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Idea Number: L1-63

PILLAR / TRANSPORT MODE	
ROAD ☐	RAIL ☐
MARINE X	CROSS MODAL ☐
Project Related to:	☐ RA1: Environment – Decarb., Sustainability & Energy Efficiency ☒ RA2: Vehicle & Vessels Technology, Design & Production ☐ RA3: Urban and Long-Distance People Mobility – Systems and Services ☐ RA4: Freight Transport & Logistics ☐ RA5: Safe, Secure and Resilient Transport Systems ☐ RA6: Transport Infrastructures ☐ RA7: Human Factors, Socio-Economics and Foresights ☐ RA8: Automation and Connectivity ☐ RA9: Enabling Environment for Innovation Implementation

Project Title:

Concept design of eco-friendly wind powered bulk carrier – Gary Muwalt



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1. Introduction

Ships are the cheapest way to carry on goods. However, they are not the most environmentally friendly constructions. Therefore, our team would like to propose concept design of new cutting-edge ship. The aim of the project is to apply innovative eco-friendly propulsion system based on sails and two LNG engines. The main assumption of the paper is to check if sails could be as competitive as conventional ship engine. In order to achieve state-of-the-art final product we implemented different types of marine software to our research area. Garry Muwalt operates between port in Lisbon and Rio De Janeiro. Initially, we generated bulk carrier data from NAPA software. In the next step we modelled ship hull in Rhinoceros 3D program. Finally, there were 4 CFD analysis carried out in STAR-CCM+. First simulation depicts behaviour of a bare hull. Second one presents hull with folded sails and LNG tank in the aft part of the ship. Third analysis shows hull with furled sails. The last simulation was carried out only on sails in order to verify the forces which act on them. The final conclusions regarding each simulation were drawn. In the last phase of our project we checked how much oil is needed to support work of the engine.

2. Selection of research area

Nowadays the European Union is posing regulations on European countries in order to reduce exhausted amount of CO₂. We are aware of the global warming and its effect on the environment. Our group would like to boost the usage of renewable sources of energy and find alternative sources for crude oil. Moreover, we were curious how to apply the sails to the bulk carrier and what was their operating principle. Therefore, to our mind came the idea to design the ship with sail propulsion system and two LNG engines which are fuelled by plug-in containers.

One of the major issues is global warming, which is caused by high emission of CO₂ to the atmosphere and water. Water is the main source of life on the Earth. Carbon dioxide affects people's health, it is hazardous for terrestrial animals, aquatic organisms and for water itself. People should be responsible and ponder about future generations' well-being. Due to these facts, we have to implicate the process of mitigating global warming effects as fast as possible.

Another aspect, which we ought to take into consideration is that oil prices are unstable. In about 10-15 years' time crude oil prices might radically increase and conventional propulsion system may not be payable. Firstly, the cost of carrying goods will go up. Secondly, customers will start to search cheaper transportation methods along with ship-owners who will be in a demand in search for cheaper sources of energy (in order to adjust to the situation and to stay competitive on the market). What is more, crude oil is not a renewable source of energy - its resources are slowly running out of. Hence our group respond to these gradual changes. Our design uses wind force which is entirely free of charge. However, we cannot fully rely on wind power. Therefore, our cutting-edge ship is supported by two LNG engines. Their portable LNG tanks (which are placed in containers) - if empty can be easily replaced by new ones (filled in advance) during the process of trans-shipment in port. Because of this, unit saves time on pumping fuel. Another reason why we choose this method is that LNG plug-in container supports the engine more effectively to crude oil.

Units powered by sails, such as yachts, can attain high speeds under the condition that the rout is long and there are relatively stable weather conditions. Our team carried out CFD analysis to check if sails application is payable unless the design

velocity is constant. We also checked how much oil is needed to support work of the engines.

Overall, our concept idea is oriented into eco-friendly solutions. We believe that, sustainability is a major factor to achieve harmony on Earth. Therefore, our project focus on different aspects i.e.: engineering, ecology, international law and economy.

3. Literature Survey

Innovative concept designs are not easily accepted by ship-owners and Classification Societies. New projects have to fulfil all regulations and restrictions. Therefore, our project is subjected to constant changes. Our main idea is inventive and realistic. However, there are not many similar ideas. As an inspiration for our project we perceive [1] "UT Wind Challenger". The ship which is able to reduce fuel consumption up to 25%. Its concept design was made by Japanese marine industry in cooperation with engineers from University of Tokyo. We believe that our idea might be also applied into reality. Moreover, our ship shaped structure is propelled by engines designed by Wärtsilä company . Board of the vessel is equipped in LNG plug-in tanks which are designed by [2] LNG tainer company. Detailed description of the tanks is contained in further part of the research thesis. What is more, norms and classification societies rules play an important role. Ship engines are dual fuel type. It means that they can use different types of fuel such as natural gas, marine diesel oil, heavy fuel oil and bio fuels, marine gas oil. Marine Gas Oil (MGO) fuel is consistent with ISO 8217:2010 (E) norm. Moreover, our design also fulfil [3] DNV rules. For example, tank which store liquefied gas is located at B/5 distance from ship sides and it is an independent tank type C. The sails shape was inspired by sails on Superyacht Falcon [6].

4. Proposed Solution-Description of Idea

In this part of the thesis we would like to describe how we assembled the design (hull, sails, superstructure) and how we carried out CFD analysis. The project which we would like to present is a modified demo project extracted from marine software - NAPA. Our aim was to design a ship hull with sails. Therefore, we decided to redesign bulk carrier demo project, which is supposed to get familiar new program users with the software as well as learn them how to set a loading conditions. Moreover, our design adopted four sails which were taken from yacht called “Maltese Falcon”. In this piece of work we also modified the hull by adding cranes, in order to make the bulk carrier more practical. These cranes are used in harbour for the purposes of self-unloading the unit. (See pictures; figure 1; Garry Muwalt)

The route of the ship is between Port of Lisbon and Port of Rio de Janeiro. (see pictures; figure 2; Map)

The algorithm below describes steps how the design and calculation process was conducted:

4.1 Theoretical lines from NAPA software were extracted

4.2 Similar sails to the ship *Maltese Falcon* were created

4.3 Ship hull model (3D) was created in Rhinoceros

Non parametric 3D ship hull shape in Rhinoceros was modelled. The hull surface was based on theoretical lines which were extracted from NAPA. The hull maintains G1 class continuity type.

4.4 LNG containers were designed and added to the ship propulsion system

Containers were designed in Rhinoceros and joined to the model. Main dimensions of ISO LNG Tainer - LNG fuel tank data provided by LNG Tainer company is in further deliberation.

4.5 Cranes, sails and LNG containers weight were estimated

Detailed description of each part is in the further part of the thesis.

4.6 Model primary stability criteria in NAPA software were checked (*see appendix 1: Stability criteria*)

- a) behaviour of the ship (i.e. in harsh storm weather conditions, heel condition, visibility criteria)
- b) stability of the unit in heavy departure ballast condition
- c) heel was estimated

4.7 CFD analysis was carried out:

- a) hull without modifications (such as: superstructure, sails, LNG containers)
- b) hull with folded sails (passive masts), cranes and LNG tank in the aft part of the ship
- c) hull with furled sails (active sails), cranes, LNG containers (lift force which acts on the sails was not estimated, the resistance prediction was calculated only in the forward direction)
- d) simulation of the lift force on the sails

4.8 Resistant and thrust results were compared

4.9 Economic fuel efficiency was calculated

5. Address potential technology gaps

The following chapter is dedicated to present the technology gaps which have been identified by our team. Mainly we will concentrate on brand new eco-friendly technology. Moreover, we will also describe elements which should be improved in the further project's development.

First thing on which we would like to focus on is solar energy. Sun is everywhere, therefore in order to make the ship much more efficient we suggest to cover the sails with perovskites materials [4]. Miss Olga Malinkiewicz (Polish scientist) was awarded for her photonics research work on *"Low cost, efficient hybrid solar cells" which is devoted to perovskites materials*. We find this innovative technology environmentally friendly and we believe that it could be applied on the sails. This application might reduce exploitation costs (by reducing fuel consumption) due to the fact, that this material itself is able to create an energy out of the sun. In addition, the material is relatively cheap and light. Therefore, sails would not be affected by large additional weight, stresses or flow around them and what is more important the price of the unit would not go up drastically because of using this material.

Second major issue is manufacturing technology. Concept design has to be elaborated in the following areas:

- 5.1 Crane construction ought to be joined with masts and deck stiffeners
- 5.2 Masts moved upward the centre of gravity and because of this, the stability decreased. Therefore, in double bottom ballast tanks should be installed which would add additional loading and as a result they would lower the centre of gravity.
- 5.3 The sails angle of attack as well as the sails area ought to be adjusted to the wind force and direction in order to reduce the heel and avoid cargo movement.
- 5.4 In further development ship may be fully propelled by sails and LNG engine, which emits significantly less amount of toxic substances.
- 5.5 Sails should be optimized in accordance with the ship route in order to reduce fuel costs and time at sea.
- 5.6 Automatic system of adjusting the sails ought to be selected in order to set sails towards the wind direction. This system should also pick the sail area in relation to the wind force.

6. Detailed design description

This chapter is devoted to describe the main design characteristic such as hull, sails and crane dimensions. In addition, in the final conclusion we calculated financial feasibility and we draw conclusions.

6.1 Main dimensions of the ship

L _{OA}	224.0	m
B	36.0	m
T	15.0	m
Displacement	101600	t

6.2 Cranes description

Cranes were selected upon the B-Delta bulk carrier board equipment. Ships named B-Delta belong to ship series designed by Deltamarin company. In many aspects we compared our results to this projects. One of the reasons why we choose similar crane type to this on B-Delta is crane capability. However, our ship- Garry Muwalt is longer and hatches for holds are much bigger to those on reference vessel. Therefore, we decided to scale the cranes to make out of them more practical design and we also increased transport cargo range in hatches. Because we enlarged cranes, we decided to do a preliminary estimation of weight and centre of gravity of the scaled objects. In the next phase, we imported this information to NAPA database in order to calculate departure ballast condition.

Deck Crane Type: MacGregor GLBE3626-2/2826gr/3026log

Drawing is attached to the project (*see pictures; figure 3; MacGregor*)

6.3 LNG fuel tanks detailed description

The first assumption was to settle cylindrical LNG tank, in the aft part of the ship, which capacity would be approximately 900m³. This LNG tank was designed to fulfil optimal content of volume. However, if the cylindrical shape would have been applied that would result in higher construction and it would entail the increase of vessel's centre of gravity and therefore minimize stability of the vessel. Because of these issues we rejected this idea and after analysing a few various approaches we decided to implement LNG plug-in

construction, which has a cuboid shape and it needs much less space. Additional advantage is that it has a low cog.

The assumed combination consist of 20 containers – each 20 feet long. They may accommodate about 905 m³ of gas (95% of fulfil). Another advantage of these containers are plug-in option. This profoundly flexible solution decreases bunkering time and consequently reduces ship-owners and port's maintenance costs. It would be sufficient if harbours would only construct a foundation for containers (instead of maintaining LNG gas stations).

Main dimensions of ISO LNG Tainer, LNG fuel tank (data provided by LNG Tainer company)

Size	40	ft
Gross volume	48	m ³
Reduction 5%	45,6	m ³
Max gross weight	30,48	t
Tare weight	9,428	t
Max payload	21,052	t
Containers number	20	
	960	m ³
Max payload	609,6	t
Tank material	stainless steel	
working pressure	6.15	bar
design temperature	-196 to +50	C
Insulation	Honeycomb/ perlite in vacuum	

6.4 Sails and masts description

In the case of UT Wind Challenger masts are hidden inside the deck resulting in the decrease of cargo space. In comparison, our bulk carrier adopted similar to DynaRig sail system because in our case cargo space plays significant role. The more room the better. The original sail system was designed and installed on superyachts S/Y Maltes Falcon. Furthermore, this system may provide additional eco-propulsion system and extra space under and on the deck. In our concept design we wanted to use four free-standing masts made of steel. Each mast has five yards which are rigidly connected to the masts and four

sails- each with individual sailing reefing system. For these reasons, sails can be progressively furled into the mast and they are trimmed to the wind in a controlled manner. This is ensured by the state of the art automatic, intelligent and specialized system which rotate masts. This system enable not only the sails to be in the best manner settled to the current weather conditions but it also has a sensor which monitor loading status of all aspects of the rig and therefore, it provides warnings data. Obviously, furled sails guarantee lessened angle of heel. Thus, the furled sails area should depend on the actual weather conditions on the Ocean. Consequently, they can be furled completely, in three quarters, in half or as we would like to (see pictures: figure 4; Rig configuration). Above all, the control panel can quickly furl all sails in an emergency. Free-standing rigs are safer and more reliable than conventional rigs in the event of failure. Traditional rigs hold the mast in the upright position by linking them with deck and for this reason they might be dangerous. If in one of them occur a failure because of high fatigue stresses or overloading, it might lead to catastrophic mast failure. Moreover, lack of standing rigs provide safe and moveable deck for the crew and facilitate the cargo handling. Furthermore, yards can rotate freely and during the navigation process, they might be aligned parallel to the ship's X axis and thereby reduce the resistance of appendix parts. Free-standing mast has only two attachment points; the upper and the lower bearing. It is easily accessible for regular inspection, service and maintenance. The sails were designed in the way that there are no gaps between them and therefore they create one coherent surface. However, each one if furled works separately. Furthermore, upper and lower edges of the sails are stretched; so there is no possibility of flogging and this fact reduces wear of the material and extend the durability of sailcloth. In addition, we can design a sail out of robust sailcloth Dacron which is cheaper in contrast to the sail made of laminate structure. Free edges of the sail (luff and leech) have cambers like Spinnaker. All of those things combined together result in the improved rigs aerodynamic efficiency in comparison to the traditional square rig.

6.5 Stability calculation

Stability calculations were conducted in NAPA. This software enables to calculate trim, heel, and depth of the vessel. We were not going to model new ship hull because there was a tutorial in NAPA and we based on this model of the vessel. Our aim was to create a simulation with trim angle equal to zero in order to decrease unnecessary impact of the additional resistance force. We also took into account IMO-WEATHER criterion and we calculated heel in the event of extreme wind – 50 m/s. In the final result the draught in the aft and fore part of the unit was the same.

Another aspect is that, the most important issues for NAPA are centre of gravity and mass of the object. Therefore, before we started all calculations we added things which we had created (such as: LNG containers, sails and cranes). Moreover, the software enables users to model everything as a points of mass and thereby, assign to them the range of mass. Besides, to calculate IMO-WEATHER criterion we had to create a “profile” of the vessel which was a wind profile that NAPA convert to wind force area. However, we had to do this step in AutoCAD and export it afterwards to NAPA as a curve. Based on the first assumption of the ship weight we could move forward and we created loading conditions which corresponded with further CFD simulation. Our aim was to predict the vessel behaviour in the most extreme conditions. Therefore, we decided to create a heavy ballast condition to check the ship behaviour in the most unlikely situation. Namely, when there is a full cargo holds in the departure condition. Hence, the first problem occurred. Heavy cranes, sails and LNG containers in the aft part of the vessel caused a trim, which consequently increased the resistance force. The only one possibility to mitigate this situation was to add ballast water. This method reduced trim to zero. The next step was to check IMO-VISIBILITY criterion. This criterion states that the visibility from the wheelhouse should be at the distance equal to 2.5 of the ship's length. Basically to avoid the problem with IMO-VISIBILITY we lifted the sails upward.

To conclude, the result of the stability calculation was based on the assumption of the following loading conditions: heavy ballast departure condition, estimation of heel – approximately 3 degrees (extreme test, result of IMO-WEATHER criteria), draught moulded - 15.652 meter, 0 trim. More information is in Appendix number 1: Stability Criteria.

6.6CFD calculation: Resistance prediction in calm water and wind resistance prediction

In this phase we carried out Computation Fluid Dynamic simulations to predict the ship resistance in calm water. This have been done in STAR CCM+ which is professional and commercial software. Our approach was to create four simulations.

Three of them was a resistance prediction of a ship in calm water:

- bare hull from NAPA (*see: pictures; figure 5; Model 1 - wake*)
- hull from NAPA with additional elements (LNG containers, cranes) and folded sails (*see: pictures; figure 6; Model 2 - wake*)
- hull from NAPA with additional elements and furled sails. (*see: pictures; figure 7; Model 3*)

The fourth and the last simulation was a wind resistance prediction on sails. Only air domain was taken into account.

To continue CFD simulation we had created a 3D ship hull model in Rhinoceros and then converted its geometry into parasolid. In the next stage we imported it as a surface mesh into STAR CCM+ and refined its shape by geometry editor which repaired model faces. When the geometry was repaired and ready to further calculations our team created mesh on the ship surface. Unfortunately, due to the fact that we did not have powerful computer which would enable advanced calculations we decided to create a volumetric control blocks model. This approach also reduced too long computation time (in some cases several days). The more precise mesh was created in the bow and stern part, the more accurate output we received (*see: pictures; figure 8; Mesh*). For instance, if the flow velocity increased in the wake direction the wind vorticity around the sails was also more accurate. Another very important thing was to do not forget about free surface mesh which is a thin layer of mesh on the border between air and water. We had to create it to get the effect of layer between Volumes of Fluid. (*See pictures, figure 9; Volumetric control blocks*).

The table number 1 presents Volumetric controls description

Table 1 Volumetric controls description

Solver models:	Cell Quality Remediation, Eulerian Multiphase, Gradients, Gravity, Implicit Unsteady, K-Epsilon Turbulence, Multiphase Equation of State, Multiphase Interaction, Realizable - Averaged Navier - Stokes, Segregated Flow, 3 - D, Turbulent, Two - Layers All y+ Wall Treatment, Volume of Fluid.			
Mesh	Relative Minimum Size		Relative Target Size	
Ship boundary mesh size	0.4 m		2 m	
Towing Tank mesh size	16 m		16 m	
Volumetric controls	Relative Size	Trimmer Anisotropic Size		
		Relative X Size	Relative Y Size	Relative Z Size
Bow_stern	0.5 m	-	-	-
Free surface - coarse	-	4.0 m	4.0 m	1.8 m
Free surface - fine	-	4.0 m	4.0 m	1.4 m
Free surface - very fine	-	4.0 m	4.0 m	1.0 m
Hull - near	-	8.0 m	1.0 m	1.0 m
Hull - nearest	1.4 m	-	-	-
Sails	2 m	1.0 m	1.0 m	1.0 m
Wake - far	-	-	2.0 m	2.0 m

The first three simulations have been done by using a Volume of Fluid solver. This indicates that two environments were taken into account: water and air.

The object was settled in a virtual towing tank domain and the particles created a flow around it. The vessel speed was assumed to be 14 knots (7.20 m/s).

This simulation only comply with the ship which moves forward. Therefore, it does not calculate final ship resistance force. In this case the accuracy of computation and quality is measured by number of cells. The first model had 2987801 cells. The second one had 3701675 cells (because of the sails

complexity). Third model had 3320254 cells. In our opinion, these outputs were correct and we applied those results into the next steps.

The resistance prediction results:

- Model – 1005528 [N]
- Model 2 –1021644 [N]
- Model 3 – 1113676 [N]

This data indicates that the third model have the greatest value of the resistance force. This is due to the fact, that there was the largest impact of the wind force on the entire calculated area. Moreover, in order to simplify the calculations in each simulation ship draught was assumed as equal.

To calculate the lift force (which acted on sails) in the third model we had to create a new simulation. It was much simpler calculation because there was only air domain. The speed of the wind was taken from the wind scatter diagram for Atlantic Ocean and was equal to the value - 19.84 knots (10.2 m/s). The table number 2 presents solver description.

Table 2 Solver description

Solver models:	Two-Layer All y+ Wall Treatment, Realizable K-Epsilon Two-Layer, K-Epsilon Turbulence, Reynolds-Averaged Navier-Stokes, Turbulent, Segregated Fluid Temperature, Ideal Gas, Segregated Flow, Gas, Gradients, Steady, Three Dimensional	
Meshes:	Polyhedral mesh	
Mesh	Relative Minimum Size	Relative Target Size
Ship boundary mesh size	0.5 m	0.5 m
Towing Tank mesh size	16 m	16 m

The fourth simulation was conducted by simplification of steady flow method. The entire process was an iteration process. This indicates that it was not an implicit unsteady process in real time (seconds). We believe that, this method is suitable for the purpose of the concept research. As a young engineers we were not certain which angle of attack to select. Therefore, we ran two separate simulations to analyse different outputs. Firstly, we analysed ship behaviour,

which sails were adjusted at the angle of 30 degrees (See pictures, figure 10; 30 degrees of wind angle attack). Secondly, we set the sails at the angle of 80 degrees towards the wind direction. (See pictures; figure 11; 80 degrees of wind angle attack). The first simulation was analysed for the normal weather conditions - wind approximately 10.2 m/s and the sails angle of attack equal to 30 degrees. At the beginning we assumed that we would receive resistance force roughly to 500000 [N]. However, we obtained resistance force equal to 719891 [N]. The result was propitious. The second test was done for side wind at the extreme angle of 80 degrees and result was slightly different - 845435 [N]. The increasing wing angle from 30 to 80 degrees resulted in larger forces. The first model had 1885367 cells and the second one had 1874860 cells. Ship speed was 14 knots. For the purpose of further calculation we choose first estimation. It was due to the fact that if ship move forward in safety manner there cannot occur strong side winds. In addition, lower amount of cells in the last two simulations was a result of smaller towing tank domain in comparison to Volume of Fluid simulation.

6.7 Cruise economy

Firstly, we had to calculate unit resistance force at the contract speed 14 knots. The simulation was carried out in Star CCM+. The resistance force which we obtained was 1024,64 kN (model without active sails). Secondly, in Excel we calculated efficient power needed to move the ship.

Table 3 Propulsion power calculation without sails

Propulsion power calculation	Model 2- without sails	
Sailing mode	Definition 1	
Speed	14	Knots
Sea Margin	15	%
LOAD (%MCR)	85	%
Estimated PS requirement without sea margin	7377	kW
Shaftline and gear losses	3.50	%
Propulsion motor brake power	10343	kW
	11 MW	
Required propulsion motor configuration	8L34DF + 6L46DF	

Table 4 Propulsion power calculation with sails

Propulsion power calculation	Model 3 - with active sails	
Sailing mode	Definition 1	
Speed	14	Knots
Sea Margin	15	%
LOAD (%MCR)	85	%
Estimated PS requirement without sea margin	2835	kW
Shaftline and gear losses	3.50	%
Propulsion motor brake power	3975	kW
	minimum 4 MW	
Required propulsion motor configuration	8L34DF	

Minimum power to move the ship calculated by program was 7377,408 [kW]-without sea margin (15%) and shaft efficiency coefficients. If we include them then minimum power is 10343 [kW]. Moreover, in STAR CCM+ we calculated thrust force obtained by the sails which were aligned at the angle of 30 degrees. The weather conditions: wind 10.2 m/s. Output force was: 719891 [N]. Because of that, the entire resistance force decreased to 393785 [N].

In the next step, we conducted another analysis. We estimated minimal power which was needed (for model number 2: without active sails but with cranes and containers) to move the ship forward at the speed 14 knots for the resistance force equal to 393785 [N]. We obtained result: 3975 [kW]. Minimal engine power was calculated taking into consideration following facts: the optimal engine work is at 85% of nominal power, the impact of the sea waves (15%), losses in a shaft (3,5%). We got the result that Garry Muwalt's engine should have minimal power equal to 10343 [kW]. At this point we draw crucial conclusion. On the one hand, if the ship uses the wind power it needs only 3975 kW. On the other hand, if the sails are folded the vessel needs 10343 kW to move forward at the contract speed. Therefore we selected dual fuel engine solution. Both engines were designed by Wärtsilä :

Wärtsilä 8L34DF Power 4000 kW

Wärtsilä 6L46DF Power 6870 kW

In the tables in the appendix number 2 we summarized the most important product data.

In the next phase we estimated cruise costs from Lisbon to Rio De Janeiro in four modes:

- 1) Sailing without sails, Gas mode
- 2) Sailing with sails, Gas mode
- 3) Sailing with sails, Diesel mode
- 4) Sailing without sails, Diesel mode

Table number 5 presents simplified economic report.

Table 5 Simplified economic report

Parameters	Unit	LNG mode, without sail	LNG mode, with sail	Diesel mode, with sail	Diesel mode, without sail
Distance between Lizbona-Rio de Janeiro	Nm	5000.0	5000.0	5000.0	5000.0
Speed	kn	14.0	14.0	14.0	14.0
Time for sailing	h	357.14	357.14	357.14	357.14
Average ME power consumed	[kW]	10343	3975	3975	10343
Parameters consumptions					
Main Engine Loading		85.00%	85.00%	85.00%	85.00%
LNG consumption engine 8L34DF	[g/kWh]	149.46	149.46	-	-
LNG consumption engine 6L46DF	[g/kWh]	147.64	-	-	-
MDO consumption engine 8L34DF	[g/kWh]	2.32	2.32	184.02	184.02
MDO consumption engine 6L46DF	[g/kWh]	0.99	-	-	190.70
LO consumption engine 8L34DF	[g/kWh]	0.40	0.40	0.40	0.40
LO consumption engine 6L46DF	[g/kWh]	0.70	-	-	0.70
Daily consumption					
Daily LNG consumption	[t]	38.69	14.35	-	-
Daily MDO consumption	[t]	0.39	0.22	17.67	49.11
Daily LO consumption	[t]	0.15	0.04	0.04	0.15

Total consumption					
Total LNG consumption	[t]	575.72	213.49	0.00	0.00
Total MDO consumption	[t]	5.74	3.32	262.89	730.78
Total LO consumption	[t]	2.29	0.57	0.57	2.29
Fuel cost					
LNG PRICE	[€]	587 €			
DIESEL PRICE	[€]	439 €			
LO PRICE	[€]	940 €			
Cost LNG	[€]	337948.77	125321.40	0.00	0.00
Cost MDO	[€]	2521.74	1457.52	115418.60	320843.69
Cost LO	[€]	2151.46	537.11	537.11	2151.46
Total cost	[€]	342621.96	127316.02	115955.71	322995.14

If we compare the data from the table number 5 *Simplified economic report* we can draw the following conclusions:

During sailing with folded (passive) sails and when both engines work in Gas mode the price of oil is approx. 19.626 thousand euro higher in comparison to Diesel mode. The same discrepancy is during sailing with furled (active) sails. However, the difference in price is only 11.360 thousand euro.

If we compare sailing with sails or without – oil and gas savings are higher. For instance, the oil expenditure in LNG mode is 215.305 thousand euro higher if we sail without sails. Almost the same situation is in Diesel mode. In comparison, cost in Diesel mode is 207.039 thousand euro higher. However, we can save more than 205 thousand euro.

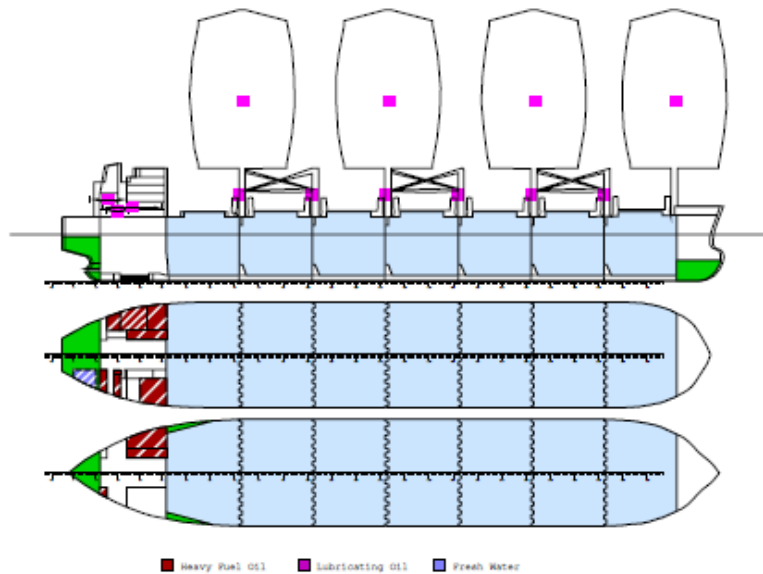
To summarize, this basic economical simulation clearly indicates that application of sails propulsion system might be highly competitive. Sails implementation may reduce ship-owners expenditures on oil and under these circumstances the price for goods transportation may lessen. Another advantage is that, the vessel not only uses reduced amount of oil. The most important issue is that unit emits less amount of exhaust fumes to the atmosphere. However, we should be aware of that, the simulations are simplified. Idea needs more advanced simulations for different wind conditions and it needs estimation of profitability of the implemented idea.

7. Source of additional information used & Appendices

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Appendix number 1: Stability criteria.



F L O A T I N G P O S I T I O N

Draught moulded	15.652	m	KM	15.22	m
Trim	0.000	m	KG	11.57	m
Heel, PS=+	0.0	deg			
TA	15.652	m	GM0	3.65	m
TF	15.652	m	GM CORR	-0.15	m
Trimming moment	0.000	tonm	GM	3.50	m

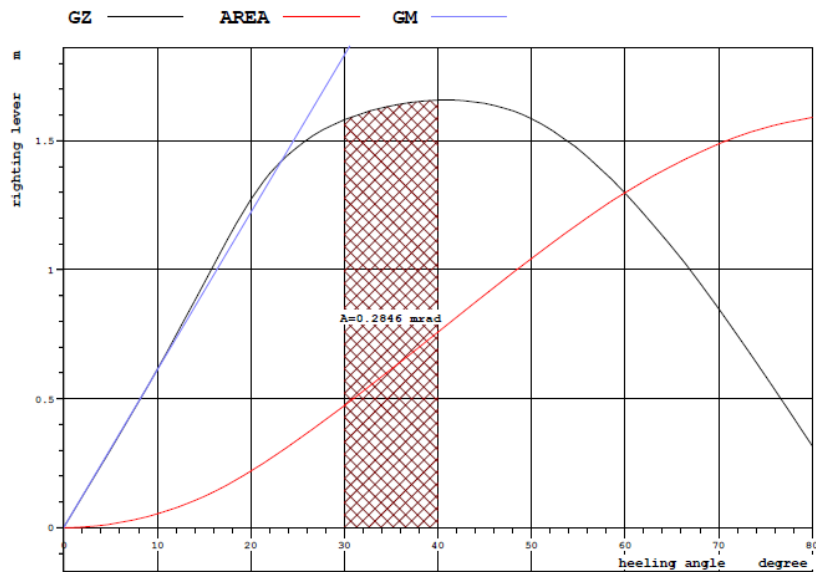
L O A D S U M M A R Y

ITEM	MASS t	LCG m	TCG m	VCG m	FRSM tm
Ballast Water	11923.0	134.37	-2.17	6.48	15237
Solid cargo	77898.9	118.19	0.00	11.92	0
Fresh Water	51.3	4.22	-7.53	15.73	0
Heavy Fuel Oil	3961.6	41.64	1.58	17.80	847
Lubricating Oil	2.4	20.62	0.00	0.78	0
	1.0	15.00	0.00	23.80	
	5.0	20.00	0.00	25.00	
	62.2	56.29	0.00	29.24	
	62.2	81.04	0.00	29.24	
	62.2	105.79	0.00	29.24	
	62.2	130.54	0.00	29.24	
	62.2	155.29	0.00	29.24	
	62.2	180.04	0.00	29.24	
	609.6	11.88	2.12	27.58	
	65.0	57.84	0.03	60.98	
	65.0	107.34	0.03	60.98	
	65.0	156.84	0.03	60.98	
	65.0	204.41	0.03	60.98	

SUMMARY	MASS t	LCG m	TCG m	VCG m	FRSM tm
DEADWEIGHT	95086.1	116.32	-0.20	11.79	16084
LIGHTWEIGHT	11454.1	87.59	1.63	9.72	
DISPLACEMENT	106540.2	113.23	0.00	11.57	16084

Appendix number 1: Stability criteria.

NAME	DESCRIPTION	FILL %	MASS t	LCG m	TCG m	VCG m	FRSM tm
Fresh Water (RHO=1 t/m3)							
APUPT1	AP Fresh water tank 1	21	51.3	4.22	-7.53	15.73	0
APUPT2	AP Fresh water tank 2	0	0.0	5.20	8.17	18.34	0
APUPT3	AP Fresh water tank 3	0	0.0	8.26	-8.45	18.32	0
SUBTOTAL			51.3	4.22	-7.53	15.73	0
Heavy Fuel Oil (RHO=0.94 t/m3)							
UNTP_21		95	543.5	68.62	13.79	19.43	423
UNTP_51		95	543.5	43.88	13.79	19.43	0
UNTS_21		95	543.5	68.62	-13.79	19.43	423
UNTS_51		95	543.5	43.88	-13.79	19.43	0
ERLPT1	ER Oil tank	90	53.8	10.16	-7.98	12.61	0
ERLPT4	ER Oil tank	95	188.9	24.75	6.60	12.38	0
ERLPT5	ER Oil tank	95	430.4	25.20	11.91	12.52	0
ERUPT1	ER Oil tank	90	94.2	14.64	-10.49	17.93	0
ERUPT2	ER Oil tank	90	20.3	14.62	-5.80	18.06	0
ERUPT4	ER Oil tank	95	434.2	27.09	-12.54	18.03	0
ERUPT7	ER Oil tank	90	139.5	13.60	11.11	17.92	0
ERUPT8	ER Oil tank	24	95.3	20.44	12.00	15.76	0
ERUPT9	ER Oil tank	95	330.7	28.17	12.60	18.02	0
SUBTOTAL			3961.6	41.64	1.58	17.80	847
Lubricating Oil (RHO=0.9 t/m3)							
MELOTANK	Main engine lo tank	9	2.4	20.62	0.00	0.78	0
S T A B I L I T Y C R I T E R I A							



RCR	TEXT	REQ	ATTN	UNIT	STAT
AREA30	Area under GZ curve up to 30 deg.	0.055	0.474	mrad	OK
AREA40	Area under GZ curve up to 40 deg. (or flood.)	0.090	0.758	mrad	OK
AREA3040	Area under curve between 30-40 deg. (or flood.)	0.030	0.285	mrad	OK
GZ0.2	Min. GZ > 0.2	0.200	1.659	m	OK
MAXGZ25	Max. GZ at an angle > 25 deg.	25.000	40.814	deg	OK
GM0.15	GM > 0.15 m	0.150	3.503	m	OK
IMOW-H	Heel due to action of steady wind (IMO-weather)	16.000	3.389	deg	OK
IMOWEATHER	IMO weather criterion	1.000	3.022		OK

Appendix number 2:

The tables attached in this appendix presents combustion parameters for each type of oil in regard to engine mode. All figures were taken from Wärtsilä product guide [5]. Combustion value 85% was calculated upon the trend line for 100%, 75% and 50 percent.

Table 6 Combustion parameters. Engine type Wärtsilä 8L34DF (4000 [kW]) [5]

8L34DF		Gas mode			
	Percent of engine operation	100.00%	75.00%	50.00%	85.00%
	LNG consumption	7 324 kJ/kWh	7 496 kJ/kWh	8 286 kJ/kWh	7 416 kJ/kWh
	MDO consumption	1.9 g/kWh	2.6 g/kWh	3.8 g/kWh	2.3 g/kWh
	LO consumption	0.4 g/kWh			
	LNG energy value	49 620 kJ/kg			
	LNG consumption	147.6 g/kWh	151.1 g/kWh	167.0 g/kWh	149.5 g/kWh
		Diesel mode			
	Percent of engine operation	100.00%	75.00%	50.00%	85.00%
	MDO consumption	187.0 g/kWh	184.0 g/kWh	191.0 g/kWh	184.0 g/kWh

Table 7 Combustion parameters. Engine type Wärtsilä 6L46DF (6870 [kW]) [5]

6L46DF		Gas mode			
	Percent of engine operation	100.00%	75.00%	50.00%	85.00%
	LNG consumption	7 248 kJ/kWh	7 387 kJ/kWh	7 776 kJ/kWh	7 326 kJ/kWh
	MDO consumption	1.0 g/kWh	1.3 g/kWh	3.2 g/kWh	1.0 g/kWh
	LO consumption	0.7 g/kWh			
	LNG energy value	49 620 kJ/kg			
	LNG consumption	146.1 g/kWh	148.9 g/kWh	156.7 g/kWh	147.6 g/kWh
		Diesel mode			
	Percent of engine operation	100.00%	75.00%	50.00%	85.00%
	MDO consumption	186.0 g/kWh	193.0 g/kWh	196.0 g/kWh	190.7 g/kWh