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THE ADVANTAGES OF USING DUAL-FUEL ENGINE COMPARED TO THE CONVENTIONAL ENGINE

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ABSTRACT

Flexible dual-fuel power technology is becoming increasingly important in a marine market where fuel oil prices are fluctuating and emission legislation is becoming ever more stringent.

The advantage of the dual-fuel technology is, without doubt, fuel flexibility. This technology makes it possible to utilise the economic and environmental superiority of gas fuel. The benefits of natural gas are low price and good environmental compatibility, thanks to its clean combustion.

The main objective of the present work is to provide a more comprehensive view of the advantages of choosing a dual fuel engine instead of the conventional engine. For this analysis will be considered two ships and will also be taken into account the Energy Efficiency Operational Indicator (EEOI).

Keywords: diesel engine, dual-fuel engine, alternative fuels, economic, Energy Efficiency Operational Indicator (EEOI)

1. INTRODUCTION

Alternative fuels got more attention as concerns escalate over exhaust pollutant emissions produced by internal combustion engines, higher fuel costs, and the depletion of crude oil. Various solutions have been proposed, including utilizing alternative fuels as a dedicated fuel in spark-ignited engines, diesel pilot ignition engines, gas turbines, and dual fuel and bi-fuel engines. Among these applications, one of the most promising options is the diesel derivative dual-fuel engine with natural gas as the supplement fuel [1].

Conventional diesel engines rely on compression ignition of an atomized liquid fuel jet injected into the high-temperature and high-pressure cylinder air charge toward the end of the compression stroke of a high-compression-ratio unthrottled reciprocating piston engine [2].

A dual-fuel engine is an internal combustion engine in which the primary fuel is mixed more or less homogeneously with the spark ignition engine in the cylinder. Unlike the spark-ignition engine, however, the air / fuel mixture is ignited by injecting a small amount of diesel fuel (the "pilot") with the piston approaching the top of the compression stroke. This diesel fuel-fuel quickly undergoes preflame reactions and ignites due to the heat of compression, just as it would in a diesel engine. The combustion of the diesel engine then ignites the air-fuel mixture in the rest of the cylinder.

Dual-fuel engines can be designed to operate interchangeably on natural gas with a diesel pilot, or 100% diesel fuel. Also, many existing diesel engines can be converted to dual-fuel operation. Preliminary economic analyses show that such conversions could be justified from the fuel cost savings alone in applications such as railroad locomotives, marine vessels, mine trucks, and diesel power generation systems.

Dual fuel engines perform best under moderate to high load, and can often equal or better the fuel-efficiency of a pure diesel under these conditions [3].

The price of natural gas relative to that of diesel or gasoline can vary widely from time to time and from one location to another. Generally, on an energy basis, natural gas and liquefied petroleum gas (LPG) sell significantly cheaper than diesel fuel and gasoline [2].

Another important element of this work is the Energy Efficiency Operational Indicator (EEOI).

EEOI is a monitoring tool for managing ship and fleet efficiency over time. The EEOI enables operators to measure the fuel efficiency of a ship in operation and to measure the effect of any changes in operation [4].

Table 3. Dimensions – Diesel Engine 6L20

Engine type	A*	A	B*	B	C*	C	D	F	Weight (tons)
6L20	3254	3108	1528	1348	1580	1579	1800	624	9.3

Table 4. Dimensions – Dual – Fuel Engine 8L20DF

Engine type	A*	A	B*	B	C	D	F	Weight (tons)
8L20DF	3973	3783	1705	1824	1824	1800	624	11.1

2. MATERIALS AND METHODS

The supply market dual-fuel (diesel-NG) marine engines are dominated by several large companies that have many years of experience in diesel engines production field. Companies, such as "MAN Diesel &Turbo SE", "Wärtsilä", "Caterpillar Inc." and "Hyundai Heavy Industries", dominate this market.

In this paper, it will be analysed two ships. For each was chosen a conventional and a dual fuel engine from Wärtsilä.

The following analysis was carried out based on two ships taken from Merchant Ships Portfolio and the calculation was made at the fuel cost of June 2019 [5], [6].

For these two ships, first, it will be evaluated the fuel consumption and then the Energy Efficiency Operational Index (EEOI).

The calculation of the EEOI coefficient was done following the IMO rules [7].

The basic expression for EEOI for a voyage is defined as:

$$\text{EEOI} = \frac{\sum_j FC_j \times C_{Fj}}{m_{cargo} \times D} \tag{1}$$

For a period or number of voyages, EEOI will be calculated with the following formula:

$$\text{Average EEOI} = \frac{\sum_i \sum_j (FC_{ij} \times C_{Fj})}{\sum_i (m_{cargo,i} \times D_i)} \tag{2}$$

where j is the fuel type, i is the voyage number, FC_{ij} is the mass of consumed fuel j at voyage i, C_{Fj} is the fuel mass to CO_2 mass conversion factor for fuel j; m_{cargo} is cargo carried (tonnes) or work done (number of TEU or passengers) or gross tonnes for passenger ships; and D is the distance in nautical miles corresponding to the cargo carried or work done.

2.1 Ship No.1 5000 DWT

The first ship is a 5000DWT General Cargo Ship. The vessel is designed as double hull, single screw propulsion, general cargo vessel for unrestricted navigation, being capable to carry general cargoes, bulk cargoes, steel coil and container [6].

Consider that the ship is equipped with an Wärtsilä 6L20 or Wärtsilä 8L20DF engine which has the following characteristics:

Table 1. Technical specification of the ship 5000DWT

General Cargo Ship		
Main Engine	1200	*kW*
Design speed	11	*Nd*
Distance	4750	MM
Tonnage	4760	*t*

Table 2. Rated power of Diesel and Dual Fuel engine (6L20 and 8L20DF)

Rated power [kW]	
Engine type	
6L20	1200
8L20DF	1480

For the estimation of consumption, to calculate the quantity of fuel, it is needed the following specific consumption, taken from the catalogue [8]:

Table 5. Specific Consumption - Wärtsilä 6L20 and Wärtsilä 8L20DF

at % load	Specific Consumption (g/kWh)		
	Diesel Engine	DF Engine	
	SFC	SPOC	SGC
100%	195.3	3.6	196.3
85%	190	4.2	195.3
75%	189.4	4.6	195.3
50%	194	5.6	197.5

It was determined the quantity of fuel for each MCR (Maximum continuous rating) load level and represented in Table 6.

Table 6. Quantity of fuel. Wärtsilä 6L20 and Wärtsilä 8L20DF

at % load	Quantity of fuel - for 1 voyage (t)		
	Diesel Engine	DF Engine	
	Diesel	Pilot Oil	Gas
100%	101.201	2.301	125.454
85%	98.455	2.684	124.814
75%	98.144	2.940	124.814
50%	100.527	3.579	126.220

Further, for each engine MCR load level, it was determined the quantity of fuel required for one, two, three and four voyages.

Table 7. Evaluate the price for 1, 2, 3 and 4 voyages at 100% load

No. voyage	Fuel Price (€) for 100% load		
	Diesel Engine	**DF Engine**	**Difference**
1	150015.465	76173.546	73841.919
2	300030.930	152347.092	147683.838
3	450046.396	228520.639	221525.757
4	600061.861	304694.185	295367.676

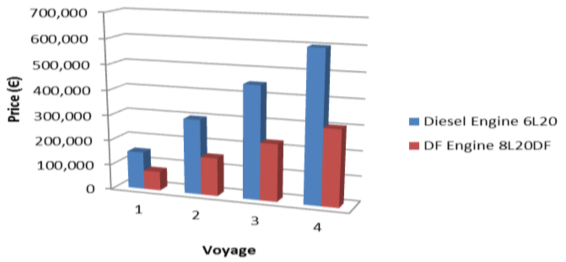

Fig. 1. Evaluate the price for 1, 2, 3 and 4 voyages, at 100% load

Table 8. Evaluate the price for 1, 2, 3 and 4 voyages at 85% load

No. voyage	Fuel Price (€) for 85% load		
	Diesel Engine	**DF Engine**	**Difference**
1	145944.385	76371.288	69573.097
2	291888.770	152742.577	139146.193
3	437833.155	229113.865	208719.290
4	583777.540	305485.154	278292.386

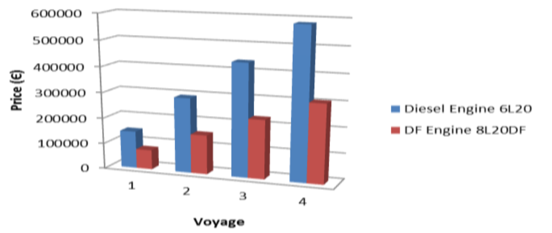

Fig. 2. Evaluate the price for 1,2,3 and 4 voyages at 85% load

Table 9. Evaluate the price for 1,2,3 and 4 voyages at 75% load

No. voyage	Fuel Price (€) for 75% load		
	Diesel Engine	**DF Engine**	**Difference**
1	145483.508	76750.232	68733.276
2	290967.016	153500.464	137466.553
3	436450.524	230250.695	206199.829
4	581934.032	307000.927	274933.105

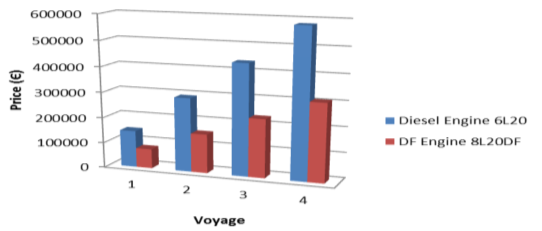

Fig. 3. The price for 1, 2, 3 and 4 voyages, at 75% load

Table 10. Evaluate the price for 1, 2, 3 and 4 voyages, at 50%

No. voyage	Fuel Price (€) for 50% load		
	Diesel Engine	**DF Engine**	**Difference**
1	149016.898	78513.070	70503.828
2	298033.797	157026.140	141007.657
3	447050.695	235539.210	211511.485
4	596067.594	314052.280	282015.313

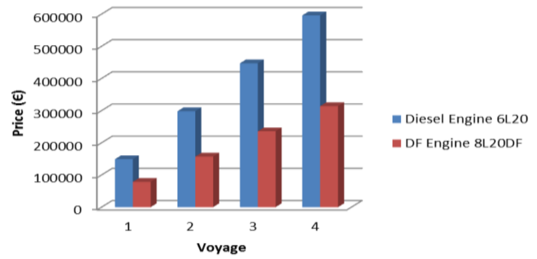

Fig. 4. Evaluate the price for 1, 2, 3 and 4 voyages at 50% load

The Energy Efficiency Operational Index (EEOI) has been calculated for each MCR load level for both types of engine: conventional and dual-fuel engine.

Table 11. EEOI (6L20 and 8L20DF)

% load	**Type of engine**	**EEOI • 10^{-6}**
100%	6L20	14.626
	8L20DF	15.885
85%	6L20	14.229
	8L20DF	15.861
75%	6L20	14.185
	8L20DF	15.898
50%	6L20	14.529
	8L20DF	16.165

To have a comprehensive picture of this coefficient, it was calculated a speed range at 85% load.

For this ship, which has the speed 11 knots, the EEOI coefficient value was determined on a range of speeds from 8.5 knots to 13.5 knots.

The calculation was realised for both engines (Figures 5 and 6).

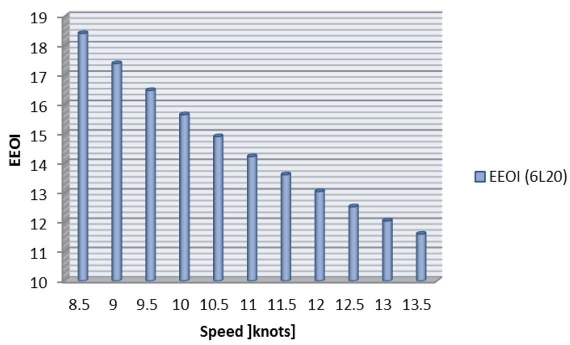

Fig. 5. EEOI – range speed (6L20)

Table 12. EEOI – range speed (6L20)

Diesel Engine 6L20				
Speed	Quantity of fuel	Voyage or time perios data		EEOI • 10^{-6}
	MDF	Cargo (t)	Distance (MM)	
8.5	127.412	4670	4750	18.415
9	120.333	4670	4750	17.392
9.5	114.000	4670	4750	16.476
10	108.300	4670	4750	15.652
10.5	103.143	4670	4750	14.907
11	98.455	4670	4750	14.229
11.5	94.174	4670	4750	13.611
12	90.250	4670	4750	13.044
12.5	86.640	4670	4750	12.522
13	83.308	4670	4750	12.040
13.5	80.222	4670	4750	11.594

Table 13. EEOI – range speed (8L20DF)

Dual Fuel Engine 8L20DF					
Speed	Quantity of fuel		Voyage or time perios data		EEOI • 10^{-6}
	Pilot Oil	Gas	Cargo (t)	Distance (MM)	
8.5	3.474	161.525	4670	4750	20.527
9	3.281	152.551	4670	4750	19.386
9.5	3.108	144.522	4670	4750	18.366
10	2.953	137.296	4670	4750	17.448
10.5	2.812	130.758	4670	4750	16.617
11	2.684	124.814	4670	4750	15.861
11.5	2.567	119.388	4670	4750	15.172
12	2.461	114.413	4670	4750	14.540
12.5	2.362	109.837	4670	4750	13.958
13	2.271	105.612	4670	4750	13.421
13.5	2.187	101.701	4670	4750	12.924

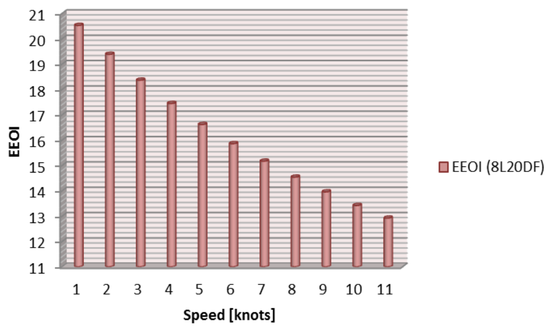

Fig. 6. EEOI – range speed (8L20DF)

2.2 Ship 2 16750 DWT

The second one is a 16750DWT General Cargo Ship.

While the hull form and propulsion parameters optimized to perfection and the steel material optimized for minimum weight this project's design is based on single two-stroke engine, fixed pitch, and highly efficient propeller [6].

Also, it was considered that the ship is equipped with a Wärtsilä 10V31 or 8V31DF engine, which has the following characteristics (Tables 16, 17 and 18).

Table 14. Technical specification of the ship 16750DWT

General Cargo Ship		
Main Engine	4400	*kW*
Design speed	11	*Nd*
Distance	4750	MM
Tonnage	4760	*t*

Table 15. Rated power of Diesel and Dual Fuel engine (10V31 and 8V31DF)

Rated power [kW]	
Engine type	
10V31	4880
8V31DF	4400

Table 16. Dimensions – Diesel Engine 8V31DF

Engine platform	A*	A	B	C	F	Weight (tons)
Wärtsilä 8V31	6175	6114	3205	3113	1496	57

Table 17. Dimensions – Diesel Engine 10V31

Engine platform	A*	A	B	C	F	Weight (tons)
Wärtsilä 10V31	6813	6754	3205	3113	1496	66.1

For the estimation of consumption, to calculate the quantity of fuel, it is required the following specific consumption, taken from the catalogue [8]:

Table 18. Specific Consumption. Wärtsilä 10V31 and 8V31DF

at % load	Specific Consumption (g/kWh)		
	Engine	DF Engine	
	SFC	SPOC	SGC
100%	172.5	3.8	177.2
85%	167.7	4.2	172.5
75%	170.6	4.1	176.3
50%	170.6	4.1	180.4

It was determined the quantity of fuel for each MCR load level and represented in Table 19.

Further, for each engine MCR load level, it was determined the quantity of fuel required for one, two, three and four voyages.

Table 19. Quantity of fuel. Wärtsilä 10V31 and Wärtsilä 8V31DF

at % load	Quantity of fuel - for 1 voyage (t)		
	Engine	**DF Engine**	
	Diesel	Pilot Oil	Gas
100%	685.911	13.624	635.295
85%	666.825	15.058	618.444
75%	678.356	14.699	632.068
50%	698.238	15.416	646.767

Table 20. Evaluate the price for 1, 2, 3 and 4 voyages at 100% load

No. voyage	Fuel Price (€) for 100% load		
	Engine	**DF Engine**	**Difference**
1	1016762.353	388666.130	628096.223
2	2033524.706	777332.260	1256192.446
3	3050287.059	1165998.390	1884288.669
4	4067049.412	1554664.519	2512384.892

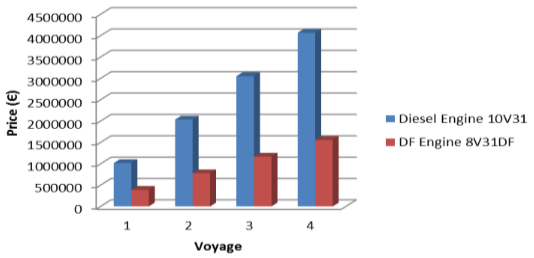

Fig. 7. The price for 1, 2, 3 and 4 voyages, at 100% load

Table 21. Evaluate the price for 1, 2, 3 and 4 voyages at 85% load

No. voyage	Fuel Price (€) for 85% load		
	Engine	**DF Engine**	**Difference**
1	988469.835	381018.719	607451.116
2	1976939.671	762037.438	1214902.233
3	2965409.506	1143056.157	1822353.349
4	3953879.341	1524074.876	2429804.465

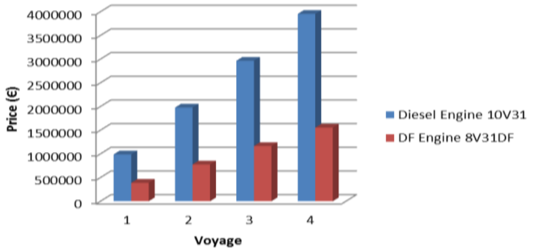

Fig. 8. The price for 1, 2, 3 and 4 voyages, at 85% load

Table 22. Evaluate the price for 1, 2, 3 and 4 voyages at 75% load

No. voyage	Fuel Price (€) for 75% load		
	Engine	**DF Engine**	**Difference**
1	1005563.231	388389.016	617174.215
2	2011126.463	776778.032	1234348.431
3	3016689.694	1165167.048	1851522.646
4	4022252.925	1553556.064	2468696.861

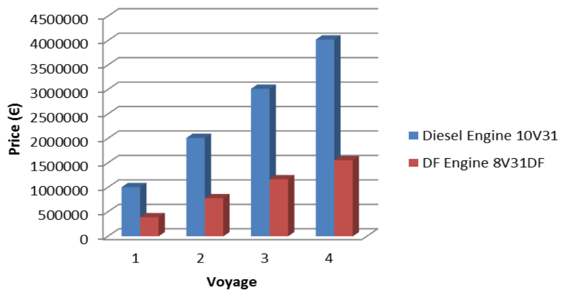

Fig. 9. The price for 1, 2, 3 and 4 voyages, at 75% load

Table 23. Evaluate the price for 1, 2 ,3 and 4 voyages at 50% load

No. voyage	Fuel Price (€) for 50% load		
	Engine	**DF Engine**	**Difference**
1	1035034.604	397977.488	637057.115
2	2070069.208	795954.977	1274114.231
3	3105103.812	1193932.465	1911171.346
4	4140138.416	1591909.954	2548228.462

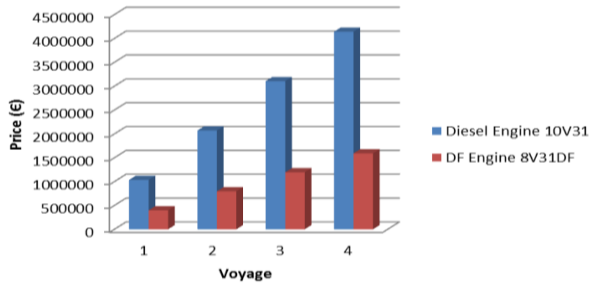

Fig. 10. The price for 1, 2, 3 and 4 voyages at 50% load

The Energy Efficiency Operational Index (EEOI) has been calculated for each MCR load level for both types of engine: conventional and dual-fuel engine.

Table 24. EEOI (10V31 and 8V31DF)

% load	**Type of engine**	**EEOI** • 10^{-6}
100%	10V31	13.787
	8V31DF	11.227
85%	10V31	13.403
	8V31DF	10.966
75%	10V31	13.635
	8V31DF	11.193
50%	10V31	14.035
	8V31DF	10.966

Just like in the case of the first ship to have a comprehensive picture of this coefficient, it was calculated a speed range at 85% load.

For this ship, which has the speed 13.5 knots the EEOI coefficient value was determined on a range of speeds ranging from 11 knots to 16 knots.

The calculation was realised for both engines.

Table 25. EEOI – range speed (10V31)

Diesel Engine 10V31				
Speed	Quantity of fuel	Voyage or time perios data		EEOI $\bullet 10^{-6}$
	MDF	Cargo (t)	Distance (MM)	
11	818.376	14500	11000	16.450
11.5	782.794	14500	11000	15.734
12	750.178	14500	11000	15.079
12.5	720.171	14500	11000	14.476
13	692.472	14500	11000	13.919
13.5	666.825	14500	11000	13.403
14	643.010	14500	11000	12.925
14.5	620.837	14500	11000	12.479
15	600.142	14500	11000	12.063
15.5	580.783	14500	11000	11.674
16	562.634	14500	11000	11.309

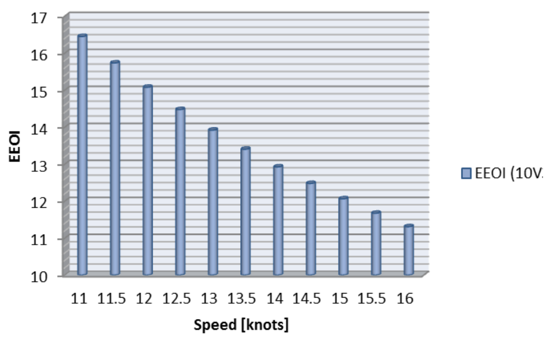

Fig.11. EEOI – range speed (10V31)

Table 26. EEOI – range speed (8V31DF)

Diesel Engine 8V31DF				
Speed	Quantity of fuel	Voyage or time perios data		EEOI $\bullet 10^{-6}$
	MDF	Cargo (t)	Distanc e (MM)	
11	18.480	759.000	14500	11000
11.5	17.677	726.000	14500	11000
12	16.940	695.750	14500	11000
12.5	16.262	667.920	14500	11000
13	15.637	642.231	14500	11000
13.5	15.058	618.444	14500	11000
14	14.520	596.357	14500	11000
14.5	14.019	575.793	14500	11000
15	13.552	556.600	14500	11000
15.5	13.115	538.645	14500	11000
16	12.705	521.813	14500	11000

3. RESULTS AND DISCUSSION

The price that should be paid for the quantity of fuel consumed by the engine is centralized in Table 27 for 5000DWT and Table 28 for 16750 DWT.

For the first ship (5000 DWT), the power of the dual-fuel engine is higher than the power of a conventional engine. It is also noted that the quantity of fuel required for engine operation is also higher for the dual-fuel engine. Even so, both engines have the power needed to operate the main engine of the ship.

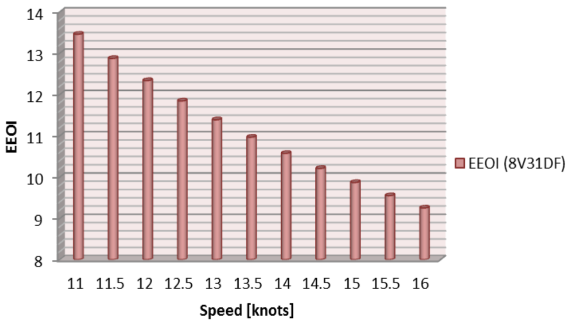

Fig.12. EEOI – range speed (8V31DF)

For the second ship (167500 DWT), things are exactly the opposite, the conventional engine power is higher than the dual-fuel engine power. Also, the quantity of fuel used is higher for the first engine type. And in this case, both engines can provide the power needed to operate the main engine of the ship.

In the first situation, the dual-fuel engine consumes less fuel than the conventional engine and in the second situation is the opposite, the conventional engine consumes less fuel than the dual-fuel engine and, yet, in both situations, the price that should be paid for the fuel is significantly smaller in the case of the dual-fuel engine.

Table 27. Fuel price - Wärtsilä 20

% load	No. voyage	Fuel Price (€) for % load	
		Diesel Engine	DF Engine
100%	1	150,015	76,174
	2	300,031	152,347
	3	450,046	228,521
	4	600,062	304,694
85%	1	145,944	76,371
	2	291,889	152,743
	3	437,833	229,114
	4	583,778	305,485
75%	1	145,484	76,750
	2	290,967	153,500
	3	436,451	230,251
	4	581,934	307,001
50%	1	149,017	78,513
	2	298,034	157,026
	3	447,051	235,539
	4	596,068	314,052

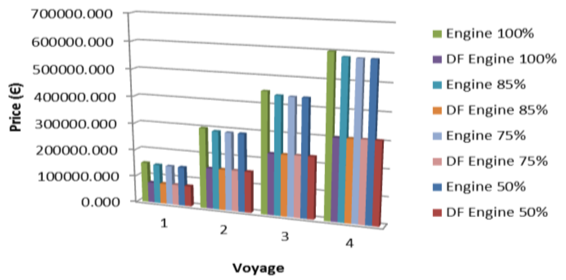

Fig. 13. Fuel price - Wärtsilä 20

Table 28. Fuel price - Wärtsilä 31

% load	No. voyage	Fuel Price (€) for % load	
		Diesel Engine	DF Engine
100%	1	1,016,762	388,666
	2	2,033,525	777,332
	3	3,050,287	1,165,998
	4	4,067,049	1,554,665
85%	1	988,470	381,019
	2	1,976,940	762,037
	3	2,965,410	1,143,056
	4	3,953,879	1,524,075
75%	1	1,005,563	388,389
	2	2,011,126	776,778
	3	3,016,690	1,165,167
	4	4,022,253	1,553,556
50%	1	1,035,035	397,977
	2	2,070,069	795,955
	3	3,105,104	1,193,932
	4	4,140,138	1,591,910

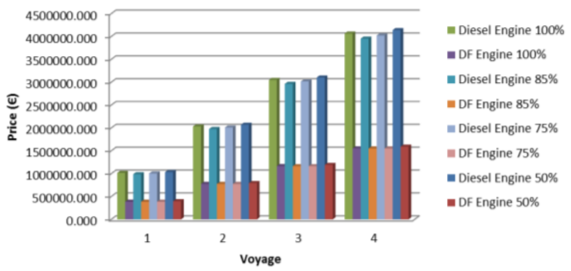

Fig. 14. Fuel price - Wärtsilä 31

Analyzing Figures 13 and 14, it can see that the most favorable case of engine operation is 85% MCR.

For this reason, it was calculated the EEOI for a speed range based on this load level.

The values of the quantity of fuel required by a voyage and the EEOI coefficient for each MCR load level were centralized in Table 27 for the 5000 DWT and in Table 28 for 16750 DWT.

It seems that in the case of the first ship, the amount of fuel it has higher value for the dual-fuel engine situation than in the case of the conventional engine.

In the case of the second ship, the amount of fuel has higher values when the conventional engine is used and lower value when dual-fuel engine is used.

In terms of calculation for more speeds, is observed a decrease of EEOI with increasing speed.

For the first ship, it is noticed that the EEOI coefficients are higher in the case of the dual-fuel engine and smaller in that conventional engine case, both in the analysis of several engine loading levels and also of the speed range.

Instead, for the second ship, it is noticed that the EEOI coefficient is smaller in the case of the dual-fuel engine and higher in that conventional engine case, both in the analysis of several engine loading levels and also of the speed range (Figures 15 and 16).

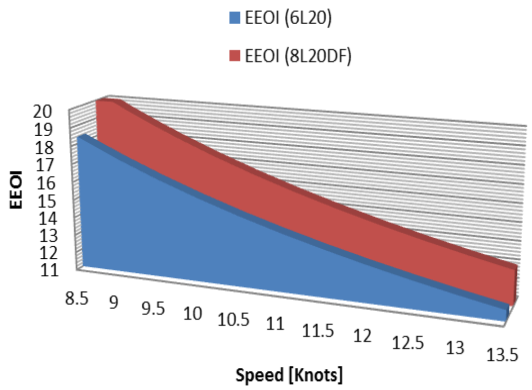

Fig. 15. Evaluation of EEOI

Table 29.Wärtsilä 6L20 and 8L20DF

% load	Type of engine	Fuel consumption (FC) at sea and in port in tonnes			Voyage or time perios data		EEOI • 10^{-6}
		MDF	Pilot fuel (MDF)	LNG	Cargo (t)	Distance (MM)	
100%	Engine	101.201			4670	4750	14.62639984
	DF Engine		2.301	125.454	4670	4750	15.88519696
85%	Engine	98.455			4670	4750	14.22947245
	DF Engine		2.684	124.814	4670	4750	15.86138789
75%	Engine	98.144			4670	4750	14.18453728
	DF Engine		2.940	124.814	4670	4750	15.89833459
50%	Engine	100.527			4670	4750	14.5290403
	DF Engine		3.579	126.220	4670	4750	16.16500541

Table 30.Wärtsilä 10V31 and Wärtsilä 8L31DF

% load	Type of engine	Fuel consumption (FC) at sea and in port in tonnes			Voyage or time perios data		EEOI • 10^{-6}
		MDF	Pilot fuel (MDF)	LNG	Cargo (t)	Distance (MM)	
100%	Engine	685.911			14500	11000	13.78702835
	DF Engine		13.624	635.295	14500	11000	11.22719959
85%	Engine	666.825			14500	11000	13.4033893
	DF Engine		15.058	618.444	14500	11000	10.9655013
75%	Engine	678.356			14500	11000	13.63517123
	DF Engine		14.699	632.068	14500	11000	11.19318641
50%	Engine	698.238			14500	11000	14.03479524
	DF Engine		15.416	646.767	14500	11000	10.9655013

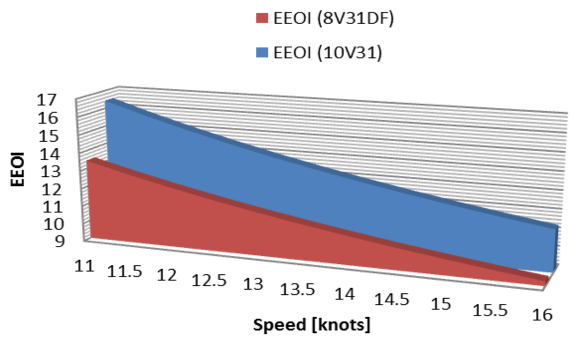

Fig. 16. EEOI Evaluation

4. CONCLUSIONS

In the present work, it was provided a general perspective of the benefits which may be obtained from the implementation of the dual-fuel engine instead of the conventional engine.

In the case of the first ship (5000 DWT), it is noticed that a higher fuel capacity is required for the ship equipped with a dual-fuel engine compared to the situation where it would be equipped with a conventional engine. It should be noted that the power of the dual-fuel engine is higher than that of the conventional engine. This situation was chosen to see the benefits of using the two variants of the same engine. The value of the EEOI coefficient is also higher for the dual-fuel engine.

In the case of the second ship, it is noted that the choice of the dual-fuel engine leads to a lower value of the fuel compared to the situation in which the ship would operate with the conventional engine.

In this situation, the value of the EEOI coefficient is lower for the dual engine and higher for the conventional engine. In this case, the dual-fuel engine is more advantageous due to the EEOI coefficient.

Eventually, despite the situation of the ship no. 1 (5000 DWT) where the dual-fuel consumes more fuel and the EEOI has a higher value for the dual-fuel engine than the conventional engine, the economic advantage of the fuel price remains the main benefit of the dual engine. The shipowner spends less money on fuel both for the ship no. 1 (5000 DWT) and for the ship no. 2 (16750 DWT), so the dual-fuel engine is more economical than the conventional engine.

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