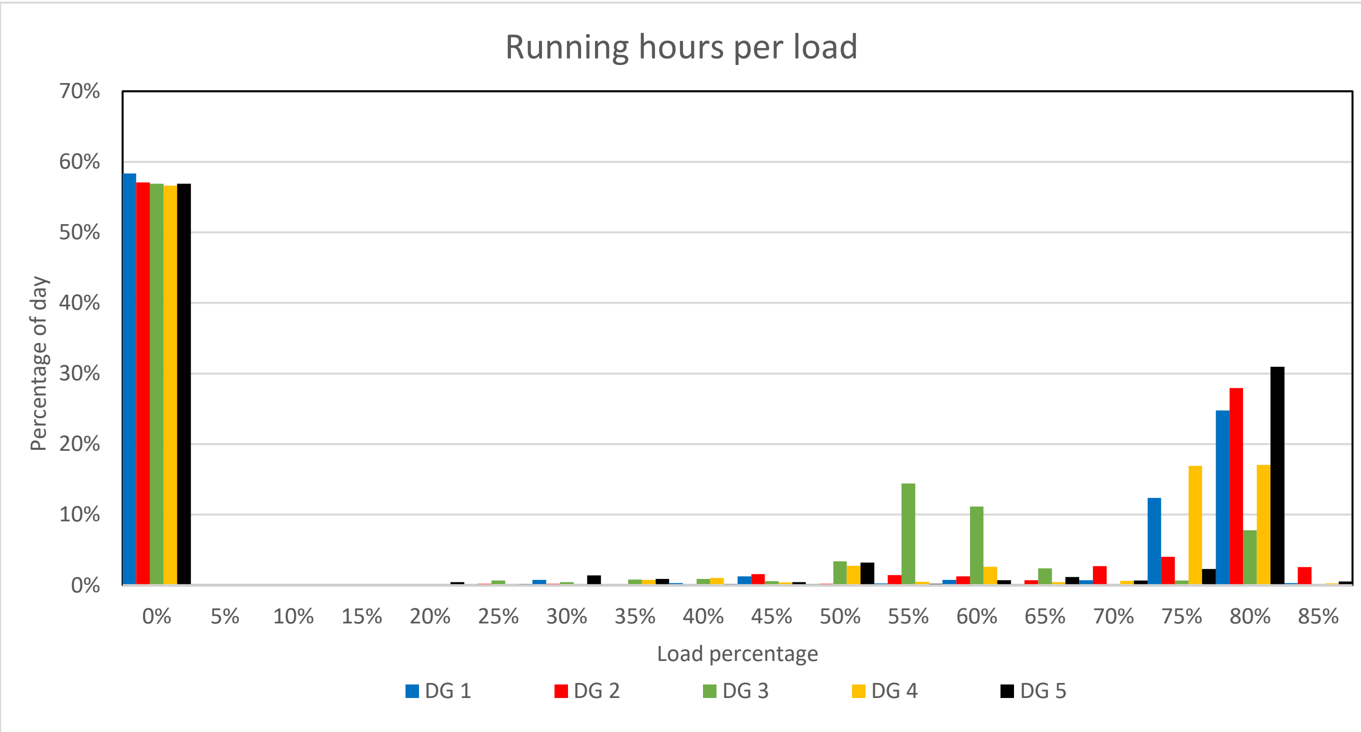

Figure 17: Running hours per load

More detailed tables can be found in *Appendix 12: Running hours per load.*

4.3. ROI

In this part, the ROI will be discussed.

4.3.1. MGO

In Figure 18 there are multiple bars. The savings-bar exists of stacked years with each their own savings in dollars. The cost-bar displays how much the investment costs. The cost-bar and the savings-bar share the same y-axis on which the amount of dollars is displayed. Thus can be seen what the savings per year are and in which year the ROI will be made. This is the ROI if the engines were only to run on MGO.

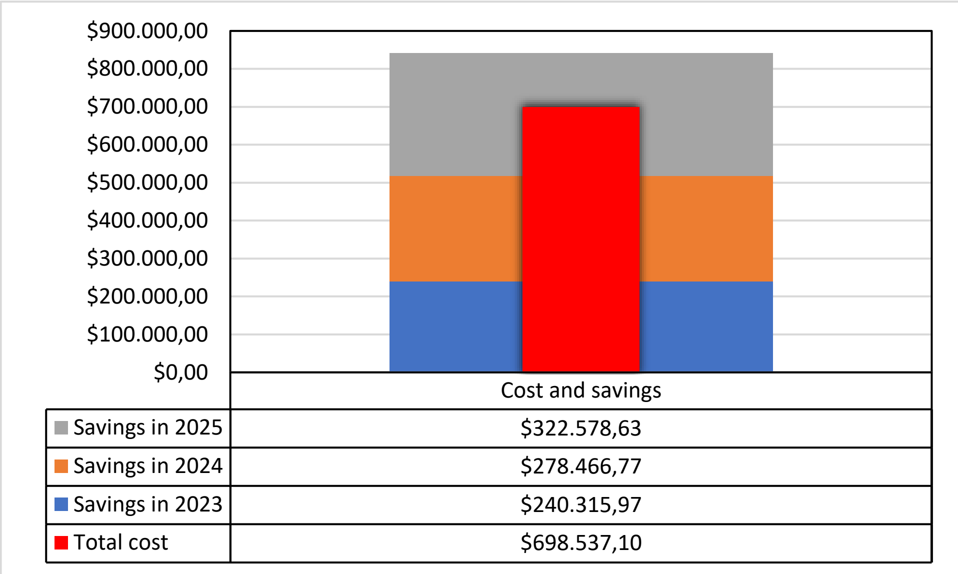

Figure 18: ROI on MGO

4.3.2. HFO

In Figure 19Figure 18 there are multiple bars. The savings-bar exists of stacked years with each their own savings in dollars. The cost-bar displays how much the investment costs. The cost-bar and the savings-bar share the same y-axis on which the amount of dollars is displayed. Thus can be seen what the savings per year are and in which year the ROI will be made. This is the ROI if the engines were only to run on HFO.

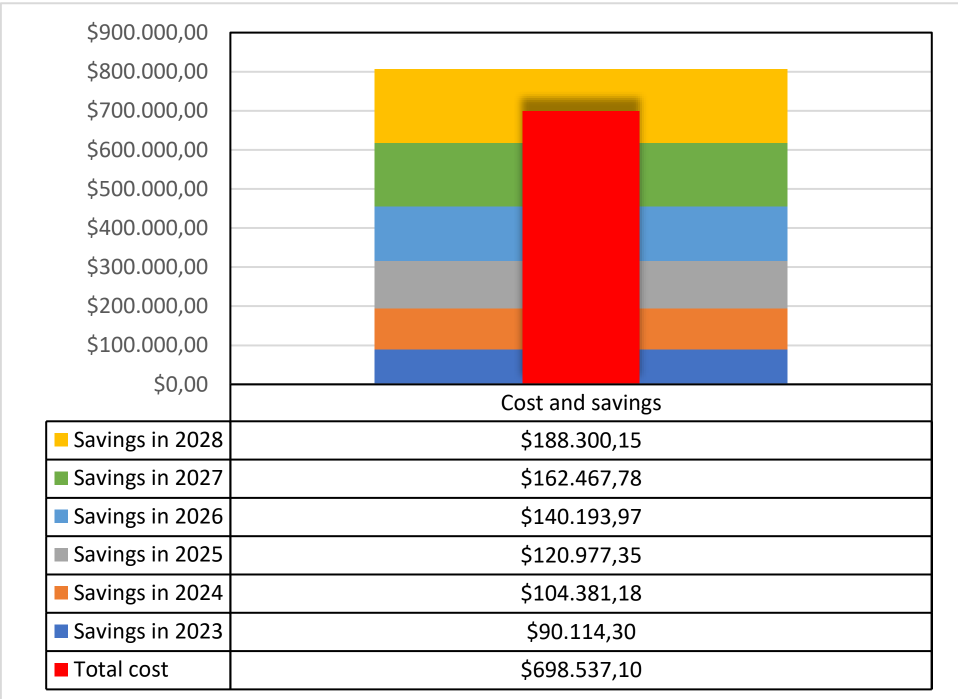

Figure 19: ROI on HFO

5. Conclusions & recommendations

In this chapter, the conclusions of the research-question and sub-questions will be discussed, as well as recommendations concerning upgrades and further research.

5.1. Sub-question 1

The first sub-question was: *"What is the difference between the real Specific Fuel Oil Consumption of the engines with the new turbos compared to the ones with the old turbos?"*

According to the results gathered in this research, there were no savings concluded for the 16ZA40S either running on MGO or HFO.

For the 12ZA40S running on MGO, the difference in SFOC was 3,5 g/kWh at 80% load with a probability of coincidence of 1%. When the engines were running on HFO, the difference in SFOC was 3,0 g/kWh at 80% load with a probability of 1%. The results for the 12ZA40S were the same as the results Wärtsilä got from their research.

The results can be found in *4.1. Difference in SFOC.*

5.2. Sub-question 2

The second sub-question was: *"At which load are the most running hours made?"* For DG 1, 2, 4 and 5, this was at 80% load. For DG 3, most running hours were made at 55% load. This can be seen in *4.2. Running hours per load.*

5.3. Sub-question 3

The third and final sub-question was: *"After which period of time will the return on investment be made?"*

As the 16ZA40S had no real fuel savings, the return of investment through saving fuel could not be made. The upgrade for the 12ZA40S running solely on MGO would have a ROI of 2 years and 203 days. For the 12ZA40S running only on HFO, the return of investment would be made in 5 years and 181 days.

5.4. Research question

The research question was: *"How much profit can be made within five years after installing new fuel saving turbos on the diesel engines of the M/S Oosterdam?"*

5.4.1. Conclusion

According to the measurements from this research, installing the TPL-type turbocharger on the 16ZA40S would not result in any profit through fuel savings within five years. The same goes for the upgrade for the 12ZA40S if it would run on just HFO, as there would be a loss of $80.402,53 within five years. If the 12ZA40S were only to run on MGO, the profit which would be made within five years would be $950.292,72.

5.4.2. Recommendations

It is not recommended to have the TPL73-A32 installed on the 16ZA40S for making profit due to saving fuel. It is however recommended to get a TPL69-A32 upgrade on DG 2 to replace the old VTR-354, if the Oosterdam would sail for another five years. If Holland America would get rid of the vessel within two years due to her age, the recommendation would be not to have an upgrade installed at all.

Wärtsilä also said that the maintenance cost would be greatly reduced when a VTR-type is replaced for a TPL-type, due to the greater simplicity of installing new parts and a lower thermal load (Wärtsilä, 2019). Further research could be conducted, where reduced maintenance cost would be taken into the calculations for ROI and profit.

6. Discussion

It was not possible to do the research exactly as proposed. There was not enough data for the load between 45% and 70%, so no fuel savings have been assumed. This was done to be on the safe side. There could be a significant difference in SFOC between these load percentages, so the profit could be higher and the ROI could be reached sooner.

In the last three weeks of the measuring period, DG 2 was surging. The engineers on board the Oosterdam decided it was best not to use DG 2 in order to prevent any damage done due to the surging. This resulted however, in a decrease of the use of DG 2 and so there are only SFOC and load measurements from before this period. This was an aspect which contributed to the lack of measuring data concerning SFOC-values at partial load. It is not certain if decrease in use could affect the results found in sub-question 2.

The measurements for the 16-cylinder engines had a great overlap and a big spread. These measurements could not be representable, as Wärtsilä did get a significant difference in SFOC-values by installing the new turbochargers on this kind of engine. The difference could be due to the tools used in the research, which may not be calibrated perfectly.

In this research, the are two scenarios for the ROI and profit. One for the engines running only on HFO and one with the engines running only on MGO. The percentage of how often the engines are running on HFO and how often they are running on MGO could affect the profit and ROI. The more the engines run on MGO, the more profit will be made. The more the engines are running on HFO, the less profit will be made. In future research, this data could be gathered along with the SFOC-values at certain loads.

Another aspect which could affect the ROI and profit, are the fuel prices. The fuel prices have been calculated through an increase of 15,9% per year. Though the increase has been predicted by experts, the real fuel prices for a certain year could still be different and thus the profit and ROI would be affected.

After the upgrade has been done, the 12-cylinder engine could be used more often to get more running hours with an engine which has the mentioned fuel savings in comparison to the 16-cylinder engines with the old turbochargers and thus without the fuel savings.

There is no real generalizability, as the market for turbocharger is ever changing and producers keep innovating as much as possible. This means other turbochargers could have higher savings and thus more profit could be earned. The SFOC-values could also be affected by wear of certain parts of the engine and this is not the same for every engine.

In conclusion, this research achieved its goal, which was to determine the profit generated by upgrading DG 2. It was unsuccessful however to determine profit generated by upgrading DG 1 and DG 3.

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Appendix 1: MGO Raw Data SFOC

DG	1	Turbocharger	ABB VTR454							
Engine type	16ZA40S									
Load [%]	Load [kW]	SFOC [g/kWh]	SFOC [kg/kWh]	SFOC [kg/	Mass flow [kg/	Engineroom temperature [°C]	Air pressure [Bar]	PMS mode	LT in	LT out
45	5301	206,4	0,206	0,000	0,304	20,4	0,979	Sea	32	34
50	6066	202,9	0,203	0,000	0,342	20	0,974	Sea	32	34
60	7037	201,7	0,202	0,000	0,394	22,3	0,999	Sea	32	35
65	7318	200,6	0,201	0,000	0,408	19,8	0,983	Sea	29	33
70	8294	201,5	0,202	0,000	0,464	22,1	0,987	Sea	32	35
70	8360	200,9	0,201	0,000	0,467	22,2	0,986	Sea	31	35
75	8658	200,8	0,201	0,000	0,483	19	0,991	Sea	31	35
75	8722	200,5	0,201	0,000	0,486	25,5	1,000	Sea	32	36
75	8744	201,3	0,201	0,000	0,489	19,5	0,976	Sea	31	35
75	8756	203,8	0,204	0,000	0,496	18,7	0,994	Sea	29	34
75	8762	199,8	0,200	0,000	0,486	18,1	0,968	Sea	31	36
75	8780	201	0,201	0,000	0,490	18	0,968	Sea	32	36
75	8784	200,2	0,200	0,000	0,488	19	0,970	Sea	31	35
75	8795	200,3	0,200	0,000	0,489	17,8	0,968	Sea	31	35
75	8722	200,5	0,201	0,000	0,486	25,5	1,000	Sea	32	36
75	8692	199,2	0,199	0,000	0,481	26	1,000	Sea	31	35
75	8656	200,1	0,200	0,000	0,481	24,2	1,008	Sea	32	36
75	8769	199,6	0,200	0,000	0,486	25,2	1,010	Sea	32	35
75	8701	199,1	0,199	0,000	0,481	28	1,012	Sea	31	35
75	8688	199,3	0,199	0,000	0,481	28,8	1,012	Sea	31	35
80	8703	199,6	0,200	0,000	0,483	26,4	1,011	Sea	31	35

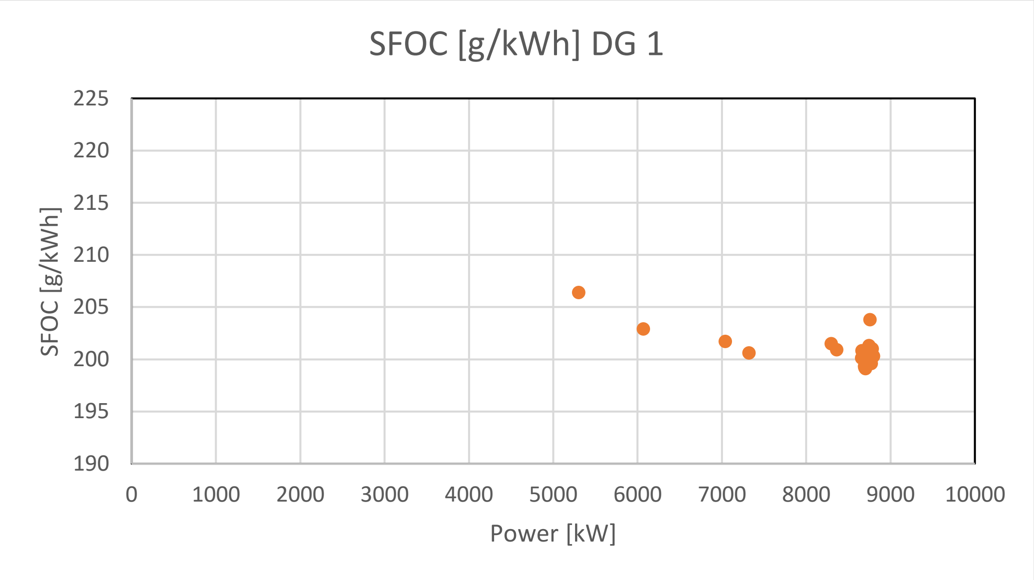
DG	2	Turbocharger	VTR-354							
Engine type	12ZA40S									
Load [%]	Load [kW]	SFOC [g/kWh]	SFOC [kg/kWh]	SFOC [kg/kJ]	Mass flow [kg/s]	Engineroom temperature [°C]	Air pressure [Bar]	PMS mode	LT in	LT out
80	6652	199,8	0,200	0,000	0,369	28	1,012	Sea	31	35
80	6615	199,5	0,200	0,000	0,367	28,8	1,012	Sea	31	35

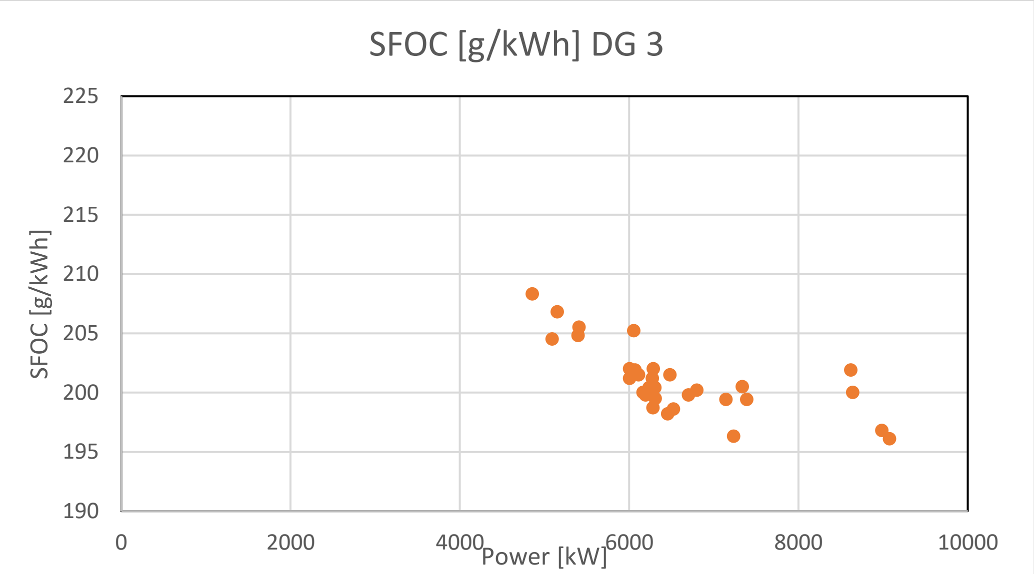
DG	3	Turbocharger	VTR-454							
Engine type	16ZA40S									
Load [%]	Load [kW]	SFOC [g/kWh]	SFOC [kg/kWh]	SFOC [kg/kJ]	Mass flow [kg/s]	Engineroom temperature [°C]	Air pressure [Bar]	PMS mode	LT in	LT out
45	4854	208,3	0,208	0,000	0,281	33,6	1,010	Manoeuvre	30	32
45	5088	204,5	0,205	0,000	0,289	24,5	0,997	Port	30	32
50	5149	206,8	0,207	0,000	0,296	35,3	1,010	Manoeuvre	31	34
50	5395	204,8	0,205	0,000	0,307	35,1	1,011	Manoeuvre	31	34
50	5404	205,5	0,206	0,000	0,308	34,2	1,012	Manoeuvre	31	34
55	6003	202	0,202	0,000	0,337	33,3	1,011	Port	31	34
55	6053	205,2	0,205	0,000	0,345	32,4	1,014	Port	30	33
55	6004	201,2	0,201	0,000	0,336	27,8	1,016	Port	30	33
55	6067	201,9	0,202	0,000	0,340	35,4	1,014	Port	30	33
55	6107	201,5	0,202	0,000	0,342	28,1	1,011	Port	31	34
55	6162	200	0,200	0,000	0,342	27,9	1,013	Port	30	33
55	6191	199,8	0,200	0,000	0,344	28,4	1,016	Port	30	33
55	6234	200,4	0,200	0,000	0,347	25,7	1,013	Port	30	33
55	6273	201,2	0,201	0,000	0,351	27,6	1,010	Port	30	33
55	6279	198,7	0,199	0,000	0,347	25,5	1,010	Port	30	33
55	6284	202	0,202	0,000	0,353	28,1	1,017	Port	30	35
55	6300	200,4	0,200	0,000	0,351	30,7	1,024	Port	32	37
55	6306	199,5	0,200	0,000	0,349	30,6	1,018	Port	32	36
60	6452	198,2	0,198	0,000	0,355	25,3	1,009	Port	30	33
60	6479	201,5	0,202	0,000	0,363	34,2	1,012	Port	30	33
60	6521	198,6	0,199	0,000	0,360	28,1	1,010	Port	30	33
60	6700	199,8	0,200	0,000	0,372	32	1,011	Port	30	32
60	6796	200,2	0,200	0,000	0,378	35,9	1,018	Port	30	33
65	7143	199,4	0,199	0,000	0,396	33,1	1,014	Port	30	34
65	7231	196,3	0,196	0,000	0,394	33,2	1,022	Port	30	34
65	7334	200,5	0,201	0,000	0,408	32,9	1,012	Port	30	34
65	7386	199,4	0,199	0,000	0,409	32,9	1,016	Port	30	34
75	8616	201,9	0,202	0,000	0,483	32,7	1,011	Port	32	36
75	8640	200	0,200	0,000	0,480	32,55	1,008	Port	32	36
80	8981	196,8	0,197	0,000	0,491	31,4	1,019	Sea	34	38
80	9074	196,1	0,196	0,000	0,494	32,8	1,019	Sea	33	37

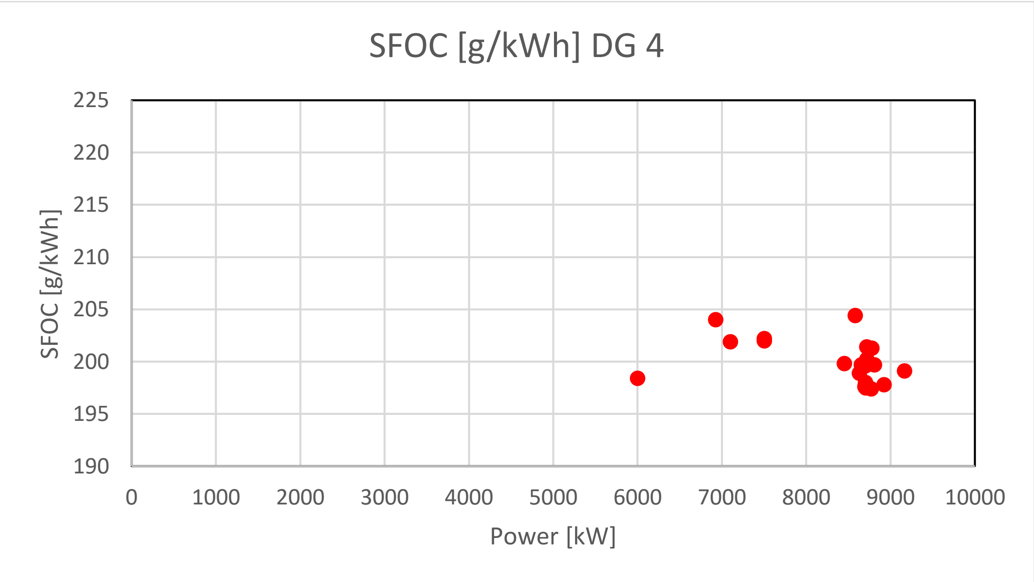
DG	4	Turbocharger	TPL73-A32							
Engine type	16ZA40S									
Load [%]	Load [kW]	SFOC [g/kWh]	SFOC [kg/kWh]	SFOC [kg/kJ]	Mass flow [kg/s]	Engineroom temperature [°C]	Air pressure [Bar]	PMS mode	LT in	LT out
55	6000	198,4	0,198	0,000	0,331	25	1,016	Port	30	34
60	6924	204	0,204	0,000	0,392	25,1	1,000	Sea	32	35
65	7100	201,9	0,202	0,000	0,398	25,5	1,013	Port	31	35
65	7503	202	0,202	0,000	0,421	39,2	1,012	Port	31	35
65	7503	202,2	0,202	0,000	0,421	39,2	1,012	Port	31	35
70	8449	199,8	0,200	0,000	0,469	20,8	0,992	Sea	34	37
70	8580	204,4	0,204	0,000	0,487	26	1,008	Sea	32	36
75	8628	198,9	0,199	0,000	0,477	30	1,012	Sea	32	36
75	8653	199,7	0,200	0,000	0,480	21,1	0,968	Sea	32	37
75	8693	197,6	0,198	0,000	0,477	24,3	0,975	Sea	32	37
75	8700	198	0,198	0,000	0,479	29,5	1,000	Sea	32	36
75	8703	199,6	0,200	0,000	0,483	26,4	1,011	Sea	32	36
75	8706	197,5	0,198	0,000	0,478	22,7	0,969	Sea	32	35
75	8711	199,7	0,200	0,000	0,483	30,1	1,010	Sea	32	36
75	8715	200,2	0,200	0,000	0,485	29,3	1,012	Sea	32	36
75	8718	201,4	0,201	0,000	0,488	25,5	0,970	Sea	32	36
75	8771	197,4	0,197	0,000	0,481	21,6	0,969	Sea	32	36
75	8778	201,3	0,201	0,000	0,491	18,5	0,994	Sea	30	34
75	8807	199,7	0,200	0,000	0,489	28,4	1,000	Sea	32	37
75	8923	197,8	0,198	0,000	0,490	33,1	1,020	Sea	30	34
80	9165	199,1	0,199	0,000	0,507	31,3	1,019	sea	30	34

DG	5	Turbocharger	TPL69-A32							
Engine type	12ZA40S									
Load [%]	Load [kW]	SFOC [g/kWh]	SFOC [kg/kWh]	SFOC [kg/kJ]	Mass flow [kg/s]	Engineroom temperature [°C]	Air pressure [Bar]	PMS mode	LT in	LT out
45	3628	207,8	0,208	0,000	0,209	34,7	0,010	Manoeuvre	30	32
45	3812	207,4	0,207	0,000	0,220	24,1	0,988	Sea	32	35
50	3820	207,2	0,207	0,000	0,220	37,2	1,011	Manoeuvre	31	34
50	3938	205,3	0,205	0,000	0,225	19,5	0,981	Sea	33	35
50	3989	205,9	0,206	0,000	0,228	37,2	1,011	Manoeuvre	31	34
50	4053	205,6	0,206	0,000	0,231	38,1	1,011	Manoeuvre	31	34
55	4552	198,8	0,199	0,000	0,251	19	0,975	Sea	32	35
65	5494	197	0,197	0,000	0,301	19,8	0,984	Sea	30	34
75	6163	196,9	0,197	0,000	0,337	24	0,988	Sea	32	36
75	6171	196,1	0,196	0,000	0,336	31,3	1,013	Port	31	35
75	6200	196	0,196	0,000	0,338	32,3	1,012	Port	32	36
75	6207	195,8	0,196	0,000	0,338	32,9	1,013	Port	31	35
75	6257	197,2	0,197	0,000	0,343	24,1	0,988	Sea	32	36
75	6352	195,3	0,195	0,000	0,345	31,4	1,014	Port	31	35
75	6367	194,7	0,195	0,000	0,344	20,8	0,992	Sea	34	37
75	6453	195,4	0,195	0,000	0,350	20,9	1,013	Port	34	37
75	6432	195,6	0,196	0,000	0,349	20,8	0,999	Port	32	36
80	6479	194,9	0,195	0,000	0,351	21,1	0,968	Sea	32	37
80	6485	196,1	0,196	0,000	0,353	25,5	0,970	Sea	32	36
80	6486	196	0,196	0,000	0,353	18,5	0,994	Sea	30	34
80	6496	195,6	0,196	0,000	0,353	22,7	0,969	Sea	32	35
80	6500	195,3	0,195	0,000	0,353	29,6	0,963	Port	31	35
80	6524	196	0,196	0,000	0,355	29,5	1,000	Sea	32	36
80	6543	195,4	0,195	0,000	0,355	24,3	0,976	Sea	32	37
80	6575	196,3	0,196	0,000	0,359	29,3	1,012	Sea	32	36
80	6584	195,3	0,195	0,000	0,357	21,6	0,969	Sea	32	36
80	6661	193,8	0,194	0,000	0,359	22,6	0,963	Port	32	36
80	6652	195	0,195	0,000	0,360	23,5	0,986	Port	32	36

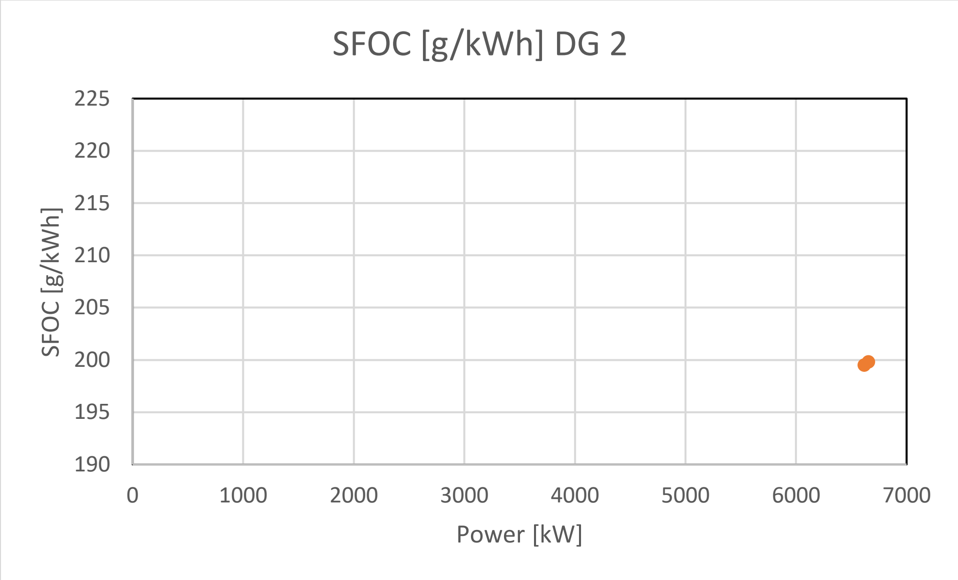
Appendix 2: MGO SFOC-Graphs 16ZA40S

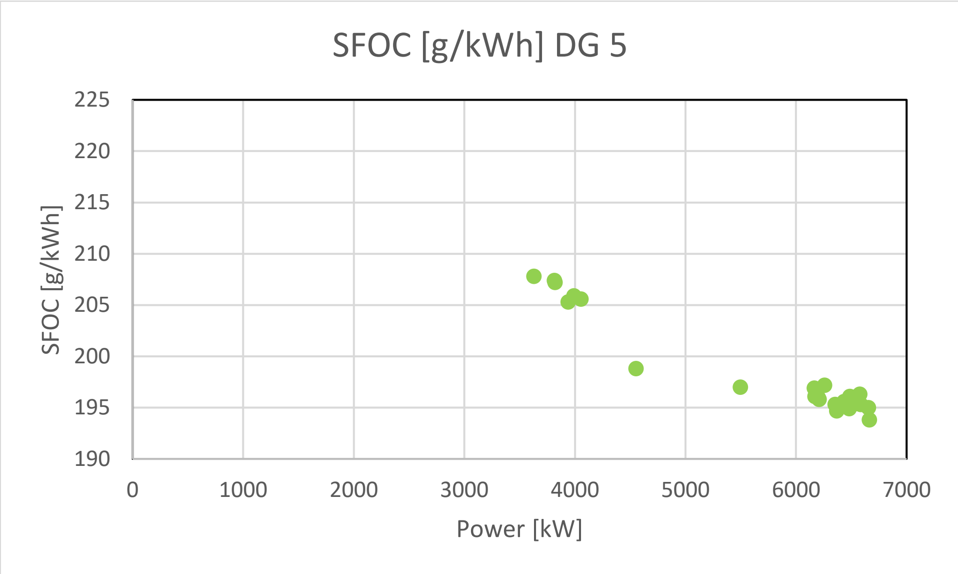




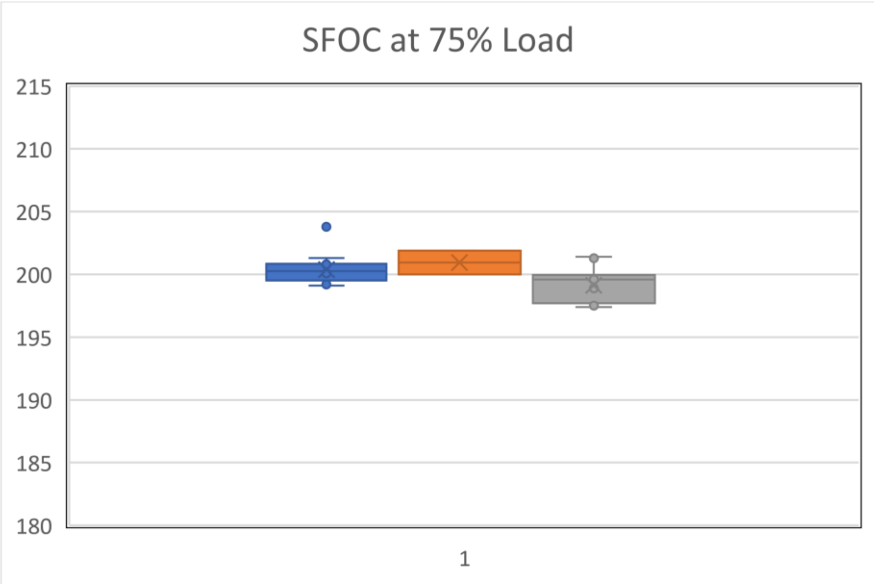


Appendix 3: MGO SFOC-Graphs 12ZA40S





Appendix 4: MGO T-test and box-and-whisker graph 75%



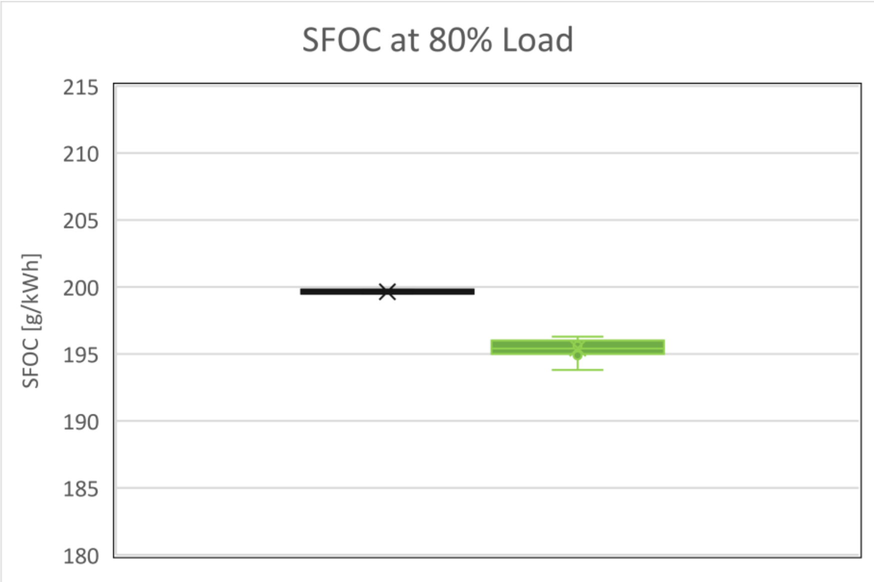
16ZA40S		
DG 1	DG 3	DG 4
200,8	201,9	198,9
200,5	200	199,7
201,3		197,6
203,8		198
199,8		199,6
201		197,5
200,2		199,7
200,3		200,2
200,5		201,4
199,2		197,4
200,1		201,3
199,6		199,7
199,1		197,8
199,3		

T-test	DG 1	DG 4
Average	200,39	199,14
Variance	1,41	1,94
Observations	14	13
Hypothesized Mean Difference [g/kWh]	0,1	
df	24	
T- statistical data	2,31	
Probability of coincidence	1%	
T critical	1,71	

T-test	DG 3	DG 4
Average	200,95	199,14
Variance	1,81	1,94
Observations	2	13

Hypothesized Mean Difference [g/kWh]	0,1
df	1
T- statistical data	1,67
Probability of coincidence	17%
T critical	6,31

Appendix 5: MGO T-test and box-and-whisker graph 80%



12ZA40S	
DG 2	DG 5
199,8	194,9
199,5	196,1
	196
	195,6
	195,3
	196
	195,4
	196,3
	195,3
	193,8
	195

T-Test	*DG 2*	*DG 5*
Average	199,65	195,43
Variance	0,05	0,50
Observations	2	11
Hypothesized Mean Difference [g/kWh]	3,5	
df	7	
T- statistical data	2,76	
Probability of coincidence	1%	
T critical	1,89	

Appendix 6: HFO Raw Data SFOC

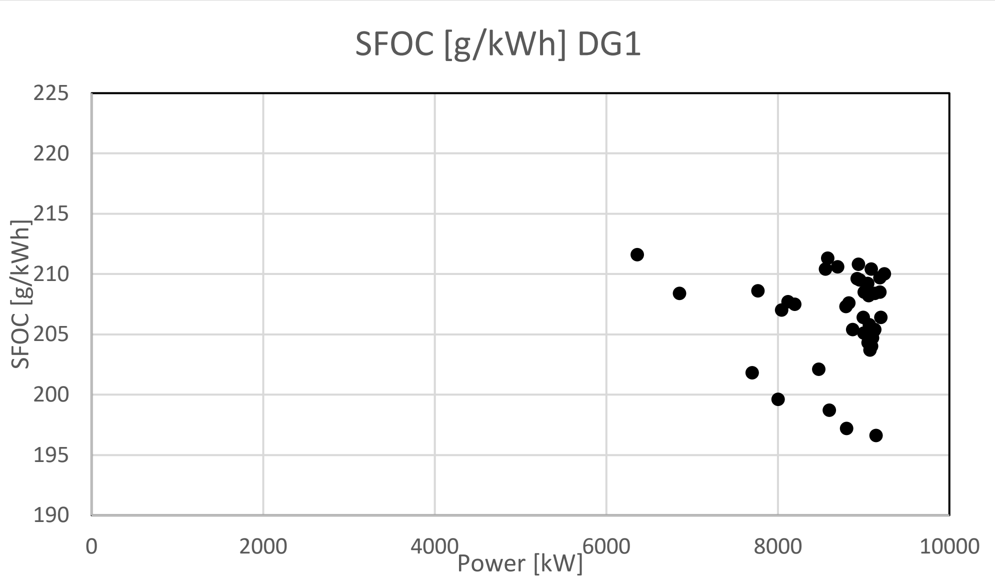
DG	1	Turbocharger	ABB VTR454							
Engine type	16ZA40S									
Load [%]	Load [kW]	SFOC [g/kWh]	SFOC [kg/kWh]	SFOC [kg/kJ]	Mass flow [kg/s]	Engineroom temperature [°C]	Air pressure [Bar]	PMS mode	LT in	LT out
55	6852	208,4	0,208	0,000	0,397	31,7	1,016	Sea	30	33
55	6359	211,6	0,212	0,000	0,374	26,6	1,011	Sea	30	32
70	8000	199,6	0,200	0,000	0,444					
70	7700	201,8	0,202	0,000	0,432					
70	8475	202,1	0,202	0,000	0,476	26,3	0,998	Sea	29	32
70	8041	207	0,207	0,000	0,462	26,1	1,009	Sea	29	33
70	8197	207,5	0,208	0,000	0,472	24	1,01	Sea	30	34
70	8118	207,7	0,208	0,000	0,468	27,2	1,01	Sea	30	34
70	7768	208,6	0,209	0,000	0,450	35,9	1,022	Sea	33	36
75	8600	198,7	0,199	0,000	0,475					
75	8791	207,3	0,207	0,000	0,506	25,7	1,005	Sea	30	34
75	8924	209,6	0,210	0,000	0,520	30,2	1,014	Sea	30	34
75	8555	210,4	0,210	0,000	0,500	38,5	1,011	Sea	31	36
75	8695	210,6	0,211	0,000	0,509	28,9	1,015	Sea	30	34
75	8580	211,3	0,211	0,000	0,504	39,1	1,007	Sea	33	37
80	9145	196,6	0,197	0,000	0,499	28,5	1,019	Sea	29	33
80	8800	197,2	0,197	0,000	0,482					
80	9073	203,7	0,204	0,000	0,513	27	0,99	Sea	30	34
80	9090	204	0,204	0,000	0,515	31,6	1,017	Sea	31	36
80	9051	204,3	0,204	0,000	0,514	31,2	1,014	Sea	32	37
80	9101	204,7	0,205	0,000	0,517	31,6	1,015	Sea	30	34
80	9089	204,8	0,205	0,000	0,517	30,9	1,02	Sea	30	35
80	9002	205,1	0,205	0,000	0,513	37,1	1,025	Sea	33	37
80	9082	205,3	0,205	0,000	0,518	31,8	1,204	Sea	32	36
80	9121	205,3	0,205	0,000	0,520	32,9	1,028	Sea	30	35
80	9128	205,4	0,205	0,000	0,521	32,8	1,019	Sea	34	38
80	8871	205,4	0,205	0,000	0,506	26,6	0,991	Sea	30	34
80	9064	205,8	0,206	0,000	0,518	31,4	1,019	Sea	34	38
80	9201	206,4	0,206	0,000	0,528	26,8	1,019	Sea	29	33
80	8996	206,4	0,206	0,000	0,516	29,2	1,02	Sea	29	33
80	8828	207,6	0,208	0,000	0,509	27,4	1,011	Sea	30	34
80	9058	208,2	0,208	0,000	0,524	37,8	1,014	Sea	32	37
80	9128	208,4	0,208	0,000	0,528	27,9	1,016	Sea	30	34
80	9006	208,5	0,209	0,000	0,522	37,3	1,017	Sea	31	36
80	9190	208,5	0,209	0,000	0,532	29,7	1,01	Sea	30	34
80	9046	209,2	0,209	0,000	0,526	37,9	1,011	Sea	32	38
80	8954	209,5	0,210	0,000	0,521	28	1,017	Sea	30	34
80	9187	209,7	0,210	0,000	0,535	30,3	1,016	Sea	30	34
80	9240	210	0,210	0,000	0,539	32,3	1,015	Sea	30	34
80	9087	210,4	0,210	0,000	0,531	36,5	1,011	Sea	31	35
80	8938	210,8	0,211	0,000	0,523	27,7	1,017	Sea	30	34

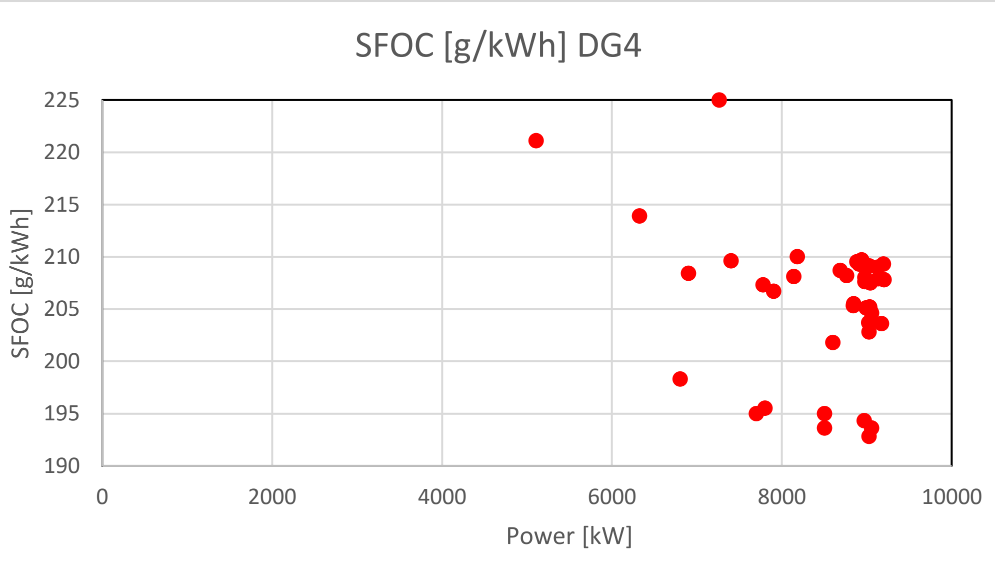
DG	2	Turbocharger	ABB VTR-354							
Engine type	12ZA40S									
Load [%]	Load [kW]	SFOC [g/kWh]	SFOC [kg/kWh]	SFOC [kg/kJ]	Mass flow [kg/s]	Engineroom temperature [°C]	Air pressure [Bar]	PMS mode	LT in	LT out
45	3910	216,7	0,217	0,000	0,235	31,7	1,014	Sea	30	32
45	3759	217,7	0,218	0,000	0,227	27,7	1,015	Sea	30	33
45	3600	207,5	0,208	0,000	0,208					
55	4867	210,6	0,211	0,000	0,285	26,6	1,011	Sea	30	32
60	5221	207,7	0,208	0,000	0,301	31,7	1,016	Sea	30	33
65	5300	206,7	0,207	0,000	0,304					
70	5922	211,9	0,212	0,000	0,349	35,9	1,022	Sea	32	36
75	6239	208,3	0,208	0,000	0,361	27,2	1,010	Sea	30	34
75	6476	202,1	0,202	0,000	0,364	26,3	0,998	Sea	29	32
80	6700	198,1	0,198	0,000	0,369					
80	6915	205,6	0,206	0,000	0,395	27	0,990	Sea	30	34
80	6700	206	0,206	0,000	0,383					
80	6749	207,6	0,208	0,000	0,389	25,7	1,005	Sea	30	34
80	6858	207,6	0,208	0,000	0,395	29,2	1,020	Sea	29	33
80	6811	207,7	0,208	0,000	0,393	26,6	0,991	Sea	30	34
85	7001	207,8	0,208	0,000	0,404	32,8	1,019	Sea	33	38
80	6796	208,3	0,208	0,000	0,393	27,4	1,011	Sea	30	34
80	6881	208,9	0,209	0,000	0,399	37,1	1,025	Sea	33	37
80	6712	210,5	0,211	0,000	0,392	28,9	1,015	Sea	30	34
80	6973	210,7	0,211	0,000	0,408	36,5	1,011	Sea	31	35
80	6895	211,2	0,211	0,000	0,405	37,3	1,017	Sea	31	36
80	6939	211,5	0,212	0,000	0,408	37,8	1,014	Sea	32	37
80	6558	211,7	0,212	0,000	0,386	39,1	1,007	Sea	33	37
80	6587	212,2	0,212	0,000	0,388	38,5	1,011	Sea	32	36
80	6913	212,3	0,212	0,000	0,408	37,9	1,011	Sea	32	38

DG	4	Turbocharger	ABB TPL73-A32							
Engine type	16ZA40S									
Load [%]	Load [kW]	SFOC [g/kWh]	SFOC [kg/kWh]	SFOC [kg/k	Mass flow [kg/s]	Engineroom temperature [°C]	Air pressure [Bar]	PMS mode	LT in	LT out
40	5104	221,1	0,221	0,061	0,313	32,9	1,014	Sea	30	33
55	6899	208,4	0,208	0,058	0,399	34,5	1,015	Sea	31	34
55	6323	213,9	0,214	0,059	0,376	29,6	1,011	Sea	30	33
60	6800	198,3	0,198	0,055	0,375					
65	7400	209,6	0,210	0,058	0,431					
65	7260	225	0,225	0,063	0,454	25,4	0,999	Manoeuvring	30	33
70	7700	195	0,195	0,054	0,417					
70	7800	195,5	0,196	0,054	0,424					
70	8599	201,8	0,202	0,056	0,482	28,7	0,998	Sea	30	34
70	7902	206,7	0,207	0,057	0,454	29,6	1,009	Sea	30	34
70	7777	207,3	0,207	0,058	0,448	36,1	1,022	Sea	29	34
70	8141	208,1	0,208	0,058	0,471	31,3	1,010	Sea	30	34
70	8181	210	0,210	0,058	0,477	28,9	1,010	Sea	30	34
75	8500	193,6	0,194	0,054	0,457					
75	8500	195	0,195	0,054	0,460					
75	9040	204,9	0,205	0,057	0,515	23,9	0,990	Sea	32	36
75	8845	205,5	0,206	0,057	0,505	23,2	0,990	Sea	32	36
75	8762	208,2	0,208	0,058	0,507	30,6	1,011	Sea	30	34
75	8686	208,7	0,209	0,058	0,504	29,8	1,015	Sea	31	35
75	8925	209,3	0,209	0,058	0,519	29,9	1,017	Sea	30	34
75	8910	209,3	0,209	0,058	0,518	30,2	1,014	Sea	31	35
75	8882	209,5	0,210	0,058	0,517	30,1	1,016	Sea	30	34
75	8939	209,7	0,210	0,058	0,521	29,9	1,016	Sea	30	34
80	9026	192,8	0,193	0,054	0,483	37,6	1,016	Sea	32	36
80	9054	193,6	0,194	0,054	0,487	37	1,017	Sea	32	36
80	8968	194,3	0,194	0,054	0,484	37,4	1,014	Sea	33	37
80	9025	202,8	0,203	0,056	0,508	32,6	1,020	Sea	32	36
80	9173	203,6	0,204	0,057	0,519	36,1	1,019	Sea	30	36
80	9021	203,7	0,204	0,057	0,510	34,7	1,024	Sea	32	36
80	9055	204,6	0,205	0,057	0,515	36,9	1,028	Sea	32	36
80	8993	205,1	0,205	0,057	0,512	39,5	1,025	Sea	31	36
80	9033	205,2	0,205	0,057	0,515	39,9	1,019	Sea	30	35
80	8842	205,3	0,205	0,057	0,504	25,9	1,005	Sea	31	36
80	9041	207,5	0,208	0,058	0,521	38,6	1,014	Sea	32	37
80	8978	207,6	0,208	0,058	0,518	35,8	1,017	Sea	30	36
80	9203	207,8	0,208	0,058	0,531	30,8	1,010	Sea	31	36
80	9133	207,9	0,208	0,058	0,527	27,1	1,020	Sea	31	36
80	8977	208	0,208	0,058	0,519	37	1,011	Sea	30	37
80	9123	209	0,209	0,058	0,530	33,2	1,015	Sea	30	35
80	9029	209,1	0,209	0,058	0,524	35,1	1,011	Sea	30	35
80	9196	209,3	0,209	0,058	0,535	35,2	1,015	Sea	30	35

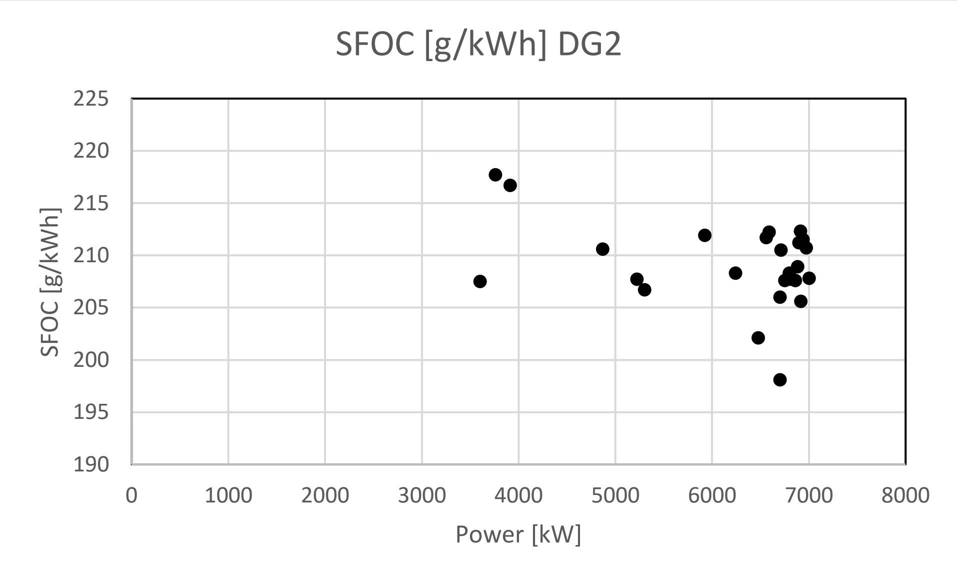
DG	5	Turbocharger	ABB TPL69-A32							
Engine type	12ZA40S									
Load [%]	Load [kW]	SFOC [g/kWh]	SFOC [kg/kWh]	SFOC [kg/kJ]	Mass flow [kg/s]	Engineroom temperature [°C]	Air pressure [Bar]	PMS mode	LT in	LT out
70	5726	206,8	0,207	0,000	0,329	36,1	1,022	Sea	29	34
70	6000	204,5	0,205	0,000	0,341					
75	6725	205,5	0,206	0,000	0,384	30	1,017	Sea	30	34
80	6748	190,9	0,191	0,000	0,358	37,6	1,016	Sea	33	37
80	6762	191	0,191	0,000	0,359	37	1,017	Sea	32	36
80	6751	191,1	0,191	0,000	0,358	37,4	1,014	Sea	32	36
80	6700	196,8	0,197	0,000	0,366					
80	6672	200,4	0,200	0,000	0,371	23,9	0,990	Sea	32	36
80	6546	201,1	0,201	0,000	0,366	23,2	0,990	Sea	32	36
80	6733	201,3	0,201	0,000	0,376	34,7	1,024	Sea	32	36
80	6762	201,6	0,202	0,000	0,379	32,6	1,020	Sea	32	36
80	6793	201,8	0,202	0,000	0,381	36,9	1,028	Sea	32	36
80	6553	202,4	0,202	0,000	0,368	25,9	1,005	Sea	31	36
80	6781	203,5	0,204	0,000	0,383	27,1	1,020	Sea	31	36
80	6638	205,3	0,205	0,000	0,379	30,1	1,016	Sea	30	34
80	6698	205,3	0,205	0,000	0,382	30,1	1,016	Sea	30	34
80	6714	205,4	0,205	0,000	0,383	37	1,011	Sea	30	37
80	6647	205,4	0,205	0,000	0,379	30	1,016	Sea	31	35
80	6702	205,6	0,206	0,000	0,383	38,6	1,014	Sea	32	37
80	6676	205,6	0,206	0,000	0,381	30,2	1,016	Sea	30	34
80	6718	205,8	0,206	0,000	0,384	35,1	1,011	Sea	30	35
80	6635	206,2	0,206	0,000	0,380	30,2	1,014	Sea	31	35
80	6467	206,5	0,207	0,000	0,371	29,8	1,015	Sea	31	35
80	6397	206,9	0,207	0,000	0,368	38,3	1,011	Sea	31	36
80	6393	207,7	0,208	0,000	0,369	36,6	1,011	Sea	31	36
85	6881	205,6	0,206	0,000	0,393	30,6	1,010	Sea	31	36

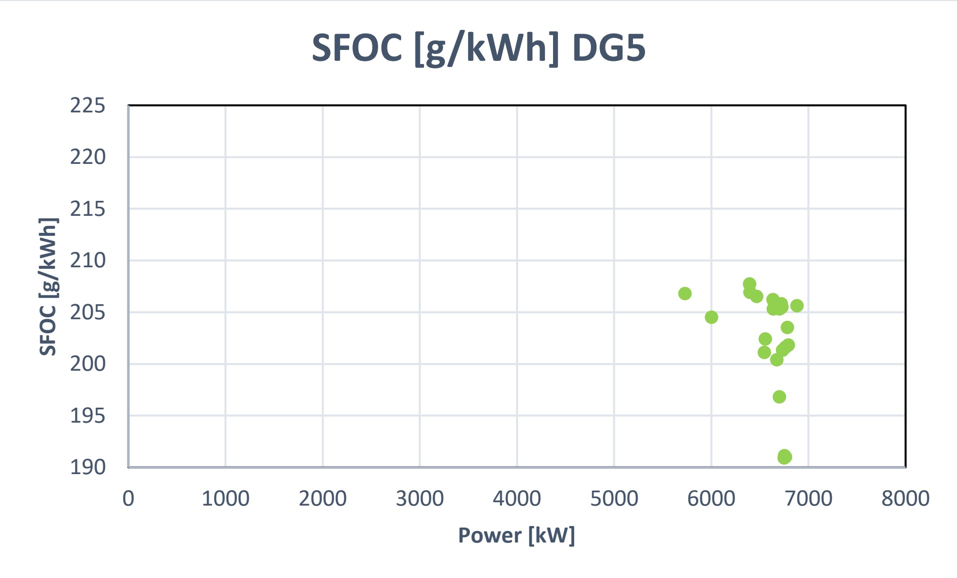
Appendix 7: HFO SFOC-graphs 16ZA40S



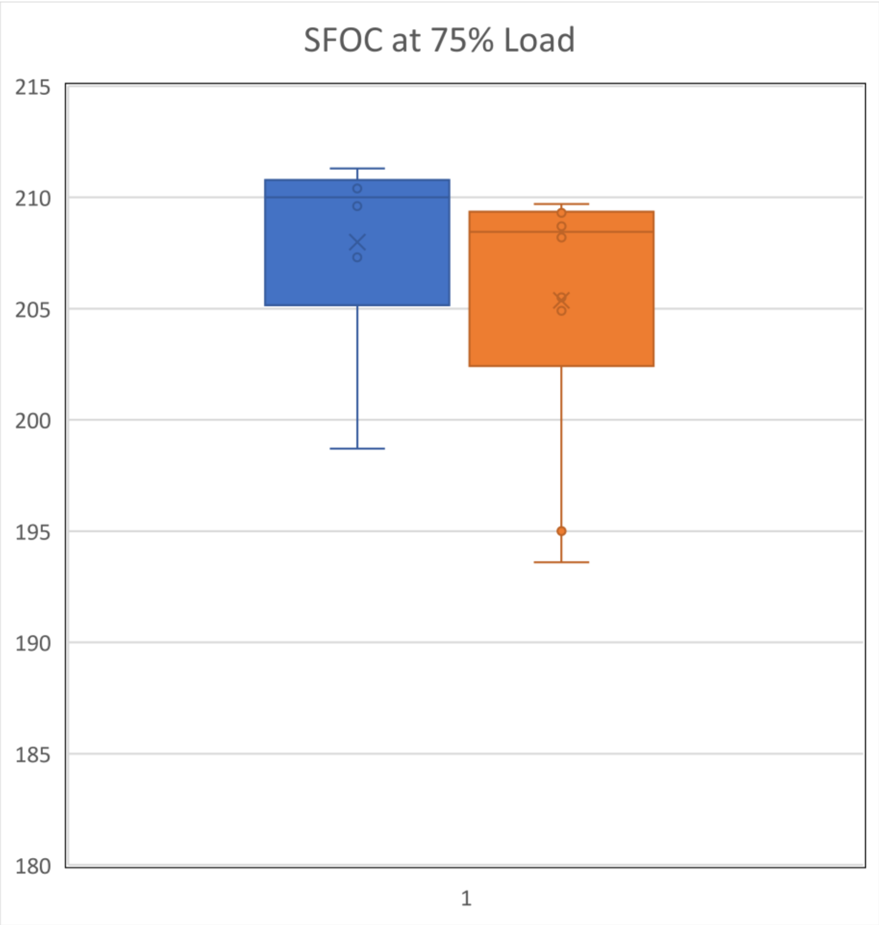


Appendix 8: HFO SFOC-graphs 12ZA40S





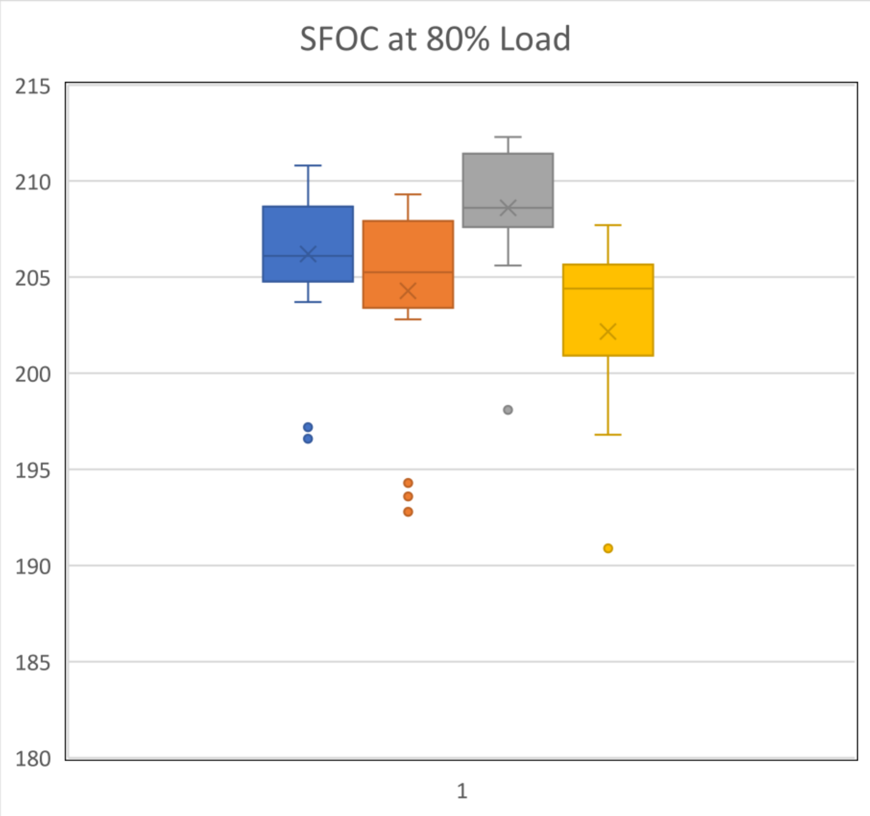
Appendix 9: HFO T-test and box-and-whisker graph 75%



16ZA40S	
DG 1	DG 4
198,7	193,6
207,3	195
209,6	204,9
210,4	205,5
210,6	208,2
211,3	208,7
	209,3
	209,3
	209,5
	209,7

T-Test	*DG 1*	*DG 4*
Average	207,98	205,37
Variance	22,59	36,90
Observations	6	10
Hypothesized Mean Difference [g/kWh]	0,1	
df	13	
T- statistical data	0,92	
Probability of coincidence	19%	
T critical	1,77	

Appendix 10: HFO T-test and box-and-whisker graph 80%



16ZA40S		12ZA40S	
DG 1	DG 4	DG 2	DG 5
196,6	192,8	198,1	190,9
197,2	193,6	205,6	191
203,7	194,3	206	191,1
204	202,8	207,6	196,8
204,3	203,6	207,6	200,4
204,7	203,7	207,7	201,1
204,8	204,6	207,8	201,3
205,1	205,1	208,3	201,6
205,3	205,2	208,9	201,8
205,3	205,3	210,5	202,4
205,4	207,5	210,7	203,5
205,4	207,6	211,2	205,3
205,8	207,8	211,5	205,3
206,4	207,9	211,7	205,4
206,4	208	212,2	205,4
207,6	209	212,3	205,6
208,2	209,1		205,6
208,4	209,3		205,8
208,5			206,2
208,5			206,5
209,2			206,9
209,5			207,7
209,7			
210			
210,4			
210,8			

T-Test	DG 1	DG 4
Average	206,20	204,29
Variance	12,13	28,38
Observations	26	18
Hypothesized Mean Difference [g/kWh]	0,1	
df	27	
T- statistical data	1,27	
Probability of coincidence	11%	
T critical	1,70	

T-Test	DG 2	DG 5
Average	208,61	202,16
Variance	12,61	27,41
Observations	16,00	22,00
Hypothesized Mean Difference [g/kWh]	3	
df	36	
T- statistical data	2,41	
Probability of coincidence	1%	
T critical	1,69	

Appendix 11: Raw Data Running Hours

05/11/2022	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load
DG 1	80%	0	4	4	80%	15	24	9				0
DG 2	75%	0	3	3	45%	3	6	3	80%	14	24	10
DG 3	25%	0	6	6	60%	6	14	8	45%	14	17	3
DG 4	80%	14	24	10				0				0
DG 5				0				0				0
06/11/2022	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load
DG 1	80%	0	5	5	85%	18	24	6				0
DG 2	80%	0	8	8	85%	19	24	5				0
DG 3				0				0				0
DG 4	80%	0	7	7	50%	7	9	2	85%	19	24	5
DG 5				0				0				0
07/11/2022	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load
DG 1	80%	0	4	4	70%	18	20	2	80%	20	24	4
DG 2	85%	0	3	3	75%	18	20	2	80%	20	24	4
DG 3	35%	3	4	1	55%	4	17	13	80%	17	18	1
DG 4	80%	0	4	4				0				0
DG 5				0				0				0
08/11/2022	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load
DG 1	60%	0	2	2	30%	2	4	2	80%	18	24	6
DG 2	65%	0	2	2	30%	2	4	2	85%	18	24	6
DG 3	45%	4	6	2	55%	2	6	4				0
DG 4				0				0				0
DG 5	50%	2	5	3	75%	5	17	12	85%	17	24	7
09/11/2022	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load
DG 1	80%	0	7	7				0				0
DG 2	85%	0	7	7				0				0
DG 3	55%	9	23	14	80%	23	24	1				0
DG 4	75%	0	5	5	75%	5	6	1	60%	6	9	3
DG 5	55%	6	9	3				0				0
10/11/2022	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load
DG 1	75%	0	15	15	70%	15	24	9				0
DG 2				0				0				0
DG 3				0				0				0
DG 4	75%	0	15	15	70%	15	24	9				0
DG 5	80%	0	15	15	70%	15	24	9				0
11/11/2022	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load
DG 1	60%	0	3	3	30%	3	6	3	80%	20	24	4
DG 2				0				0				0
DG 3	30%	4	6	2	55%	6	18	12				0
DG 4	75%	19	24	5				0				0
DG 5	60%	0	4	4	30%	5	6	1	80%	18	24	6
12/11/2022	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load
DG 1	80%	0	24	24				0				0
DG 2				0				0				0
DG 3				0				0				0
DG 4	80%	0	24	24				0				0
DG 5	80%	0	24	24				0				0

13/11/2022	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load
DG 1	80%	0	24	24				0				0
DG 2				0				0				0
DG 3				0				0				0
DG 4	80%	0	24	24				0				0
DG 5	80%	0	24	24				0				0
14/11/2022	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load
DG 1	80%	0	24	24				0				0
DG 2				0				0				0
DG 3				0				0				0
DG 4	80%	0	24	24				0				0
DG 5	80%	0	24	24				0				0
15/11/2022	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load
DG 1	80%	0	24	24				0				0
DG 2	80%	3	24	21	50%	1	3	2				0
DG 3				0				0				0
DG 4	80%	0	24	24				0				0
DG 5	50%	1	3	2	80%	0	1	1				0
16/11/2022	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load
DG 1	80%	0	24	24				0				0
DG 2	80%	0	24	24				0				0
DG 3				0				0				0
DG 4	80%	0	24	24				0				0
DG 5				0				0				0
17/11/2022	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load
DG 1	80%	0	24	24				0				0
DG 2	80%	0	24	24				0				0
DG 3	40%	11	13	2	80%	14	24	10				0
DG 4	80%	0	24	24				0				0
DG 5				0				0				0
18/11/2022	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load
DG 1	80%	0	16	16	75%	16	24	8				0
DG 2	80%	0	16	16	75%	16	24	8				0
DG 3	80%	0	16	16	40%	16	18	2				0
DG 4	80%	0	16	16	75%	16	24	8				0
DG 5				0				0				0
19/11/2022	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load
DG 1	45%	0	4	4				0				0
DG 2	25%	0	2	2	10%	23	24	1				0
DG 3				0				0				0
DG 4	25%	0	2	2	10%	23	24	1				0
DG 5				0				0				0
20/11/2022	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load
DG 1	45%	0	3	3	80%	3	24	21				0
DG 2	45%	0	3	3	80%	3	20	17	85%	20	24	4
DG 3	30%	2	4	2	60%	4	24	20				0
DG 4	45%	0	3	3	80%	3	20	17	80%	20	24	4
DG 5	80%	22	24	2				0				0

21/11/2022	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load
DG 1	80%	0	24	24				0				0
DG 2	80%	0	24	24				0				0
DG 3				0				0				0
DG 4	80%	0	24	24				0				0
DG 5	80%	0	24	24				0				0
22/11/2022	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load
DG 1	80%	0	9	9	35%	9	11	2	75%	22	24	2
DG 2	80%	0	4	4	40%	4	6	2	80%	22	24	2
DG 3	40%	10	12	2	65%	12	21	9				0
DG 4	80%	0	9	9	40%	9	12	3	65%	20	22	2
DG 5	80%	0	9	9	80%	22	24	2				0
23/11/2022	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load
DG 1	80%	0	2	2	75%	2	24	22				0
DG 2	80%	0	2	2	75%	2	24	22				0
DG 3				0				0				0
DG 4	50%	22	24	2				0				0
DG 5	80%	0	2	2	75%	2	22	20	50%	22	24	2
24/11/2022	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load
DG 1	80%	0	3	3	70%	3	7	4				0
DG 2	60%	3	9	6	55%	22	24	2				0
DG 3	50%	9	24	15				0				0
DG 4	80%	0	3	3	65%	3	6	3	35%	6	8	2
DG 5	65%	5	8	3	50%	8	22	14	25%	22	24	2
25/11/2022	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load
DG 1	55%	23	24	1				0				0
DG 2				0				0				0
DG 3				0				0				0
DG 4	60%	0	21	21	35%	22	24	2				0
DG 5	20%	20	23	3				0				0
26/11/2022	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load
DG 1	50%	0	3	3	80%	3	24	21				0
DG 2	55%	0	3	3	80%	3	4	1	80%	15	24	9
DG 3				0				0				0
DG 4	80%	6	24	18				0				0
DG 5	80%	5	24	19				0				0
27/11/2022	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load
DG 1				0				0				0
DG 2	75%	0	1	1	80%	1	24	23				0
DG 3	65%	10	22	12				0				0
DG 4				0				0				0
DG 5	80%	0	1	1	40%	1	3	2				0
28/11/2022	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load
DG 1	75%	0	1	1	80%	1	24	23				0
DG 2	80%	0	20	20	45%	20	21	1				0
DG 3				0				0				0
DG 4	75%	0	1	1	80%	1	24	23				0
DG 5				0				0				0

29/11/2022	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load
DG 1	80%	0	18	18	45%	18	21	3				0
DG 2				0				0				0
DG 3				0				0				0
DG 4	80%	0	19	19				0				0
DG 5	45%	18	21	3	80%	21	24	3				0
30/11/2022	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load
DG 1				0				0				0
DG 2				0				0				0
DG 3				0				0				0
DG 4				0				0				0
DG 5	80%	0	24	24				0				0
01/12/2022	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load
DG 1	40%	21	24	3				0				0
DG 2				0				0				0
DG 3				0				0				0
DG 4	60%	0	4	4	40%	4	12	8				0
DG 5	80%	0	21	21	50%	21	24	3				0
02/12/2022	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load
DG 1	45%	19	22	3	80%	22	24	2				0
DG 2	65%	0	5	5	55%	5	10	5				0
DG 3	55%	0	19	19				0				0
DG 4	45%	20	24	4				0				0
DG 5	45%	19	22	3	80%	22	24	2				0
03/12/2022	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load
DG 1	80%	0	24	24				0				0
DG 2				0				0				0
DG 3				0				0				0
DG 4	75%	0	10	10	75%	13	24	11				0
DG 5	80%	0	24	24				0				0
04/12/2022	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load
DG 1	80%	0	24	24				0				0
DG 2				0				0				0
DG 3				0				0				0
DG 4	75%	0	24	24				0				0
DG 5				0				0				0
05/12/2022	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load
DG 1	80%	0	6	6	45%	6	9	3	80%	18	24	6
DG 2	80%	18	24	6				0				0
DG 3	60%	10	18	8				0				0
DG 4				0				0				0
DG 5				0				0				0
06/12/2022	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load
DG 1	80%	0	7	7				0				0
DG 2	80%	0	7	7	45%	7	9	2				0
DG 3	55%	10	20	10				0				0
DG 4				0				0				0
DG 5				0				0				0

07/12/2022	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load
DG1	80%	0	9	9	80%	12	24	12				0
DG2				0				0				0
DG3	60%	10	20	10				0				0
DG4				0				0				0
DG5				0				0				0
08/12/2022	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load
DG1	45%	0	5	5	80%	19	24	5				0
DG2				0				0				0
DG3	55%	13	20	7				0				0
DG4				0				0				0
DG5				0				0				0
09/12/2022	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load
DG1	80%	0	12	12	55%	21	24	3				0
DG2				0				0				0
DG3				0				0				0
DG4				0				0				0
DG5				0				0				0
10/12/2022	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load
DG1	75%	0	24	24				0				0
DG2	70%	0	24	24				0				0
DG3				0				0				0
DG4				0				0				0
DG5				0				0				0
11/12/2022	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load
DG1	70%	0	24	24				0				0
DG2	70%	0	2	2				0				0
DG3				0				0				0
DG4				0				0				0
DG5				0				0				0
12/12/2022	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load
DG1	80%	0	7	7				0				0
DG2	80%	0	7	7	45%	7	9	2				0
DG3	55%	10	20	10				0				0
DG4				0				0				0
DG5				0				0				0
13/12/2022	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load
DG1	80%	0	6	6	45%	6	9	3				0
DG2	80%	18	24	6				0				0
DG3	60%	10	18	8				0				0
DG4				0				0				0
DG5				0				0				0
14/12/2022	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load
DG1	80%	0	3	3	70%	3	7	4				0
DG2	60%	3	9	6	55%	22	24	2				0
DG3	50%	9	24	15				0				0
DG4	80%	0	3	3	65%	3	6	3				0
DG5	65%	5	8	3	50%	8	22	14				0

15/12/2022	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load
DG 1	55%	23	24	1				0				0
DG 2				0				0				0
DG 3				0				0				0
DG 4	60%	0	21	21	35%	22	24	2				0
DG 5	20%	20	23	3				0				0
16/12/2022	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load
DG 1	45%	0	5	5	80%	19	24	5				0
DG 2				0				0				0
DG 3	55%	13	20	7				0				0
DG 4				0				0				0
DG 5				0				0				0
17/12/2022	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load
DG 1	40%	21	24	3				0				0
DG 2				0				0				0
DG 3				0				0				0
DG 4	60%	0	4	4	40%	4	12	8				0
DG 5	80%	0	21	21	50%	21	24	3				0
18/12/2022	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load
DG 1	80%	0	24	24				0				0
DG 2	80%	0	24	24				0				0
DG 3	40%	11	13	2	80%	14	24	10				0
DG 4	80%	0	24	24				0				0
DG 5				0				0				0
19/12/2022	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load
DG 1	80%	0	24	24				0				0
DG 2				0				0				0
DG 3				0				0				0
DG 4	75%	0	24	24				0				0
DG 5				0				0				0
20/12/2022	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load
DG 1	80%	0	24	24				0				0
DG 2				0				0				0
DG 3				0				0				0
DG 4	75%	0	24	24				0				0
DG 5				0				0				0
21/12/2022	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load
DG 1				0				0				0
DG 2				0				0				0
DG 3	60%	11	24	13				0				0
DG 4	55%	0	9	9				0				0
DG 5				0				0				0
22/12/2022	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load
DG 1				0				0				0
DG 2				0				0				0
DG 3	75%	0	6	6	55%	6	17	11	60%	17	24	7
DG 4	75%	0	6	6				0				0
DG 5				0				0				0

23/12/2022	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load
DG 1	75%	21	24	3				0				0
DG 2	75%	21	24	3				0				0
DG 3	60%	0	20	20				0				0
DG 4	70%	21	24	3				0				0
DG 5				0				0				0
24/12/2022	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load
DG 1	75%	0	8	8				0				0
DG 2	80%	0	24	24				0				0
DG 3	80%	10	24	14				0				0
DG 4	75%	0	24	24				0				0
DG 5	80%	2	24	22				0				0
25/12/2022	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load
DG 1	75%	1	24	23				0				0
DG 2	80%	0	6	6	45%	7	11	4	55%	21	23	2
DG 3	80%	0	6	6				0				0
DG 4	75%	0	6	6	50%	6	24	18				0
DG 5	80%	0	6	6				0				0
26/12/2022	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load
DG 1	75%	0	24	24				0				0
DG 2	80%	19	24	5				0				0
DG 3	60%	6	11	5	80%	11	16	5				0
DG 4	75%	1	24	23				0				0
DG 5	80%	1	18	17				0				0
27/12/2022	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load
DG 1				0				0				0
DG 2				0				0				0
DG 3				0				0				0
DG 4	75%	0	6	6	75%	14	24	10				0
DG 5	80%	2	6	4	65%	6	11	5	80%	11	24	13
28/12/2022	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load
DG 1	75%	0	18	18	60%	18	24	6				0
DG 2				0				0				0
DG 3				0				0				0
DG 4	75%	0	18	18				0				0
DG 5	80%	0	18	18	60%	18	24	6				0
29/12/2022	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load
DG 1	60%	0	5	5	30%	5	16	11	75%	22	24	2
DG 2				0				0				0
DG 3				0				0				0
DG 4				0				0				0
DG 5	65%	0	5	5	35%	5	17	12	80%	17	24	7
30/12/2022	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load
DG 1				0				0				0
DG 2				0				0				0
DG 3	35%	10	16	6				0				0
DG 4	35%	16	24	8				0				0
DG 5	80%	0	3	3	50%	3	6	3	30%	6	24	18

31/12/2022	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load
DG1	75%	1	24	23				0				0
DG2				0				0				0
DG3	80%	0	6	6				0				0
DG4	75%	0	6	6	50%	6	24	18				0
DG5	80%	0	6	6				0				0
01/01/2023	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load
DG1	75%	0	24	24				0				0
DG2				0				0				0
DG3				0				0				0
DG4	75%	0	24	24				0				0
DG5	80%	0	6	6				0				0
02/01/2023	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load
DG1	75%	0	24	24				0				0
DG2				0				0				0
DG3				0				0				0
DG4	75%	0	24	24				0				0
DG5	80%	0	24	24				0				0
03/01/2023	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load
DG1	75%	1	24	23				0				0
DG2				0				0				0
DG3				0				0				0
DG4	75%	0	24	24				0				0
DG5	80%	0	24	24				0				0
04/01/2023	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load
DG1	75%	0	6	6	75%	18	24	6				0
DG2				0				0				0
DG3	55%	6	18	12				0				0
DG4	75%	0	6	6	75%	18	24	6				0
DG5	80%	0	6	6				0				0
05/01/2023	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load
DG1	75%	1	24	23				0				0
DG2				0				0				0
DG3				0				0				0
DG4	75%	0	24	24				0				0
DG5	80%	0	24	24				0				0
06/01/2023	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load	Load	time start	time stop	running hours in load
DG1	75%	0	6	6	75%	22	24	2				0
DG2				0				0				0
DG3	55%	6	22	16				0				0
DG4	75%	0	6	6	75%	22	24	2				0
DG5	80%	0	6	6				0				0

Appendix 12: Running hours per load

Table 9

Load	Percentage of running time spent in load	percentage of total time spent in load
0%	3%	59%
5%	0%	0%
10%	0%	0%
15%	0%	0%
20%	0%	0%
25%	0%	0%
30%	2%	1%
35%	0%	0%
40%	1%	0%
45%	3%	1%
50%	0%	0%
55%	1%	0%
60%	2%	1%
65%	0%	0%
70%	2%	1%
75%	29%	12%
80%	57%	24%
85%	1%	0%
90%	0%	0%
95%	0%	0%
100%	0%	0%

Figure 20: DG 1

Table 10

Load	Percentage of running time spent in load	percentage of total time spent in load
0%	0%	58%
5%	0%	0%
10%	0%	0%
15%	0%	0%
20%	0%	0%
25%	0%	0%
30%	0%	0%
35%	0%	0%
40%	0%	0%
45%	4%	2%
50%	0%	0%
55%	3%	1%
60%	3%	1%
65%	2%	1%
70%	6%	3%
75%	9%	4%
80%	65%	27%
85%	6%	3%
90%	0%	0%
95%	0%	0%
100%	0%	0%

Figure 21: DG 2

Table 11

Load	Percentage of running time spent in load	percentage of total time spent in load
0%	0%	58%
5%	0%	0%
10%	0%	0%
15%	0%	0%
20%	0%	0%
25%	2%	1%
30%	1%	0%
35%	2%	1%
40%	2%	1%
45%	1%	1%
50%	8%	3%
55%	33%	14%
60%	26%	11%
65%	5%	2%
70%	0%	0%
75%	2%	1%
80%	18%	8%
85%	0%	0%
90%	0%	0%
95%	0%	0%
100%	0%	0%

Figure 22: DG 3

Table 12

Load	Percentage of running time spent in load	percentage of total time spent in load
0%	0%	57%
5%	0%	0%
10%	0%	0%
15%	0%	0%
20%	0%	0%
25%	0%	0%
30%	0%	0%
35%	2%	1%
40%	2%	1%
45%	1%	0%
50%	6%	3%
55%	1%	0%
60%	6%	3%
65%	1%	0%
70%	1%	1%
75%	39%	17%
80%	40%	17%
85%	1%	0%
90%	0%	0%
95%	0%	0%
100%	0%	0%

Figure 23: DG 4

Table 13

Load	Percentage of running time spent in load	percentage of total time spent in load
0%	0%	58%
5%	0%	0%
10%	0%	0%
15%	0%	0%
20%	1%	0%
25%	0%	0%
30%	3%	1%
35%	2%	1%
40%	0%	0%
45%	1%	0%
50%	7%	3%
55%	1%	0%
60%	2%	1%
65%	3%	1%
70%	2%	1%
75%	5%	2%
80%	72%	30%
85%	1%	0%
90%	0%	0%
95%	0%	0%
100%	0%	0%

Figure 24: DG 5

Table 14

Load	Percentage of running time spent in load	percentage of total time spent in load
0%	0%	58%
5%	0%	0%
10%	0%	0%
15%	0%	0%
20%	0%	0%
25%	0%	0%
30%	1%	1%
35%	1%	0%
40%	1%	0%
45%	2%	1%
50%	4%	2%
55%	5%	2%
60%	6%	3%
65%	2%	1%
70%	3%	1%
75%	21%	9%
80%	52%	22%
85%	1%	1%
90%	0%	0%
95%	0%	0%
100%	0%	0%

Figure 25: Total

Appendix 13: Turbocharger cost

ROI CALCULATION CASE 1

WÄRTSILÄ

Calculation from Excel File

- 12ZA40S FOR IMO engines
- Engine running 4000 rhs/year
- Fuel price 480 €/ton
- 2 x VTR354 SIKO spares+work 450 k€
- Performance Upgrade price 622 k€
- Fuel Savings = 57 k€/y (considering 4000 rhs/y fuel price 480 €/ton)
- Maintenance savings = 13,1 k€/year (average value)

- **ROI = 2,4 years**

2 x TPL's UPGRADE PRICE	k€	622
2 x VTR's SIKO costs	k€	450
power per cylinder	kW	720
number of cylinders	pcs	12
engine power	kW	8640
hours per year	h/y	4000
fuel cost	€/ton	480
Lifecycle costs 2 x TPL's	k€	512
Lifecycle costs 2 x VTR's	k€	670
SIKO lifecycle VTR and TPL	hours	48000

INPUT DATA
OPTIONAL DATA

LOAD DATA	
Loads	time
%	%
100	0
85	15
75	75
50	10
25	0

Results		
Yearly SFOC SAVING	k€ /y	57,0
Years between SIKO	y	12
Yearly OPEX savings	k€ /y	13,17
ROI	years	2,45

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