Bachelor's project

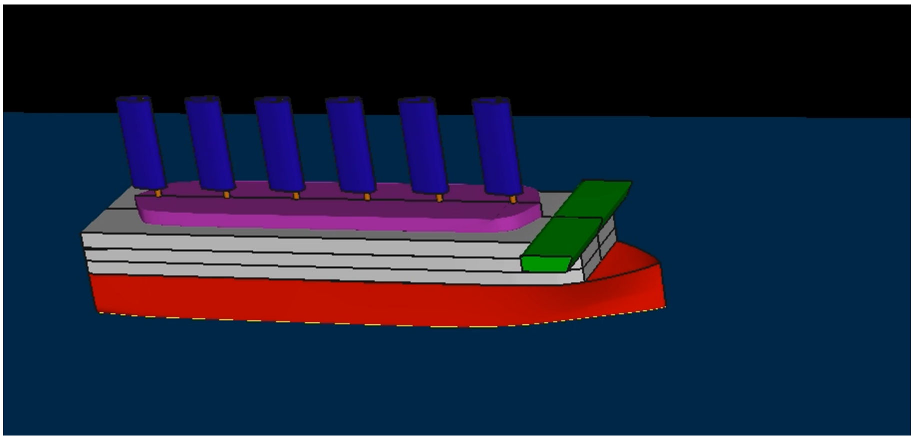
NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Ocean Operations and Civil Engineering

Emil Andrè Huseklepp Tunli

Is wingsail a viable option ?

Bachelor's project in Ship Design
Supervisor: Håvard Vollset Lien
Co-supervisor: Steinar Aasebø

May 2020



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1 Forord

Innholdet i denne oppgaven står for forfatterens regning. Jeg startet arbeidet med oppgaven januar 2021 og ble ferdig mai 2021. På grunn av en pågående SARS coronavirus pandemi ble alle møter og samtaler gjort digitalt på Microsoft teams via internett. Takk til Veileder ved NTNU i Ålesund er Håvard Vollset Lien, og kontaktperson / faglig veileder ved Ulstein AS er Steinar Aasebø for ROPAX krav og wingsail veiledning, Olav Rognebakke veiledning om DNV standard for WAPS.

Sted, dato

signatur

Abstract

Wind assisted propulsion technology have become more relevant after the discovery of fossil fuels impact on the environment. Rising fuel and CO2 tax is making fuel saving technologies such as wingsail more profitable. The purpose of this thesis is to investigate how wingsail can be implemented and estimate a reduction of fuel consumption and CO2 emission. This thesis uses a ROPAX ferry with route Grislehamn-Eckerö. Using momentum theorem, the wingsail forward drive force was calculated by using the monthly dominant wind direction and average wind speed fuel savings was calculated by subtracting the total energy used with wingsail from the total diesel consumption without wingsail . The calculation show that under the conditions on the route Grislehamn-Eckerö was a 1.6% fuel saving possible. The results varied from 8.4% in April to 0,1% in may. Wind direction was the most determining factor for the low fuel savings throughout the year. Calculations using more frequent wind data could get higher fuel savings. Further research on weather statistic for fuel calculation is necessary.

1.1 Sammendrag norsk

Vind assistert framdrift teknologier har blitt mer relevant siden oppdagelsen av at menneskeskapt CO2 har påvirkning som en drivhusgass. Stigende drivstoff og CO2 avgifter gjør det lønnsomt å satse på drivstoffbesparende teknologier som wingsail. Hensikten med denne oppgaven er å undersøke hvordan Wingsail kan bli tatt i bruk og estimere drivstoff og CO2 besparelser. Denne oppgaven bruker en ROPAX ferje med rute Grislehamn-Eckerö. Ved å bruke momentum teori ble Wingsailet forrovervirkende drivkraft var beregnet ved den dominante vindretningen og vindens gjennomsnittshastighet. Trekke ifra det totale energi forbruket. Drivstoffbesparelser ble beregnet ved å trekke drivstoff forbruket når skipet bruker både wingsail ifra drivstofforbruket når skipet bare bruker diesel motor. Beregningene viser at 1,6% drivstoffbesparelser var mulig under forholdene på ruten mellom Grislehamn-Eckerö. Resultatene varierte ifra 8,4% i april til 0,1% i mai. Vind retningen var den mest avgjørende faktoren for de lave drivstoff besparelsene gjennom året. Beregninger med mer detaljert vind data kan gi høyere drivstoff besparelser. Videre undersøkelser om værstatistikk for drivstoff besparelser er nødvendige.

Symbols, abbreviations and concepts

1.2 Wind calculation terms

α is angle of true wind from forward position
A is the projected area to the wind at height h
Δ is the vessels mass
P is the wind pressure

1.3 Ship terms

$\vec{F_{heel}}$ is the force acting on the transverse stability.
H is the vertical center of hydrodynamic resistance to the wind force
LOA is length over all
LCB is the longitudinal center of buoyancy.
LCG is the longitudinal center of buoyancy.
VCG is the vertical center of gravity.
VCB is the vertical center of boyancy.
KM is the distance of baseline to the metercenter
GM is the distance between center of gravity and meter center
AP is the aft ward perpendicular.
FP is the forward perpendicular.
MS is the point in the center of the length between FP and AP.

1.4 Airfoil terms

NACA 0025 is a standard airfoil created and tested by National Advisory Commission for Aeronautics.

1.5 Wind terms

NNE is north north-east or 22.5^o
ENE is east north-east or 67.5^o
ESE is east south-east or 112.5^o
SSE is south south-east or 157.5^o
SSW is south south-west or 202.5^o
WSW is west south-west or 247.5^o
WNW is west north-west or 292.5^o
NNW is north nort-west or 337.5^o

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2 Introduction

Wind powered ships was the dominant way of transportation for millenniums. Wind was becoming less relevant during the industrial revolution. Oil and coal offered a faster and a more reliable travel time. Since coal and oil power are independent of external weather conditions. Wind assisted propulsion technology have become more relevant after the discovery of fossil fuels impact on the environment. There are several competing technologies that harness the power of the wind. The Flettner rotor consists of a spinning cylinder which uses the Magnus effect to accelerate the wind aft wards. Kite sail or skysails uses a kite to catch the wind at a higher altitude. More traditional sails are such as square rigging which catches the wind to drive the ship forward. Bermuda rig is the most common type installed on sailing yacht today and acts like an aerofoil by redirecting the wind from a side way direction to an aft ward direction which creates a forward drive force. Wingsail acts in a similar way only with an actual foil instead of sheets. A design was created in order to calculate resistance stability and strength analysis to insure the feasibility of the wingsail. NACA experiment with airfoil 0025 Bullivant (1941) was used in order to find the lift and drag coefficient. A excel spreadsheet calculating wingsail drive force and fuel consumption by using wind direction, wind speed, route (with course length and direction) and ship speed as input. The program was used to calculate fuel reduction under different condition throughout the year.

This thesis is written for the company Ulstein. It is a technological report about possible reduction in fuel consumption by applying wingsail technology. Bound4Blue wingsail was used as an example for a provider of such technology. Eckerolinjen which is a ROPAX ferry with a route Grislehamn- Eckerö was chosen as a subject for this experiment. Bound4blue n.d. states ”The system has been conceived as a complementary propulsion system, which produces effective thrust from existing winds, reducing the main engine power required and, therefore, delivering fuel consumption and pollutant emissions reductions of up to 40% and it ensures a payback period under 5 years.” This thesis will investigate how wingsail can be implemented and fuel consumption.

3 Literature review

A numerical method for the design of ships with wind-assisted propulsion Viola et al. (2015) was useful in order to design a ship with wingsail in an effective way. Modern windships Hansen, Bloch, and Jens (2000) were useful to find demands and limitations in design with wingsail. Tests of the NACA 0025 and 0035 airfoils in the full-scale wind tunnel Bullivant (1941) were useful to find lift and drag coefficient on the wingsail. DNVGL standard ST0511 Wind assisted propulsion systems DNVGL (2019)(b) were useful in order to calculate possible hazardous conditions for the wingsail. Windfinder n.d. was a use full reference for wind statistic.

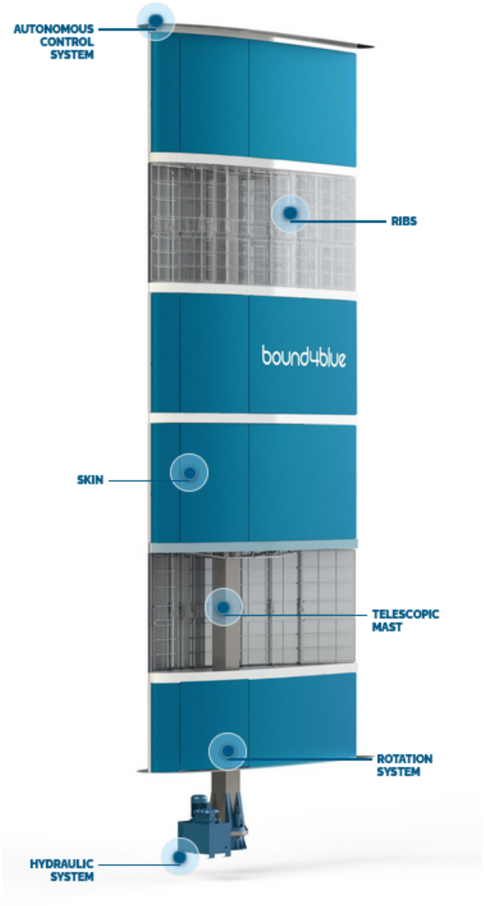


Figure 1: Bound4blue foldable wingsail

4 Wingsail theory

There are several providers of wingsail technology and solutions to deploy the wingsails such as telescopic, cloth or foldable. Bound4blue uses a foldable NACA 0025 foil profile for their rigid wingsail design. The wingsail uses a solid wingsail composed of panels that can fold on top of each other to minimise the wind impact when out of operation.

4.1 How it works

Wingsail works in the same way as an airplane wing. It accelerates the wind aftward which by Newton´s third law creates a force in the opposite direction. This force is what drives a sailing ship forwards.
Bermuda rig is the most common type of rigging. Wingsail uses the same principle as bermuda rig only that it has a three dimensional form rather than sheets. With a solid form it is no need for manual labor to adjust the sails by the wind. The wingsail adjust automatically after the optimal angle of attack.

4.2 Demands for wingsail

Modern wind ship Hansen, Bloch, and Jens (2000) suggested the following demands for modern ships powered by wind.

1. Must be handled automatically without requiring more crew.

2. Must not interfere with the cargo handling.
3. Must not jeopardise the safety of the vessel.
4. Must be steady and reliable with a minimum of maintenance.
5. Must be suitable for navigation upwind as the power from the propellers will shift the apparent wind forward.
6. The air draught of the rig above a reasonable ballast water line must not be more than 60 m for passage of bridges.
7. Must be reasonably easy to retrofit on existing ships.

4.3 Extreme loads

DNVGL (2019)(b) ST0511 2.2.2. put the following criteria A risk assessment addressing all aspects of design, equipment and operation shall be carried out. The following aspects shall be included:
- Severe weather (storm, ice)
- Overspeed
- Vibrations
- Control system failure
- Component failure
- Fire
- Overload
- Static electricity
- Human error.

according to DNVGL (2019)(b) ST0511 2.4.3.3.1 extreme wind loads shall be calculated from the angle of most impact. The most demanding load for the ships stability is with the wind perpendicular to the ships length with the wing sails parallel.

5 Sailing Theory

Bound4blue uses a NACA 0025 airfoil profile for their wingsail. National Advisory committee for aeronautics made a series of wind tunnel tests on the 0025 airfoil described in the report on NACA wind tunnel tests. Bullivant (1941).

5.1 Wind calculation

Momentum theory was used to calculate wingsail loads. In order to make a prediction about the ships fuel savings a mathematical model for predicting the sails propulsion force was needed.

The wind that is acting on the wingsail is called apparent wind. Apparent wind gets distorted compared to true wind by the ships motions. We can convert true wind speed and direction to apparent wind speed and direction by using formula (1) and (2).

$$W_{apparent} = \sqrt{W_{true}^2 + V_{ship}^2 + 2W_{true}V_{ship}\cos\alpha_{true}} \tag{1}$$

$$\beta_{apparent} = \arccos\frac{W_{true}\cos\alpha_{true} + V_{ship}}{W_{apparent}} \tag{2}$$

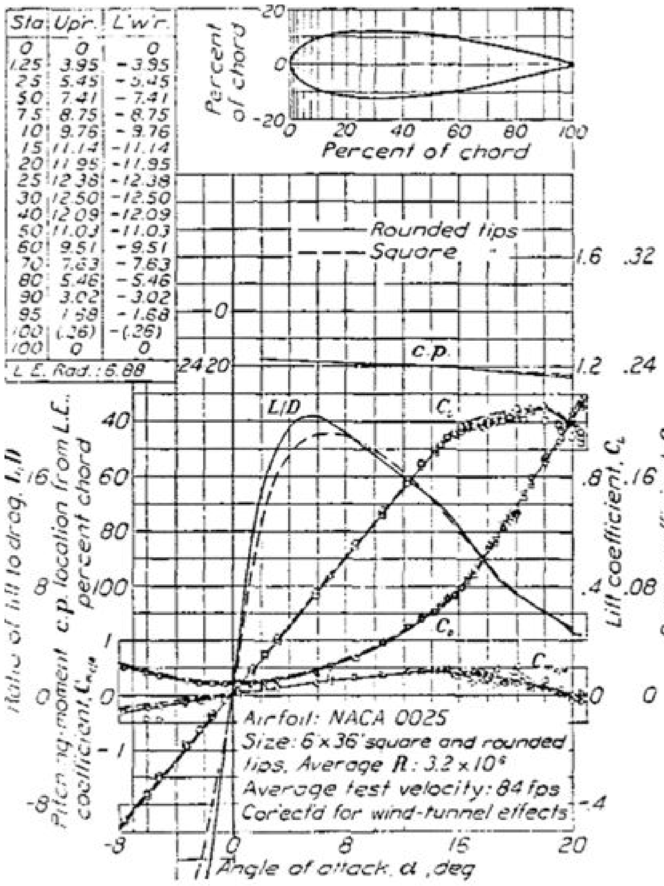


Figure 2: NACA 0025 airfoil. Aspect ratio form wind tunnel testing 1941.

5.2 Wingsail calculation

$$L = C_L \frac{1}{2} \rho W_{apparent}^2 A \tag{3}$$

$$D = C_D \frac{1}{2} \rho W_{apparent}^2 A \tag{4}$$

By using formula (3) and (4) lift and drag can be calculated.
A is the area of the wing. ρ is the density of air $1.225, kg/m^3$ was used. Lift coefficient C_L and drag coefficient C_D was found using NACA wind tunnel test on airfoil 0025 Bullivant (1941) shown in figure 2.
The wing position is a function of angle of attack and apparent wind direction. Since lift always act perpendicular on the wing while drag acts parallel with the wing we can use the wing position to find the total forward and sideways force.The wing position is calculated using formula 5.

$$\theta_{wing} = \beta_{apparent} - \gamma_{angle-of-attack} \tag{5}$$

By using the wing position we can calculate the heeling force and the forward force as shown in formula (6) and (7).

$$F_{heel} = L \cos\theta + D \sin\theta \tag{6}$$

$$F_{forward} = L \sin\theta - D \cos\theta \tag{7}$$

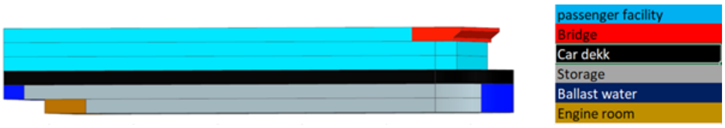


Figure 3: First basic 3D GA. Made using CAD program Simen NX

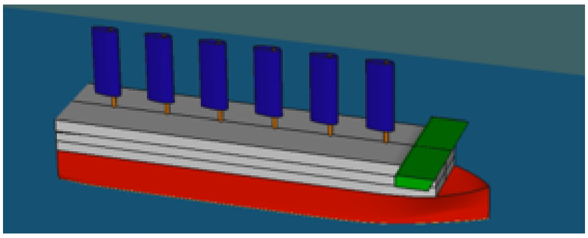


Figure 4: Ship with 6 wingsail 20X8

6 Ship design with wingsail

The ships main task is to transport passengers and cars on a 25 nautical mile long sea voyage. The ship design made in thesis is made in order to do calculations with wing sails on the route between Grislehamn-Eckerö.

6.1 Design demands

The ship has the following customer demands:
1. Length over all (LOA) max 130 meters
2. Max breadth 25meters
3. 2000 passengers and areas for tax free stores.
6. 400 lane-meters
7. Max draught 5.5 meters
8. Service speed 14 knots
9. Trial speed 17 knots
10. Range 2800 nautical miles at 14 knots
11. Crew 140

6.2 Design process

Bottom up approach was chosen for this design as there are no similar ships that currently uses wingsail. The first step was to locate essential systems such as car carrying systems, passenger facility, crew accommodations, life boats, bridge and engine room. The first basic GA is show in figure 3.

The wingsail was placed on top of the superstructure to provide the most airflow. Bound4blue offers two wingsail dimensions 30x12 and 20x8. 4 30X12 wingsails could be fitted on the ship as shown in figure 5 this would have created considerable more lift. 20x8 was chosen to keep the height under 60 meter after suggestion from Modern Windship Hansen, Bloch, and Jens (2000) as shown in figure 4

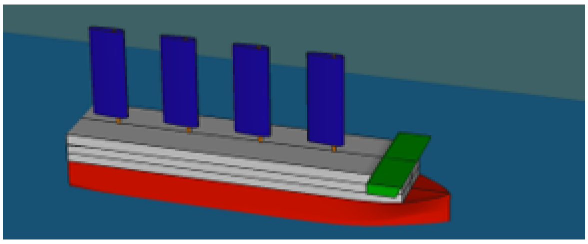


Figure 5: ship with 4 wingsail 30X12

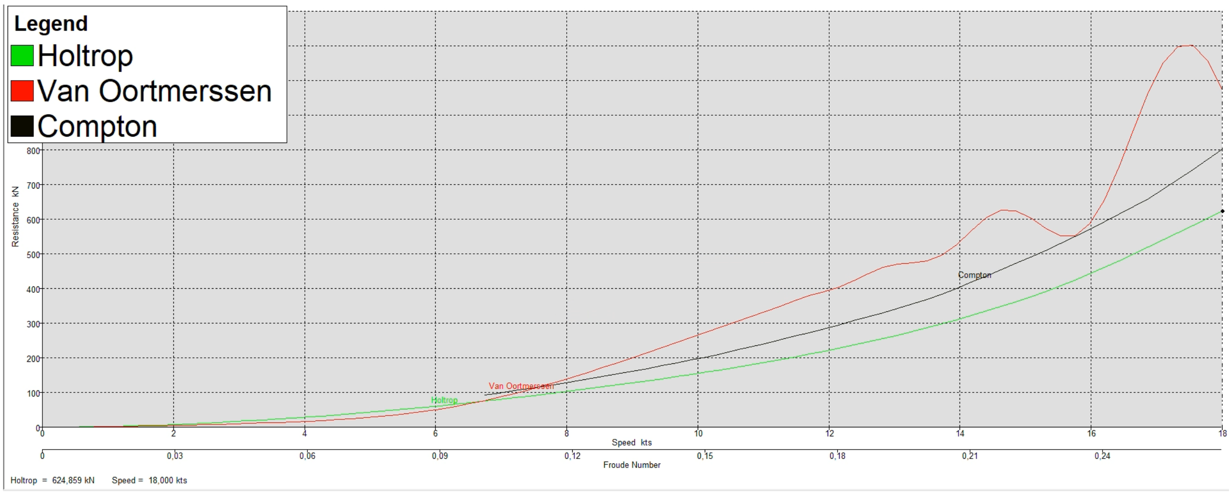


Figure 6: Resistance curve. Holtrop, van Oortmerasen and Compton

The next step was to make a basic hull design which fit the design demands. The hull design was then used to calculate hydro statics and resistance curve shown in figure 6.
The engine room was moved forward of MS in order to correct LCG to LCB. The weight and stability calculation shows that the GM was shorter than 0,25m. The material of superstructure was changed from steel to aluminium in order to increase the GM.

6.3 About the design

The Design is outfitted with 6 20x8 Bound4blue wing sails. The wingsail dimensions was to keep the ship height below 60 meters as the larger 30x12 meter wingsail would make the ship too tall. 6 sails was the most amount of sail that could be fitted on the ship without interfering with the car carrying system. Fitting as many tall and thin wingsail is beneficial instead of few and wide in order to maximise the forward drive force as presented in chapter 3.4 in the article "A numerical method for the design of ships with wind-assisted propulsion" Viola et al. (2015).

The ship uses diesel electric as the main power system. The system is composed by four Wärtsilä 8L32 generators which provide 18480Kw combined.

The ship hull has a straight bow. The Hull is divided into watertight compartments by 7 transverse bulkheads and 3 longitudinal bulkheads in accordance to DNVGL (2019)(a) RU-SHIP, Pt 3, Ch 2, section 2202007 . The free board height is 5,7 meters.The ship has aft and forward doors for loading and offloading cars.
The design consist of 8 decks. The top 4 Decks A-D are reserved for passengers and the top deck has an outdoor area. The muster station and life boats are located in A deck. The car

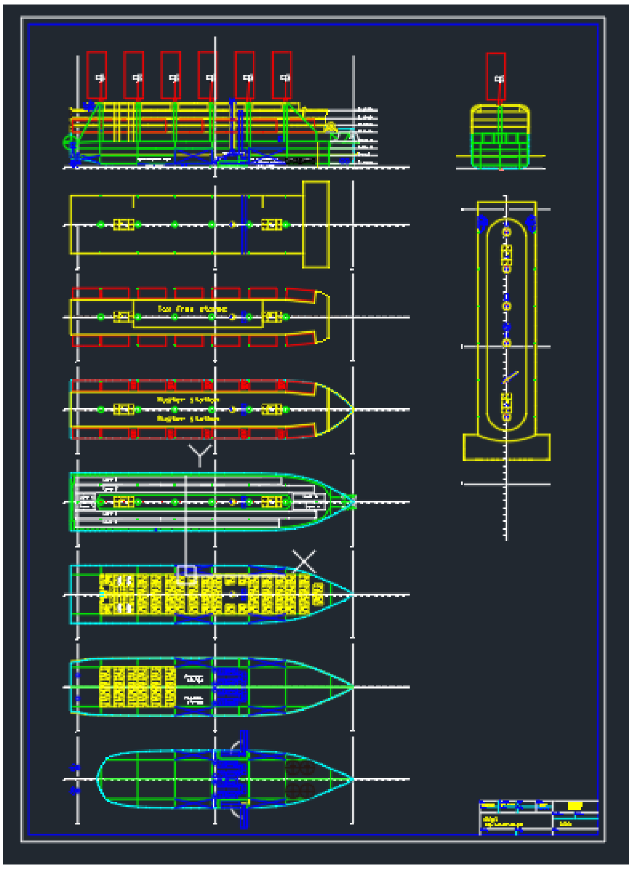


Figure 7: Final GA

lanes are located on deck 3. The crew area is located in deck 1 and 2. final design is shown in figure 7

6.4 Stability

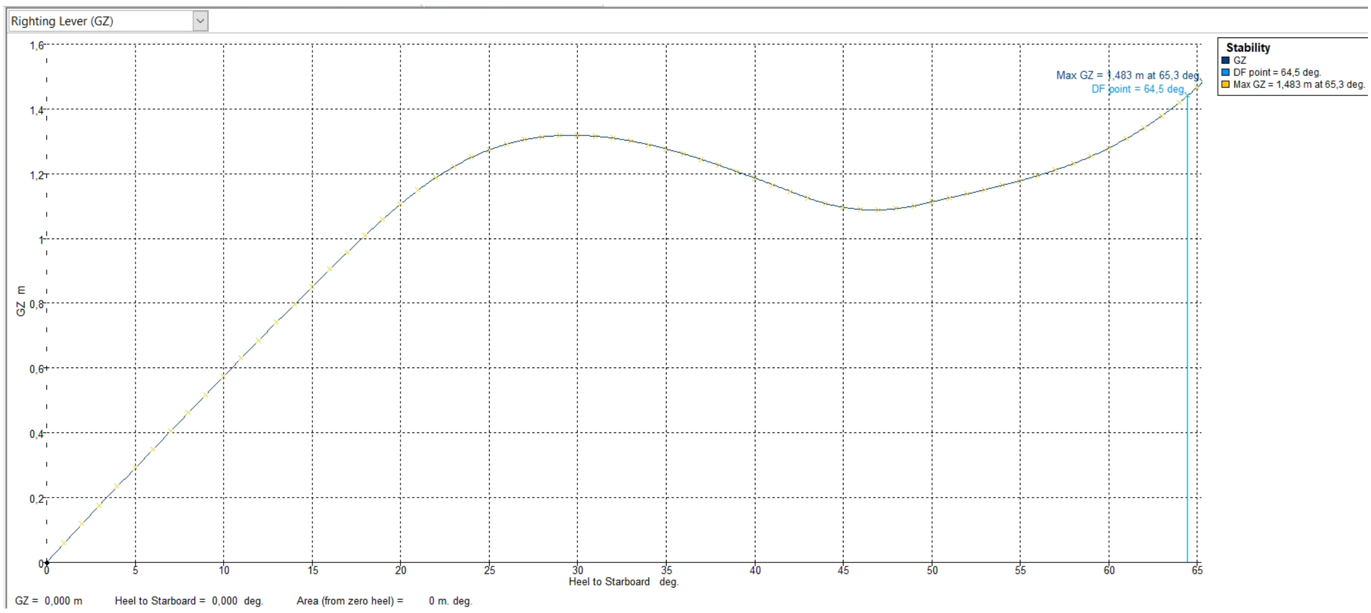
The ships ability to resist rotation around the forward axis is known as transverse stability. The GZ value describes the righting arm the ship has to correct its heeling angle. The GZ arm creates an righting moment with the ships mass. The ship is in equilibrium when the ships GZ value times the ships weight equals the moment acting on the ship.

6.4.1 Static stability

Hydrostatic stability was found by adding the mass and location of every object with a mass over 1 tonne in the ship. The DATA was added into maxsurf stability. Maxsurf uses the hull to find the meter center and compare it to the center of mass found in weight calculations. Maxsurf used these values to create a GZ curve and a still water bending moment.

6.4.2 Wind impact on stability

The sideways wind force have an impact on the ships stability and act perpendicular to the ships length. The sideways wind force drive the ship in a side way direction which creates a resistance acting perpendicular to the ships length. The side way wind and resistance forces act



GZ = 0,000 m

Heel to Starboard = 0,000 deg.

Area (from zero heel) = 0 m. deg.

Figure 8: GZ curve Maxsurf stability

in opposite direction and creates an moment that have a impact on the ships sideways stability.

$$H_w(\theta) = K\left(\frac{PA(h-H)}{g\Delta}\right)\cos^n(\theta) \tag{8}$$

$$H_w = K\left(\frac{F_{heel}(h-H)}{g\Delta}\right) \tag{9}$$

6.4.3 Stability while sailing

The heeling angle is a function of the heeling moment and the ships ability to counter act the heeling moment wich is called a GZ-curve. The GZ curve calculated for this ship is shown in figure 8.

6.4.4 Heeling angle

According to DNVGL (2019)(b) shall the maximum true wind speed be calculated using formula 10.

$$v_{we} = 44\left(\frac{h_L}{10}\right)^{0.5} \tag{10}$$

v_{we} will for this ship be 54 m/s. This will add up to a heeling arm of 1,1m with locked raised sails and the wind facing the ships side perpendicular. The ship will be able to counter act this heeling arm at 22^o heeling angle. 54 m/s is higher than the highest speed measured in the Baltic ocean. Under this condition the WASP unit would go out of operation and lower its height from 20m to 6,8m this would reduce the heeling angle to 14^o. In operation with 25 m/s wind with locked raised sail would the ship have an heeling angle of 5^o. in $8m/s$ wind would the ship have an 0.5^o heeling angle. adaptive stabilizing tanks could create an righting lever of 0,45m this is equal to righting up a 8.5^o heeling angle.

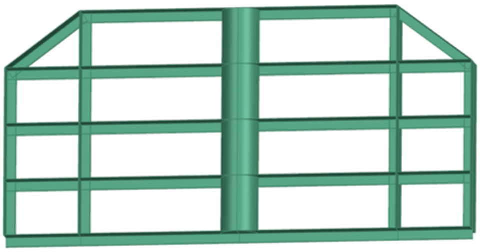
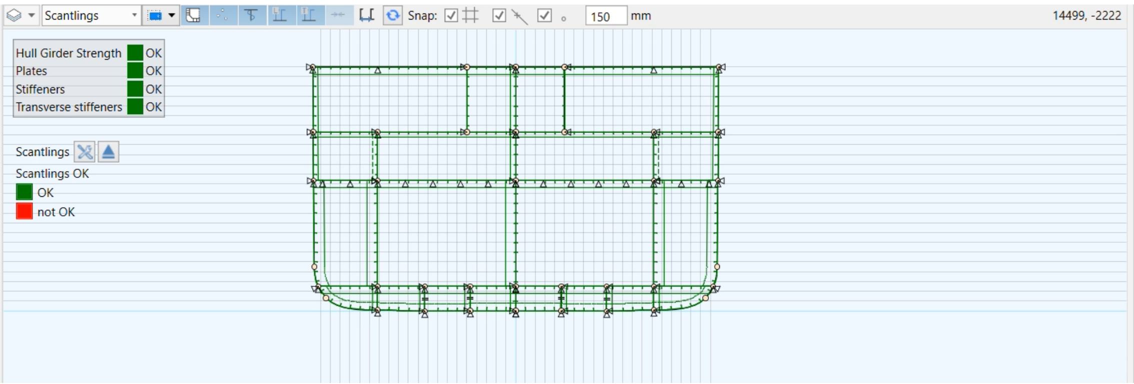


Figure 9: superstructure Wingsail support NX



Hull Girder Strength	🟩	OK
Plates	🟩	OK
Stiffeners	🟩	OK
Transverse stiffeners	🟩	OK

Scantlings

Scantlings OK

🟩 OK

🟥 not OK

Figure 10: , cross section # 95, Hull girder calculations in DNV nauticus hull

6.5 Strength analysis

6.5.1 Global strength

The still water bending moment for hogging and sagging is necessary to calculate the strength of the hull girder. Hogging and sagging condition was calculated using Maxsurf stability. The bending moments was inserted into Nauticus hull shown in figure 12 and 13. The global strength analysis was done in nauticus hull as shown in figure 10. The standard plate thickness was sett to 10 mm. Plate thickness was raised to 15mm in the keel, T-topp and longitudinal bulkhead. Longitudinal stiffener dimension is sett to HP-Bulb: HP 80x5, HP 120x8, Hp 180x10 and transverse girder Welded tbar: T315x100x12/15, T450x120x12/25

6.5.2 Wingsail support structure

The wingsail is supported by the aluminium superstructure shown in figure 9.The highest moment acting on the wingsail support structure was calculated to be $3.1X10^6$. This is under 54 m/s wind.

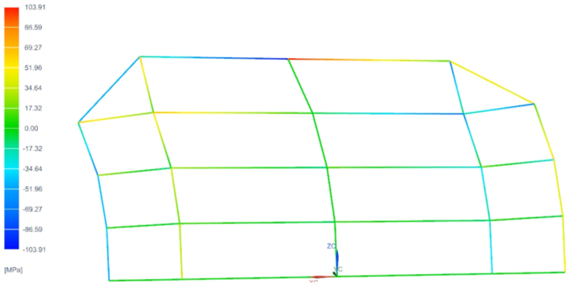


Figure 11: Superstructure, wingsail support FEM analysis NX nastran

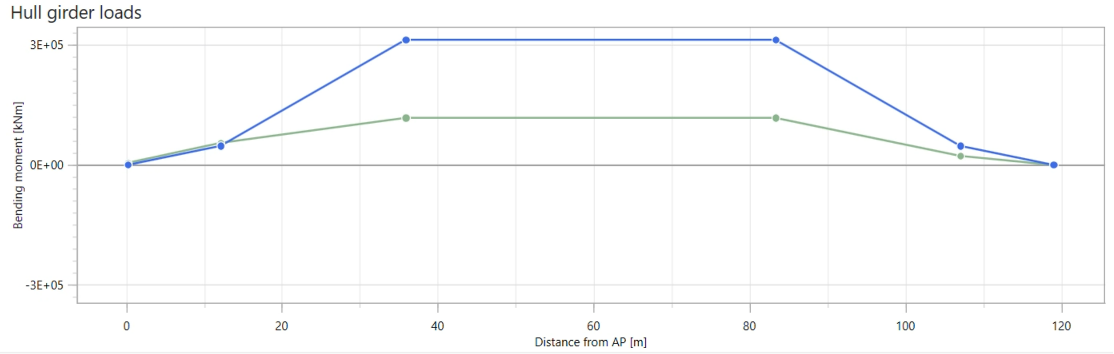


Figure 12: Stillwater bending moments seagoing hogging

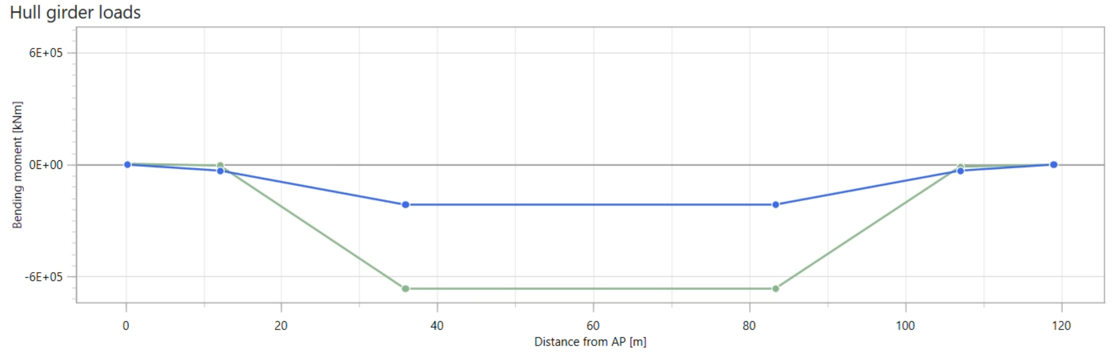


Figure 13: Stillwater bending moments seagoing sagging

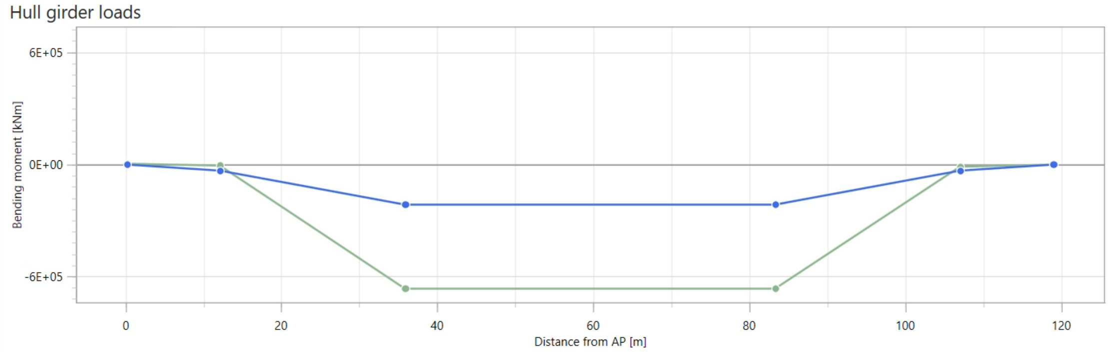


Figure 14: Time table from eckerolinjen

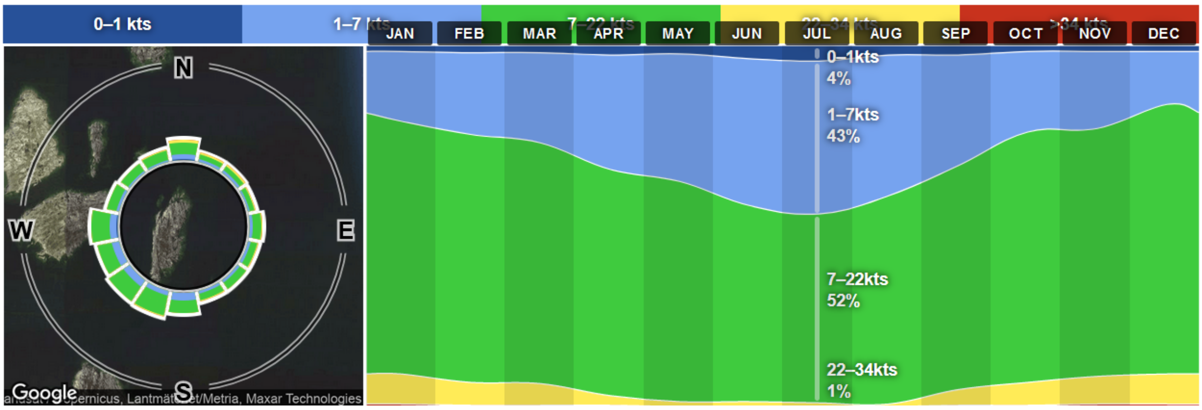


Figure 15: wind statistics Kapellskär,Soderarm https : //www.windfinder.com ,windstatistics, kapellskar,soderarm

7 Sailing the route

Time table was found at Eckerolinjen n.d. The current ferry makes three tour-re-tours in the weekend as shown in figure 14. Travel time must be lower than 2 hours to make three tours a day. This is a condition for the calculations.

The Van Oortmerssen Resistance curve was chosen to represent the ship hydrodynamic Resistance shown in figure 6. In order to make an estimate about fuel savings a route must be sett up.

The different conditions was found using statistic from WindfinderWindfinder n.d. for a nearby measuring station as shown in figure 20.
The standard route shown in figure 16 is the shortest route. It is also the route that the current ferry uses. A excel spreadsheet was created to converted wind speed and direction, ship speed, route direction and distance into fuel usage. Then a comparison between on the same route using only diesel fuel and using wingsail was done in order to find fuel reduction.

7.1 Wind condition

The wind conditions during a year is shown in figure 15. There is most wind from between west and south. The wind speed is most often between 3,6 - 11,3 m/s. The wind gives higher fuel reduction in perpendicular wind.

The wingsail south wind is shown in figure 17. This wind direction is good for sailing and has more than a 45^o wind direction at the lowest. West wind is shown in figure 18. The lowest wind direction here is 17^o which is not good for sailing. West south-west. Wind is shown in figure 19. This wind condition is one of the least favourable wind condition used in this thesis. There are wind directions as low as 6^o. The dominant wind direction and average wind speed is shown in figure 20. This data was used to calculate yearly fuel savings.

Figure 16: Standard route

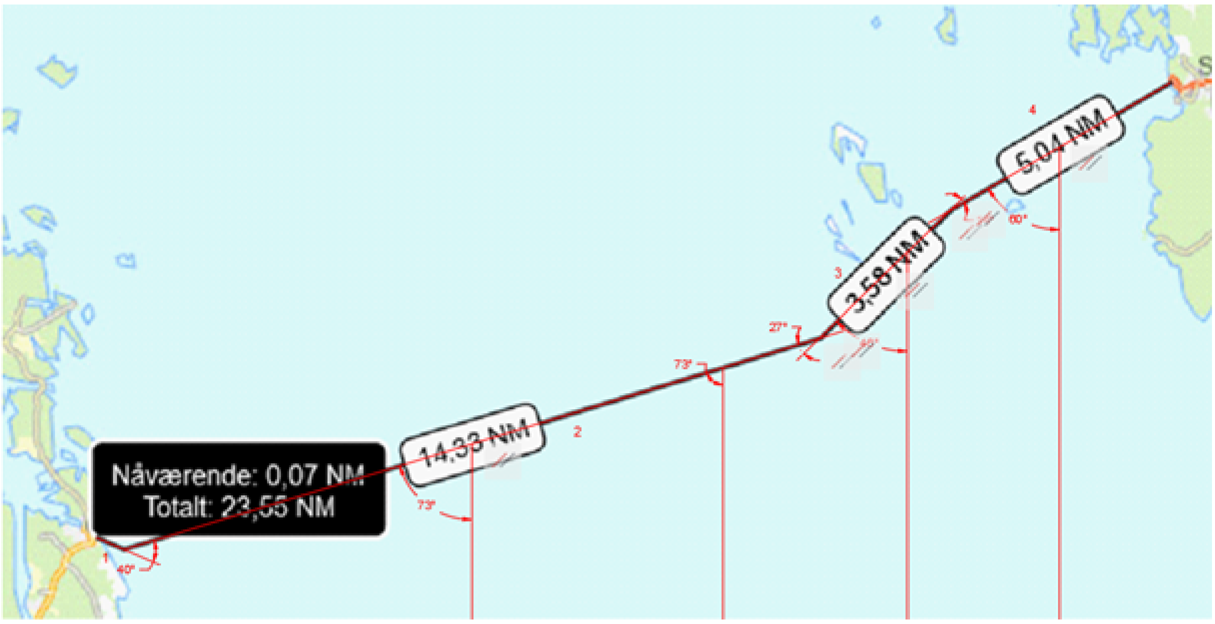


Figure 17: South wind standard route

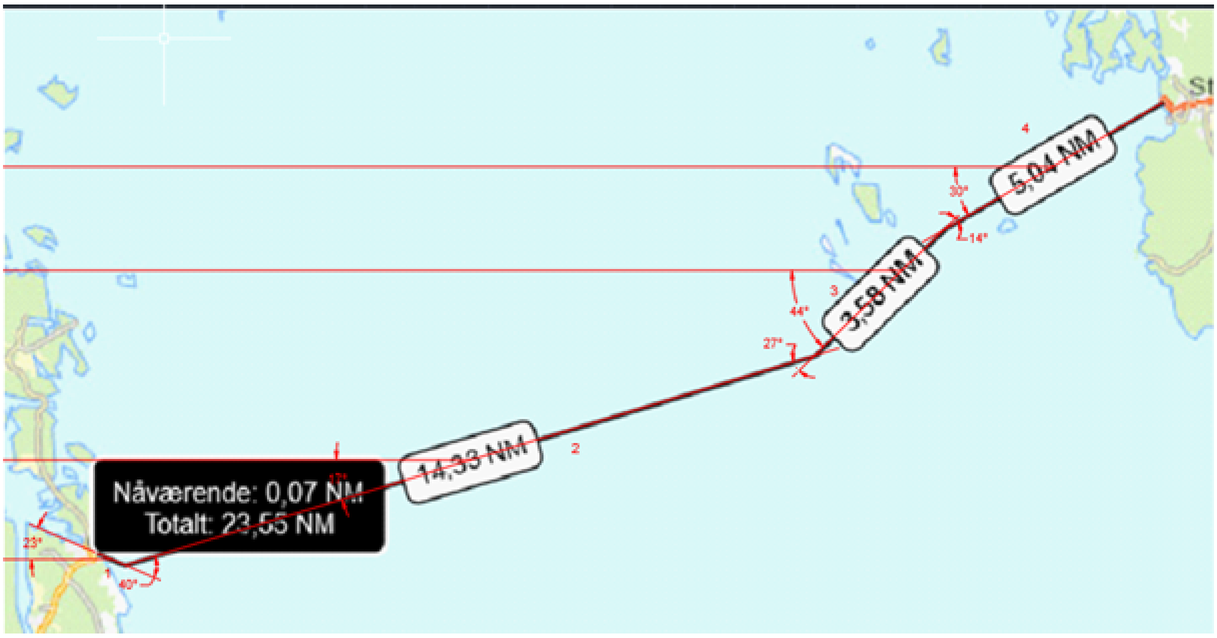


Figure 18: West wind standard route

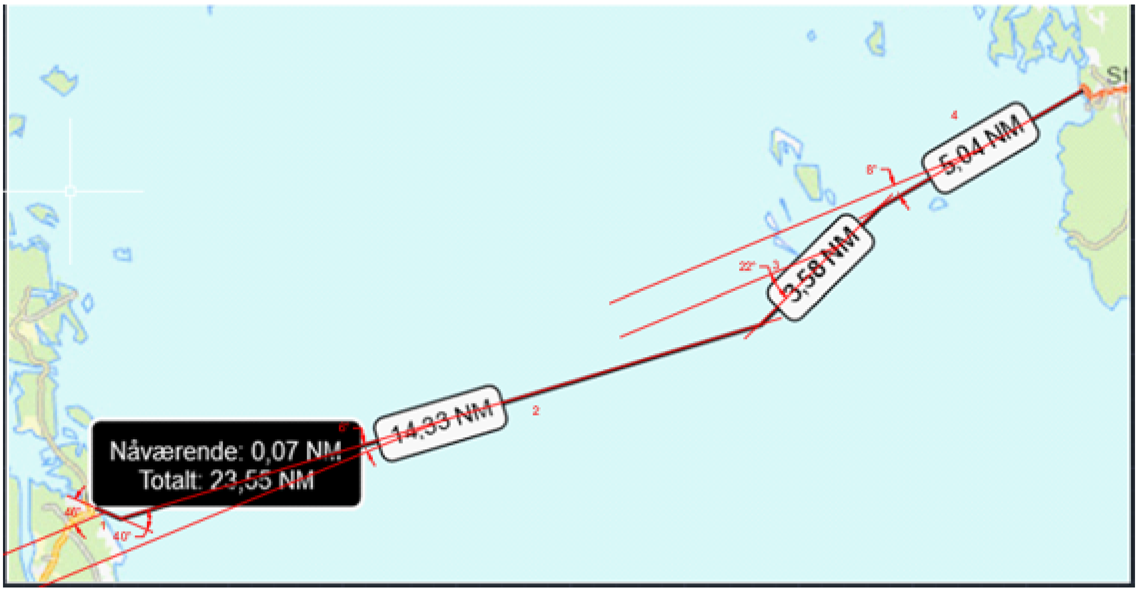


Figure 19: West southwest wind standard route

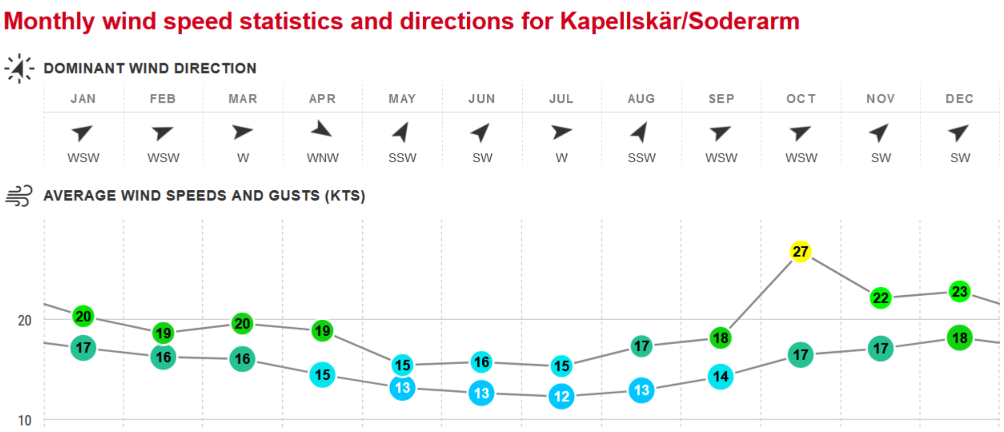


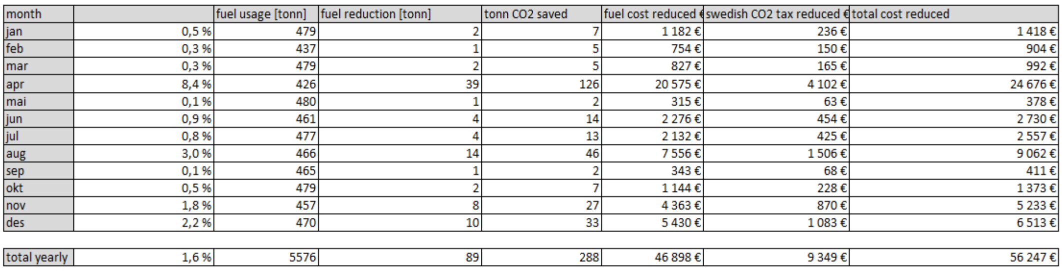
Figure 20: Monthly average wind speed statistics and dominant directions for Kapellskär/Soderarm from windfinder website Windfinder n.d.

7.2 Yearly fuel savings hybrid drive

Windfinder n.d. was used in order to find dominant wind direction and average wind speed for each month as shown in figure 20. Fuel price was found using website Marinemethanol n.d. from January 2020 where it was 525€/tonne for marine gas oil. Since the ship is going to travel in Swedish waters it will pay Swedish carbon tax. Swedish carbon tax was set to 126€/tonne in 2020Taxfoundation n.d. This tax is very likely to increase in near future as it has during the last year.

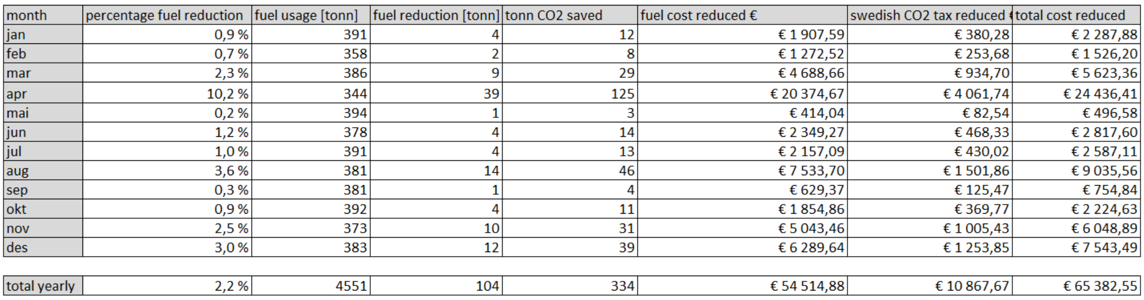
7.3 Design result

Calculations on stability and strength design was within the boundary. The design is feasible.



month		fuel usage [tonn]	fuel reduction [tonn]	tonn CO2 saved	fuel cost reduced €	swedish CO2 tax reduced €	total cost reduced
jan	0,5 %	479	2	7	1 182 €	236 €	1 418 €
feb	0,3 %	437	1	5	754 €	150 €	904 €
mar	0,3 %	479	2	5	827 €	165 €	992 €
apr	8,4 %	426	39	126	20 575 €	4 102 €	24 676 €
mai	0,1 %	480	1	2	315 €	63 €	378 €
jun	0,9 %	461	4	14	2 276 €	454 €	2 730 €
jul	0,8 %	477	4	13	2 132 €	425 €	2 557 €
aug	3,0 %	466	14	46	7 556 €	1 506 €	9 062 €
sep	0,1 %	465	1	2	343 €	68 €	411 €
okt	0,5 %	479	2	7	1 144 €	228 €	1 373 €
nov	1,8 %	457	8	27	4 363 €	870 €	5 233 €
des	2,2 %	470	10	33	5 430 €	1 083 €	6 513 €
total yearly	1,6 %	5576	89	288	46 898 €	9 349 €	56 247 €

Figure 21: yearly fuel reduction, 14 knot ship speed, 3 tour-re-tours a day



month	percentage fuel reduction	fuel usage [tonn]	fuel reduction [tonn]	tonn CO2 saved	fuel cost reduced €	swedish CO2 tax reduced	total cost reduced
jan	0,9 %	391	4	12	€ 1 907,59	€ 380,28	€ 2 287,88
feb	0,7 %	358	2	8	€ 1 272,52	€ 253,68	€ 1 526,20
mar	2,3 %	386	9	29	€ 4 688,66	€ 934,70	€ 5 623,36
apr	10,2 %	344	39	125	€ 20 374,67	€ 4 061,74	€ 24 436,41
mai	0,2 %	394	1	3	€ 414,04	€ 82,54	€ 496,58
jun	1,2 %	378	4	14	€ 2 349,27	€ 468,33	€ 2 817,60
jul	1,0 %	391	4	13	€ 2 157,09	€ 430,02	€ 2 587,11
aug	3,6 %	381	14	46	€ 7 533,70	€ 1 501,86	€ 9 035,56
sep	0,3 %	381	1	4	€ 629,37	€ 125,47	€ 754,84
okt	0,9 %	392	4	11	€ 1 854,86	€ 369,77	€ 2 224,63
nov	2,5 %	373	10	31	€ 5 043,46	€ 1 005,43	€ 6 048,89
des	3,0 %	383	12	39	€ 6 289,64	€ 1 253,85	€ 7 543,49
total yearly	2,2 %	4551	104	334	€ 54 514,88	€ 10 867,67	€ 65 382,55

Figure 22: yearly fuel reduction, 12 knot ship speed, 3 tour-re-tours a day

8 Wingsail result

The route calculations was done both ways between Grislehamn-Eckerö to get accurate data. Dominant wind direction and average wind speed was used. Resistance was calculated for the hull design in Maxsurf Resistance with van Oortmerssen method shown in figure 6.

8.1 Only diesel engine

With only diesel engine is all energy on board provided by diesel. The ship uses 5170 kg diesel on a tour-re-tour. The ship takes 3 tour-re-tours a day which amount to 5665 tonne diesel on a yearly basis.

8.2 Only sail

The calculations on only sail is made by comparing the ships trajectory when only using engine and only using wingsail. With only sail is ship speed a function of wind speed and direction. Other systems need to use electric energy provided by diesel generators. Therefore will the ship use diesel even if it is completely driven forward by sail. The ship can save as much as 65% by only using sail in 12 m/s wind. This would mean a tour-re-tour time of 6 hours. The time sailing the route increases rapidly with decreasing wind speed as shown in figure 23. The ship would not be able to make three tour-re-tours a day and is therefore not an option.

8.3 Hybrid drive

Both wind and engine drives the ship forward with hybrid drive. The engine provides the power that the sail lacks to maintain desired speed.The engine steps up when the wind provides less force and diesel consumption increases.

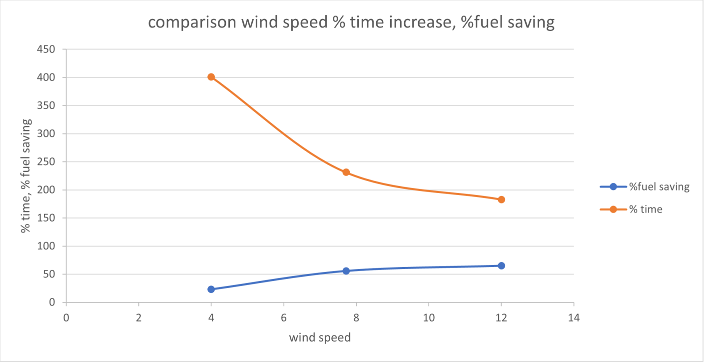


Figure 23: only sail. comparison wind speed fuel saving time increase. 100% = 1,68 h

8.3.1 Fuel saving with hybrid drive

South wind (figure 17) gives 18% fuel savings at 14 knots ship speed and 12 m/s wind speed as shown in figure 24. Slowing the ship speed 2 knots gives 4% decreased fuel consumption at the most as a cause of increased wingsail drive. It also gives a 22% decrease in fuel consumption as a cause of decreased resistance regardless of increased wind drive.

8.3.2 Yearly fuel saving

A yearly fuel saving estimate was done using data from Windfinder n.d. shown in figure 20.The total fuel cost saved in a year is a combination of fuel cost and CO2 cost. The estimate gives a prediction of a 2.2% yearly fuel consumption reduction shown in figure 21.

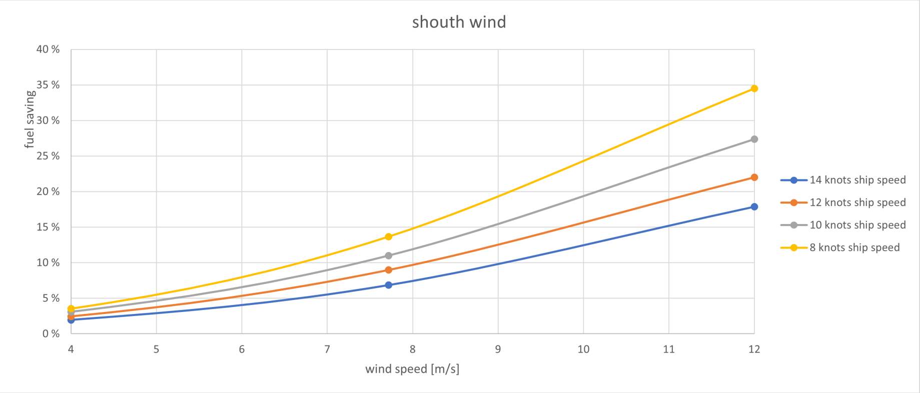


Figure 24: south wind comparison fuel saving individual speed, hybrid compared to only diesel drive

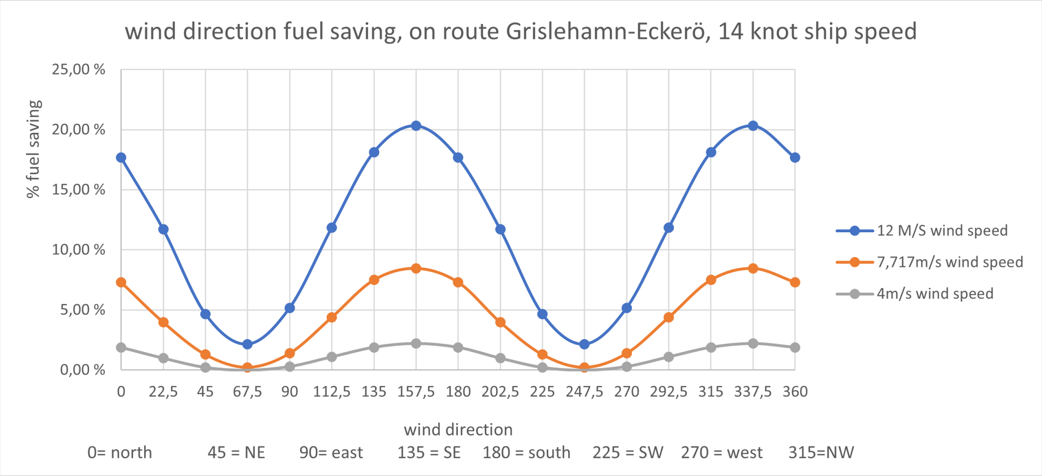
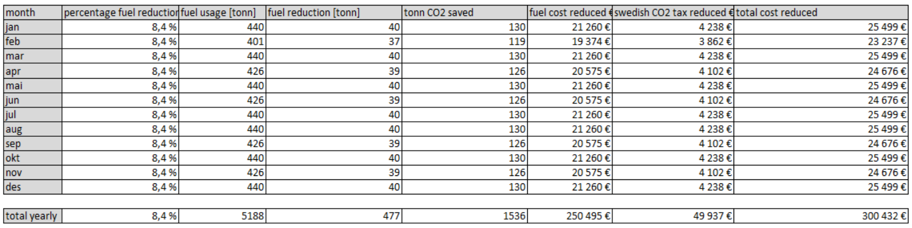


Figure 25: wind direction comparison. 14 knots ship speed with wingsail compared to no wingsail

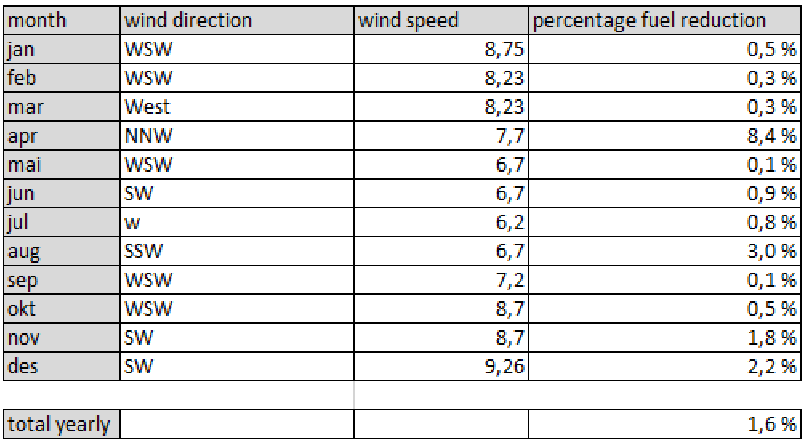
8.3.3 Possible fuel saving

The results varied from 8.4% to 0,1%. Wind speed is not under high fluctuation. Wind direction was the most determining factor for the low fuel savings throughout the year. The April conditions gives a 8.4% fuel saving with a NNW wind direction and a 7.7m/s wind speed. By extending April condition throughout a year gives a 300 000 € fuel cost reduction. April conditions shows what could be achieved with a more advantageous wind direction.



month	percentage fuel reductio	fuel usage [tonn]	fuel reduction [tonn]	tonn CO2 saved	fuel cost reduced €	swedish CO2 tax reduced €	total cost reduced
jan	8,4 %	440	40	130	21 260 €	4 238 €	25 499 €
feb	8,4 %	401	37	119	19 374 €	3 862 €	23 237 €
mar	8,4 %	440	40	130	21 260 €	4 238 €	25 499 €
apr	8,4 %	426	39	126	20 575 €	4 102 €	24 676 €
mai	8,4 %	440	40	130	21 260 €	4 238 €	25 499 €
jun	8,4 %	426	39	126	20 575 €	4 102 €	24 676 €
jul	8,4 %	440	40	130	21 260 €	4 238 €	25 499 €
aug	8,4 %	440	40	130	21 260 €	4 238 €	25 499 €
sep	8,4 %	426	39	126	20 575 €	4 102 €	24 676 €
okt	8,4 %	440	40	130	21 260 €	4 238 €	25 499 €
nov	8,4 %	426	39	126	20 575 €	4 102 €	24 676 €
des	8,4 %	440	40	130	21 260 €	4 238 €	25 499 €
total yearly	8,4 %	5188	477	1536	250 495 €	49 937 €	300 432 €

Figure 26: monthly fuel reduction, 14 knot ship speed, 3 tour-re-tours a day, April condition for 1 year



month	wind direction	wind speed	percentage fuel reduction
jan	WSW	8,75	0,5 %
feb	WSW	8,23	0,3 %
mar	West	8,23	0,3 %
apr	NNW	7,7	8,4 %
mai	WSW	6,7	0,1 %
jun	SW	6,7	0,9 %
jul	w	6,2	0,8 %
aug	SSW	6,7	3,0 %
sep	WSW	7,2	0,1 %
okt	WSW	8,7	0,5 %
nov	SW	8,7	1,8 %
des	SW	9,26	2,2 %
total yearly			1,6 %

Figure 27: Monthly fuel, wind direction savings, 14 knot ship speed, 3 tour-re-tours a day,

9 Discussion

Monthly dominant wind direction is used to predict fuel savings. This could give an inaccurate result as the dominant wind direction shows which wind direction that occur most often in a month. The calculations could give more favourable results if the daily dominant wind direction was used instead of monthly. Figure 15 shows that there is wind from more favourable wind directions. This is not the case in figure 20 which was used in calculations.

Wind direction and speed has a large impact on fuel savings as shown in figure 25. The monthly dominant wind direction is more often than not between west to south-west as shown in figure 27. September is the month with most fuel savings, this is because of the favourable wind direction from north north-west. There would be more beneficial usage of wingsail in an environment with more north-west to North or south east to south wind direction. This is shown in figure 25.

10 Conclusion

The 1.6% fuel reduction figure 21 is not as high as stated by Bound4blue Bound4blue n.d. Payback time would depend on the cost of installation and components but could become more profitable with rising carbon tax.

10.1 Fuel savings

It is estimated that the ship can save around 1.6% of the yearly fuel cost by using wingsail as shown in figure 21. Using dominant wind direction does not give a very accurate prediction but are likely to give a worse prediction of fuel savings than in a real scenario since the dominant wind direction is unfavorable in terms of fuel saving as shown in figure 25. By slowing the ship the impact of wingsail increases as the apparent wind comes more perpendicular to the ship. Slowing the speed from 14kts to 12kts reduces 22% fuel in itself by reduction in resistance. The wingsail manage to add 0.6% extra fuel reduction as shown in figure 22.

10.2 Payback time

The annual cost savings of 56 247€ predicted in this thesis as shown in figure 21. That would amount to 281 235€ in 5 years. It is possible that this thesis show conservative estimate on fuel reduction. A comparison between October condition and April in figure 27 condition show the difference in wind direction has a large impact on fuel saving. Further calculation with daily dominant wind direction instead of monthly wind direction is more accurate and could give a different prediction.

10.3 Predictions for the future

The profitability of this systems wold increase when international pressure for higher CO2 tax increases.

11 Recommendations

11.1 Strategical

The fuel savings from wing sails calculated in this thesis is not enough alone to reach the demand for reduced CO2 emission. The wingsail could work favorable for instillation of a hybrid system with battery-diesel propulsion system. The wind could increase the time of battery propulsion in a diesel-battery hybrid system. There could also be beneficial to lower the speed and instead add more ferries to the same route.

11.2 Tactical

The wingsail could have a positive effect on the aesthetic design of the ship. Wingsail could give positive advertisement to the ferry as public interest in reducing CO2 emission increases.

12 Summary

A Design was created and in order to calculate stability, strength and resistance. Wingsail drive and drag force was calculated by using momentum theory. Dominant wind direction and average wind speed was used. An excel spreadsheet was created to calculate fuel consumption. Result show a 1.6% fuel reduction. There is a possibility that more detailed DATA would have estimated higher reduction in fuel consumption..

References

Bound4blue (n.d.). *Rigid wingsail system.* URL: `https://bound4blue.com/en/wingsail`. (accessed: 06.05.2021).

Bullivant, W Kenneth ((1941)). “Tests of the NACA 0025 and 0035 airfoils in the full-scale wind tunnel”. In: *Annual Report-National Advisory Committee for Aeronautics* 27, p. 91.

DNVGL ((2019)[a]). “General arrangement design”. In: *DNVGL* Part 3 Hull, pp. 4–25.

– ((2019)[b]). “Wind assisted propulsion systems”. In: *DNVGL* ST-0511, pp. 4–25.

Eckerolinjen (n.d.). *Time table GRISSLEHAMN - ECKERÖ.* URL: `https://www.eckerolinjen.se/en/timetable`. (accessed: 13.05.2021).

Hansen, Knud E, Martin Rosander Bloch, and OV Jens ((2000)). “Modern windships”. In: *Copenhagen: Knud E Hansen.*

Marinemethanol (n.d.). *Fuel price comparison.* URL: `http://www.marinemethanol.com/?nav=meohp`. (accessed: 06.05.2021).

Taxfoundation (n.d.). *Looking Back on 30 Years of Carbon Taxes in Sweden.* URL: `https://taxfoundation.org/sweden-carbon-tax-revenue-greenhouse-gas-emissions/`. (accessed: 06.05.2021).

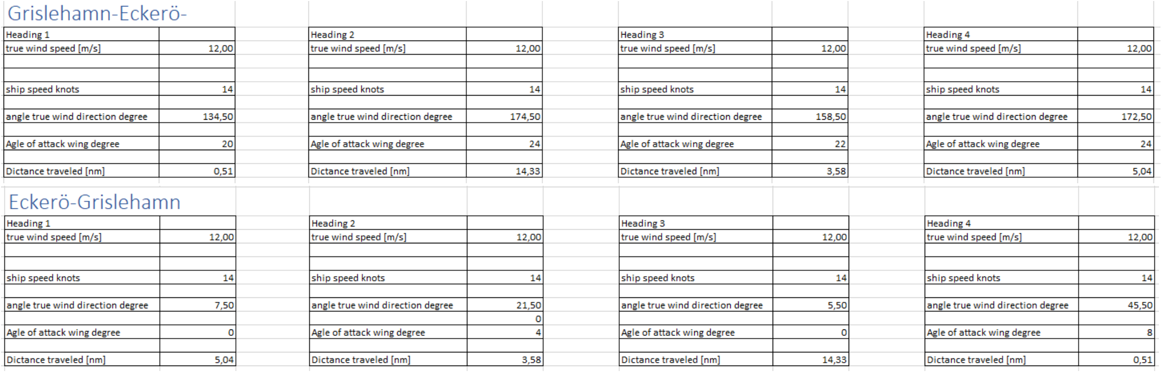
Viola, Ignazio Maria et al. ((2015)). “A numerical method for the design of ships with wind-assisted propulsion”. In: *Ocean Engineering* 105, pp. 33–42.

Windfinder (n.d.). *windstatistics/kapellskar$_s$oderarm.* URL: `https://www.windfinder.com/windstatistics/kapellskar_soderarm`. (accessed: 06.05.2021).

A Appendix: A

A.1 Excel spreadsheet fuel consumption

Input Excel spreadsheet:
Converts true wind to apparent wind. Lift and drag coefficient is extruded by VLOOKUP command from a table for NACA 0025 airfoil Aspect ratio form wind tunnel testing 1941. Converts lift and drag to propulsion force and heeling force.



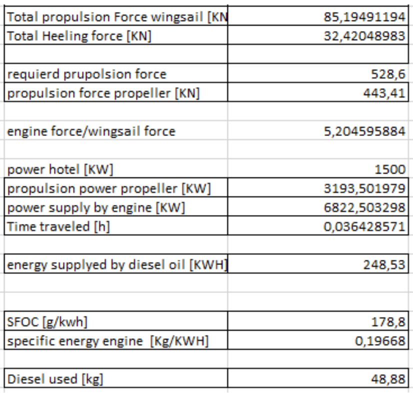
Grislehamn-Eckerö-

Heading 1		Heading 2		Heading 3		Heading 4	
true wind speed [m/s]	12,00	true wind speed [m/s]	12,00	true wind speed [m/s]	12,00	true wind speed [m/s]	12,00
ship speed knots	14	ship speed knots	14	ship speed knots	14	ship speed knots	14
angle true wind direction degree	134,50	angle true wind direction degree	174,50	angle true wind direction degree	158,50	angle true wind direction degree	172,50
Agle of attack wing degree	20	Agle of attack wing degree	24	Agle of attack wing degree	22	Agle of attack wing degree	24
Dictance traveled [nm]	0,51	Dictance traveled [nm]	14,33	Dictance traveled [nm]	3,58	Dictance traveled [nm]	5,04

Eckerö-Grislehamn

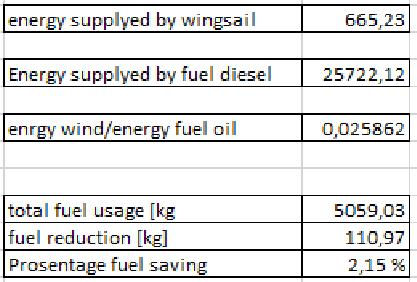
Heading 1		Heading 2		Heading 3		Heading 4	
true wind speed [m/s]	12,00	true wind speed [m/s]	12,00	true wind speed [m/s]	12,00	true wind speed [m/s]	12,00
ship speed knots	14	ship speed knots	14	ship speed knots	14	ship speed knots	14
angle true wind direction degree	7,50	angle true wind direction degree	21,50	angle true wind direction degree	5,50	angle true wind direction degree	45,50
			0				
Agle of attack wing degree	0	Agle of attack wing degree	4	Agle of attack wing degree	0	Agle of attack wing degree	8
Dictance traveled [nm]	5,04	Dictance traveled [nm]	3,58	Dictance traveled [nm]	14,33	Dictance traveled [nm]	0,51

The spreadsheet then calculates the necessary engine power to maintain speed. Fuel consumption is calculated by multiplying the engine power by time and specific energy.



Total propulsion Force wingsail [KN	85,19491194
Total Heeling force [KN]	32,42048983
requierd prupolsion force	528,6
propulsion force propeller [KN]	443,41
engine force/wingsail force	5,204595884
power hotel [KW]	1500
propulsion power propeller [KW]	3193,501979
power supply by engine [KW]	6822,503298
Time traveled [h]	0,036428571
energy supplyed by diesel oil [KWH]	248,53
SFOC [g/kwh]	178,8
specific energy engine [Kg/KWH]	0,19668
Diesel used [kg]	48,88

Total fuel consumption is calculated by summing diesel used on each heading. The percentage fuel saving is calculated by comparing fuel consumption without wingsail to consumption with wingsail.



energy supplyed by wingsail	665,23
Energy supplyed by fuel diesel	25722,12
enrgy wind/energy fuel oil	0,025862
total fuel usage [kg	5059,03
fuel reduction [kg]	110,97
Prosentage fuel saving	2,15 %

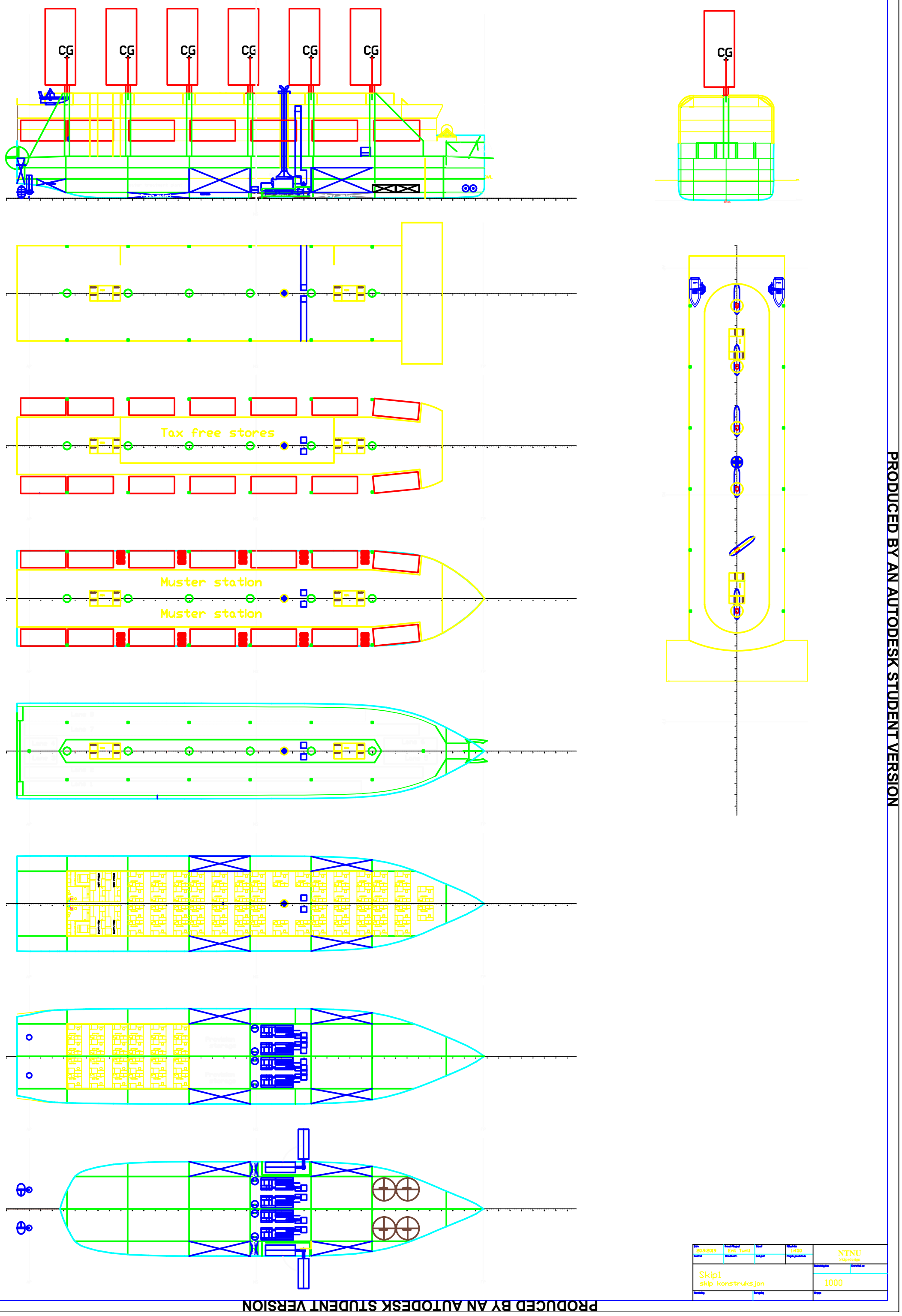
Eckerö-Grislehamn

Heading 1		Heading 2		Heading 3		Heading 4			
true windspeed	12,00	true windspeed	12,00	true windspeed	12,00	true windspeed	12,00		
								energy supplyed	39,09
shipspeed knots	14	shipspeed knots	14	shipspeed knots	14	shipspeed knots	14		
								Energy supplyed	13112,73
angle true wind	7,50	angle true wind	21,50	angle true wind -	5,50	angle true wind -	45,50		
			0					enrgy wind/ener	0,00
Agle of attack w	0	Agle of attack w	4	Agle of attack w	0	Agle of attack w	8		
Distance travel	5,04	Distance travel	3,58	Distance travel	14,33	Distance travel	0,51	total fuel usage	2579,01
energy used [KV	2833,56	energy used [K	1963,34	energy used [KV	8056,61	energy used [KV	259,22		
Diesel used [kg]	557,30	Diesel used [kg]	386,15	Diesel used [kg]	1584,57	Diesel used [kg]	50,98		
shipspeed m/s	7,20	shipspeed m/s	7,20	shipspeed m/s	7,20	shipspeed m/s	7,20		
Apparent wind a	4,69	Apparent wind a	13,47	Apparent wind d	3,44	Apparent wind d	28,73		
Apparent wind [	19,2	Apparent wind [	18,9	Apparent wind [	19,2	Apparent wind [	17,8		
Cord lenth [m]	8	Cord lenth [m]	8	Cord lenth [m]	8	Cord lenth [m]	8		
Height [m]	20	Height [m]	20	Height [m]	20	Height [m]	20		
width [m]	1,387	width [m]	1,387	width [m]	1,387	width [m]	1,387		
density air [kg/	1,225	density air [kg/	1,225	density air [kg/m	1,225	density air [kg/m	1,225		
Kinematick visc	0,000015	Kinematick visc	0,000015	Kinematick visc	0,000015	Kinematick visc	0,000015		
Reynolds numb	10220628	Reynolds numb	10072770	Reynolds numbe	10230128	Reynolds numbe	9496127		
lift coeficient	0	lift coeficient	0,25	lift coeficient	0	lift coeficient	0,5		
drag coeficient	0,005	drag coeficient	0,008	drag coeficient	0,005	drag coeficient	0,015		
lift on wing [N]	0	lift on wing [N]	17478,19136	lift on wing [N]	0	lift on wing [N]	31068,59775		
drag on wing [N]	359,901623	drag on wing [N]	559,3021237	drag on wing [N]	360,5709647	drag on wing [N]	932,0579325		
wing position de	4,69	wing position de	9,47	wing position de	3,44	wing position de	20,73		
propulsion force	0	propulsion force	2,874466423	propulsion force	0	propulsion force	10,99780763		
Heeling force w	0,029416016	Heeling force w	17,33218641	Heeling force wi	0,021620341	Heeling force wi	29,38687821		
drag Forces win	0,358697472	drag Forces win	0,551686511	drag Forces win-	0,359922188	drag Forces win-	0,871708319		
Total propulsion	-2,15218483	Total propulsion	13,93667947	Total propulsion	-2,159533128	Total propulsion	60,75659586		
Total Heeling fo	0,176496097	Total Heeling fo	103,9931185	Total Heeling fo	0,129722044	Total Heeling fo	176,3212692		
requierd propul	528,6	requierd propul	528,6	requierd propul	528,6	requierd propul	528,6		
propulsion force	530,75	propulsion force	514,66	propulsion force	530,76	propulsion force	467,84		
engine force/wi	-246,6108753	engine force/wi	36,92869034	engine force/wi	-245,775129	engine force/wi	7,700289944		
power hotel [KV	1500	power hotel [KV	1500	power hotel [KW	1500	power hotel [KW	1500		
propulsion powe	3822,59518	propulsion powe	3706,719604	propulsion powe	3822,648104	propulsion powe	3369,512162		
power engine [K	7870,991967	power engine [K	7677,866007	power engine [K	7871,080174	power engine [K	7115,853603		
Time traveled [	0,36	Time traveled [	0,255714286	Time traveled [H	1,023571429	Time traveled [H	0,036428571		
SFOC [g/kwh]	178,8	SFOC [g/kwh]	178,8	SFOC [g/kwh]	178,8	SFOC [g/kwh]	178,8		
specific energy	0,19668	specific energy	0,19668	specific energy	0,19668	specific energy	0,19668		
power wingsail [	-30,13058762	power wingsail [	195,1135126	power wingsail [	-30,2334638	power wingsail [	850,592342		
energy from win	-10,84701154	energy from win	49,8933125	energy from win	-30,94610973	energy from win	30,98586389		

Grislehamn-Eckerö-

Heading 1		Heading 2		Heading 3		Heading 4	
true windspeed [m/s]	12,00	true windspeed [m/s]	12,00	true windspeed [m/s]	12,00	true windspeed [m/s]	12,00
shipspeed knots	14	shipspeed knots	14	shipspeed knots	14	shipspeed knots	14
angle true wind direction degree	134,50	angle true wind direction degree	174,50	angle true wind direction degree	158,50	angle true wind direction degree	172,50
Agle of attack wing degree	20	Agle of attack wing degree	24	Agle of attack wing degree	22	Agle of attack wing degree	24
Distance traveled [nm]	0,51	Distance traveled [nm]	14,33	Distance traveled [nm]	3,58	Distance traveled [nm]	5,04
energy supplyed by diesel oil [KWH	248,53	energy supplyed by diesel oil [KW	7765,48	energy supplyed by diesel oil [KV	1873,52	energy supplyed by diesel oil [KWH	2721,86
Diesel used [kg]	48,88	Diesel used [kg]	1527,31	Diesel used [kg]	368,48	Diesel used [kg]	535,34
shipspeed m/s	7,20	shipspeed m/s	7,20	shipspeed m/s	7,20	shipspeed m/s	7,20
Apparent wind direction degree	98,04	Apparent wind direction degree	166,37	Apparent wind direction degree	132,02	Apparent wind direction degree	161,55
Apparent wind [m/s]	8,6	Apparent wind [m/s]	4,9	Apparent wind [m/s]	5,9	Apparent wind [m/s]	4,9
Cord lenth [m]	8	Cord lenth [m]	8	Cord lenth [m]	8	Cord lenth [m]	8
Height [m]	20	Height [m]	20	Height [m]	20	Height [m]	20
width [m]	1,387	width [m]	1,387	width [m]	1,387	width [m]	1,387
density air [kg/m^3]	1,225	density air [kg/m^3]	1,225	density air [kg/m^3]	1,225	density air [kg/m^3]	1,225
Kinematick viscosity [m^2/s]	0,000015	Kinematick viscosity [m^2/s]	0,000015	Kinematick viscosity [m^2/s]	0,000015	Kinematick viscosity [m^2/s]	0,000015
Reynolds number	4610095	Reynolds number	2602670	Reynolds number	3157326	Reynolds number	2639728
lift coeficient	1,025	lift coeficient	1	lift coeficient	1,05	lift coeficient	1
drag coeficient	0,16	drag coeficient	0,2	drag coeficient	0,18	drag coeficient	0,2
lift on wing [N]	15010,7462	lift on wing [N]	4667,633	lift on wing [N]	7212,514	lift on wing [N]	4801,501
drag on wing [N]	2343,14087	drag on wing [N]	933,5266	drag on wing [N]	1236,431	drag on wing [N]	960,3003
wing position degree	78,04	wing position degree	142,37	wing position degree	110,02	wing position degree	137,55
propulsion force wingsail [KN]	14,68479557	propulsion force wingsail [KN]	2,850003	propulsion force wingsail [KN]	6,776679	propulsion force wingsail [KN]	3,240692
Heeling force wingsail [KN]	5,403414972	Heeling force wingsail [KN]	-3,12652	Heeling force wingsail [KN]	-1,307489	Heeling force wingsail [KN]	-2,89479
drag Forces wingsail [KN]	0,485643582	drag Forces wingsail [KN]	-0,7393	drag Forces wingsail [KN]	-0,423292	drag Forces wingsail [KN]	-0,70859
Total propulsion Force wingsail [KN	85,19491194	Total propulsion Force wingsail [	21,53584	Total propulsion Force wingsail [	43,19983	Total propulsion Force wingsail [K	23,69567
Total Heeling force [KN]	32,42048983	Total Heeling force [KN]	-18,7591	Total Heeling force [KN]	-7,844935	Total Heeling force [KN]	-17,3687
requierd prupolsion force	528,6	requierd prupolsion force	528,6	requierd prupolsion force	528,6	requierd prupolsion force	528,6
propulsion force propeller [KN]	443,41	propulsion force propeller [KN]	507,06	propulsion force propeller [KN]	485,40	propulsion force propeller [KN]	504,90
engine force/wingsail force	5,204595884	engine force/wingsail force	23,54513	engine force/wingsail force	11,23616	engine force/wingsail force	21,30788
power hotel [KW]	1500	power hotel [KW]	1500	power hotel [KW]	1500	power hotel [KW]	1500
propulsion power propeller [KW]	3193,501979	propulsion power propeller [KW]	3651,989	propulsion power propeller [KW]	3495,96	propulsion power propeller [KW]	3636,433
power supply by engine [KW]	6822,503298	power supply by engine [KW]	7586,648	power supply by engine [KW]	7326,6	power supply by engine [KW]	7560,722
Time traveled [h]	0,036428571	Time traveled [h]	1,023571	Time traveled [h]	0,255714	Time traveled [h]	0,36
SFOC [g/kwh]	178,8	SFOC [g/kwh]	178,8	SFOC [g/kwh]	178,8	SFOC [g/kwh]	178,8
specific energy engine [Kg/KWH]	0,19668	specific energy engine [Kg/KWH	0,19668	specific energy engine [Kg/KWH	0,19668	specific energy engine [Kg/KWH]	0,19668
power wingsail [KW]	1192,728767	power wingsail [KW]	301,5018	power wingsail [KW]	604,7976	power wingsail [KW]	331,7393
energy from wingsail [KWh]	43,44940509	energy from wingsail [KWh]	308,6086	energy from wingsail [KWh]	154,6554	energy from wingsail [KWh]	119,4262

energy supplyed by wingsail [KWH]	
Energy supplyed by fuel diesel [KWh]	
enrgy wind/energy fuel oil	
total fuel usage [kg]	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Tax free stores
Muster station
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Dato
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Konstr/Tegnet
Emil Tunli
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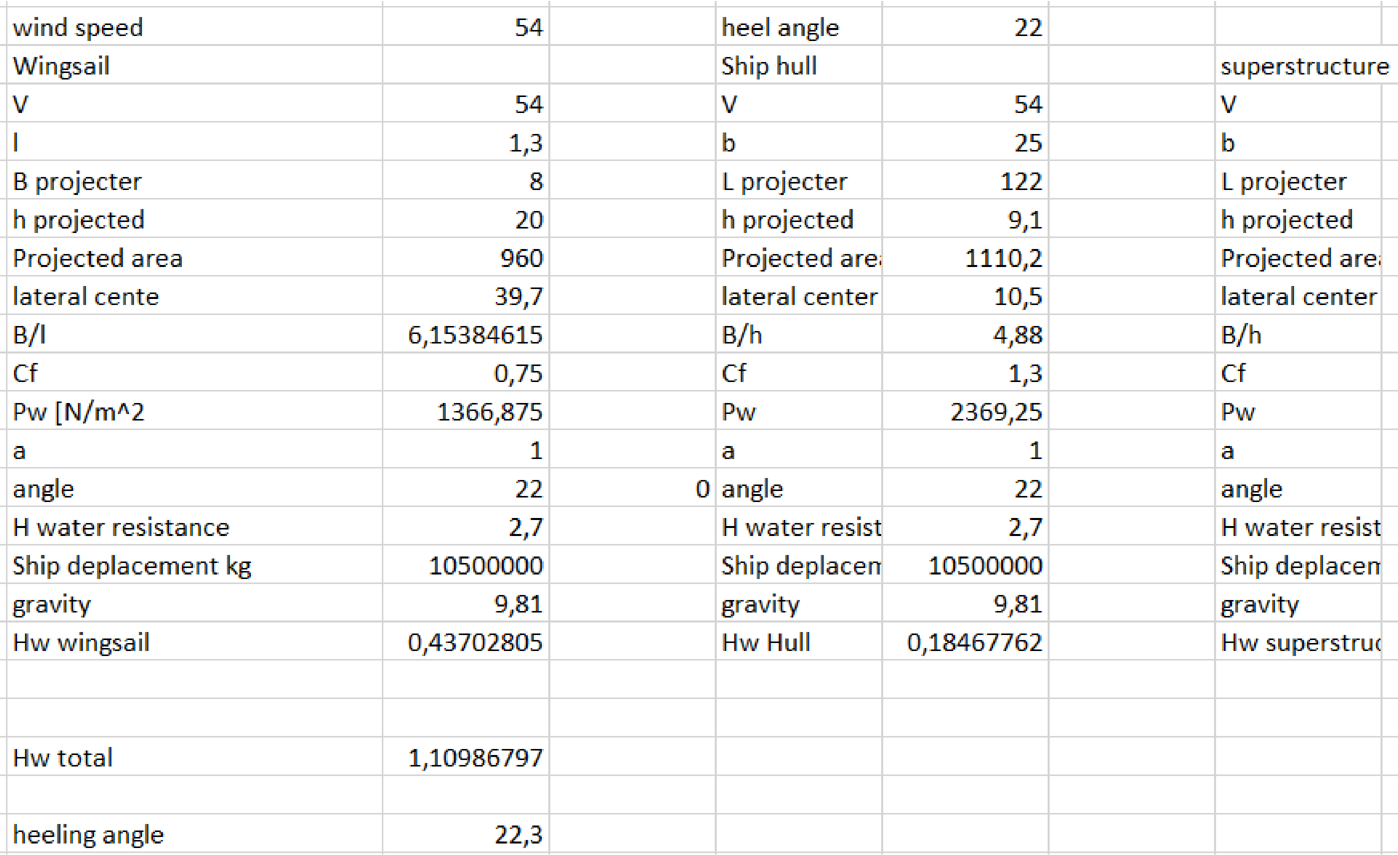
A.2 Heeling spreadsheet



wind speed	54		heel angle	22		
Wingsail			Ship hull			superstructure
V	54		V	54		V
l	1,3		b	25		b
B projecter	8		L projecter	122		L projecter
h projected	20		h projected	9,1		h projected
Projected area	960		Projected are	1110,2		Projected are
lateral cente	39,7		lateral center	10,5		lateral center
B/l	6,15384615		B/h	4,88		B/h
Cf	0,75		Cf	1,3		Cf
Pw [N/m^2	1366,875		Pw	2369,25		Pw
a	1		a	1		a
angle	22	0	angle	22		angle
H water resistance	2,7		H water resist	2,7		H water resist
Ship deplacement kg	10500000		Ship deplacem	10500000		Ship deplacem
gravity	9,81		gravity	9,81		gravity
Hw wingsail	0,43702805		Hw Hull	0,18467762		Hw superstruc
Hw total	1,10986797					
heeling angle	22,3					

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