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Ship propulsion using wind, batteries and diesel-electric machinery

Dimensioning of a propulsion system using wind, batteries and diesel-electric machinery

Degree project in the Marine Engineering Programme

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CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2016

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Cover:

[The Buckau, a Flettner rotor ship. (George Grantham Bain Service, n.d)]

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Abstract

Wind energy is a resource that is not used to any great extent in the shipping industry since the advent of the internal combustion engine in the 1920s. Since then, wind power is utilized at sea in less extent until recent years. In this report, the authors will investigate how a ship that runs on wind power can reduce its bunker consumption, both directly and indirectly through wind energy. Directly is how the wind energy can relieve the engines on board and indirectly how a ship, with the help of wind assistance, can have smaller equipment on board to decrease the fuel consumption. The ship model for this report has a diesel-electric machinery and batteries that will help reduce consumption. To carry out this work the authors created a numerical model ship in MATLAB that imitates a Panamax tanker. This ship was installed with a Flettner rotor, a kite and a wind turbine in three different scenarios to see how they can reduce consumption. According to the mathematical values the Flettner rotor was the most effective at utilizing wind power and could save up to 9038 US dollar each day. However, this report has limited itself to look at the ship and its propulsion under conditions with ideal wind direction.

Keywords: Shipping, wind, propulsion, machinery, Flettner rotor, kite, wind turbine

Sammanfattning

Vindkraft är en resurs som inte har utnyttjas i någon stor utsträckning inom sjöfarten sedan förbränningsmotorns intåg på 1920-talet. Sedan dess har vindkraft utnyttjats i mindre och mindre utsträckning fram till de senaste åren. Författarna ska i denna rapport se hur ett fartyg som körs med vindkraft kan minska sin bunkerförbrukning, både direkt och indirekt med hjälp av vindkraft. Direkt är hur vind kan, med hjälp av vindassistans, avhjälpa huvudmaskinern ombord och indirekt hur fartyget kan dimensionera ner utrustningen ombord för att minska bränsleförbrukningen. Detta fartyg körs med ett dieselelektriskt system med stöd av batterier som ska hjälpa till att få ner förbrukningen. För att genomföra denna rapport så skapades ett matematiskt modellskepp i MATLAB som efterliknades en Panamax tanker. Detta fartyg kördes med Flettner rotor, drake och vindturbin i tre olika scenarion för att se hur dessa kan minska förbrukningen. Enligt dessa matematiska modeller som rapporten fick fram, så var det Flettner rotor som var det mest effektiv på att utnyttja vindkraften och kunde spara upp till 9038 US dollar. Dock har denna rapport begränsat sig till att titta på fartyget och dess framdrivning under förhållanden med ideal vindriktning.

Nyckelord: Sjöfart, vind, framdrivning, maskinrum, Flettner rotor, drake, vindturbin

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Jonas Sandell & Jonas Segerlind, Gothenburg, May, 2016

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Nomenclature

α	Spin ratio, Relation between the speed of the wind and the circumferential speed of the Flettner rotor, dimensionless
	Lift to drag angle, degrees ϑ
	Elevation angle of the kite, degrees ρ
	Density of air, kg/m^3
A	Area, m^2
C_D	Drag coefficient for the kite, dimensionless
C_L	Lift coefficient for the kite, dimensionless
C_M	The moment coefficient, dimensionless
D	Drag force, W
F	Total Force, N
F_w	Total force of kite, N
F_x	Total force in x-direction, N
$h_{KiteHeight}$	The operating height of the kite, m
L	Lift force, W $\dot{m}$
	Mass flow, kg/h
P	Power, w
p_∞	Pressure at infinity distance from actuator disc, Pa
p_a	Pressure at a, Pa p_b
	Pressure at b, Pa
P_b	Brake power of main engine, W
P_d	Power delivered to propeller, W P_e
	The effective (towing) power, W
$P_{L\&D}$	The lift and drag forces combined, W
P_{motor}	Power needed to rotate the Flettner rotor, W
P_t	Thrust power delivered by the propeller to water, W
R	Length of tether line, m
V	Velocity, m/s
V_1	Velocity at 1, m/s
V_2	Velocity at 2, m/s
V_a	Velocity at a, m/s
V_{ak}	Apparent wind velocity, m/s
V_b	Velocity at b, m/s V_{ship}
	Speed of the ship, m/s
V_{True}	True wind velocity at 10 meters above sea level, m/s
$V_{TrueAtKite}$	True wind velocity at kite, m/s
$V_{WindDir}$	Angle of the true wind in relation to the ship, degrees

Glossary

Anode	In an electrolytic cell the anode is the positive polarity contact and where the oxidation occurs.
Block coefficient	The ratio between a rectangular box around the ships outer dimensions and the volume occupied by the submerged ship in the same box.
CAPEX	Short for "Capital Expenses", which means the initial costs to buy, for example, a ship.
Cathode	This is where the negative polarity in an electrolytic cell is and the reduction occurs.
Computational Fluid Dynamics	CFD is a branch of fluid mechanics that uses numerical analysis and algorithms, which are usually based on Navier–Stokes equations, to solve and analyze problems that involve fluid flows.
CSI	A comprehensive tool which is used by leading international cargo owners to evaluate the environmental performance of their providers of sea transport.
Current collector	Helps the electrons to travel from the anode to the cathode.
Deadweight tonnage	A ship's weight carrying capacity and does not include the weight of the ship itself.
DNV-GL	An international certification body and classification society.
ESI	ESI evaluates the greenhouse gas emission that is released by a ship.
Liquid electrolyte	This produces an electrically conducting solution in the battery.

Lloyd’s Register — A technical and business services organisation and a maritime classification society.

Marine Diesel Oil — A fuel oil that consists of both gasoil and heavy fuel oil.

MCR — Maximum continuous rating is defined as the maximum output power that an engine is capable of producing continuously under normal conditions.

OPEX — Short for "Operating Expenses", which sums up the cost for everything concerning operation, systems with more.

Panamax — Panamax vessels have specific dimensions so that they meet the Panama requirements for passing through the Panama canal.

Planetary boundary layer — The lowest part of the atmosphere and its behavior is directly influenced by its contact with a planetary surface.

Polymeric membrane — A separator placed between a battery’s anode and cathode to prevent electrical short circuits.

Revolutions per minute — RPM is a measure of the frequency of rotation.

Tacking — A sailing maneuver where the ship sail a zigzag course upwind by repeatedly executing such a maneuver.

USD/mt — US dollar per metric ton.

Wake — The region of recirculating flow immediately behind a moving body, caused by viscosity, which may be accompanied by flow separation and turbulence..

1 Introduction

Using wind energy as a propulsion source is not a new concept, sails have been used since the Ubaid period (c. 6000 -4300 BC) (Carter, 2012) and were used in commercial shipping until early 20th century when diesel engines started to take over the market. In recent years wind, as an energy source, is making a comeback in the form of kites, Flettner rotors and sails. Flettner rotors on ships were patented in September 1922 by Anton Flettner and had the advantage over regular sails that the rotor, according to Allenström, Li & Ran (2012), could utilize the wind at a 20 to 30 degree angle (see figure 2.3), while a sail could only utilize the wind at a minimum of 45 degree angle or otherwise the sailing ship had to tack.

The land based industry is using wind resources better than the marine industry. On land there are a lot of utilization of the nature's renewable resources; wind, high situated water, solar power and waves. In recent decades technology has evolved a lot to take advantage of these sources of energy on land more and more efficient. At sea these technologies is not as widely spread, but this is about to change as several studies, experiments and field experience suggests. In the study by Traut, Wood, Gilbert, Walsh, Bows, Filippone and Stansby (2014), high potentials for energy savings is presented. According to Traut et al. (2014), a typical 5500 dwt (deadweight tonnage), slow-steaming general cargo carrier sailing the specific route between Varberg and Gillingham could on average yield 193-373 kW from a Flettner rotor and 127-461 kW from a kite, which is about 10-45 per cent of the total power on the ship.

With global warming as a worldwide issue, reduction of greenhouse gases from the shipping industry would help the environment and slow down the global warming (IMO, 2015). According to IMO (International Maritime Organisation) (2015), the shipping industry was responsible for 2.2% of the international emissions of CO_2. Another big concern is the peak oil event, that is when the world oil production will reach its peak and start to decline (Hubbert, 1956). This was predicted wrongly by M. King Hubbert to happen between 1965 and 1971 in the US (Hubbert, 1956), but in more recent studies it is said to happen in 2025 (Hirsch, 2005). Some reports suggest that the peak oil debate is not about how drastic the oil production will stop and its consequences, but rather on what kind of fuel that will continuously replace petroleum products with over time (Noreng, 2012). This has been discussed and debated and there is still no definitive answer to when the world's natural oil supply will be depleted (Ingles & Denniss, 2010), or even if it is going to be depleted (BP, 2015). Some argue even that society should completely stop using fossil fuels and only use renewable energy (Teske, S., Sawyer, S. and Schäfer, O. 2015).

An another factor to the development of renewable energy is the oil price. The price of oil is currently the lowest since April 2003 (Nasdaq, 2016) and investing in renewable energy is expensive. According to Bos (2015), the oil price will rise again because at the moment OPEC (Organizing of the Petroleum Exporting Countries) is pumping more oil into the market than is needed to meet the current demand. During this process, OPEC does not make any profit (Petroff & Yellin, 2015), but OPEC hope that the lower price will force out other actors from the oil market (Bos, 2015). When the price increases again, the hope is that more companies will invest in renewable energy on board their ships and this will hopefully both increase their profit and help the environment (Watson, 2016).

1.1 Purpose

The main purpose of this report is to explore ways to use wind and batteries on a diesel-electric ship and form the basis for future research projects in this subject. The aim of this report is to show that a ship can reduce its environmental impact by reducing the fuel consumption whilst keeping the same speed.

1.2 Questions

How much can the bunker consumption be reduced on ships whilst using wind energy as an extra propulsion force?

- How much power is achieved through the use of wind energy?
- Is it better to use rotors, wind turbines or a kites to take advantage of the wind energy?
- How can the batteries be used in conjunction with the wind systems?

1.3 Delimitations

This report will be limited to the study of a specific model of a real ship that sails in waters in which the ship can utilize the natural resources. This report will focus on the implementation and the dimension of batteries, wind systems and the engine system. The waste heat recovery will not be discussed, neither will the hull, the propeller, the increased maintinance work or what kind of vessel the different systems is best suitable for. A life-cycle assessment (LCA) will not be done in this report. This report will not consider the lateral forces and the extra resistance that occur when utilizing the wind. This report is limited to one set weather condition and its effect on the ships propulsion.

2 Background and Theory

In this chapter the wind technologies, batteries and diesel-electric machinery will be described and how they work. Other relevant reports will also be presented.

2.1 Flettner rotor

The Flettner rotor was patented 1922 by Anton Flettner and is a device that utilize wind energy to propel a ship with the Magnus effect. The geometry of a Flettner rotor is a tall and wide cylinder with an end-disc on top (see figure 2.1). The Flettner rotor does not spin because of the wind, which is a common misconception, but instead it spins with the help of an electrical motor as described in the report by Pearson (2014). This means that some power is required to operate the Flettner rotor, but the lift force exceed that power which means that the total energy outcome is positive as shown in the report by Traut et al. (2014).

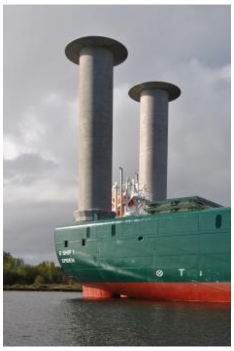

Figure 2.1: Two Flettner rotors at the bow of the German RoLo cargo ship E-Ship 1, (kaKstn, 2010) CC BY-SA.

The Magnus effect was named after the German scientist Gustav Magnus in 1852 (Seifert, 2012). The effect appears when a rotating body is subjected to a moving fluid. Seifart (2012) describes that when a fluid encounters a rotating body, in a Flettner rotor's case air encounters a rotating cylinder, the air accelerates on the side that moves in the same direction as the flow and decelerates on the side that moves in the opposite direction as the flow. This is because of the friction between the cylinder surface and the air. The difference in the velocity of the fluid on each side causes a differential pressure that acts on the cylinder and creates a pushing force perpendicular to the onflow of the fluid, as can be seen in figure 2.2 (Seifert, 2012).

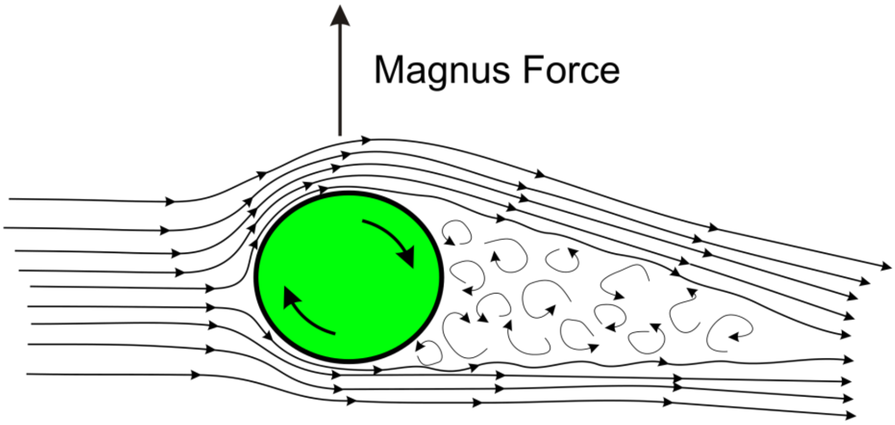

Figure 2.2: Sketch of Magnus effect with streamlines and turbulent wake, (Rdurkacz, 2013) CC BY-SA.

The perpendicular force means that the Flettner rotor can not utilize the wind when the onflow is zero degrees onto the ships course or from astern. According to Allenström et al. (2012), the Flettner rotor could utilize the wind down to 3040 degrees and up to 140-150. Even if the force from the rotor is perpendicular, the most effective angle of the wind is not 90 degrees because The Flettner rotor has a drag force that the fluid flow creates. If the wind angle is 90 degrees onto the ship, the drag force only acts as a resistance for the rotor motor. If the wind, as explained by Allenström et al. (2012), has an angle so that the resulting force between the lift and drag is in the direction of the ships beam the drag force is benefital. Figure 2.3 show the angles of which the ship can utilize the wind. The green areas show where the most power can be produced. Less energy can be produced in yellow areas and in red areas, the power output is negative because the Flettner rotor’s air resistance is higher than the delivered pushing force.

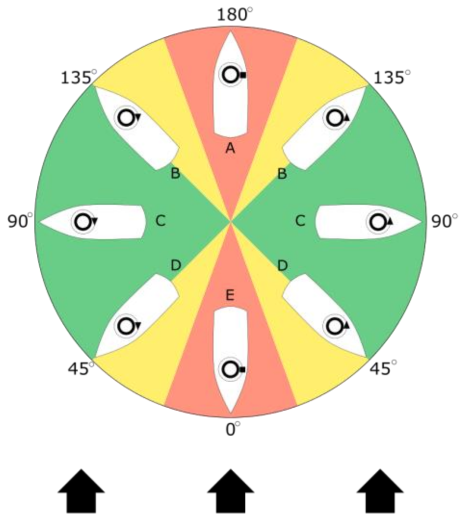

Figure 2.3: Wind direction relative to a ship with a Flettner rotor and at which angle the Flettner rotor can utilize the wind (Amada44, 2015) CC BY-SA.

Since the rotor’s effect is determined by the differential pressure over the cylinder, more effect will be provided if there is a difference in pressure over the whole cylinder. The function of the end-disc is to keep the low and the high pressure separated on the top of the cylinder. If there was no end-disc the differential pressure would leak at the top of the rotor which would produce vortices that decreases the efficiency of the Flettner rotor (Allenström et al., 2012).

The implementation of an end-disc was first proposed by Ludwig Prandtl in 1924 and it would come to show that it greatly increased the lift force created by the rotor as explained in the report from Seifert (2012). The size of the end-disc is expressed as a ratio of the rotor diameter and, according to Seifert (2012), the effect of the end-disc is largely dependent on the spin ratio (α). Spin ratio is the relation between the apparent wind and the circumferential speed. For lower spin ratios (< 1) and higher spin ratios (>3), an end disc of lower size induces less drag. At the middle ground of spin ratios (1 <α< 3), the larger size of an end disc is more beneficial for the lift and drag ratio (Seifert, 2012).

There are few commercial shipping companies that have incorporated Flettner rotors on board new ships or retrofitted Flettner rotors on their old ships (Lloyd's Register Marine, 2015). E-Ship 1 is a ship, which was launched year 2010, with a deadweight of 10,000 tonnes and has four Flettner rotors installed. These Flettner rotors have a height of 27 meters and a diameter of 4 meters (Traut et al. 2014). According to Enercon (2015), E-ship 1 can achieve a fuel consumption reduction of about 15 per cent in good wind conditions thanks to the four Flettner rotors on board.

Another example of a commercial ship with Flettner rotors installed is the M/V Estraden, that is owned by the shipping company Bore Ltd. There are two Flettner rotors retrofitted on M/V Estraden, which were installed at two different occasions, one in 2014 and the other in 2015 (Bore Ltd, 2016). The rotors were provided by the Finnish company Norsepower and have a height of 18 meters and diameter of 3 meters. They can provide 2 MW of extra propulsion power each (Bore Ltd, 2016).

When calculating a Flettner rotors performance, several variables need to be taken into consideration. As explained by Allenström et al. (2012), the factor that contributes to the lift and drag coefficient is the spin ratio(α). The apparent wind is the true wind added to the relative wind, which is dependent on the ship speed over ground. This relation has a great effect on the power output from all wind propulsion. This is shown in the equations below, where a lesser apparent wind means less effect. The lift and drag coefficients are, as explained by Allenström et al. (2012), hard to acquire since the institutions and companies, that has access to full scale data, are very uneager to share it. Allenström et al. (2012) countered this by using a Computational Fluid Dynamics (CFD) program and validated their results to experimental data from the report by Reid (1924). But in the report by Traut et al. (2014), they assumed values which according to themselves were in line with the report by Craft, Johnson, & Launder (2014). The mathematical model that was used by Traut et al. (2014) are based on five equations. The equations for lift force and drag force are

$$L = \frac{1}{2}\rho A V_a^2 C_L \tag{2.1}$$

$$D = \frac{1}{2}\rho A v_a^2 C_D \tag{2.2}$$

These are added to each other and multiplied with the speed of the ship.

$$P_{L\&D} = (L + D) * V_{Ship} \tag{2.3}$$

The parameters that determines the power required by the motor to spin the rotor is expressed by

$$P_{motor} = \frac{1}{2}\rho A V_a^3 C_M \alpha \tag{2.4}$$

Where C_M is the momentum coefficient which according to Traut et al. (2014) is in line with anecdotal evidence from Flettner himself.

The propulsion effect that a Flettner rotor can produce is

$$P_{propulsion} = P_{L\&D} - P_{motor} \tag{2.5}$$

2.2 Kite-sail

The kite pulls the ship along with the power produced by the kite utilizing the wind. The system is attached at the forecastle of the ship as shown in figure 2.4. The geometry is formed so that a low pressure and a high pressure area is formed on each side of the kite that generates the lift force. The lift force pulls the ship and reduces the required power from the engine to obtain a certain speed, which leads to less fuel consumption (Traut et al, 2014).

To control the flight path of the kite, a control pod is used that pulls the control tether line to the left and right to create a butterfly trajectory and the benefit of doing this is a higher propulsion force, as shown in a report by Loyd (1980). The reason, as explained by Loyd (1980), is that when the kite is moved so that the line is parallel to the wind, the kite motion is moving crosswind. This increases the kite speed above the wind speed and thus providing more force. The Kite technology requires a launching and retrieving system and the company Skysails' solution is to use a hydraulic telescopic mast that deploys and returns the kite (Skysails GmbH, 2016). The mast raises the kite and unfolds it to let the wind catch it, then the winch emancipates until the operation height is reached. The retrieving process is the same as launching but in reverse (Skysails GmbH, 2016).

Kites can also be used for generating electricity (Kim & Park, 2010), although this has not yet been proven at sea. The technology exists and Skysails is a company developing kites that generate electricity. Their system generates electricity by extending the tether line that rotates a drum which is connected to a generator. A crosswind kite, which is the type of kite often used for ships, is able to perform a pumping motion by utilizing the different parts of the trajectory (Argatov & Silvennoinen, 2010). By doing this, and implementing a special winch

that pulls the kite towards the ship during the low force part and slack during the high force part, electricity can be generated by the kite.

Figure 2.4: Ship equipped with a kite (Katze, 2012) CC BY-SA.

Earth has a planetary boundary layer, that means the air speed is close to zero at the ground but increases with altitude. This effect is called the wind gradient and are shown in figure 2.5, Where u_0 is the onflow speed of the wind and $u_{(y)}$ is the speed at different altitude. At the ground, y = 0, $u_{(y)} = 0$ and at an altitude outside the boundary layer, above the doted line, $u_{(y)} = u_0$. The kite utilizes this effect and can thus be affected by a higher and more steady apparent wind velocity than that at the lower heights, as shown in the report by Leloup, Roncin, Behrel, Bles, Leroux, Jochum & Parlier (2014).

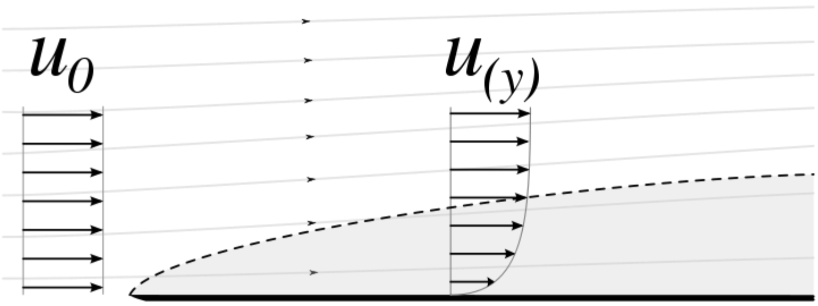

Figure 2.5: Wind Gradient (Ariadacapo, 2011) CC BY-SA.

According to Lloyd's Register Marine (2015), there are only two ships in operation that has a kite on board, where one of these is a prototype. However, according to Lloyd's Register Marine (2015), there are three more underway. The ship M/S Beluga was the first newly built vessel co-powered by wind using a towing kite system in 2008 by the company Skysails GmbH (Brabeck, 2008).

The following equations is one of many different ways of describing a kite mathematically. The equations for the kite is from both the report by Traut et al. (2014) and Allenström et al. (2012).

The wind gradient effect is an important effect as explained above and Allenström et al. (2012) uses the wind profile law equation (2.6) to incorporate it:

$$V_{TrueAtKite} = V_{True} * \left(\frac{h_{KiteHeight}}{10}\right)^{(1/7)} \quad (2.6)$$

The kite height is expressed with simple trigonometry as (2.7):

$$h_{KiteHeight} = R * sin\vartheta \quad (2.7)$$

The apparent wind speed is calculated with the following equation (2.8):

$$V_{ak} = \sqrt{(V_{TrueAtKite} * cos(V_{WindDir}) + V_{ship})^2 + (V_{TrueAtKite} * sin(V_{WindDir}))^2} \quad (2.8)$$

The force provided by the kite is calculated with the following equation (2.9). Where epsilon is the lift to drag angle.

$$F_w = \frac{L}{cos} \quad (2.9)$$

The lift and drag forces are calculated with the same equations as for the Flettner rotor but the lift and drag constants are changed.

2.3 Wind turbines

Windmills have been used for centuries in Holland, England and the Greek islands to pump water, grind grain and saw wood (White, 2011). Modern wind turbines are used to generate electric power and the total capacity in the world 2015, using wind power, was 434.9 GW, which is 16.5% higher than in 2014 (Education World Wind Energy Association, 2016). China is world leading in total capacity of wind energy at 148 GW, while Denmark is world leading in using electricity from wind energy. 42 per cent of the total power in Denmark is produced by wind turbines (Energinet.dk, 2016).

The most common wind turbine is the propeller mill, an example of a horizontal-axis wind turbine (HAWT). HAWTs require extensive bracing and gear systems when combined with an electric generator, but they are effective. The other kind of wind turbines are vertical-axis wind turbines (VAWT), which has a simplified gearing and strength requirements (White, 2011).

In 1920, A. Betz predicted the ideal frictionless efficiency of a propeller windmill by calculating its efficiency from an actuator disc (White, 2011). In the area around the disc, the pressure is high on the attack side of the blade but discontinuity of the pressure as it has a low pressure on the backside (see figure 2.6). Downstream the velocity of the wind is slower than upstream, making V_1 higher than V_2. The wind on the blades will have a force on it making a momentum at the base and to hold it rigid, there needs to be a force opposite to the force of the wind on the blades (White, 2011). The wind forms a force that pushes the blades, making them rotate. This also creates a tipping force, that is not to any use on land, where there is a solid base that holds the windmill rigid.
At sea this force
could be utilized by making some extra thrust to the ship (Carlson & Nilsson, 2014).

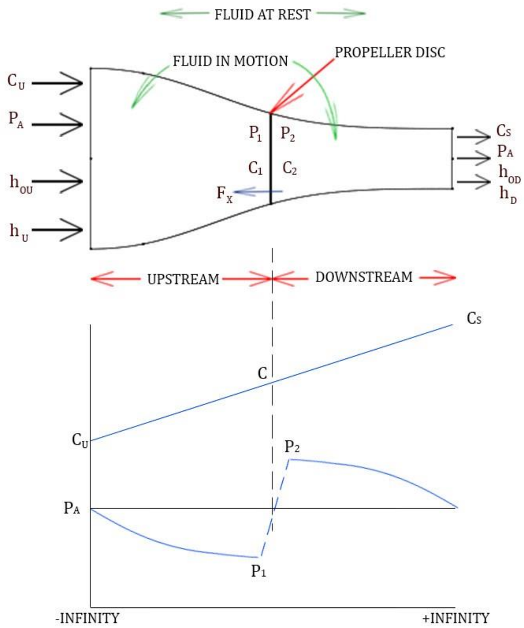

Figure 2.6: Pressure and speed over an actuator disc. (Prj1991, 2013) CC BYSA.

PROPit is a project about how to utilize the wind power on board ships with wind turbines and is a cooperation between Chalmers University of Technology, Scandinavian Wind, Region Västra Götaland, Lloyd's Register Marine and Stena Line with the support of Wallenius Marine AB and The Swedish Energy Agency.

The idea of PROPit is that tankers can have wind turbines that are able to be folded on deck when they are not in use. When folded they produce less air resistance. In this project they made a prototype of a Panamax oil tanker that had wind turbines mounted and found that if a ship has two 1 MW wind turbines mounted, the fuel savings would be around 16% and at a price of 402.5 USD/mt[1], the ship used in this project, calculated

[1] Price at Rotterdam's port, retrieved from www.bunkerindex.com, 2016-04-29

to use around 1667 metric tonnes every year, could save around 670 835 USD per year (Carlson & Nilsson, 2015).

A risk assessment was made by the researchers in this project and they discovered 29 potential risks, however, none of the risks were high enough to stop the project of installing wind turbines on ships (Carlson & Nilsson, 2015). The five most significant risks were analyzed further by Lloyd’s Register Marine and from a class point of view the design was deemed acceptable. This five risks were that the foundation fails, the turbine cannot return to the position ready for stowing, the cables are not properly installed on the ship, the turbine becomes loose when folded and the turbine cannot be folded.

In this project PROPit also interviewed different sections in the shipping industry to get an idea of what the industry was thinking about the utilization of wind power on board ships. Some of the concerns raised were the requirement for new skills in operation and maintenance, noise from the turbines and the icing of the wings. But one thing that was positive from the companies was the clean shipping index (CSI) and environmental shipping index (ESI) that gives them discounts for having a reduced environmental impact (Carlson & Nilsson, 2015).

There were six key factors that were identified that would predict if this project was going to be successful; the oil price, public investment incentives, frontrunners, on board ambassadors and charters supporting the innovation, Nordic market as role model and risk analysis for both safety and working environment (Carlson & Nilsson, 2015).

The following equations are taken from White (2011). To calculate the force, a control-volume-horizontal-momentum relation applied between section 1 and 2

$$\sum F_x = -F = \dot{m}\,(V_2 - V_1) \qquad (2.10)$$

similar relation just before and after the disc

$$\sum F_x = -F + (p_b - p_a)A = \dot{m}\,(V_a - V_b) = 0 \qquad (2.11)$$

these two gives the propeller force

$$F = (p_a - p_b)A = \dot{m}\,(V_1 - V_2) \qquad (2.12)$$

At an ideal flow, and applying the incompressible Bernoulli equation, the pressure can be found 1 to b:

$$p_\infty + \frac{1}{2}\ {}_1^2 = p_b + {}_2 \quad 1 \quad {}^2 \quad \rho V$$

$$\_\rho V \quad (2.13)$$

and a to 2: 1

$$+\frac{1}{2} \quad 2 \quad {}_2$$

$$p_a \qquad \rho V \qquad = p_\infty + \_\rho V_2 \tag{2.14}$$

2 Which gives

$$p_b - p_a = \frac{1}{2}\rho(V_1^2 - V_2^2) = \rho V\,(V_1 - V_2) \tag{2.15}$$

$$V = \frac{1}{2}(V_1 + V_2) \tag{2.16}$$

The power extracted by the disc

$$P = FV = \rho A V^2(V_1 - V_2) = \frac{1}{4}\rho A(V_1^2 - V_2^2)(V_1 + V_2) \tag{2.17}$$

The maximum power that can be extracted at a given wind speed V_1

$$P_{max} = \frac{8}{27}\rho A V_1^3 \tag{2.18}$$

The maximum available power

$$P_{avail} = \frac{1}{2}\rho A V_1^3 \tag{2.19}$$

By dividing the power extracted by the disc with the maximum available power, the power coefficient that show the maximum possible efficiency of an ideal frictionless wind turbine. P_{max} divided with P_{avail} will give the highest efficiency of a wind turbine, which is called ideal Betz number ($C_{p,max}$) and is 0.593. A wind turbine can therefore never take out more energy from wind than 59.3 per cent of the potential energy in wind (White, 2011). This happens because the wind after the turbine will have a slower speed then the wind before the turbine.

2.4 Batteries

The first boat that used batteries for propulsion was lunched at 1838 in St. Petersburg, Russia. It was developed by Moritz Hermann von Jacobi for Tsar Nicholas I. It had zinc batteries that weighed more than 180 kg and could travel at a speed just below one and a half knot. Jacobi continued his research and one year later the boat could reach almost the double speed thanks to better batteries (The Engineering and Technology History Wiki, 2014). This boat was only 8.5 meters and had room for 14 passengers. The problem with this ship was that the fumes, caused by the batteries, were dangerous for the passengers and crew (Swanson, 2015). This project was therefore abandoned. By the end of the 19th century electric boats dominated the market for small boats. But the internal combustion engine took over the market in 1920 and batteries, as a propulsive force, was forgotten (The Engineering and Technology History Wiki, 2014). Batteries have recently made a comeback on board ships, both as primary source on fully electric ships and as an extra source of power on hybrid ships, that primarily uses combustion engines and can use batteries as an extra source of energy (Swanson, 2015).

Batteries can be used in two different ways on board a ship. One way is to have smaller combustion engines on board and having these engines always running at optimum load. This means that when the ship is steaming at slow speed, some of the engine power are used to charge the batteries for later use. Then when the ship is at full speed, the batteries are used to relive the engines and keep the specific fuel oil consumption down and therefore the ship's total fuel consumption is kept to a minimum (Nikolajsen, 2014).

The other way is to have the whole ship only running on the power of batteries and making the ship a zero-emission ship by having no combustion engines and recharging its batteries by plug-in or utilizing forces of nature as wind, waves or solar. In this way the ship has no direct pollution impact (Nikolajsen, 2014).

There are two different main types of batteries, primary cells and secondary cells, where the primary cells are not rechargeable and secondary cells are rechargeable (Burrows, Holman, Parsons, Pilling & Price, 2009). Primary cells are not used on board ships as a propulsive force and will therefore not be discussed any further in this report. The most commonly used secondary cells are made of lead-acid, which are used in cars, and lithium-ion (LiOn), which are used in everyday things such as cellphones, laptops and cordless power tools (Burrows et al., 2009). Batteries use electrochemistry, where there is an anode and a cathode that electrons travel between. A lithium-ion battery usually consists of lithium cobalt oxide (LiCoO2) as cathode, graphite as anode, copper as anode current collector and aluminum as cathode current collector. In between the anode and the cathode, lithium-ion batteries have a separator made of a polymeric membrane and liquid electrolyte, that consist of lithium salts (Burrows et al., 2009).

The electrolyte acts as a conductive pathway for the cations to be able to go from the positive electrodes to the negative during discharge. The reason why lithium is so commonly used in batteries is because it is the lightest metal in the periodic table, and therefore a lighter battery will not be possible to create in the regular way batteries are made today (Burrows et al., 2009).

In the shipping industry, focus have mainly been based on Li-ion cells with cathodes made of nickel manganese cobalt oxide (LiNiMnCoO2) or iron-phosphate (FeO_4P) (DNV-GL, 2015). Both of these represent a good balance between safety, energy, power density, cycle life and cost. DNV-GL (2015) also expect the cost of battery systems to decline in the near future.

There are several ships today that are using batteries as its primary source of power. Two of these ships are Ampere and Movitz and one ship that is still under development, ReVolt (DNV-GL, 2015).

The first electric car and passenger ferry in the world was Ampere that entered into service at early 2015. Ampere was built by Fjellstrand in conjunction with Siemens because the concession license for the ferry line between Lavik and Oppedal in the

Sognefjord expired in 2015 and the Norwegian ministry wanted to use ships with a low enviromental impact and Fjellstrand's idea won the contract (Ship-technology, 2016).

Ampere is 80 meters long and travels across the fjord 34 times per day at a speed around 10 knots with two electric motors, each with an output of 450 kW (Martini, 2016). Both engines are powered by ten-ton lithium-ion batteries that have a combined capacity of 1'000 kWh, which is enough to power the two engines for a little more than one hour and then they need to be recharged. One problem was the power grid in the area. The power grid was to weak to be able to recharge the batteries during the short time that the ferry was at dock without taking all the available power in the area. This problem was solved by having a set of batteries at the dock that is recharged slowly by the medium voltage grid between the ferries arrivals and when the ferry arrives. When the ferry arrive it is recharged from the battery buffer at the dock without effecting the power grid in the area (Martini, 2016). The power in the area is generated exclusively from hydroelectric plants making it a zero emission ship both directly and indirectly (Ship-technology, 2016).

ReVolt is a project in Norway that is under development to use only batteries as its energy source for propulsion. The advantages, according to DNV-GL (2015) with ReVolt is that it has no direct emissions, high efficiency of 97%, low maintenance, low OPEX and low charge rate, which means that the batteries on ReVolt will last longer, approximately 15 years. The CAPEX will be around the same as a conventional diesel-powered ship, 10 million US dollars, and according to DNV-GL (2015) the lifetime cost will be around 34 million US dollars lower in 30 years time compared with conventional diesel-powered ship. This is because batteries require almost no maintenance and therefore shippers can save money on crewing. The plan for ReVolt is that it will have no onboard crew (Adams, 2014).

ReVolt require around 2300 kWh at average weather and 5500 kWh when it is a bad weather at its cruising speed, 6 knots (Tvete, 2014a). The low speed makes the ship resistance go down greatly (MAN Diesel and Turbo, 2011) and it will only be at 120 kW at the intended route. ReVolt has batteries with a capacity of 5422 kWh and a deadweight of 1250 metric tonnes. It has a cruising range of 100 nm when the batteries are fully charged (Tvete, 2014b).

Sweden has also made its own fully electric ferry, E/S Movitz. It is a ferry that operates in Stockholms center between Solna Strand and Gamla Stan, it was lunched in August 2014 (Sundström, 2014). It is a small ferry, 23 meters long and 4 meters wide, and has two electric engines with a power of 125 kW each, but Movitz only needs 90 kW to make its cruising speed of 9 knots. Movitz gets its power from batteries made of nickel-metal-hydrid (NiMH) which have a capacity of 180 kWh (Green City Ferries, 2014). These batteries can be fully charged in ten minutes when the ferry is at the dock. Instead of using diesel engines, that would consume around 50 cubic meters of fuel each year, it saves the environment around 130 ton carbon dioxide, 1.5 ton nitrogen oxide and 80 kilos of particles (Echandia Marine, 2014).

2.5 Diesel-electric

A diesel-electric system on a ship often consists of gen-sets, which is a diesel engine driving an alternator, main switchboards, frequency converters or variable speed drives, electric propulsion motors and a propeller (MAN Diesel and Turbo, 2016). The several steps between the generator and the propulsion motor creates heat that needs to be transferred away from the components. The generator and the propulsion motor are the biggest sources of heat loss, but all together the heat loss is equal to an efficiency loss of, according to MAN Diesel and Turbo (2016), 7.7 - 9.7 per cent. This efficiency loss can be compared to the shaft efficiency that, according to MAN Diesel and Turbo (2011), often is about 99 per cent. The advantage with diesel-electric, that are relevant for this report, are the adaptation possibilities (MAN Diesel and Turbo, 2016). They will increase the efficiency of the system by being able to run the engines at an efficient load and the propeller can be driven at its designed rpm (revolutions per minute), which increases the propeller efficiency and such the diesel-electric system as well. There are several other advantages as well, but none of them being relevant to this report.

3 Methods

To answer the questions set up in the degree project, a case study in MATLAB has been performed. In MATLAB the authors modeled a vessel to install the wind propulsion systems on and perform the case study upon. A literature study has not been performed but in order to validate our own models data has been gathered from scientific articles.

In order to get a good assumption of the power that can be provided by the different wind propulsion systems that are examined in the case study, articles providing good models of the systems have been read. Equations from Traut et al. (2014), Allenström et al. (2012) and Leloup et al. (2014), explained in previous section, has been used to get good models that show the power provided. However, the authors have only used one set condition. To get a better view of how the systems perform over time, weather data must be gathered and evaluated. Nevertheless, this is not in the scope of this degree project. Instead averaged data from Carlson & Nilsson (2014) has been used.

3.1 Build up of the ship in MATLAB

The scripts used in the modeling was given to the authors by Francesco Baldi, a PhD student at Chalmers departement of Shipping and Marine Technology, and rewritten by the authors to match their purpose. The mathematical model of the vessel is ideal, meaning that it operates in ideal conditions. Wind does not affect the vessel resistance and calculations are done using calm water resistance. The MATLAB script can be studied further in the appendix.

The aim of this degree project is to present a model of a vessel that is likely to operate on long routes so that the time of potential favorable winds would increase and such the potential for fuel savings. The weather has not be investigated and analyzed, instead data from Carlson & Nilsson (2014) has been used. Their average wind velocities on the specific route between New York and Amsterdam were used since it provides good potential for utilizing the wind that is according to Carlson & Nilsson (2014), often from Southwest to Northeast and between 6.2 and 10.8 meters per second.

When considering a diesel-electric system for powering of the vessel propulsion there were two main factors involved. One being that a diesel-electric system is highly adaptable for different operating conditions, which in this case is the varying power produced by the wind propulsion systems. The other factor is that the authors wanted to utilize batteries for propulsion in their model, and the easiest way of doing that is to have a diesel-electric system.

Before the values received from MATLAB were put into the equations from Traut et al. (2014), Allenström et al. (2012) and Leloup et al. (2014), the authors validated their models by testing the given equations with the published values from respective author.

This in order to see if the equations gave realistic values as well as if they were reliable depending on different input values.

3.1.1 Vessel dimensions

The vessel chosen for this model is of a typical Panamax tanker. The input values for the ship are made up, but MAN´s publication "Propulsion trends in tankers" (2013) was used as a reference to what dimensions a typical Panamax tanker has.

Table 3.1: Vessel dimensions

Vessel speed	14.5 Knots
Draft	12.2 m
Lengt at water line (LWL)	225 m
Width	32.26
Block coefficient	0.7953
Displacement	75’000 tonnes

3.1.2 Engines

The thought process of choosing engines for this model has not been extensive, the power needed by the ship was the most deciding factor. For the case study it was decided to have four engines, this for adaptation possibilities in relation to the power gained from the wind and the batteries. The ship of which this project is basing the study upon need 7200 kW to cruise at a speed of 14.5 knots. The needed power divided by four gives the power for each engine i.e 1800 kW. However, the engines should not be operated at maximum continuous rating (MCR) at cruise speed so an engine margin and a light running margin of 20 per cent in total is added (MAN Diesel and Turbo, 2011). Each engine will then need to provide 2250 kW.

To make the engines adapt with the wind systems, intervals of where they should start and stop was added. The intervals are;

0 kw ≤ One engine ≤ 2250 kW

2250 kw < Two engines ≤ 4500 kW

4500 kw < Three engines ≤ 6750 kW

6750 kw < Four engines ≤ 9000 kW

The authors implemented the efficiency disadvantage of the diesel-electric drive as described by MAN Diesel and Turbo (2016). This was done by lowering the efficiency of the η_s (Shaft efficiency) by 10 per cent by multiplying η_s with 0.9. The shaft efficiency is how much frictional losses occur in the shaft, which is very low on ordinary shafts with bearings according to Man Diesel and Turbo (2011). The chosen engine for this model is shown in table 3.2.[1]

Table 3.2: Wärtsilä 32 generating set, 6L32 with 450 kW/cyl

Cylinder bore	320 mm
Generator voltage	0.4 - 13.8 kV
Piston stroke	400 mm
Generator efficiency	0.95 - 0.97
Cylinder output	450 kW/cyl
Fuel specification	MDO
Speed	750 rpm at 50 Hz
Mean effective pressure	28.9 bar
700 cSt/50°C	7200 sR1/100°C
Piston speed	9.6, 10.0 m/s
SFOC	174 g/kWh at ISO conditions

3.1.3 Flettner rotor

In the Flettner rotor model it is assumed that the apparent wind is equal to the true wind speed, which means that the apparent wind is directly perpendicular to the vessel course. This is almost ideal and is done for simplification.

Table 3.3: Values of the Flettner rotor

Area of the rotor	400 m^2
Air density	1.225 kg/m^3
Lift coefficient	12.5
Drag coefficient	0.2
Moment coefficient	0.2
Spin ratio	3.5

3.1.4 Kite

The equations for the kite is explained in chapter two, therefore, no further description is presented here. However, realistic values for the kite dimensions were needed to be chosen.

A static kite was chosen to be used in the simulation. This is because each operational condition is static since the input values are not influenced by anything.

[1] Values are taken from http://www.wartsila.com/products/marine-oil-gas/engines-generatingsets/generating-sets/wartsila-genset-20

Table 3.4: Values of the kite

Area of the kite	640 m^2
Air density	1.225 kg/m^3
Lift coefficient	1
Drag coefficient	0.286
Spin ratio	3.5
Length of tether line, R	300

3.1.5 Wind turbine

The wind turbine model used in the simulation builds on equations from Royal Academy of Engineering (n.d.) and Massachusetts Institute of Technology (Kalmikov, & Dykes, n.d.). Our model is simplified and the power that the wind turbine produces is used as electric power to charge the batteries and to directly unload the main engines via the electrical grid. The tipping force is also included in the power given by the wind turbine to unload the needed propulsion of the engine.

Table 3.5: Values of the wind turbine

Radius (r)	20m
Swept area (A)	$\pi * r^2 \rightarrow 1256\ m^2$
Air density (ρ)	1.225 kg/m^3
Turbine efficiency, C_P	0.4

3.2 xyExtract Graph Digitizer

xyExtract is a software that is used to extract data from a 2D graph contained in a graphic file. The program was used to get the values of our engine consumption in to a matrix. By Fransesco Baldi at Chalmers two graphs was given. One was the graph of an engine's specific fuel oil consumption at fixed speed and the other one showed an engine's specific fuel oil consumption at variable speed. These two graphs were put into xyExtract in order to obtain values. In xyExtract you specify X min, X max, Y min and Y max and then the user put dots where the user want the values from. From this program the values for the engine model are obtained in a text file. These text files were then loaded in MATLAB at our engine model to see how our engines specific fuel oil consumption change at different power outputs. The files that were used from xyExtract were "SFOC_constant_speed.txt" and "Load_speed_ratio.txt". Some values from the variable speed were also put directly in the MATLAB code under the "Matrix.m" script.

4 Results and Analysis

4.1 Validation of numerical models

To validate the numerical models of this report, the values from Traut et al. (2014) and Allenström et al. (2012) will be compered with this reports values for validation.

4.1.1 Flettner rotor

Allenström et al. (2012) show a power reduction between 31-79 per cent using their 120 rpm rotor, 416 m^2 rotor area and with a ship speed between 12-16 knots and a true wind speed between 6-15 m/s. The total power required at 16 knots is 12 MW. They include angles in their calculations and their results are based on four rotors.

The report from Traut et al. (2014) show a power reduction span between 19.3-37.3 per cent but have spatical power spikes up to 80 per cent. Their data is averaged over time and the wind data is gathered from specific routes. The total power required for the ship is 1000 kW at slow steaming.

The values of this report models are in line with the values from Traut et al. (2014) and Allenström et al. (2012). The Flettner rotor provide a power reduction between 20-66 per cent, values taken from tables 4.2-4.7. The rotor has the size of 400 m^2 which is slightly smaller than those of Allenström et al. (2012).

As seen above the results from the examined reports and this project are in line with each other. The biggest difference is the angles. Since their results include angles and apparent speeds, they get lower results than those of this project. The apparent wind speeds of this project is the same as the true wind speeds.

4.1.2 Kite

Allenström et al. (2012) show a power reduction between 8-58 per cent at a ship speed between 12-16 knots and wind speed between 9-15 m/s. The total power needed for this condition is 10 MW.

The values from Traut et al. (2014) show an average power reduction of 12.7-46 per cent with 1000 kW of total needed power at slow steaming. Spatical peaks of about 2.5 MW is shown, which is 250 per cent of the total needed power at slow steaming.

According to Brabeck (2008), their system can reduce the fuel consumption by 10-35 per cent and spatical moments of 50 per cent with ideal winds. The calculated values that was gathered from the authors MATLAB model, show a power reduction between 10-20 per cent. This power reduction is low compared with the examined reports. This is however because the kite model of this project is static and the examined reports have kites, which are of the crosswind type.

4.1.3 Wind turbine

The values from the report by (Carlson & Nilsson, 2015) show fuel savings between 0-16 per cent at a total power requirement at 12.24 MW. The authors values from MATLAB show a power reduction between 11-31 per cent.

4.2 Batteries

As found in the literature several ships have batteries as a main source of energy for propulsion. But the distances that can be traveled is limited because of the low power density.

However, if the winds would be such that the engines are relieved of 1.5 MW, three engines would need too run, but on low load. This will increase the specific fuel oil consumption (SFOC). To decrease the SFOC, batteries can be used to provide power so that only two engines are needed. Calculations, made by the authors, show that if three engines are running and the wind provides 1.5 MW of propulsion power.

$$7346 - 1500 = 5846 \rightarrow 5846 - (2700 * 2) = 446. \tag{4.1}$$

This means that the batteries would only need to provide 446 kW, and by using the Ampere batteries once again, the batteries would only need to weigh

$$446 * 24 * 10/1000 \approx 107 \tag{4.2}$$

tons to provide the engine with 446 kw for 24 hours which is a much more reasonable way of using batteries for longer distances.

The power that batteries can give in relation to the volume, the 40 foot battery containers, which Corvus Energy provides, were used. According to Corvus energy (2016) one 40 foot container, which has the volume of 76.3 cubic meters, can provide about 1365 kWh. This means that they have the power to volume ratio of 17.9 kWh per cubic meter. The volume needed to provide 1 MW for 24 hours would then be 1341 cubic meters.

4.3 Values from MATLAB

In this chapter the values from the MATLAB model are presented in the tables.

4.3.1 Tables

Table 4.1: Power provided kW by the different technologies at a different true wind speeds

	Wind turbine	Flettner	Kite
12 m/s	2269	3046	900
11 m/s	1937	2580	798
10 m/s	1639	2150	702
9 m/s	1373	1755	611
8 m/s	1138	1398	528
7 m/s	931	1079	450
6 m/s	751	799	378
5 m/s	595	559	313

Table 4.2: Power kW required by the Engines at 14.5 knots ship speed and 12 m/s true wind speed with different wind systems

	P_e (without wind)	P_e (with wind)	P_t	P_d	P_b
No wind assistance	4357	4357	3880	6538	7346
Wind turbine	4357	2088	1860	3117	3502
Flettner rotor	4357	1311	1168	2105	2366
Kite	4357	3457	3079	5104	5735

Table 4.3: Power kW required by the Engines at 14.5 knots ship speed and 11 m/s true wind speed with different wind systems

	P_e (without wind)	P_e (with wind)	P_t	P_d	P_b
No wind assistance	4357	4357	3880	6538	7346
Wind turbine	4357	2421	2156	3576	4018
Flettner rotor	4357	1777	1583	2700	3034
Kite	4357	3559	3170	5263	5913

Table 4.4: Power kW required by the Engines at 14.5 knots ship speed and 10 m/s true wind speed with different wind systems

	P_e (without wind)	P_e (with wind)	P_t	P_d	P_b
No wind assistance	4357	4357	3880	6538	7346
Wind turbine	4357	2719	2421	4001	4496
Flettner rotor	4357	2208	1966	3280	3685

Kite	4357	3656	3256	5413	6082

Table 4.5: Power kW required by the Engine at 14.5 knots ship speed and 9 m/s true wind speed with different wind systems

	P_e (without wind)	P_e (with wind)	P_t	P_d	P_b
No wind assistance	4357	4357	3880	6538	7346
Wind turbine	4357	2984	2658	4390	4933
Flettner rotor	4357	2602	2318	3834	4308
Kite	4357	3746	3336	5554	6240

Table 4.6: Power kW required by the Engines at 14.5 knots ship speed and 8 m/s true wind speed with different wind systems

	P_e (without wind)	P_e (with wind)	P_t	P_d	P_b
No wind assistance	4357	4357	3880	6538	7346
Wind turbine	4357	3220	2868	4742	5328
Flettner rotor	4357	2960	2636	4354	4892
Kite	4357	3830	3411	5686	6389

Table 4.7: Power kW required by the Engines at 14.5 knots ship speed and 7 m/s true wind speed with different wind systems

	P_e (without wind)	P_e (with wind)	P_t	P_d	P_b
No wind assistance	4357	4357	3880	6538	7346
Wind turbine	4357	3426	3052	5057	5682
Flettner rotor	4357	3279	2920	4832	5429
Kite	4357	3907	3480	5810	6528

Table 4.8: Power kW required by the Engine at 14.5 knots ship speed and 6 m/s true wind speed with different wind systems

	P_e (without wind)	P_e (with wind)	P_t	P_d	P_b
No wind assistance	4357	4357	3880	6538	7346
Wind turbine	4357	3606	3212	5336	5995
Flettner rotor	4357	3559	3170	5261	5912
Kite	4357	3979	3544	5924	6656

Table 4.9: Power kW required by the Engine at 14.5 knots ship speed and 5 m/s true wind speed with different wind systems

	P_e (without wind)	P_e (with wind)	P_t	P_d	P_b
No wind assistance	4357	4357	3880	6538	7346
Wind turbine	4357	3762	3350	5579	6269

Flettner rotor	4357	3798	3383	5637	6334
Kite	4357	4044	3602	6029	6774

Table 4.10: Specific fuel oil consumption (g/kWh) at different true wind speeds and with a ship speed of 14.5 knots

	No wind assistance	Wind turbine	Flettner rotor	Kite
12 m/s	176.6	177.31	174.12	176.97
11 m/s	176.6	180.58	173.34	178.8
10 m/s	176.6	195.33	176.97	182.1
9 m/s	176.6	175.33	191.98	185.9
8 m/s	176.6	176.96	174.67	190.1
7 m/s	176.6	176.92	176.83	192.8
6 m/s	176.6	180.32	178.75	193.9
5 m/s	176.6	186.69	188.49	176.91

Table 4.11: How much fuel the engines consumes each hour kg/h at different true wind speeds and with a ship speed of 14.5 knots

	No wind assistance	Wind turbine	Flettner rotor	Kite
12 m/s	1297	621	412	1015
11 m/s	1297	726	526	1057
10 m/s	1297	878	652	1108
9 m/s	1297	865	827	1160
8 m/s	1297	943	854	1215
7 m/s	1297	1005	960	1259
6 m/s	1297	1081	1057	1291
5 m/s	1297	1170	1194	1198

Table 4.12: How much money the ship can save each day at 14.5 knots with a MDO price of 425.33 US-Dollar per metric ton with a changing wind speed

	Wind turbine	Flettner rotor	Kite
12 m/s	6904	9038	2882
11 m/s	5836	7874	2452
10 m/s	4278	6585	1936
9 m/s	4414	4801	1398
8 m/s	3618	4521	844
7 m/s	2981	3443	396
6 m/s	2207	2456	69
5 m/s	1297	1056	1010

4.3.2 Comments on tables

Table 4.1 show the effect produced by the individual systems at changing true wind speeds, which is the same as apparent wind speed in this project.

Tables 4.2-4.9 show the effects on the engine system when using either a Flettner rotor, kite or wind turbine. In all tables the ship has the same speed, 14.5 knots but with each table the true wind speed changes by 1 m/s.

In table 4.10 the specific fuel oil consumption with different wind systems installed and changing true wind speeds is presented. The big drops in SFOC is because of an another engine is started.

Table 4.11 show the amount of fuel spent by the engines in kilograms per hour. It has a clear trend of increased fuel consumption with lower wind speeds.

Table 4.12 show the money that can be saved at different wind speeds and wind systems. The price for the fuel that this table is based on is 425.33 US-Dollar per metric ton.

There are clear trends in all tables. The power reduction decreases with lower wind speeds, the fuel consumption increases with increased power requirements and the money saved is affected by this. There are however some trend breaking points in the tables and those are the interval of 10-9 m/s for the wind turbine, 9-8 m/s for the Flettner rotor and 6-5 m/s for the kite. These are all points where an extra engine is starting. The reason that they are starting is that the required power raises above 2250, 4500 and 6750 kW respectively. The easiest way to locate points where a engine starts or stops is to look at table 4.10 and find an interval where a sudden drop of the SFOC occurs.

5 Discussion

5.1 Method discussion

The choice to use MATLAB as a simulator of the ship has proven useful. With MATLAB it was easy to see how the engine system will react when affected by the wind propulsion systems. Complementing this with a CFD would have been useful, but time and knowledge by the authors were limited. A literature study on the subject would have been hard since the data on how the engine systems react to the wind is scarce. A case study was the better choice but it can still be improved. However, to model the wind systems was more complicated than expected by the authors and are thus not at their full potential. As the wind propulsor systems are modeled in MATLAB, a better way of retrieving more accurate values could be to use values from articles as effect inputs only.

5.2 Reliability and Validity

The reliability issue of this report may lay in that most of the fact found in this subject were from companies, that are impartial. But by complementing the companies information with the MATLAB model and other similar reports, the authors could get a good view and analyze the gathered data. With the help of all the gathered information, the numbers in this report could be validated. Some issues with the validation of the numbers were that all the reports found had a wide range of power that the wind systems could deliver under different conditions. Also the MATLAB model, made for this report, does not take in account for the extra air resistance or the waves created by the wind. Those two factors would cover a whole report in them self.

A person with more knowledge and experience on wind propulsors, multivariable calculus, liner algebra and CFD would been able to increase the reliability and validity of this report.

5.3 Discussion on results

A lot of the information gathered about the efficiency and performance of the systems is from companies, such as Skysails and Enercon. The authors are critical to the information, which were obtained from these companies, as it is in these companies own best interest to make their own systems seem better than any other companies. Instead of relying on their information entirely, their information were used as guidance. The values in themselves are unnecessary to discuss because of the different conditions surrounding the models and their installations.

5.3.1 Validation of Flettner rotor

The values that were used for the validation of the Flettner rotor model was taken from both Allenström et al. (2012) and Traut et al. (2014). To validate the model, their intervals of achieved power reduction was compared with this reports power reduction. The results show that the numerical model show a power reduction that is in line with theirs. However, their models include wind directions, which this report do not, this means that there will be a difference because of the different apparent wind speeds and drag forces. The angles used in this report are the ideal angles which means that all the power provided by the Flettner rotor is used for propulsion.

An exact comparison is hard to achive due to the operating conditions surrounding the different installations values varies alot, such as deadweight, wind speed, ship speed, wind direction etc.

As the model is built, all the forces are directed backwards in the ship direction. This will give a fault in the values but the most important fact still remains and works, which is that the power output is largely related to the apparent wind.

5.3.2 Validation of Kite

The values that were used for the validation of the kite model was also taken from Allenström et al. (2012) and Traut et al. (2014). The gathered values from their results that are presented in section 4.1.2 are in line with the values from this report.

5.3.3 Validation of Wind Turbine

To do a validation of the wind turbine model, values from Carlson & Nilsson (2014) were compered to the authors MATLAB values and showed that the differences between the two reports were high, but in this report the values are taken from ideal conditions while Carlson & Nilsson (2014) values are calculated for a specific route. Even though the values differ, the values in this report are still reliable when looked at the set conditions.

5.4 Choice of ship

A Flettner rotor require deck space for installation, as well as the height it has creates limitations on what ships and where on ships it can be installed. To install a Flettner rotor on a container ship would create great challenges with safety and space since there is very little space left to utilize a Flettner rotor, both in terms of wind and deck area, but a kite could be installed since it does not need a lot of space. But for this report, a ship on which all three different systems could be installed. The safety reason being that in port the loading and unloading of the containers would create an extra obstacle for the crane operators to operate around. But a tanker would have the needed deck area to install a Flettner rotor, if it is large enough.

The other aspect considered when choosing a ship was the route and average wind on the selected route that the ship would likely operate within. Several simplifications on the weather were made, as the model does not take those into consideration. The model do not give a true picture on how they would behave in the reality. This is however not a deciding factor for the conclusion of this report. The model's values suggests, what are also shown in the literature, that it is sufficient for this case.

The reason for choosing diesel-electric is the good adaptation possibilities of operating conditions, which in turn means good efficiency of the engines. This is because the engines will be dimensioned in such a way that they can be used within the service load that according to MAN Diesel and Turbo (2016) is about 85 per cent. But the down side to diesel-electric drive is the electric efficiency between the generator and the propeller motor. Between these points there are a loss of 10 per cent in efficiency (MAN Diesel and Turbo, 2016). But the main reason to choose to have diesel-electric engines is to by able to use the energy stored in batteries in a simple way.

As stated above the reason for choosing diesel-electric drive was so that the efficiency of the engines could be kept and use the wind as a propulsion source at the same time. One could also choose a big engine with a electronic fuel system. This allows for adjusted injection timing, which can help achieve the optimum specific fuel oil consumption at lower loads. This is done by timing the fuel injection so that the top pressure is achieved at any load.

With the results from how much power that can be utilized from wind, dimensioning of the systems is easier. The engines will not be changed because of the simple fact that a ship need redundancy for times when the winds are too weak. Wind systems can not replace engines because of uncertainty of the wind.

The values provided by the MATLAB model can be discussed. Even if the results were tried to make as realistic as possible, there are several factors that are not included in the equations. Such as the increased resistance from the lateral forces and the interactions between the different wind propulsion systems at certain wind conditions.

The possibility for storage of the wind energy is limited. There was no way found by the authors to generate electricity with the help of a Flettner rotor. Kites can be used to generate electricity by having a pulsing kite. This is however not utilized on board vessels as of yet and the literature on the subject is scarce. Wind turbines can be used to generate electicity but no data of how much have been found.

Before looking at the SFOC tables, it should be mentioned that the lowest SFOC, which the selected engines can provide, is in the region of 174 g/kWh at ISO conditions. This report wanted to incorporate the usage of batteries along with the wind and as discussed in section 4.2, the batteries are a unreasonable source of energy for a whole overseas trip. There are several operating conditions where the SFOC consumption rises because of the wind power that is provided. The engines are relieved and are not required to provide the same amount of power which decreases the thermal efficiency.

Looking at the result tables, there are, as mentioned in section 4.4, three points where an extra engine is started because of the decrease in received wind power. These points show where the usage of batteries can be useful. Instead of starting another engine at, for example, the 10-9 m/s point for the wind turbine the batteries can be used as a buffer so that an extra engine does not need to be started. But at this point, just before another engine is started, the engines that are running are at their MCR. That means the SFOC is high, 20 g/kWh more than optimum, which can be seen in table 4.10. If the batteries is large enough they could provide the needed power to get the SFOC down to 175 g/kWh with two engines running, which will decrease the fuel consumption by approximately 244 kg/h. We only need to subtract the fuel consumption at 9 m/s by the fuel consumption at 12 m/s. The reason for subtracting with the value at 12 m/s is that table 4.2 shows the same results as if batteries would relive the engines with 994 kW from the values at table 4.5.

$$865 - 621 = 244 \tag{5.1}$$

So by relieving the engines by 22 per cent which is 994 kW, the ship can operate on only two engines and bring down the SFOC to a point where the fuel consumption is reduced by 244 kg/h.

If we take a look at table 4.10 and look at the kite between 6-5 m/s we see a big drop in SFOC. The reason for this is same as for the example above. To keep only two engines running with a good SFOC batteries would need to provide the difference between table 4.9 and 4.2 which is about 1 MW. The Flettner rotor point between 9-8 m/s in table 4.10 would require about 2 MW to keep the SFOC low and only two engines running, using the same method of counting as in section 4.2 this would require 2688 cubic meters of batteries to relive the engines for 24 hours. The volume is critical on board ships since the main portion of it must contain the cargo and is therefore the bigger factor in the battery limitations.

Another way of lowering the SFOC can be to increase the load by having the engines charging the batteries. This is however not possible in this MATLAB model since the engines start and stop only in relation to the required power, not SFOC.

6 Conclusion

6.1 Questions of the report

The power that can be acquired from the wind by using Flettner rotors, kites or wind turbines ranges from 528 kW to 1398 kW with a true wind speed of 8 m/s, depending on several factors, such as wind speed, wind direction, vessel particulars and the wind systems. The wind energy that can be utilized is therefore very various.

The results and theory indicate that the Flettner rotor can produce more effect than the other systems at the same conditions and being more versatile.

The batteries are best used to relive the engines at certain operating conditions when the wind increases or decreases the SFOC.

The fuel consumption can be reduced approximatly 82-443 kg/h at a true wind speed of 8 m/s. It is dependent on the wind, ship speed and ship dimensions. But the bunker consumption can also be reduced a lot by implementing the use of batteries in the right operation conditions.

6.2 Accuracy analysis

The authors of this report think that the computer models in MATLAB could have been done by someone with a deeper knowledge of multivariable calculus and linear algebra. But the conclusions are reliable since they are not opposed in any great regard by the literature.

6.3 Questions for further study

In further study, a more thorough study on the usage possibilities of batteries in conjunction with wind could be made. Also a deeper study of wind turbines on board and the balance by finding the optimal combination of yaw offset angle, rotor speed and pitch angle are a good question for a further study.

Bibliography

Adams, S. D. (2014). *ReVolt – next generation short sea shipping*. Retrieved from https://www.dnvgl.com/news/revolt-next-generation-short-sea-shipping7279

Allenström, B., Li, D., & Ran, H. (2012). *System impact when using wind, wave and solar energy* (Effship report nr 6, SSPA Report No.: RE4009542601-00-A). Gothenburg: Effship - a project for sustainable shipping.

Amanda44. (2015). *Points of sail for rotorships* [Online image]. Retrieved from https://commons.wikimedia.org/wiki/File:Points_of_sail_for_rotorships.svg

Argatov, I., & Silvennoinen, R. (2010). *Energy conversion efficiency of the pumping kite wind generator*. Renewable Energy, volume(35), 1052 - 1060. doi:10.1016/j.renene.2009.09.006

Ariadacapo. (2011). *Laminar boundary layer scheme* [Online image]. Retrieved from https://commons.wikimedia.org/wiki/File:Laminar_boundary_layer_scheme.svg

Bore Ltd. (2016). *Successful installation of second Norsepower Rotor Sail onboard M/V Estraden*. Retrieved 2016-04-10 from http://www.bore.eu /successful-installation-of-second-norsepower-rotor-sail-onboard-mv-estraden/

Bos, J. (2015, December 7). *Oil Prices: What's going on? - An Animation* [Video file]. Retrieved from https://www.youtube.com/watch?v=hyqp rG1pDzE

BP. (2015). *BP Technology Outlook*. Retrieved from http://www.bp.com/ content/dam/bp/pdf/technology/bp-technology-outlook.pdf

Brabeck, S. (2008). *Skysails - Using Wind Power Profitably*. Bremen, Germany: Skysails GmbH. Retrieved from http://www.ship-efficiency.org/onTEAM/pdf/Brabeck.pdf

Burrows, A., Holman, J., Parsons, A., Pilling, G. & Price, G. (2009). *Chemistry3: Introducing inorganic, organic and physical chemistry*. Oxford;New York;: Oxford University Press.

Carlson, O. & Nilsson, P. (2014). *Development and Demonstration of New Technology for the use of Wind Turbines on Ships*. Göteborg: Chalmers University of Technology.

Carlson, O. & Nilsson, P. (2015). *Wind Turbines on Ships*. Göteborg: Chalmers University of Technology.

Carter, R. (2012). Watercraft. In D.T. Potts (Ed.), *A companion to the archaeology of the ancient Near East* (pp. 347–354). Chichester, West Sussex: Wiley-Blackwell.

Craft, T., Jognson, N., & Launder, B. (2014). *Back to the Future? A Re-examination of the Aerodynamics of Flettner-Thom Rotors for Maritime Propulsion*. (Flow Turbulence Combust, volume 92, pp 413–427) doi:10.1007/s10494-013-9486-4

Corvus Energy. (2016) *Containerized Energy Storage System: 40' Container Configuration*. Retrieved from http://corvusenergy.com/containerized-energystorage-system/

DNV-GL. (2015). *In focus – the future is hybrid: a guide to use of batteries in shipping*. Retrieved from https://www.dnvgl.com/Images /DNV%20GL%20In%20Focus%20Battery_tc m8-24901.pdf

Echandia Marine. (2014). *The worlds first supercharged electric ferry*. Retrieved 2016, 10 February from http://www.echandiamarine.com/green-city-ferries.html

Education World Wind Energy Association. (2016, 10 February). *The world sets new wind installations record: 63,7 GW new capacity in 2015*. Retrieved from http://www.wwindea.org/the-world-sets-new-wind-installations-record637-gw-new-capacity-in-2015/

ENERCON. (2015). *Class renewal for the 'E-Ship 1'*. Retrieved from http://www.enercon.de/en/news/news-detail/cc_news/show/News/classrenewal-for-the-e-ship-1/

Energinet.dk. (2016, 15 January). *New record-breaking year for danish wind power*. Retrieved from http://energinet.dk/DA/El/Nyheder/Sider/Danskvindstroem-slaar-igen-rekord-42-procent.aspx

George Grantham Bain Service, Prints & Photographs Division, Library of Congress. (n.d.). *Buckau - FLATTNER ship*. [Online image]. LC-B2-6297-11. Retrieved from http://www.loc.gov/pictures/item/ggb2006013176/ Bibliography

Green City Ferries. (2014). *Movitz Världens första superladdade elfärja*. Retrieved 2016, 14 February from http://www.greencityferries.com/swedish/ boatfleet/movitz/

Hirsch, R., Bezdek, R. & Wendling, R. (2005). *Peaking of world oil production: Impacts, mitigation, & risk management*. Retrieved from http://www.netl.doe.gov/publications/others/pdf/Oil_Peaking_NETL.pdf

Hubbert, M. K. (1956). *Nuclear energy and the fossil fuels* (Shell Development Company, Publication Number 95). Retrieved from http://www.hubbertpeak.com/hubbert/1956/1956.pdf

IMO. (2015). *Third Greenhouse Gas Study 2014*. Retrieved from http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Documents/Third%20Greenhouse%20Gas%20Study/GHG3%20Executive%20Summary%20and%20Report.pdf

Ingles, D. & Denniss, R. (2010). *Running on empty? The peak oil debate*. Retrieved from http://library.uniteddiversity.coop/Energy/Peak_Oil/ Running_on_empty-The_peak_oil_debate.pdf

KaKstn (2010). *Cargo E-Ship 1, Emder Hafen, CN-03* [Online image]. Retrieved from https://commons.wikimedia.org/wiki/File:Cargo_EShip_1,_Emder_Hafen,_CN-03.jpg

Kalmikov, A. & Dykes, K. (n.d.). *Wind Power Fundamentals*. Retrieved from http://web.mit.edu/windenergy/windweek/Presentations/Wind%20Energy%20101.pdf

Katze, F. (2012). *Theseus-Quelle WesselsReederei* [Online image]. Retrieved from https://commons.wikimedia.org/wiki/File:Theseus-Quelle_WesselsReederei.jpg

Kim, J., & Park, C., (2010). *Wind power generation with a parawing on ships, a proposal*. Energy, volume(35), 1425-1432. doi:10.1016/j.energy.2009.11.027

Leloup, R., Roncin, K., Behrel, M., Bles, G., Leroux, J.-B., Jochum, C., and Parlier, Y. (2014). *A continuous and analytical modeling for kites as auxiliary propulsion devoted to merchant ships, including fuel saving estimation*. Renewable Energy, volume (86), 483-496. doi:10.1016/j.renene.2015.08.036

Lloyd's Register Marine. (2015). *Wind-powered shipping. Southhampton, UK: Lloyd's Register Group Limited*. Retrived from http://www.lr.org/en/marine/

Loyd. M.L. (1980). *Crosswind kite power (for large-scale wind power production)*. Journal of Energy, Vol. 4, No. 3, pages. 106-111. doi: 10.2514/3.48021 Luchsinger, R. (2013). Pumping

Cycle Kite Power. In Ahrens, U., Diehl, M., & Schmehl, R. (Ed.). (2013). *Airborne Wind Energy* (s. 47-64). Berlin Heidelberg: Springer-Verlag.

MAN Diesel and Turbo. (2011). *Basic Principles of Ship Propulsion*. Copenhagen SV, Denmark: MAN Diesel and Turbo

MAN Diesel and Turbo. (2013). *Propulsion trends in Tankers*. Copenhagen SV, Denmark: MAN Diesel and Turbo

MAN Diesel and Turbo. (2016). *Diesel electric Drives - A brief guideline how to engineer a diesel-electric propulsion system*. Copenhagen SV, Denmark: MAN Diesel and Turbo

Martini, F. (2016). *Setting a Course for Carbon-Free Shipping*. Retrieved from http://www.siemens.com/innovation/en/home/pictures-ofthe-future/mobility-and-motors/electromobility-electric-ferries.html

Nasdaq. (2016, February 23). *Crude Oil*. Retrieved from http://www.nasdaq.com/markets/crude-oil.aspx

Nikolajsen, C. (2014). *Scandlines Green Agenda*. Retrieved from https://www.nabu.de/imperia/md/content/nabude/verkehr/140619-nabuzero_emission_ferries-scandlines_nikolajsen.pdf

Noreng, Ø. (2012). *Peak oil – En ekonomisk analys* (Report to the Expert Group on Environmental Studies, 2012:2). Retrieved from http://www.ems.expertgrupp.se/Uploads/Documents/30-marsEMS2012_2.pdf

Petroff, A. & Yellin, T. (2015, November 23). What it costs to produce oil. *CNN*. Retrieved from http://money.cnn.com/interactive/economy/thecost-to-produce-a-barrel-of-oil/

Pearson, D. R.(2014). *The use of Flettner rotors in efficient ship design*. BMT Defence Services Ltd, UK

Prj1991 (2013). *Slipstream Theory* [Online image]. Retrieved from https://commons.wikimedia.org/wiki/File:Slipstream_Theory.jpg

Rdurkacz (2013). *Sketch of Magnus effect with streamlines and turbulent wake* [Online image]. Retrieved from https://commons.wikimedia.org/wiki /File:Sketch_of_Magnus_effect_with_streamlines_and_turbulent_wake.svg

Royal Academy of Engineering. (n.d.). *Wind Turbine Power Calculations* Bibliography

RWE npower renewables: Mechanical and Electrical Engineering Power Industry. Retrieved from http://www.raeng.org.uk/publications/other/23wind-turbine

Seifert, J. (2012). *A review of the Magnus effect in aeronautics*. Applied Energy, Volume(55), 17-45. Doi:10.1016/j.paerosci.2012.07.001

Ship-technology. (2016). *Ampere Electric-Powered Ferry, Norway*. Retrieved from http://www.ship-technology.com/projects/norled-zerocat-electricpowered-ferry/

Skysails GmbH. (n.d.). *Skysails Propulsion for Cargo Ships*. Retrieved 2016-04-10, from http://www.skysails.info/english/skysails-marine/skysailspropulsion-for-cargo-ships/

Skysails GmbH. (n.d.). *Power System*. Retrieved 2016-04-26, from http://www.skysails.info/english/power/power-system/

Sundström, A. (2014, April 28). Stockholm laddar för eldrivna båtar. *Dagens Nyheter*. Retrieved from http://www.dn.se/sthlm/stockholm-laddarfor-eldrivna-batar/

Swanson, W. (2015). *The Elco Story*. Retrieved from http://www.elcomotor yachts.com/history-of-elco.shtml

Teske, S., Sawyer, S. & Schäfer, O. (2015) *energy [r]evolution*. Retrieved from http://www.greenpeace.org/international/Global/international/publications/climate/2015/Energy-Revolution-2015-Full.pdf

The Engineering and Technology History Wiki. (2014). *Electric Boats*Retrieved from http://ethw.org/Electric_Boats

Tolgraven, P (2016, 18 April). *Citi: Därför kan oljepriset stiga*. Retrieved from http://www.affarsvarlden.se/ravaror/article3970774.ece

Traut, M., Gilbert, P., Walsh, C., Bows, A., Filippone, A., Stansby, P. & Wood, R., (2014). *Propulsive power contribution of a kite and a Flettner rotor on selected shipping routes*. (Applied Energy, Volume 113, 362-372). doi:10.1016/j.apenergy.2013.07.026

Tvete, H. A. (2014a). *DNV GL's research within Autonomous Systems: Nor-Shipping workshop: Professional Insight on Unmanned Ships*. Retrieved from http://www.unmanned-ship.org/munin/wpcontent/uploads/2015/06/MUNIN-Workshop-1-2-DNVGL-DNVGL%E2%80%99s-research-within-Autonomous-Systems.pdf

Tvete, H. A. (2014b). *THE NEXT REVOLT*. Retrieved from http://gcaptain.com/wp-content/uploads/2014/09/ReVolt-Details.pdf

Vidal, J. (2005, 21 April). The end of oil is closer than you think. *The Guardian*. Retrieved from https://www.theguardian.com/science/2005/apr/21/oilandpetrol.news

Watson, B. (2016, 13 February). Have we reached the tipping point for investing in renewable energy?. *The Guardian*. Retrieved from http://www.theguardian.com/sustainable-business/2016/feb/13/renewableenergy-investment-fossil-fuel-divestment-investor-summit-climate-change

White, F. M. (2011). *Fluid mechanics*. New York, NY: McGraw-Hill

A Appendix

A.1 Matlab code

In this section all of the codes, which were used in MATLAB to get the results, are shown. The main function, which calls all other functions, are called "Run.m". If the whole process was prepared properly, you will only need to put all the inputs values in the "Input.m" and then call "Run.m" to get all the values.

A.1.1 Run.m

```
clear all; clc;
%% No wind power format
        shortg ; run Input.m ;
        run MainPropulsion_No_wind.m ;
        A1 = ans.power ;
        A2 = ans.efficiency.bsfc_me ;
        A3 = ans.other.mfr_fuel ;
        A4 = 0 ;
%% Turbine format shortg ;
        run Input.m ; run
        W_Turbine.m ;
        run MainPropulsion_Turbine.m ;
        B1 = ans.power ;
        B2 = ans.efficiency.bsfc_me ;
        B3 = ans.other.mfr_fuel ;
        B4 = P_Wind ;
%% Rotor format shortg ; run Input.m ; run
        W_Flettner_rotor.m ; run
        MainPropulsion_Flettner.m ;
        C1 = ans.power ;
        C2 = ans.efficiency.bsfc_me ;
        C3 = ans.other.mfr_fuel ;
        C4 = P_Wind ;
%% Kite format shortg ; run
        Input.m ;
```

```
    run W_Kite.m ;
    run MainPropulsion_Kite.m ;
    D1 = ans.power ;
    D2 = ans.efficiency.bsfc_me ;
    D3 = ans.other.mfr_fuel ;
    D4 = P_Wind ;
%% Result
    Wind_Power = [ A4 B4 C4 D4 ]
    Result_Power = [
    A1.P_E_utansegel A1.P_E A1.P_T A1.P_D A1.P_B
    B1.P_E_utansegel B1.P_E B1.P_T B1.P_D B1.P_B
    C1.P_E_utansegel C1.P_E C1.P_T C1.P_D C1.P_B
    D1.P_E_utansegel D1.P_E D1.P_T D1.P_D D1.P_B
    ]
    Result_SFOC = [A2 B2 C2 D2] Result_Fuel = [A3
    B3 C3 D3] format longg ;
    Result_Saved_cost = −([B3 C3 D3] − A3) * 10^−3 *
    425.33 * 24 % saved money per day in dollar
```

A.1.2 Input.m

This is the file where all our input values are written.

```
% Ship design values (as a Panamax) are taken from
% http://marine.man.eu/docs/librariesprovider6/technical−
% papers/propulsion−trends−in−bulk−carriers.pdf?sfvrsn=16

% And engine values (Genset 32, 6L32, 50 Hz/750 rpm, % 500 kW/cyl, 4
engines * 2880 kW) from Wartsila.
% http://www.wartsila.com/products/marine−oil−gas/engines
% −generating−sets/generating−sets/wartsila−genset−20


%% Operational
% Ship speed [kn] operational.v = 14.5 ;

% True wind speed at 10 meters up [m/s] operational.tw = 13 ;

% Ship draft [m] operational.T = 12.2 ;

% Increased resistance due to fouling [−] operational.fouling = 0 ;

% Sea water temperature [degC] operational.T_SW = 10 ;

% Shaft generator power [kW] operational.P_SG = 0 ;



%% Design

% Ship length at water line [m]
```

```
%(page 16 propulsion trends bulk MAN) design.LWL= 225 ;

% Ship (design) block coefficient [−]
% (page 16 propulsion trends bulk MAN) design.CBdes = 0.7953 ;

% Ship width [m]
% (page 16 propulsion trends bulk MAN) design.B = 32.26 ;

% Ship (design) draft [m]
% (page 16 propulsion trends bulk MAN) design.Tdes = 12.2 ;

% Ship displacement [ton]
% (page 16 propulsion trends bulk MAN) design.DISPdes = 75000 ;

% Form factor [−]
% (if nothing else is specified, leave to 0) design.FA = −2 ;

% Propeller diameter [m]
% (taken from page 20 basic propulsion from MAN) design.DPROP = 7.2 ;

% Propeller pitch (design) [m]
% (page 20 basic propulsion MAN) design.Pdes = 5.04 ;

% Propeller area ration [−]
% (taken from page 18 basic propulsion from MAN) design.ARATIO = 0.75 ;

% Propeller, number of blades [−] design.Z = 4 ;

% Propeller type: 'FPP' or 'CPP' ; (our choose) design.PTYPE = 'FPP' ;

% Engines Maximum continuous rating [kW] included 15% sea % margin and 10%
engine margin at 90% SMCR 8100 kW from
% http://www.wartsila.com/products/marine−oil−gas/engines
% −generating−sets/generating−sets/wartsila−genset−20

% the power to drive all electric equipment onboard design.MCR_ME = 9000 ;

% Engine Maximum speed [rpm] (Wartsila 32 generating set) design.RPMmax_ME = 1000 ;
```

```
% Engine Minimum bsfc [g/kWh] (Wartsila 32 generating set) design.BSFCmin_ME = 174 ;

% Our ship type
% ( this script can only make calculatens for a tanker) design.SHIP_TYPE = 'Tanker' ;

%% Assumptions
% Our hull efficency assumptions.ETA_R = 1.035 ;

% Shaft efficiency − 10% because of losses when you
% use diesel electric engine set up assumptions.ETA_S = 0.99 − 0.10 ;
```

A.1.3 The four MainPropulsion files

This is the MATLAB file for MainPropulsion_Turbine.m, MainPropulsion_Flettner.m, MainPropulsion_Kite.m and MainPropulsion_No_wind.m. The all look the same and has the same function, the only thing that is different between them are that the P_wind section in the script changes depending if the script are to calculate the power given by the Flettner rotor, kite, wind turbine or neither of these.

In this script, MainPropulsion_No_wind.m, P_Wind is equal to 0, "P_Wind = 0".
In MainPropulsion_Turbine.m it says, instead of "P_Wind = 0", "run W_Turbine.m". In MainPropulsion_Flettner.m "run W_Flettner_rotor.m" and in MainPropulsion_Kite.m "run W_Kite.m".

```
function relevant_outputs = MainPropulsion(operational,design, assumptions,P_Wind) %
% This function is the main function of the propulsion module. It is
% used for the prediction of the required propulsion power for a % given ship at given
operational conditions.
%
% The model uses the HARVALD AND GULDHAMMER method for the prediction
% of the calm water resistance of the ship, inclusive of the thrust % deduction and wake fraction
coefficients.
%
% In addition, the model uses the WAGENINGEN B−SERIES for the % prediction of the
performance of the propeller given its design % inputs.
%
% The code needs two main inputs:
%
% OPERATIONAL variables: This input is to be provided in the form of a % structure with the following
elements:
% − operational.v:            Ship speed [kn]
% − operational.T:            Ship draft [m]
% − operational.fouling           Increased resistance due to fouling [−]
% − operational.T_SW           Sea water temperature [degC]
% − operational.P_SG           Shaft generator power [kW]
%
% DESIGN parameters: This input is to be provided in the form of a % structure with the following
elements:
% − design.LWL:            Ship length at water line [m]
% − design.CBdes:            Ship (design) block coefficient [−]
```

```
% –
design.B:                          Ship width [m]
% – design.Tdes:                       Ship (design) draft [m]
% – design.DISPdes: Ship displacement [ton]
% – design.Fa:                               Form factor [–] (if nothing else is specified,
% leave to 0)
% – design.DPROP                       Propeller diameter [m]
% – design.Pdes                           Propeller pitch (design) [m]
% – design.ARATIO                       Propeller area ration [–]
% – design.Z                                 Propeller, number of blades [–]
% – design.PTYPE                            Propeller type: 'FPP' or 'CPP' ;
% – design.MCR_ME                       Engine Maximum continuous rating [kW]
% – design.RPMmax_ME                Engine Maximum speed [rpm]
% – design.BSFCmin_ME                Engine Minimum bsfc [g/kWh]
%
% ASSUMPTIONS on efficiencies and other values:
% – assumptions.ETA_R                   Rotational efficiency                (1.035)
% – assumptions.ETA_S                   Shaft efficiency                     (0.99)
%
% NOTE: In its current state, the model is designed for predicting the
% power requirement for TANKERS. For operation with other ship types
% (e.g. containerships, RoRos, etc) modification to the code are % required.
%
%% Input file
% This file contains all the input values run Input.m ;

%% P_Wind
% This file contains the math for the power given by the wind
P_Wind = 0 ;

%% Reading general inputs
% Checking if there is any input for the rotational efficiency if isfield(assumptions,'ETA_R')
        ETA_R = assumptions.ETA_R ; else
        ETA_R = 1.035 ; end
% Checking if there is any input for the Shaft efficiency if isfield(assumptions,'ETA_S')
        ETA_S = assumptions.ETA_S ; else
      ETA_S = 0.99 ;
end
% Checking if the Shaft generator power has been given if
isfield(operational,'P_SG')
        P_SG = operational.P_SG ; else
      P_SG = 0 ;
end
```

```
%% Processing some inputs speed_ms = operational.v *
```

0.5144444 ;

```
%% Effective power (P_E) (effective Towing power) calm_water_resistance =
```

```
CalmWaterResistance(operational,design) ; relevant_outputs.power.P_E_utansegel =
```

```
calm_water_resistance * speed_ms ; relevant_outputs.power.P_E =
```

```
relevant_outputs.power.P_E_utansegel − P_Wind ;
```

```
relevant_outputs.power.P_E(relevant_outputs.power.P_E < 0) = 0 ;
```

```
%% Thrust power (P_T)
```

```
% (Thrust power delivered by the propeller to water) thrust_deduction =
```

```
ThrustDeduction(operational,design) ; wake_fraction = WakeFraction(operational,design) ;
```

```
relevant_outputs.efficiency.eta_hull = (1 − thrust_deduction) /
```

```
(1 − wake_fraction) ; relevant_outputs.power.P_T = relevant_outputs.power.P_E /
```

```
relevant_outputs.efficiency.eta_hull ;
```

```
%% Propeller power (P_D) (Power delivered to propeller) propeller_input.wake_fraction =
```

```
wake_fraction ; propeller_input.thrust = relevant_outputs.power.P_T / (speed_ms) /
```

```
(1 − thrust_deduction) ; propeller_output = Propeller(propeller_input,operational,design) ;
```

```
relevant_outputs.efficiency.eta_o = propeller_output.eta_o ; relevant_outputs.power.P_D =
```

```
relevant_outputs.power.P_T / relevant_outputs.efficiency.eta_o / ETA_R ;
```

```
%% Engine power output (P_B) (Brake power of main engine) relevant_outputs.power.P_B =
```

```
relevant_outputs.power.P_D / ETA_S + operational.P_SG ;
```

```
%% Engine fuel consumption (mfr) (kg/h) engine_input.P_B =
```

```
relevant_outputs.power.P_B ; engine_input.rpm = propeller_output.rpm ;
```

```
relevant_outputs.efficiency.bsfc_me = MainEngine
```

```
(engine_input,design) ;
```

```
relevant_outputs.other.mfr_fuel = relevant_outputs.power.P_B *
```

```
relevant_outputs.efficiency.bsfc_me * 1e−3 ;
```

```
%% Other relevant outputs relevant_outputs.other.thrust_deduction = thrust_deduction ;
```

```
relevant_outputs.other.wake_fraction = wake_fraction ;
```

```
relevant_outputs.other.propeller_speed = propeller_output.rpm ;
```

A.1.4 CalmWaterResistance.m

Calculates the calm water resistance of the vessel

```
function R_CW = CalmWaterResistance(operational,design)
%
% This function calculates the calm water resistance of a % ship given certain input
parameters.
%
% NOTE: In its current state, the code can only handle a
% TANKER vessel. Modifications in the code are required
% to handle different ship types
```

%
%

```
MODEL INPUT: The model accepts to input vectors:
% – operational variables (REQUIRED)
% – ship parameters (OPTIONAL)
%
% OPERATIONAL VARIABLES: This input is to be provided in % the form of a
structure with the following elements:
% – operational.v:                    Ship speed [kn]
% – operational.T:                    Ship draft [m]
% – operational.fouling                Increased resistance
%                    due to fouling [–]
% – operational.T_SW                    Sea water temperature [degC]
%
% PARAMETERS: This input is to be provided in the form of a % structure with the
following elements:
% – design.LWL:                    Ship length at water line [m]
% – design.CBdes:                    Ship (design) block coefficient [–]
% – design.B:                    Ship width [m]
% – design.Tdes:                    Ship (design) draft [m]
% – design.DISPdes: Ship displacement [ton]
% – design.Fa:                    Form factor [–] (if nothing else is
%                    specified, leave to 0)
% – design.SHIP_TYPE Ship type. For the moment it can be:
%                    'Tanker'
%                     'Containership'
%
%%% NOTE %%%
% This code is only valid for TANKERS % This can be
seen:
% – In the wake factor
% – In the thrust deduction factor
% – In the air resistance coefficient
%
%%% IN ADDITION
% For the Tanker, the C_R coefficient is calculated
% assumint prismatic coefficient 0.8
% For the Containership, the C_R coefficient is calculated
% assumint prismatic coefficient 0.7

% %%% STANDARD PARAMETERS
% L_WL = 178.9 ;
% CB = 0.7953 ;
```

```
% B =
32.2
;
% T =
10.98 ;
% disp = 50872 ;
% STD_parameters = [L_WL CB B T disp 0] ;

%% Reading ship parameters
LWL = design.LWL ; % Length between perpendiculars (m) CBdes = design.CBdes ; %
Block coefficient
```

```
B = design.B ; % Bredth (m)
Tdes = design.Tdes ; % Draught (m)
DISPdes = design.DISPdes ; % Displacement (ton)
FA = design.FA ; % Form factor
SHIP_TYPE = design.SHIP_TYPE ; % Ship type

%% Reading ship operational variables v_kn = operational.v ; % Ship speed (kn)
eps_fouling = operational.fouling ; % Fractional increase
% due to fouling (If fouling = 0.15, the resistance is
% increased by 15%)
T = operational.T ; % Draft if
isfield(operational,'T_SW')
        T_SW = operational.T_SW ; else
      T_SW = 25 ;
end

% Unit conversion, when necessary v = v_kn * 0.51444 ; % Ship
speed, kn −> m/s
% Constants g = 9.81 ; % Gravitational acceleration %%% Calculation of water
properties rho_SW = SeaWaterDensity(T_SW,34) ; % Density (kg/m3) % ni_SW
= ((43.4233 − 31.38 * rho_SW/1000) * (T_SW+20)^
% (1.72*rho_SW/1000−2.202) + 4.7478 − 5.779 * rho_SW/1000)
% * 1e−6 ; % (Pa)
mi_SW = SeaWaterViscosity(T_SW,'C',34,'ppt') ; Fn = v * (g *
LWL)^(−0.5) ; % Froude number

% Calculation of displacement and block coefficient for
% different draft
CB = 1 − (1 − CBdes) * (Tdes/T)^(1/3) ; % Updating the block
coefficient disp_ton = DISPdes * (CB/CBdes) * (T/Tdes) ;
% Updating the displacement
%
disp = disp_ton / rho_SW * 1e3 ; % Volume displacement
%%% Calculation of the wetted surface switch
SHIP_TYPE case 'Tanker'
              S = 0.99 * (disp/T + 1.9 * LWL * T) ; case 'Containership'
              S = 0.995 * (disp/T + 1.9 * LWL * T) ;
end
```

```
%%% Frictional resistance coefficient
Re = v * LWL * rho_SW / mi_SW ;
C_F = (0.075 / (log10(Re) − 2)^2) * (1 + eps_fouling) ;

%%% Incremental resistance coefficient
C_A = (0.5 * log10(disp) − 0.1 * log10(disp)^2) * 1e−3 ;

%%% Air Resistance coefficient
C_AA = 0.07 * 1e−3 ;

%%% Residual resistanced M =
LWL * disp^(−1/3) ; switch
SHIP_TYPE case 'Tanker'
        CR_45 = polyval([189331 −133987 36767 −4746.5
        281.61 −5.18],Fn) ;
        CR_5 = polyval([153906 −114943 33803 −4780 322.84 −7.67],Fn) ;
        C_R_diag = (CR_45 * (5 − M) + CR_5 * (M − 4.5)) /
        0.5 * 1e−3; % CR Equation dC_R_BT = 0.16 * (B/T − 2.5) * 1e−3 ; %
        Correction for deviation of the B/T factor from 2.5 dC_R_form = 0 ; % For
        now the form correction is equal to 0 dC_R_bulb = max(−0.4,−0.1−1.6*Fn)
        * 1e−3; % Bulbous bow correction
    case 'Containership'
        C_R_diag = polyval([81964 −69372 23700 −4017 339.1
        −10.91],Fn) * 1e−3 ; dC_R_bulb = (250 * Fn − 90) * C_R_diag / 100 ;
        % Bulbous bow correction dC_R_BT = 0.16 * (B/T − 2.5) * 1e−3 ;
        dC_R_form = 0 ; % For now the form correction is equal to 0
end

C_R = C_R_diag + dC_R_BT + dC_R_form + dC_R_bulb ;

% Total coefficient
C_tot = C_F + C_A + C_AA + C_R ;
% Corrected coefficient for matching results
C_tot = C_tot * 0.89 ;
% Total calm water resistance R_CW = C_tot / 2 * rho_SW * S *
v^2 * 10^−3;


end function[sea_water_density] = SeaWaterDensity(varargin)
```

```
%
% This function calculates sea water density given % its temperature and
salinity (if available).
%
% Only water temperature, in degrees Celsius, is required
% as input

if nargin == 1 temperature = varargin{1} ;
salinity = 0.033 ; else
    temperature = varargin{1} ; salinity = varargin{2} ;
end

    A= 8.23997e−1−4.0644e−3*temperature+7.6455e−5* temperature^2−...
8.3332e−10*temperature^3+5.4961e−12*temperature^4;

B=    −5.5078e−3+    9.7598e−5*temperature−    1.6218e−6*

temperature^2; C= 4.6106e−4;

for i = 1 : length(temperature) water_density = 999.842594 +
    6.793952e−2*temperature −...
        9.095290e−3*temperature^2+ 1.001685e−4...
        *temperature^3− 1.120083e−6*temperature^4+...
        6.536336e−9*temperature^5;

    sea_water_density(i) = water_density + A*salinity +
    B*salinity^1.5+C*salinity^2;

end

sea_water_density = sea_water_density' ;

end


function mu = SeaWaterViscosity(T,uT,S,uS)
     % SW_Viscosity                Dynamic viscosity of seawater
    %=================================================================
```

```
% USAGE: mu = SW_Viscosity(T,uT,S,uS)
%
% DESCRIPTION:
%                Dynamic viscosity of seawater at atmospheric pressure (0.1 MPa)
%                     using Eq. (22) given in [1] which best fit the data of [2], [3]
%                   and [4]. The pure water viscosity equation is a best fit to the
%         data of [5]. Values at temperature higher than the normal
% boiling temperature are calculated at the saturation pressure. %
% INPUT:
%    T = temperature
%    uT = temperature unit
%         'C' : [degree Celsius] (ITS−90)
%         'K' : [Kelvin]
%         'F' : [degree Fahrenheit]
%         'R' : [Rankine]
%    S = salinity
%    uS = salinity unit
%         'ppt': [g/kg] (reference−composition salinity)
%         'ppm': [mg/kg] (in parts per million)
%         'w' : [kg/kg] (mass fraction)
%         '%' : [kg/kg] (in parts per hundred)
%
%          Note: T and S must have the same dimensions
%
% OUTPUT:
%         mu = dynamic viscosity [kg/m−s]
%
%           Note: mu will have the same dimensions as T and S
%
% VALIDITY: 0 < T < 180 C and 0 < S < 150 g/kg;
%
% ACCURACY: 1.5%
%
% REVISION HISTORY:
% 2009−12−18: Mostafa H. Sharqawy (mhamed@mit.edu), MIT
%                − Initial version
% 2012−06−06: Karan H. Mistry (mistry@mit.edu), MIT
%                 − Allow T,S input in various units
%                  − Allow T,S to be matrices of any size
%
% DISCLAIMER:
```

```
%                       This software is provided "as is" without warranty of any kind.
%           See the file sw_copy.m for conditions of use and licence.
%
% REFERENCES:
%           [1] M. H. Sharqawy, J. H. Lienhard V, and S. M. Zubair,
%             Desalination and Water Treatment, 16, 354−380, 2010.
%          (http://web.mit.edu/seawater/)
%           [2] B. M. Fabuss, A. Korosi, and D. F. Othmer, J.,
%                            Chem. Eng. Data 14(2), 192, 1969. [3] J. D. Isdale, C. M.
%                          Spence, and J. S. Tudhope, Desalination, 10(4), 319 − 328,
%      1972
%                         [4] F. J. Millero, The Sea, Vol. 5, 3 80, John Wiley, New York,
%      1974
%                      [5] IAPWS release on the viscosity of ordinary water substance
%      2008
%=================================================================

%% CHECK INPUT ARGUMENTS

% CHECK THAT S&T HAVE SAME SHAPE if ~isequal(size(S),size(T)) error('check_stp:
S & T must have same dimensions');
end

% CONVERT TEMPERATURE INPUT
switch lower(uT) case 'c' case 'k'
      T = T − 273.15; case 'f'
      T = 5/9*(T−32); case 'r'
      T = 5/9*(T−491.67); otherwise error('Not a recognized temperature unit. Please use
   ''C'',
      ''K'', ''F'', or ''R'''); end
```

```
% CONVERT SALINITY TO PPT switch
lower(uS) case 'ppt' case 'ppm'
          S = S/1000; case 'w'
          S = S*1000; case '%'
          S = S*10;
     otherwise error('Not a recognized salinity unit. Please use ''ppt'',
          ''ppm'', ''w'', or ''%''');
end

% CHECK THAT S & T ARE WITHIN THE FUNCTION RANGE if
~isequal((T<0)+(T>180),zeros(size(T))) warning('Temperature is out of range for Viscosity
function
     0<T<180 C'); end

if ~isequal((S<0)+(S>150),zeros(size(S))) warning('Salinity is out of range for Viscosity
     function
     0<S<150 g/kg'); end

%% BEGIN S =

S/1000;

a = [
     1.5700386464E-01
     6.4992620050E+01 -9.1296496657E+01
     4.2844324477E-05
     1.5409136040E+00
     1.9981117208E-02
    -9.5203865864E-05
     7.9739318223E+00
    -7.5614568881E-02
     4.7237011074E-04 ];

mu_w = a(4) + 1./(a(1)*(T+a(2)).^2+a(3));


A = a(5) + a(6) * T + a(7) * T.^2; B = a(8) + a(9) * T +
a(10)* T.^2; mu = mu_w.*(1 + A.*S + B.*S.^2);

end
```

A.1.5 ThrustDeduction.m

Calculates the thrust deduction for the vessel, which estimates the effect of the fact that the propeller "sucks in" water from the front of the ship. It is used in the estimation of the ship required thurst.

```
function t_corr = ThrustDeduction(operational,design)
%
% This function calculates the Thrust Deduction Coefficient (t) for a
% given ship according to the formula provided in the Harvald and % Guldhammer method.
%
% The input is provided as two structure: one for design variables and
% one for operational variables
%
% The "design" strcuture contains the following fields:
% − design.CBdes = Design Block coefficient [−]
% − design.FA = Form factor: −2 for U−shape aft, 0 for N−shape aft,
% +2 for V−shape aft
% − design.DPROP = Propeller diameter [m]
% − design.LWL = Ship length on the water line [m]
% − design.B = Ship bredth [m]
% − design.DISPdes = Ship displacement [ton]
% − design.Tdes = Design draft [m]
% − design.SHIP_TYPE Ship type. For the moment it can be:
%                               'Tanker'
%                                 'Containership'
%
% The "operational" structure contains the following fields:
% − operational.T = Draft [m]

%% Reading the design input
LWL = design.LWL ;
CBdes = design.CBdes ;
FA = design.FA ;
DPROP = design.DPROP ; B =
design.B ;
DISPdes = design.DISPdes ;
Tdes = design.Tdes ;
SHIP_TYPE = design.SHIP_TYPE ; % Ship type

%% Reading the operational input T =
operational.T ; if isfield(operational,'T_SW')
      T_SW = operational.T_SW ; else
      T_SW = 25 ; % If no value for the seawater temperature is provided, it is assumed equal to 25
      degrees Celsius
end
```

```
%% Processing input
CB = 1 − (1 − CBdes) * (Tdes/T)^(1/3) ; % Updating the block
coefficient disp_ton = DISPdes * (CB/CBdes) * (T/Tdes) ;
```

```
% Updating the displacement
% rho_SW = SeaWaterDensity(T_SW,34) ; % Density (kg/m3) disp = disp_ton /
rho_SW * 1e3 ; % Volume displacement
```

```
d = 0.625 * B / LWL + 0.08 ; e = 0.165 − 0.25 * B / LWL ; f = 825 −
8060 * B / LWL + 20300 * (B/LWL)^2 ;

t1 = d + e / (f * (0.98 − CB)^3 + 1) ; t2 = −0.01 * FA ; t3 =
  2 * (DPROP / LWL − 0.04) ;

  t = t1 + t2 + t3 ;

  M = LWL / disp^(1/3) ; % Length−over−displacement


  switch SHIP_TYPE case
       'Tanker'
               t_corr = t − 0.26 + 0.04 * M ;
               % Correction factor according to Kristensen case
       'Containership' t_corr = t ;
  end


  end


  function[sea_water_density] = SeaWaterDensity(varargin)
  %
  % This function calculates sea water density given its temperature and % salinity (if available).
  %
  % Only water temperature, in degrees Celsius, is required as input

  if nargin == 1 temperature = varargin{1} ;
       salinity = 0.033 ;
  else temperature = varargin{1} ; salinity =
       varargin{2} ;
  end

                    A= 8.23997e−1−4.0644e−3*temperature+7.6455e−5*temperature^2−...
  8.3332e−10*temperature^3+5.4961e−12*temperature^4;

  B= −5.5078e−3+ 9.7598e−5*temperature− 1.6218e−6*temperature^2; C= 4.6106e−4;

  for i = 1 : length(temperature) water_density = 999.842594 +
       6.793952e−2*temperature −...
               9.095290e−3*temperature^2+ 1.001685e−4...
```

```
            *temperature^3− 1.120083e−6*temperature^4+...
            6.536336e−9*temperature^5;

      sea_water_density(i) = water_density + A*salinity + B*salinity^1.5
      + C*salinity^2;

end


end
```

A.1.6 WakeFraction.m

Calculates the wake fraction for the vessel, which estimates the effect of the fact that the propeller does not work in an undisturbed flow, but in the ship's wake. It is used to calculate the required propeller power.

```
function w_corr = WakeFraction(operational,design)
%
% This function calculates the Wake Factor Coefficient (w) for a given % ship according to the formula
provided in the Harvald and Guldhammer % method.
%
% The input is provided as two structure: one for design variables and
% one for operational variables
%
% The "design" strcuture contains the following fields:
% − design.CBdes = Design Block coefficient [−]
% − design.FA = Form factor: −2 for U−shape aft, 0 for N−shape aft,
% +2 for V−shape aft
% − design.DPROP = Propeller diameter [m]
% − design.LWL = Ship length on the water line [m]
% − design.B = Ship bredth [m]
% − design.DISPdes = Ship displacement [ton]
% − design.Tdes = Design draft [m]
% − design.SHIP_TYPE Ship type. For the moment it can be:
%                              'Tanker'
%                                'Containership'
%
% The "operational" structure contains the following fields:
% − operational.T = Draft [m]

%% Reading design input LWL =
design.LWL ;
CBdes = design.CBdes ;
FA = design.FA ;
DPROP = design.DPROP ;
B = design.B ;
DISPdes = design.DISPdes ;
Tdes = design.Tdes ;
```

```
SHIP_TYPE = design.SHIP_TYPE ; % Ship type

%% Reading operational input
```

```
T = operational.T ; if
isfield(operational,'T_SW')
        T_SW = operational.T_SW ; else
                                                T_SW = 25 ; % If no value for the seawater temperature is provided,
        % it is assumed equal to 25 degrees Celsius end

%% Processing input
CB = 1 − (1 − CBdes) * (Tdes/T)^(1/3) ; % Updating the block
coefficient disp_ton = DISPdes * (CB/CBdes) * (T/Tdes) ;
% Updating the displacement
% rho_SW = SeaWaterDensity(T_SW,34) ; % Density (kg/m3) disp = disp_ton /
rho_SW * 1e3 ; % Volume displacement

a = 0.1 * B / LWL + 0.149 ; b = 0.05 * B / LWL + 0.449 ; c = 585 −
5027 * B / LWL + 11700 * (B/LWL)^2 ;
```

```
w1 = a + b / (c * (0.98−CB)^3 +1) ; w2 = 0.025 * FA / (100 *
(CB−0.7)^2 + 1) ; w3 = −0.18 + 0.00756 / (DPROP/LWL + 0.002) ;

w = w1 + w2 + min(w3,0.1) ;

M = LWL / disp^(1/3) ; % Length−over−displacement

switch SHIP_TYPE case
    'Tanker'
        w_corr = w * 0.7 − 0.45 + 0.08 * M ;
        % Correction factor according to Kristensen case
    'Containership' w_corr = w ;
end


end


function[sea_water_density] = SeaWaterDensity(varargin)
%
% This function calculates sea water density given its temperature and % salinity (if available).
%
% Only water temperature, in degrees Celsius, is required as input

if nargin == 1 temperature = varargin{1} ;
    salinity = 0.033 ;
else temperature = varargin{1} ; salinity =
varargin{2} ; end
```

```
            A= 8.23997e−1−4.0644e−3*temperature+7.6455e−5*temperature^2−...
  8.3332e−10*temperature^3+5.4961e−12*temperature^4;

B= −5.5078e−3+ 9.7598e−5*temperature− 1.6218e−6*temperature^2; C= 4.6106e−4;

for i = 1 : length(temperature) water_density = 999.842594 + 6.793952e−2*temperature
        −...
            9.095290e−3*temperature^2+ 1.001685e−4...
            *temperature^3− 1.120083e−6*temperature^4+...
            6.536336e−9*temperature^5;

        sea_water_density(i) = water_density + A*salinity + B*salinity^1.5
        + C*salinity^2;

end


end
```

A.1.7 Propeller.m

Calculates the required operating conditions of the propeller. Given two inputs, calculates the remaining variables, among others propeller efficiency.

```
function output = Propeller(input,operational,propeller_parameters) %
% INPUT: This function finds the operational condition of a Wageningen % propeller for given
parameters and for given conditions of:
% − input.thrust                    Thrust [kN] (T)
% − input.torque                    [kNm] (Q)
% − input.PDrel                     Relative pitch / diameter ratio [−] (R)
% − input.rpm                       Propeller speed [rpm] (N)
%
% NOTE: At least ONE of the previous must be given if the propeller is
% a FPP, at least TWO if is a CPP
%
% In addition, the wake fraction has to be provided:
% − input.wake_fraction             Wake Fraction [−]
%
% OPERATIONAL variables: This input is to be provided in the form of a % structure with the following
elements:
% − operational.v:                  Ship speed [kn]
%
% DESIGN parameters: This input is to be provided in the form of a % structure with the following
elements:
% − design.DPROP                    Propeller diameter [m]
% − design.Pdes                     Propeller pitch (design) [m]
% − design.ARATIO                   Propeller area ration [−]
% − design.Z                        Propeller, number of blades [−]
% − design.PTYPE                    Propeller type: 'FPP' or 'CPP' ;
```

```
%
% outputs are all the four variables in the order as previously listed
% (T,Q,R,N). If a different order is required, it should be given as
% last input (e.g. ,'QTRN')
%
% Note that when only Thrust and Torque are given the algorithm is
% slower because it needs to find a zero for a 2−variables function,
% which requires a slower and more ineffective algorithm. This % option is therefore
discouraged.

%% Checking the propeller type (FPP or CPP) if
isfield(propeller_parameters,'PTYPE')
        PTYPE = propeller_parameters.PTYPE ; else
        PTYPE = 'FPP' ; % If no field for PTYPE is given, it is assumed to
        % be a CPP
end
% If the propeller is a FPP, the PDrel is fixed to 1 if strcmp(PTYPE,'FPP')
input.PDrel = 1 ;
elseif strcmp(PTYPE,'CPP') input.rpm =
        operational.rpm ;
end
```

```
%% Reading inputs if isfield(input,'thrust')
thrust = input.thrust ; if isfield(input,'torque')
torque = input.torque ; op_mode = 'TQ' ;
        elseif isfield(input,'rpm') rpm =
                input.rpm ; op_mode = 'TN' ;
        elseif isfield(input,'PDrel') PDrel = input.PDrel ; op_mode = 'TR' ; else error('Something is wrong
        in the input structure. Check it!')
        end
  elseif isfield(input,'torque') torque =
        input.torque ; if isfield(input,'rpm')
        rpm = input.rpm ; op_mode = 'QN' ;
        elseif isfield(input,'PDrel') PDrel = input.PDrel ; op_mode = 'QR' ; else error('Something is wrong
        in the input structure. Check it!')
        end
  elseif isfield(input,'rpm') rpm = input.rpm ; if isfield(input,'PDrel') PDrel = input.PDrel ; op_mode =
        'RN' ; else error('Something is wrong in the input structure. Check it!')
```

```
    end
else error('Something is wrong in the input structure. Check it!')
end

%% Reformatting the inputs as required v_kn =
operational.v ;
propeller_parameters.wake_fraction = input.wake_fraction ; PDdes =
propeller_parameters.Pdes / propeller_parameters.DPROP ;


%% Performing the calculations switch op_mode case {'TQ','QT'} out_calc =
@(R,N) sum(abs(Wageningen([v_kn N R], propeller_parameters) − [thrust
torque R N])) ;
        [PDrel , rpm]= fsolve(out_calc,[1 propeller_parameters(6)]) ;
% case {'TR','RT'} out_calc = @(N) (Wageningen([v_kn N PDrel], propeller_parameters) − [thrust
    0 0 0]) * [1 0 0 0]' ; rpm = fzero(out_calc,[20 200]) ; temp = Wageningen([v_kn rpm
    PDrel],propeller_parameters) ; torque = temp(2) ;
% case {'TN','NT'} out_calc = @(R) (Wageningen([v_kn rpm R],propeller_parameters)
        − [thrust 0 0 0]) * [1 0 0 0]' ;
        PDrel = fzero(out_calc,[0 1.5]) ; temp = Wageningen([v_kn rpm
        PDrel],propeller_parameters) ; torque = temp(2) ;
% case {'QR','RQ'} out_calc = @(N) (Wageningen([v_kn N PDrel],propeller_parameters)
        − [0 torque 0 0]) * [0 1 0 0]' ; rpm =
        fzero(out_calc,[50 150]) ;
        temp = Wageningen([v_kn rpm PDrel],propeller_parameters) ; thrust = temp(1) ;
% case {'QN','NQ'} out_calc = @(R) (Wageningen([v_kn rpm R],propeller_parameters)
        − [0 torque 0 0]) * [0 1 0 0]' ;
        PDrel = fzero(out_calc,[0.1 1.5]) ; temp = Wageningen([v_kn rpm
        PDrel],propeller_parameters) ; thrust = temp(1) ;
% case {'RN','NR'} temp = Wageningen([v_kn rpm PDrel],propeller_parameters) ; thrust =
    temp(1) ; torque = temp(2) ;
end

%% Calculating the efficiency advance_velocity = operational.v * 0.51444444 * (1 −
input.wake_fraction) ; open_water_efficiency = thrust * advance_velocity / (torque * 2 * pi * rpm /
60) ;
```

```
%% Writing the output output.thrust = thrust ; output.torque = torque ;
output.rpm = rpm ; output.pitch = propeller_parameters.Pdes * PDrel ;
output.eta_o = open_water_efficiency ;

end function output = Wageningen(operational,parameters)



v_kn = operational(1) ; % Ship speed (kn) n_rpm = operational(2) ; %
Propeller speed (rpm) PDrel = operational(3) ; % Fraction of design pitch

w = parameters.wake_fraction ; % Ship Wake factor
D = parameters.DPROP ; % Propeller diameter (m)
Z = parameters.Z ; % Number of blades
Ar = parameters.ARATIO ; % Blade area ratio
PDdes = parameters.Pdes / D ; % Pitch/Diameter ratio % Check if there is
any correction factor for the K_T if isfield(parameters,'KTcorr')
        KTcorr = parameters.KTcorr ; else
      KTcorr = 1 ;
end
% Check if there is any correction factor for the K_T if
isfield(parameters,'KQcorr')
        KQcorr = parameters.KQcorr ; else
      KQcorr = 1 ;
end


v = v_kn * 0.514444 ; % Ship speed, [m/s] n = n_rpm / 60 ;
% propeller speed, [rps]

va = v * (1−w) ; % Propeller advance speed, [m/s] J = va ./ n / D ; %
Advance coefficient, []
PD = PDdes * PDrel ; % Pitch/diameter ratio []

C_KT = [0.00880496 , 0 , 0 , 0 , 0 , 0 ;
      −0.204554 , 1 , 0 , 0 , 0 , 0 ;
      0.166351 , 0 , 1 , 0 , 0 , 0 ;
      0.158114 , 0 , 2 , 0 , 0 , 0 ;
      −0.147581 , 2 , 0 , 1 , 0 , 0 ;
      −0.481497 , 1 , 1 , 1 , 0 , 0 ;
      0.415437 , 0 , 2 , 1 , 0 , 0 ;
```

0.0144043, 0 , 0 , 0 , 1 , 0 ;
−0.0530054, 2 , 0 , 0 , 1 , 0 ;
0.0143481 , 0 , 1 , 0 , 1 , 0 ;
0.0606826 , 1 , 1 , 0 , 1 , 0 ;
−0.0125894 , 0 , 0 , 1 , 1 , 0 ;
0.0109689 , 1 , 0 , 1 , 1 , 0 ;
−0.133698 , 0 , 3 , 0 , 0 , 0 ;
0.00638407 , 0 , 6 , 0 , 0 , 0 ;

−0.00132718 , 2 , 6 , 0 , 0 , 0 ;
0.168496 , 3 , 0 , 1 , 0 , 0 ;
−0.0507214 , 0 , 0 , 2 , 0 , 0 ;
0.0854559 , 2 , 0 , 2 , 0 , 0 ;
−0.0504475 , 3 , 0 , 2 , 0 , 0 ;
0.010465 , 1 , 6 , 2 , 0 , 0 ;
−0.00648272 , 2 , 6 , 2 , 0 , 0 ;
−0.00841728 , 0 , 3 , 0 , 1 , 0 ;
0.0168424 , 1 , 3 , 0 , 1 , 0 ;
−0.00102296 , 3 , 3 , 0 , 1 , 0 ;
−0.0317791 , 0 , 3 , 1 , 1 , 0 ;
0.018604 , 1 , 0 , 2 , 1 , 0 ;
−0.00410798 , 0 , 2 , 2 , 1 , 0 ;
−0.000606848 , 0 , 0 , 0 , 2 , 0 ;
−0.0049819 , 1 , 0 , 0 , 2 , 0 ;
0.0025983 , 2 , 0 , 0 , 2 , 0 ;
−0.000560528 , 3 , 0 , 0 , 2 , 0 ;
−0.00163652 , 1 , 2 , 0 , 2 , 0 ;
−0.000328787 , 1 , 6 , 0 , 2 , 0 ;
0.000116502 , 2 , 6 , 0 , 2 , 0 ;
0.000690904 , 0 , 0 , 1 , 2 , 0 ;
0.00421749 , 0 , 3 , 1 , 2 , 0 ;
5.6522e−05 , 3 , 6 , 1 , 2 , 0 ;
−0.00146564 , 0 , 3 , 2 , 2 , 0] ;

C_KQ = [0.00379368 , 0 , 0 , 0 , 0 , 0 ;
0.00886523 , 2 , 0 , 0 , 0 , 0 ;
−0.032241 , 1 , 1 , 0 , 0 , 0 ;
0.00344778 , 0 , 2 , 0 , 0 , 0 ; −0.0408811 , 0 , 1 , 1 , 0 , 0 ;
−0.108009 , 1 , 1 , 1 , 0 , 0 ;
−0.0885381 , 2 , 1 , 1 , 0 , 0 ;
0.188561 , 0 , 2 , 1 , 0 , 0 ;
−0.003708710 , 1 , 0 , 0 , 1 , 0 ;
0.00513696 , 0 , 1 , 0 , 1 , 0 ;
0.0209449 , 1 , 1 , 0 , 1 , 0 ;
0.00474319 , 2 , 1 , 0 , 1 , 0 ;
−0.00723408 , 2 , 0 , 1 , 1 , 0 ;
0.00438388 , 1 , 1 , 1 , 1 , 0 ; −0.0269403 , 0 , 2 , 1 , 1 , 0 ;
0.0558082 , 3 , 0 , 1 , 0 , 0 ;

0.0161886 , 0 , 3 , 1 , 0 , 0 ;
0.00318086 , 1 , 3 , 1 , 0 , 0 ;
0.015896 , 0 , 0 , 2 , 0 , 0 ;
0.0471729 , 1 , 0 , 2 , 0 , 0 ;
0.0196283 , 3 , 0 , 2 , 0 , 0 ;
−0.0502782 , 0 , 1 , 2 , 0 , 0 ;
−0.030055 , 3 , 1 , 2 , 0 , 0 ;
0.0417122 , 2 , 2 , 2 , 0 , 0 ;
−0.0397722 , 0 , 3 , 2 , 0 , 0 ;

```
        -0.00350024 , 0 , 6 , 2 , 0 , 0 ;
        -0.0106854 , 3 , 0 , 0 , 1 , 0 ;
        0.00110903 , 3 , 3 , 0 , 1 , 0 ;
        -0.000313912 , 0 , 6 , 0 , 1 , 0 ;
        0.0035985 , 3 , 0 , 1 , 1 , 0 ;
        -0.00142121 , 0 , 6 , 1 , 1 , 0 ;
        -0.00383637 , 1 , 0 , 2 , 1 , 0 ;
        0.0126803 , 0 , 2 , 2 , 1 , 0 ;
        -0.00318278 , 2 , 3 , 2 , 1 , 0 ;
        0.00334268 , 0 , 6 , 2 , 1 , 0 ;
        -0.00183491 , 1 , 1 , 0 , 2 , 0 ;
        0.000112451 , 3 , 2 , 0 , 2 , 0 ;
        -2.97228e-05 , 3 , 6 , 0 , 2 , 0 ;
        0.000269551, 1 , 0 , 1 , 2 , 0 ;
        0.00083265 , 2 , 0 , 1 , 2 , 0 ;
        0.00155334 , 0 , 2 , 1 , 2 , 0 ;
        0.000302683 , 0 , 6 , 1 , 2 , 0 ;
        -0.0001843 , 0 , 0 , 2 , 2 , 0 ;
        -0.000425399 , 0 , 3 , 2 , 2 , 0 ;
        8.69243e-05 , 3 , 3 , 2 , 2 , 0 ;
        -0.0004659 , 0 , 6 , 2 , 2 , 0 ;
        5.54194e-05 , 1 , 6 , 2 , 2 , 0] ;


KT = sum(C_KT(:,1) .* J.^C_KT(:,2) .* PD.^C_KT(:,3) .* Ar.^C_KT(:,4) .* Z.^C_KT(:,5)) * KTcorr ;
KQ = sum(C_KQ(:,1) .* J.^C_KQ(:,2) .* PD.^C_KQ(:,3) .* Ar.^C_KQ(:,4) .*
Z.^C_KQ(:,5)) * KQcorr ;

        eta_O = J * KT / (2*pi * KQ) ; % Open water efficiency
        Q = KQ * 1024 * n^2 * D^5 * 1e-3 ; % Torque [kN]
        Pb = Q * n * 2*pi ; % Brake Power [kW]
        Pt = Pb * eta_O ; % Effective Power [kW]
        T = KT * 1024 * n^2 * D^4 * 1e-3; % Thrust [kN]



output = [T Q PDrel n_rpm] ;

end
```

A.1.8 MainEngine.m

It simply calculates the efficiency of the main engine, and therefore the required fuel flow. It should also include (it does not, at the moment) a check that the engine does not operate outside its operational limits.

```
function bsfc_me = MainEngine(input,design) %
```

```
% This function simulates the behaviour of a main engine in terms of % its efficiency. The function takes into account engine speed and
% power and uses them in a sort of "efficiency map"
%
% Required input:
% – input.rpm
% – input.P_B
% – design.MCR_ME
% – design.RPMmax_ME
% – design.BSFCmin_ME
%
% Note: the tables are generated based on the Wartsila 32 generating
% set engine by the authors of this report
% run Matrix.m

%% Assigning the efficiency tables 4–stroke
MATRIX_FOURSTROKE_FIXED_SPEED = [E] ;
MATRIX_FOURSTROKE_VARIABLE_SPEED = [R] ;

MATRIX_FOURSTROKE = [MATRIX_FOURSTROKE_FIXED_SPEED ;
MATRIX_FOURSTROKE_VARIABLE_SPEED] ;

bsfcFunction = scatteredInterpolant(MATRIX_FOURSTROKE(:,1),
MATRIX_FOURSTROKE(:,2),MATRIX_FOURSTROKE(:,3)) ;

%% How many engines to run

if (input.P_B > 9000) ; design.MCR_ME = NaN
elseif (input.P_B <= 9000) && (input.P_B > 6750) ; design.MCR_ME = 9000 ;
elseif (input.P_B <= 6750) && (input.P_B > 4500) ; design.MCR_ME = 6750 ;
elseif (input.P_B <= 4500) && (input.P_B > 2250) ; design.MCR_ME = 4500 ;
elseif (input.P_B <= 2250) ; design.MCR_ME = 2250 ;
end ;

%% Adimensionalising the inputs power_ad = input.P_B /
design.MCR_ME ; speed_ad = input.rpm /
design.RPMmax_ME ;

%% Calculating the real efficiency bsfc_me = bsfcFunction(power_ad,speed_ad) *
design.BSFCmin_ME ;
```

A.1.9 Matrix.m

```
% Matrix with the engine SFOC run Input.m


%% fixed

A = importdata('SFOC_constant_speed.txt') ;


X   = A.data(:,1) ;
Y   = zeros(81,1) + 1 ;
Z   = (A.data(:,2) + design.BSFCmin_ME) / design.BSFCmin_ME ;

[X, SortIndex] = sort(X) ;
Y   = Y(SortIndex) ;
Z   = Z(SortIndex) ;

A = [X Y Z] ;

E = flipud(A) ;

%% Matrix with varied speed, C = X and D = Y

C = [
0.951669E+00
0.958953E+00
0.958953E+00
0.950759E+00
0.935281E+00
0.907967E+00
0.960774E+00
0.978073E+00
0.985357E+00
0.982625E+00
0.974431E+00
0.950759E+00
```

0.928907E+00
0.907056E+00
0.877921E+00
0.968968E+00
0.994461E+00
0.100721E+01
0.100630E+01
0.997193E+00
0.976252E+00
0.957132E+00
0.937102E+00
0.917982E+00
0.882473E+00
0.848786E+00
0.978073E+00
0.100448E+01
0.100994E+01
0.987177E+00
0.956222E+00
0.927086E+00
0.892489E+00
0.853338E+00
0.819651E+00
0.985357E+00
0.100266E+01
0.101176E+01
0.977162E+00
0.949848E+00
0.915250E+00

```
0.886115E+00
0.849696E+00
0.816920E+00
0.795979E+00
0.992640E+00
0.100083E+01
0.101358E+01
0.984446E+00
0.953490E+00
0.913429E+00
0.877921E+00
0.831487E+00
0.765933E+00
0.101540E+01
0.995372E+00
0.973520E+00
0.948027E+00
0.907967E+00
0.874279E+00
0.836950E+00
0.800531E+00
0.734977E+00
0.101631E+01
0.999924E+00
0.968968E+00
0.946206E+00
0.910698E+00
0.850607E+00
0.805083E+00
0.758649E+00
0.705842E+00
0.101813E+01
0.986267E+00
0.948938E+00
0.906146E+00
0.848786E+00
0.800531E+00
0.738619E+00
0.693096E+00
0.658498E+00
] ;

D = [
0.860034E+00
0.834739E+00
```

0.801012E+00
0.774030E+00
0.755481E+00
0.752108E+00
0.890388E+00
0.854975E+00
0.822934E+00
0.779089E+00
0.752108E+00
0.709949E+00
0.691400E+00
0.681282E+00
0.676223E+00
0.910624E+00
0.870152E+00
0.822934E+00
0.777403E+00
0.736931E+00
0.689713E+00
0.662732E+00
0.642496E+00
0.629005E+00
0.613828E+00
0.612142E+00
0.935919E+00
0.897133E+00
0.694772E+00
0.642496E+00
0.600337E+00
0.578415E+00
0.563238E+00
0.554806E+00
0.553120E+00
0.957842E+00
0.937605E+00
0.623946E+00
0.563238E+00
0.536256E+00
0.519393E+00
0.509275E+00
0.505902E+00
0.502530E+00
0.505902E+00
0.984823E+00
0.976391E+00
0.546374E+00
0.499157E+00
0.473862E+00
0.456998E+00
0.450253E+00
0.445194E+00
0.450253E+00

```
0.494098E+00
0.458685E+00
0.435076E+00
0.419899E+00
0.406408E+00
0.399663E+00
0.394604E+00
0.394604E+00
0.399663E+00
0.443508E+00
0.414840E+00
0.386172E+00
0.372681E+00
0.362563E+00
0.352445E+00
0.347386E+00
0.347386E+00
0.352445E+00
0.391231E+00
0.342327E+00
0.315346E+00
0.298482E+00
0.288364E+00
0.283305E+00
0.278246E+00
0.279933E+00
0.286678E+00
] ;

[Cx, SortIndex] = sort(C);
Dx = D(SortIndex);

V = [Cx Dx];

Vx = flipud(V) ;

V = Vx ; B = (V(:,2) + design.BSFCmin_ME) / design.BSFCmin_ME; A =

importdata('Load_speed_ratio.txt');

X   = A.data(:,1) ;
Y   = A.data(:,2) ;

Z   = zeros(81,1) ;

Xx = (X * design.MCR_ME) / design.MCR_ME ;
Yx = (Y * operational.v) / operational.v ;

M = flipud(Yx);

R = [V(:,1) M B] ;
```

A.1.10 W_Flettner_rotor.m

This is the file where the simulation of the Flettner rotor is done with the equations that were explained in the theory chapter.

```
%% Flettner rotor ;

A = 175 ;
        % cross−sectional area of the rotor density = 1.225
; % kg/m^3
V_true = operational.tw ;
        %m/s
V_ship = operational.v * 1852/3600 ;
```

```
        %m/s

V_a = V_true ;
        % Apparent wind speed, Ship speed does not affect V_a
        % because we assume it having the angle of 90 degrees.

C_L = 12.5 ;
        % lift coefficient; assumptions can change
C_D = 0.2 ;
        % drag coefficient; assumptions can change C_M = 0.2 ;
        % moment coefficient alfa = 3.5 ;
        % spin ratio V_rotor/V_a l
=0.5*density*A*V_a^2*C_L ;
        % lift force d
=0.5*density*A*V_a^2*C_D ;
        % drag force p_L_D =
(l+d)*V_ship ;
        % power delivered by the flettner rotor p_motor
=0.5*density*A*V_a^3*C_M*alfa ;
        % power consumed by the motor p_prop = (
p_L_D – p_motor )/1000 ; % kW power contribution

P_Flettner = p_prop ;
P_Wind = P_Flettner ;
```

A.1.11 W_Kite.m

In this file that simulates the kite performance and given forces.

```
        %% Kite two density =
        1.225 ;
                % Air density, Kg/m^3
        C_Lw = 1 ;
                % Lift coefficient
        C_Dw = 0.286 ;
                % Drag coefficient
        A = 640 ;
                % Kite crossection area, m^2
        VWindDir = 0 ;
                % Direction of true wind Vtrue =
        operational.tw ;
                % True Wind speed at 10 m above sea level, m/s Shipspeed = operational.v *
        1852/3600 ;
                % Ship speed in; m/s theta =
        30*pi/180 ;
                % Angle of kite elevation in relation to vessel R= 300 ;
                % Length of the tether line hKiteheight = R*sin(theta) ;
                % The height that the kite flies
```

```
    VTrueAtKite = Vtrue*(Kiteheight/10)^(1/7) ;
            % True wind speed at kite, m/s

    V_a = sqrt((VTrueAtKite*cos(WindDir)+Shipspeed)^2+(VTrueAtKite* sin(WindDir)^2)) ;
    % Apparent wind at kite, m/s

    L_w=0.5*C_Lw*density*V_a^2*A ;
            % Lift force
    D_w=0.5*C_Dw*density*V_a^2*A ;
            % Drag force epsilon =
    atan(L_w/D_w) ; % Lift to drag angle
    F_w = sqrt(L_w^2 + D_w^2)/1000 ;
    P_Kite = F_w ;
    P_Wind = P_Kite ;
```

A.1.12 W_turbine.m

This is the file that simulates the wind turbine.

```
%% Wind turbin
% http://www.raeng.org.uk/publications/other/23-wind-turbine

format longg

density = 1.225 ;            % Air density r = 20 ;          % Blade length
A = pi * r^2 ;                                                   % Swept area
C_p = 0.4 ;                                                        % Turbine efficency
W = 10 ; V =
8 ;
alpha = 80 * pi / 180 ;

V_a = sqrt(W^2 + V^2 - 2 * W * V * cos(alpha)) ; % Apperent wind


P_Turbine = 0.5 * density * A * V_a ^ 3 * C_p ;
P_Wind = P_Turbine * 10 ^-3 ;
```

A.2 xyExtract files

In this section the values that are taken from xyExtract are shown. These files are used in "Matrix.m" in MATLAB to calculate the fuel oil consumption.

A.2.1 SFOC_constant_speed.txt

This is the file that contains the values from the SFOC at constant speed graph, which were taken from the graph by the authors.

X	Y
0.249524E+00	0.257922E+02
0.257143E+00	0.251688E+02
0.262222E+00	0.246234E+02
0.268571E+00	0.240779E+02
0.273651E+00	0.233766E+02
0.281270E+00	0.228312E+02
0.288889E+00	0.219740E+02
0.299048E+00	0.210390E+02
0.309206E+00	0.200260E+02
0.316825E+00	0.192468E+02
0.321905E+00	0.185455E+02
0.330794E+00	0.178442E+02
0.337143E+00	0.171429E+02
0.347302E+00	0.162857E+02
0.357460E+00	0.151948E+02
0.367619E+00	0.141818E+02
0.376508E+00	0.134026E+02
0.384127E+00	0.126234E+02
0.393016E+00	0.120000E+02
0.400635E+00	0.112987E+02
0.408254E+00	0.105974E+02
0.418413E+00	0.966234E+01
0.427302E+00	0.903896E+01
0.437460E+00	0.841558E+01
0.450159E+00	0.755844E+01
0.462857E+00	0.693506E+01
0.474286E+00	0.623377E+01
0.489524E+00	0.561039E+01
0.500952E+00	0.514286E+01
0.513651E+00	0.467532E+01
0.522540E+00	0.436364E+01
0.531429E+00	0.412987E+01
0.549206E+00	0.366234E+01
0.568254E+00	0.327273E+01
0.587302E+00	0.280519E+01
0.600000E+00	0.264935E+01
0.617778E+00	0.218182E+01
0.635556E+00	0.194805E+01
0.646984E+00	0.179221E+01
0.659683E+00	0.155844E+01
0.671111E+00	0.140260E+01
0.683810E+00	0.124675E+01
0.697778E+00	0.935065E+00
0.715556E+00	0.701299E+00
0.734603E+00	0.545455E+00
0.753651E+00	0.233766E+00
0.768889E+00	0.155844E+00
0.781587E+00	0.779221E−01
0.794286E+00	0.779221E−01

```
0.808254E+00 0.155844E+00
0.822222E+00 0.233766E+00
0.837460E+00 0.233766E+00
0.853968E+00 0.311688E+00
0.869206E+00 0.623377E+00
```

```
0.894603E+00 0.109091E+01
0.908571E+00 0.140260E+01
0.920000E+00 0.179221E+01
0.933968E+00 0.218182E+01
0.944127E+00 0.257143E+01
0.956825E+00 0.280519E+01
0.964444E+00 0.319481E+01
0.974603E+00 0.358442E+01
0.987302E+00 0.397403E+01
0.996190E+00 0.436364E+01
0.302857E+00 0.205714E+02
0.352381E+00 0.157403E+02
0.362540E+00 0.147273E+02
0.884444E+00 0.857143E+00
0.100000E+01 0.459740E+01
0.292698E+00 0.217403E+02
0.285079E+00 0.224416E+02
0.295238E+00 0.214286E+02
0.271111E+00 0.239221E+02
0.277460E+00 0.232208E+02
0.252063E+00 0.256364E+02
0.313016E+00 0.196364E+02
0.326984E+00 0.182338E+02
0.343492E+00 0.165974E+02
0.380317E+00 0.130909E+02
0.371429E+00 0.138701E+02
0.387937E+00 0.122338E+02
```

A.2.2 Load_speed_ratio.txt

This is the file where the values that are taken from the graph, by the authors, that shows the ratio between load and speed.

X	Y
0.500076E+00	0.124789E+00
0.503718E+00	0.128162E+00
0.507360E+00	0.131535E+00
0.512822E+00	0.136594E+00
0.519196E+00	0.139966E+00
0.523748E+00	0.143339E+00
0.528300E+00	0.146712E+00
0.532853E+00	0.151771E+00
0.539226E+00	0.156830E+00
0.541957E+00	0.160202E+00
0.551973E+00	0.168634E+00
0.561077E+00	0.175379E+00
0.567451E+00	0.182125E+00
0.572003E+00	0.187184E+00
0.580197E+00	0.195616E+00
0.584750E+00	0.200675E+00
0.590212E+00	0.204047E+00
0.594765E+00	0.212479E+00
0.609332E+00	0.225970E+00
0.614795E+00	0.231029E+00
0.619347E+00	0.237774E+00
0.630273E+00	0.251265E+00
0.633915E+00	0.258010E+00
0.645751E+00	0.271501E+00
0.651214E+00	0.278246E+00
0.663961E+00	0.293423E+00
0.669423E+00	0.301855E+00
0.673976E+00	0.308600E+00
0.681259E+00	0.315346E+00
0.691275E+00	0.330523E+00
0.701290E+00	0.347386E+00
0.712215E+00	0.362563E+00
0.720410E+00	0.374368E+00
0.724962E+00	0.382799E+00
0.729514E+00	0.389545E+00
0.734977E+00	0.399663E+00
0.747724E+00	0.418212E+00
0.753187E+00	0.426644E+00
0.758649E+00	0.436762E+00
0.765023E+00	0.446880E+00
0.775038E+00	0.467116E+00
0.779590E+00	0.475548E+00
0.784143E+00	0.485666E+00
0.788695E+00	0.494098E+00
0.794158E+00	0.502530E+00
0.798710E+00	0.510961E+00

0.802352E+00 0.517707E+00
0.805994E+00 0.522766E+00
0.809636E+00 0.532884E+00
0.813278E+00 0.539629E+00
0.818740E+00 0.551433E+00
0.823293E+00 0.559865E+00
0.827845E+00 0.568297E+00
0.833308E+00 0.583474E+00
0.846965E+00 0.607083E+00
0.852428E+00 0.620573E+00
0.858801E+00 0.635750E+00
0.864264E+00 0.649241E+00
0.869727E+00 0.659359E+00
0.875190E+00 0.669477E+00
0.877921E+00 0.679595E+00
0.884294E+00 0.689713E+00
0.897041E+00 0.725127E+00
0.902504E+00 0.736931E+00
0.908877E+00 0.752108E+00
0.913429E+00 0.767285E+00
0.919803E+00 0.779089E+00
0.924355E+00 0.790894E+00
0.927997E+00 0.801012E+00
0.932549E+00 0.812816E+00
0.937102E+00 0.826307E+00
0.942564E+00 0.838111E+00
0.948027E+00 0.851602E+00
0.952580E+00 0.866779E+00
0.957132E+00 0.878583E+00

```
0.962595E+00 0.895447E+00
0.968968E+00 0.910624E+00
0.976252E+00 0.927487E+00
0.987177E+00 0.962901E+00
0.990819E+00 0.976391E+00
0.996282E+00 0.100000E+01
```