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Quantitative Analysis of Fuel Consumption and Fuel Sediments Separation as a Function of Fuel Type and Ship Operation Mode on Product/Chemical Tanker Example

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ABSTRACT

Fuel consumption onboard is influenced on several factors but most crucial is ship operation mode and fuel type in use. Conventual fuel preparation process onboard consists of several stages. One of the most essential processes is centrifugal separation treatment operation onboard, which consists of introducing fuel into the field of high centrifugal field, where impurities and sediments are separated from fuels. The quantity of separated sediments and impurities from the fuel is essential for accurate calculating the remaining fuel quantity on board (ROB). The purpose of this paper is to determine and verify the influence of potential factors that can affect the quantity of fuel consumption and separated sediments quantity from the fuel based on actual data from real product/chemical tanker powered by conventional fuels. By means of statistical analysis the average values, minimums, maximums, standard deviations, and variations, median and modes, standard errors for separated sludge from fuel, heavy fuel consumption (HSHFO) and diesel fuel consumption (LSMGO) during entire observed period and during specific operations modes are obtained. Furthermore, regression formulas between separated sediments from fuel vs fuel consumption during each ship operation mode are generated. Finally, by means of single and multifactorial analysis significant influence of ship operations mode on fuel consumption and separated quantity has been confirmed. This research contributed to find relations more accurately between separated sediments quantity to fuel consumption that might be used for more accurate emission calculation.

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1 Introduction

During ship exploitation, the fuel intended for consumption undergoes through various preparation process to meet technical and technological requirements set by diesel engine manufacturer in terms of cleanliness and water content. Fuel preparation process consists of heating, settling, centrifugal separation and filtration. The mentioned centrifugal separation is the most essential fuel treatment operation on board, which consists of introducing fuel into the field of high centrifugal force, where impurities and sediments are separated from fuels. The quantity of separated sediments and impurities from the fuel is essential for calculating the exact fuel consumption and remaining fuel quantity on board (ROB). The quantity of separated sediments and impurities fuel may depend on various factors such as: fuel chemical composition, fuel water content, fuel storage method, etc. However, during ship operation, all these factors cannot be established or measured onboard. For this research, factors such as consumed fuel quantity, consumed fuel type and the type of ship operations mode are defined and statistical analysis regarding separated fuel sediments quantity is performed based on actual data from ship. With this analysis influence of different ship operations modes, fuel type and consumed fuel quantity on the quantity of separated sediments and impurities[1] from the fuel is established.

[1] In this paper, all separated components from the fuel by means of centrifugal separation are hereinafter in this paper called sludge, according to [17]. These components mostly consist of insoluble elements in the fuel that have a higher specific density than the fuel itself, mostly consisting of elements of Na, K, Ca, Mg, water, ash and heavy abrasive particles (mainly Si and Al).

Results obtained by this research could be utilized for more accurate usage of "top-down" method for inventory emission assessment. There are two methods used in emission assessment as mentioned in Knežević et al. [1], "top-down" method and "bottom-up" method. "Top-Down" method has been presented by several studies in the past, such as Endresen et al. [2], Olivier et al. [3], Corbett et al. [4] and are based on the data on the total marine fuel sold to ship operator. Although this method might be favourable from data collecting standpoint, several challenges arise from different information's between quantities of consumed fuel and fuel sold. Besides this, specific ship information and ship operational pattern is not considered in this method. Furthermore, another, "bottom-up" method have been developed where ship's particulars have been considered. Numerous such studies have been made, as Cullinane et al. [5] where emission has been calculated based on estimated fuel consumption for vessel at berth. Some additional "bottom-up" studies are conducted like Zakić et al. [6], Radonja et al. [7], Dujmović et al. [8]. Therefore, results of this study might significantly contribute to improve accuracy of "top-down" method for particular vessel size/type.

Although, as mentioned, numerous studies have been made to process and simulate vessel fuel consumption quantity in different operational modes, the authors are not aware that research with similar methodology and outcomes has been conducted. However, some topics and areas in this research are covered in previous papers. The accuracy of fuel consumption calculation and separated fuel sediments quantity as a function of consumed fuel is presented in Dujmović et al. [9]. Simulation and application of marine fuel oil purifier and sludge generation based on fuel flow through purifier bowl on Alfa Laval S series purifier is described by Ying et al. [10]. Trodden et al. [11] describes methodology for associating ship activity with corresponding segments of data stream from a commercially available monitoring system. Thanh et al. [12] develop simplified ship fuel consumption model for ocean going container vessels by different sizes based on regression models. Bocchetti et al. [13] presents a statistical model which allows prediction of fuel consumption from set of navigational parameters and mission profile. Li et al. [14] presents calculation model of ship fuel consumption and provide energy consumption assessment index for single ship. Furthermore, different vessels type operational pattern-based fractions of total service time is presented in Banks et al. [15]. Besides this, VLCC[2] tanker operational pattern is presented by Iordanidis et al. [16].

2 Methodology and data sources

The research is based on extracts from official engine logbook from the product/chemical tanker. Due to the shipowner's confidentiality and data protection requirements, detailed information about the ship cannot be fully disclosed, and therefore the observed ship is hereinafter designated as M/V Vessel.

2.1 Data source particulars

The M/V Vessel is a product/chemical tanker with 49999 DWT and 29991 GT. It is powered by the two-stroke diesel engine MAN B&W 6G50ME-C9.5 with of MCR 7800 kW at 89.3 rpm. The specific consumption of the main engine is 163 + 5% g/kWh while burning diesel fuel with 42676.8 kJ/kg of lower heating value (LHV). In addition, three Auxiliary Engines Hyundai Himsen 6H21/32 are installed, each with an MCR 960 kW power at 720 rpm. The consumption of auxiliary engines is 186 + 5% g/kWh at nominal load. The exhaust boiler is of the Aalborg OL Automatic type, with a capacity of 18000 kg/h at 7 kg/cm^2 working pressure. The auxiliary steam boiler is of the Aalborg OC-TCi type, with furnace capacity of 2000 kg/h at 7 kg/cm^2 steam pressure.

Engine log extracts consist of two separate physical records:

1. Records of daily sounding (measurement) and content transfer of sludge tanks in engine room,
2. Fuel consumption flow meters statuses taken at any given time-significant moments.

The data processed in this paper reefers to period from 22.02.2020 to 31.08.2020. The sample size selected is based on the data availability.

Daily sounding records consists of a one measurement per day of fuel separator sludge tank content and transferring records from one tank to another. The impact of separator consumed process water is considered by subtracting its amount from generated sludge. Therefore, the consumed process water is taken from the separator manufacturer instruction manual [18] as:

– HFO separator – Alfa Laval S948 – process water consumption is taken as 153 ltr/day for flushing frequency 60 min,
– DO separator – Alpha Laval P615 – process water consumption is taken as 178 ltr/day for flushing frequency 120 min,
– LO separator – Alpha Laval P615 – process water consumption is taken as 178 ltr/day for flushing frequency 120 min.

Fuel consumption records are based on fuel consumption flow meters readings that are registered in regular time periods (at 1200 hrs every day) and during changeover ship operation status (mode). Therefore, fuel consumption flow meter readings in engine room logbook were registered in the following moments and ship states:

– SBE – "Stand-By Engine" – Propulsion plant prepared for departure
– SOSP – "Start Of Sea Passage" – Start of a sea-journey (exiting port/anchorage limits)

[2] VLCC – Very Large Crude Carrier

- NOON – “Noon” – Regular daily flowmeter readings at 1200 hrs LT (local time)
- ESOP – “End Of Sea Passage” – End of the sea-journey (entering port/anchorage limits)
- FWE – “Finished With Engine” – Propulsion plant finished with operation/manoeuvring
- ANCH – “Anchorage” – Vessel secured at anchorage and propulsion plant is set on stand-by status.

The mentioned M/V Vessel use two different types of fuel during her operations:

- HSHFO – Heavy fuel with high sulphur content, >0.5% S
- LSMGO – low-sulphur diesel light diesel, <0.1% S

Therefore, in addition to the previously mentioned recordings during ship operation changeover, fuel consumption flowmeter readings were also recorded in engine room logbook during changeovers of fuel type consumption from HSHFO to LSMGO, according to the requirements of international and local regulations for exhaust gas emissions. The vessel is equipped with exhaust gas scrubber to ensure compliance of global IMO SOx emission while consuming heavy fuel with high sulphur content. As per available data in engine log book extract [19] on 25.07.2022. average sulphur content of HSHFO onboard was 3.014%.

To obtain a more uniform time periods distribution required for analysis fuel consumption flowmeters readings taken at different time points during day are minimized and grouped into periods of “one day”. The duration of “one day” is considered from 1200 hrs to 1200 hrs next day, a 24 hrs period but “one day” also includes the day duration of 25 hours and 23 hours, respectively, depending on the changing ships clock time while sailing through different time zones.

Defined basic ship’s operations modes during this research are:

1. Sailing,
2. Anchorage/Anchoring,
3. Manoeuvring and Port Stay (Mixed Operations)

In addition to the defined basic ship operations modes, a mixed ship operation mode definition is also used, whenever ship undergoes through two or more basic operations during “one day” period.

Accordingly, the following variables were collected and extrapolated from the engine room logbook extract used for analysis:

- The date and time,
- State of the ship’s operation (navigation, manoeuvring/ port, anchorage) – nominal variable,
- Increase in fluid levels in the fuel separator sludge tank – continuous numerical variable,
- HSHFO main engine consumption – continuous numerical variable,
- HSHFO auxiliary engines consumption – continuous numerical variable,
- HSHFO steam generator consumption – continuous numerical variable,
- LSMGO main engine consumption – continuous numerical variable,
- LSMGO auxiliary engines consumption – continuous numerical variable,
- LSMGO steam generators consumption – continuous numerical variable,
- LSMGO inert gas generator consumption – continuous numerical variable,
- LSMGO HPP unit (High pressure pumps unit for cleaning/maintenance) consumption – continuous numerical variable.

2.2 Calculation methodology

The statistical analysis was performed with Microsoft Excel 2019 MSO program package, ver. 1808 with an additional tool pack set Analysis ToolPak-VBA.

Sample size for required confidence levels is calculated with Sample Size Calculator [20].

Modelling of descriptive statistics for continuous numerical variables are based on Šošić et al. [21], (1-8). Therefore, mean is calculated as per model (1):

$$\bar{x} = \frac{x_1 + \cdots + x_n}{N} \tag{1}$$

where N is number of samples, while standard error is calculated

$$SE = \frac{\sigma}{\sqrt{N}} \tag{2}$$

where σ is standard deviation. Standard deviation is calculated:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{N}(X_i - \bar{x})^2}{N}} \tag{3}$$

Median is calculated as per formula (4):

$$M_e = \begin{cases} x_{\frac{(n+1)}{2}}\ ; & \frac{N}{2} \neq INT \\ \dfrac{x_{(\frac{n}{2})} + x_{((\frac{n}{2})+1)}}{2}; & \dfrac{N}{2} = INT \end{cases} \tag{4}$$

and standard variance is calculated:

$$\sigma^2 = \frac{\sum_{i=1}^{N}(X_i - \bar{x})^2}{N} \tag{5}$$

Kurtosis is calculated:

$$Kurt = \frac{\mu_4}{\sigma^4} \tag{6}$$

where μ_4 is fourth standardized moment calculated with model (7):

$$\mu_4 = \frac{\sum_{i=1}^{N}(X_i - \bar{x})^2}{N} \quad (7)$$

while skewness is calculated as per model (8):

$$Skew = \frac{\sum_{i=1}^{N}(X_i - \bar{x})^3}{\sigma^3 * (N-1)} \quad (8)$$

Correlation is presented by means of using Pearson correlation coefficient [21] and is calculated:

$$\rho_{x,y} = \frac{\sum_{i=1}^{N}(X_i - \bar{x})(Y_i - \bar{y})}{\sigma_X * \sigma_Y} \quad (9)$$

where σ_X and σ_Y are standard deviation of X and Y respectively. Therefore, correlation coefficient is calculated:

$$r = \frac{\sum_{i=1}^{n} x_i y_i - n\,\bar{x}\bar{y}}{\sqrt{(\sum_{i=1}^{n} x_i^2 - n\bar{x}^2)(\sum_{i=1}^{n} y_i^2 - n\bar{y}^2)}} \quad (10)$$

Linear regression is presented with model (11):

$$y = a + b * x \quad (11)$$

where b is calculated:

$$b = \frac{\sum_{i=1}^{n} x_i y_i - n\,\bar{x}\bar{y}}{\sum_{i=1}^{n} x_i^2 - n\bar{x}^2} \quad (12)$$

and a is calculated:

$$a = \bar{y} - b * \bar{x} \quad (13)$$

F-test is calculated as per model (14):

$$F = \frac{\sigma_1^2}{\sigma_2^2} \quad (14)$$

While T-test is used to compare mean values of different data groups as per model (15):

$$t = \frac{(\bar{x} - \mu)\sqrt{N}}{\sigma} \quad (15)$$

where μ is mean value of complete population.

Analysis of Variance (ANOVA) is used to establish significant statistical difference between means from several samples and is calculated based on Šošić et al. [21], Tab. 1.

3 Analysis results

3.1 Ship operation modes distribution

The total distribution of hours spent in certain ship operation modes based on the total sum of hours is described in Tab. 2 and Fig. 1.

Table 2 Distribution of hours spent in individual ship operations modes 02/2020-08/2020 – M/V Vessel

Ship's operations mode	Number of hours	%
Sailing	2871	62,1%
Anchorage	362,28	7,8%
Manoeuvring/Port	1391,92	30,1%
Total	4625,2	100,0%

Source: Authors

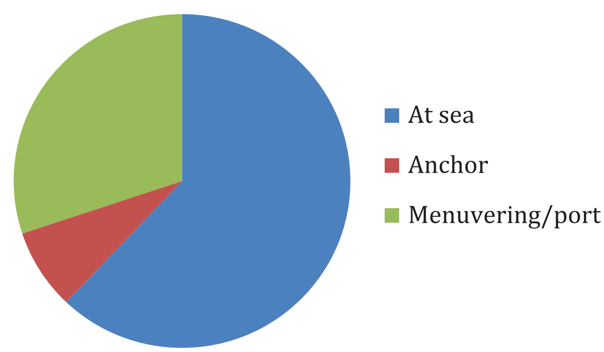

Figure 1 Distribution of hours spent in individual ship operations modes 02/2020 – 08/2020 – M/V Vessel

Source: Authors

Table 1 Analysis of one-way ANOVA

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares (MS)	F
Within	$SS_w = \sum_{j=1}^{k}\sum_{j01}^{l}(X - \bar{X}_j)^2$	$df_w = k - 1$	$MS_w = \frac{SS_w}{df_w}$	$F = \frac{MS_b}{MS_w}$
Between	$SS_b = \sum_{j=1}^{k}(\bar{X}_j - \bar{X})^2$	$df_b = n - k$	$MS_b = \frac{SS_b}{df_b}$	
Total	$SS_b = \sum_{j=1}^{n}(\bar{X}_j - \bar{X})^2$	$df_t = n - 1$		

Source: [21]

3.2 Analysis of the sludge separation from fuel during complete observation period

The observed sample was for 192 days, or 193 of total noon records. The total observed period was from 21.02.2020 to 31.8.2020. The total number of observations during this period were:

- 193 records of separator sludge tank soundings,
- 55 records of fluid transfer from purifier sludge tank,
- 414 records fuel consumption flowmeter readings and calculated fuel consumption for monitored previous period.

Records of fuel consumption flow meter status and calculated fuel consumption are boiled down to total of 193 regular intervals (noon to noon).

During mentioned period of 192-days there were total of 414 fuel flowmeter recordings in engine log book. This sample size would represent statistical dataset of 10 million entries with a 5% confidence interval. A 10 million fuel flowmeter logbook entries would represent the entire service life of a ship that is ranging from 18 -25 years as per Euronav [22].

The total number of purifier sludge tank quantity measurements is 192 performed during period of 193 days (avg. one measurement per day). This sample size, with 192 samples would adequately represent dataset of 347 samples with a 5% confidence interval, as per Sample Size Calculator [20].

The basic descriptive statistics analysis of aggregated input data for fuel consumption (HSHFO and LSMGO) and the separated sludge collected in the purifier sludge tank over observed period is shown in Tab. 3.

From the box plot (Fig. 2) it is visible that the HSHFO daily consumption value is scattered much wider than the daily consumption of LSMGO fuel. This can be explained that diesel fuel is used only in sulphur emission control areas and when entering ports where ship speeds are lower and consequently lower fuel consumption.

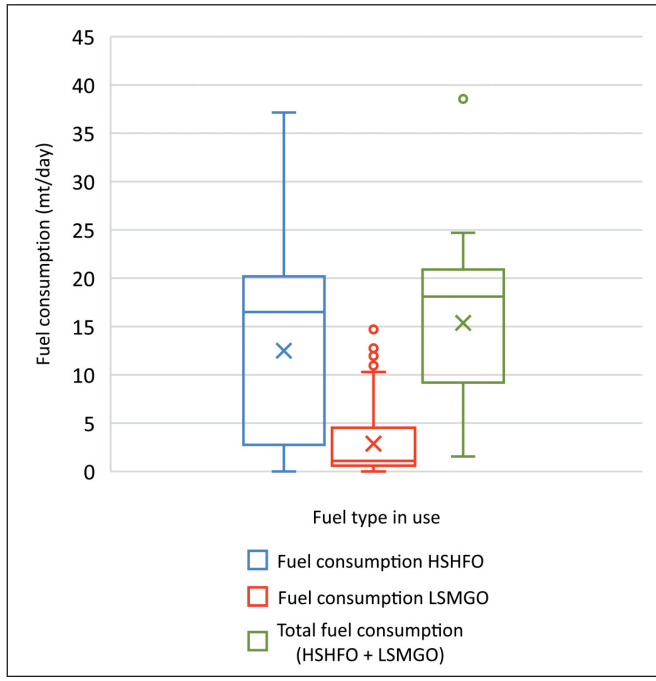

Figure 2 Box plot of averages, quartiles and max. daily fuel consumption over a complete period 02/2020 – 08/2020 – M/V Vessel

Source: Authors

Table 3 Basic descriptive statistical analysis of fuel consumption and separated sludge for the period 02/2020 – 08/2020 – M/V Vessel

Sludge generation		Fuel consumption HSHFO		Fuel consumption LSMGO		Total fuel consumption	
Mean	0,143	Mean	12,493	Mean	2,877	Mean	15,370
Standard Error	0,009	Standard Error	0,635	Standard Error	0,243	Standard Error	0,490
Median	0,140	Median	16,500	Median	1,100	Median	18,100
Mode	0,140	Mode	0,000	Mode	0,600	Mode	20,000
Standard Deviation	0,119	Standard Deviation	8,828	Standard Deviation	3,375	Standard Deviation	6,814
Sample Variance	0,014	Sample Variance	77,926	Sample Variance	11,389	Sample Variance	46,425
Kurtosis	8,809	Kurtosis	-1,328	Kurtosis	1,811	Kurtosis	-0,636
Skewness	2,069	Skewness	-0,284	Skewness	1,580	Skewness	-0,361
Range	0,900	Range	37,150	Range	14,700	Range	37,000
Minimum	-0,02	Minimum	0,000	Minimum	0,000	Minimum	1,550
Maximum	0,900	Maximum	37,150	Maximum	14,700	Maximum	38,550
Sum	27,6	Sum	2411,1	Sum	555,3	Sum	2966,4
Count	193	Count	193	Count	193	Count	193
Largest (1)	0,900	Largest (1)	37,15	Largest (1)	14,700	Largest (1)	38,550
Smallest (1)	0,000	Smallest (1)	0,000	Smallest (1)	0,000	Smallest (1)	1,550
Confidence Level (95,0%)	0,017	Confidence Level (95,0%)	1,253	Confidence Level (95,0%)	0,479	Confidence Level (95,0%)	0,967

Source: Authors

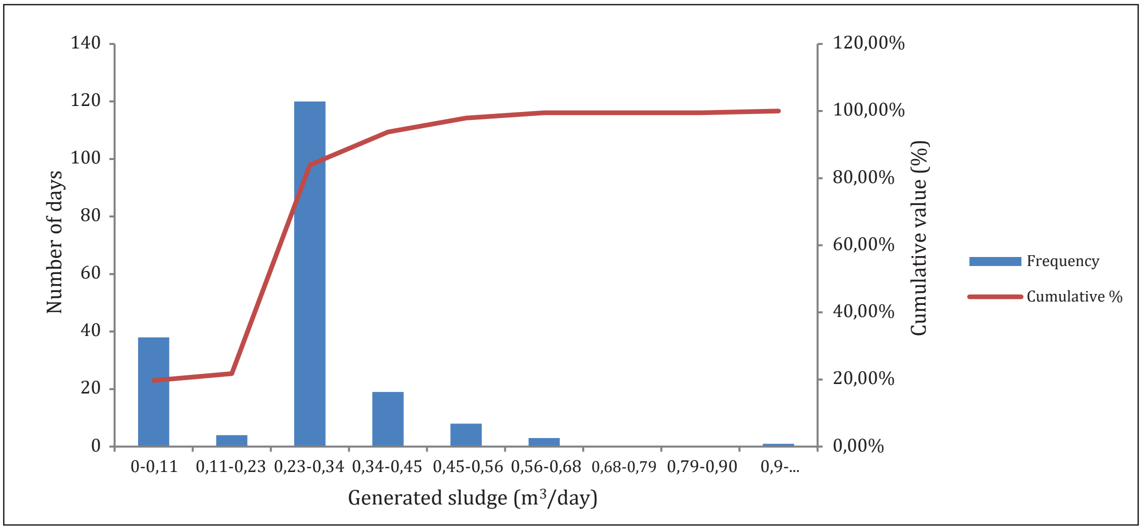

Figure 3 Histogram of the generated sludge per day from fuel by means of centrifugal separator during period 02/2020 – 08/2020 – M/V Vessel

Source: Authors

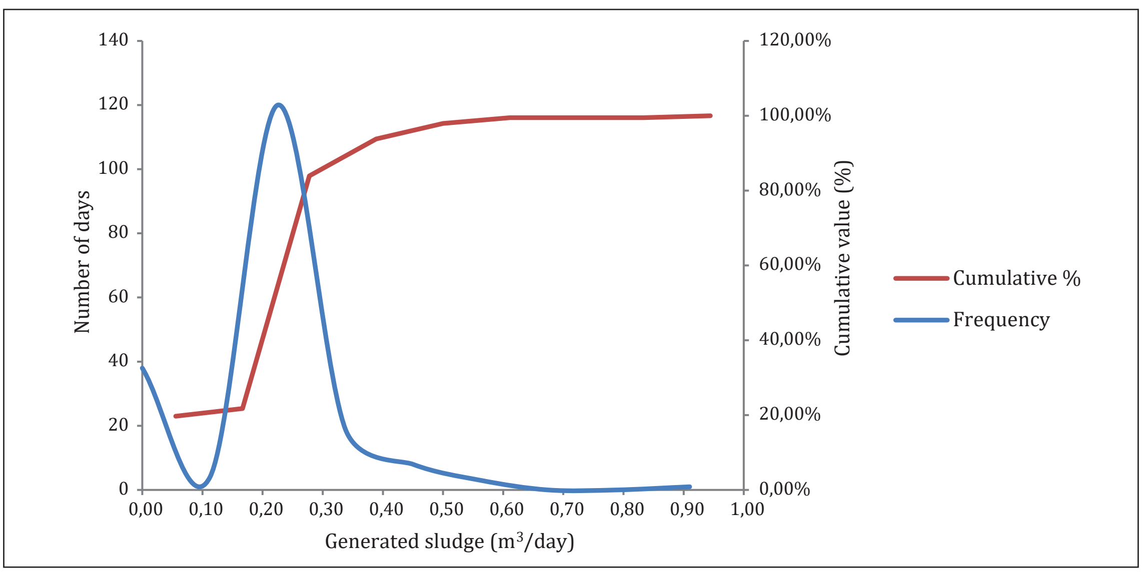

Figure 4 Distribution and cumulative frequency of the generated sludge per day from fuel by means of centrifugal separator during period 02/2020 – 08/2020 – M/V Vessel

Source: Authors

Minimum recorded value for separated sludge is -0.02 and was measured on 20.07.2020. Since in the mentioned period there were not any recorded content transfer operations to/from purifier sludge tank, we can attribute this reading as an error due to:

1. incorrectly performed sounding,
2. inability to accurately perform sounding due to ship operating conditions,
3. a decrease of sludge temperature in tank[3],
4. an increase of sludge temperature in tank on level above water evaporation.

Therefore, for further analysis this value is increased to zero.

For the generated sludge per day histogram following calculation of the distribution classes is performed as per model (16) and data are distributed acc. to Tab. 4.

[3] the temperature purifier sludge tank is not recorded in the engine room logbook

Table 4 Distribution of the separated sludge in m^3 per day period 02/2020 – 08/2020 – M/V Vessel

Bin	Frequency	Cumulative %
0-0,11	38	19,69
0,11-0,23	4	21,76
0,23-0,34	120	83,94
0,34-0,45	19	93,78
0,45-0,56	8	97,93
0,56-0,68	3	99,48
0,68-0,79	0	99,48
0,79-0,90	0	99,48
0,9-...	1	100,00

Source: Authors

Number of distribution classes for sludge generation/ day for histogram is calculated by means of $2^k \geq n$ test where n=193 days and results are determined to be 8 and confirmed by model (16):

$$2^k = 2^8 = 256 \geq 193 \quad (16)$$

Therefore, the amount of sludge generation per day by means of centrifugal separator is presented in histogram (Fig. 3) and distribution diagram in Fig. 4.

In order to compare the separated sludge distribution (Fig. 3) to normal distribution, a zero hypothesis is set: "separated sludge frequency and the normal distribution are similar". To test the differences of both distributions, the Kolmogorov-Smirnov test is used, and result is shown in Tab. 5.

Table 5 Calculated values for testing similarity of separated sludge with the Kolmogorov-Smirnov test

Count	193,000
Mean	0,143
Stand. dev.	0,119027571
Maximum diff.	0,3344

Source: Authors

Critical values are taken from the table of critical values [23], where for n=193, the limit value for α=0.05 is calculated in (17).

$$Critical\ value = \frac{1,36}{\sqrt{n}} = 0,09789 \quad (17)$$

According to model (17), for 95% reliability is then confirmed that:

$$Maxium\ diff. > Critical\ value \quad (18)$$

and thus, it is confirmed that the values are not normally distributed, i.e. we reject the set hypothesis that the distribution of the separated sludge per day is based on normal distribution.

The overall dependence of the separated sludge from fuel in relation to total fuel consumption is analysed and the data dispersion is obtained where the data correlation is 0.2345 and is shown in Tab. 6.

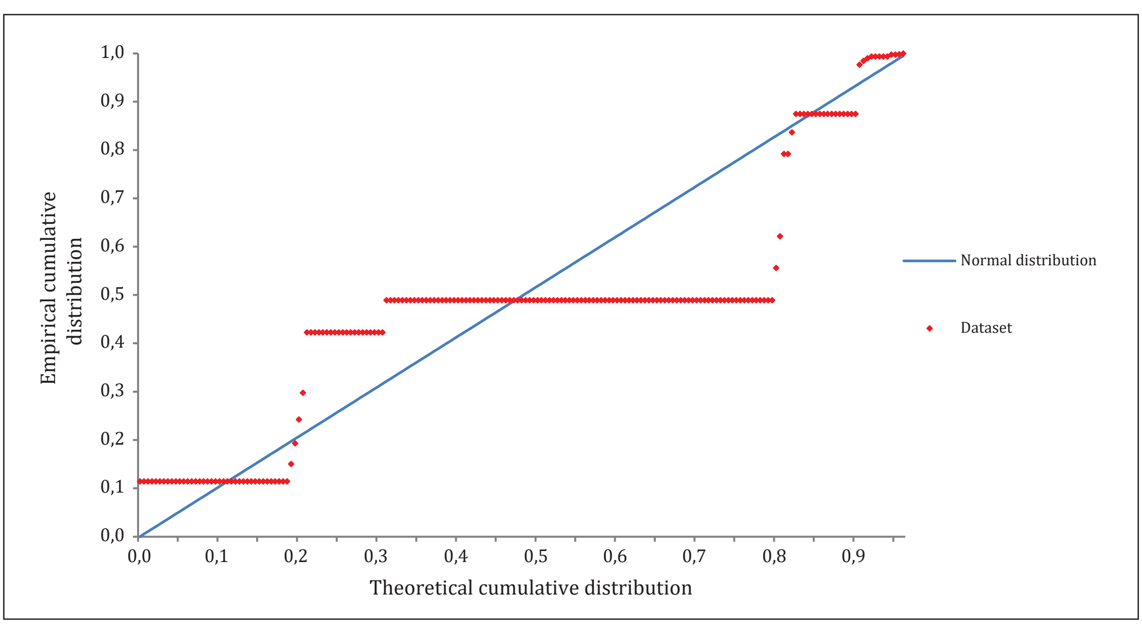

Figure 5 Probability-Probability (P-P) plot of normal distribution cumulative frequency and sludge generation dataset cumulative frequency

Source: Authors

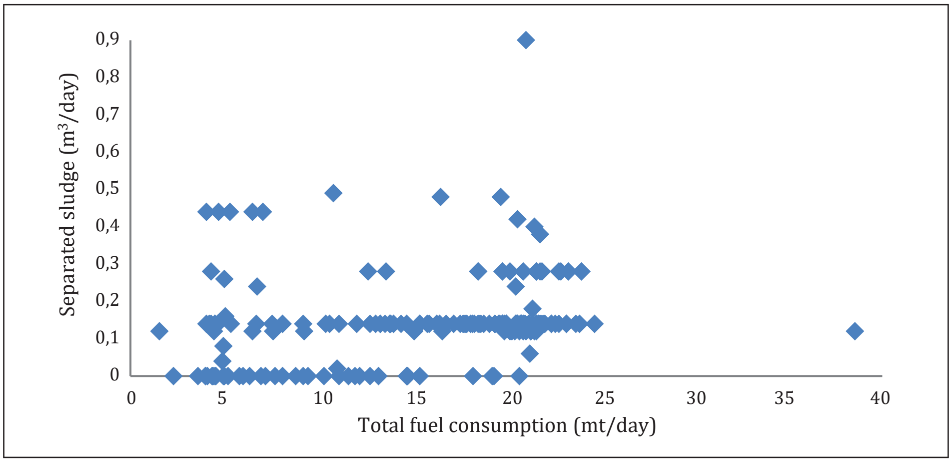

Figure 6 Dependence of the separated sludge to the total fuel consumption for the period 02/2020 – 08/2020 – M/V Vessel

Source: Authors

Table 6 Data correlation of the separated sludge in relation to the total fuel consumption for the period 02/2020 – 08/2020 – M/V Vessel

Correlation

	Sludge gen.	**Cons. HSHFO**	**Cons. LSMGO**	**Total**
Sludge gen.	1,0000			
Cons. HSHFO	0,2949	1,0000		
Cons. LSMGO	-0,2979	-0,7199	1,0000	
Total	0,2345	0,9390	-0,4373	1,0000

Source: Authors

The dependence of separated sludge quantity to the total fuel consumption is described with linear regression formula (19):

$$y = 0{,}004x + 0{,}080 \quad (19)$$

where R^2 = 0.055. Calculated linear regression data are shown in Tab. 7.

In case of using logarithmic regression model (20):

$$y = 0{,}043 \ln(x) + 0{,}030 \quad (20)$$

where R^2 = 0.049. In the case of generating polynomial regression of the second order, and model (21) is obtained:

$$y = -0{,}00003x^2 + 0{,}004x + 0{,}076 \quad (21)$$

where R^2 = 0.055.

Table 7 Calculation of linear regression for generated sludge in relation to the total fuel consumption during the period 02/2020 – 08/2020 – M/V Vessel

Regression Statistics	
Multiple R	0,2345
R Square	0,0550
Adjusted R Square	0,0500
Standard Error	0,1160
Observations	193,0000

ANOVA

	df	*SS*	*MS*	*F*	*Signif. F*
Regression	1,0000	0,1496	0,1496	11,1142	0,0010
Residual	191,0000	2,5706	0,0135		
Total	192,0000	2,7202			

	Coeff's	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95,0%*	*Upper 95,0%*
Intercept	0,0802	0,0207	3,8836	0,0001	0,0395	0,1209	0,0395	0,1209
Total fuel cons.	0,0041	0,0012	3,3338	0,0010	0,0017	0,0065	0,0017	0,0065

Source: Authors

3.3 Analysis of the sludge separation from fuel during different ship operations modes

Due to the possibility ship operation mode influence on the amount of separated sludge from the fuel, we observe it in relation to different ship operations.

During the total period of 192 days, according to the distribution in Tab.1., total of 105 full days ship was employed in navigation. During this period, in case of 80 days the amount of separated sludge from the fuel was 0.14 m^3/day.

During the ship stay on anchorage, through 14 full days, 8 full days the production of separated sludge were 0 m^3/day. The amount of separated sludge during manoeuvring and relocation in ports has two maximums of 0.14 m^3/day and 0 m^3/day respectively.

3.3.1 Analysis of the sludge separation from fuel during navigation

The basic descriptive statistics analysis of aggregated input data for fuel consumption (HSHFO and LSMGO) and the separated sludge collected in the purifier sludge tank during 105 full days while ship was employed in navigation is shown in Tab. 8.

The dispersion of the fuel consumption values during the navigational period should be lower than during entire observed period. Obtained values for the minimum and maximum (indicated with grey colour in Tab. 8) represent single dataset of the observed variable and they significantly stand out from other values, which are more grouped. By comparing that dataset with M/V Vessel machinery plant technical details (i.e. main engine power, specific fuel consumption) obtained minimum and maximum values are found to be "technically impossible". Therefore, further analysis is performed by examining the engine logbook extract [19] and is confirmed that the maximum value for fuel consumption figure (37,150) is obtained during observed period of 46.8 hours, which does not correspond to the 1-day methodology taken. Moreover, the fuel consumption minimum value (1,450) corresponds to fuel consumption measured during period of 1.2 hours, which does not correspond to the research methodology taken. In this case, these two parameters are rejected from observation/calculation to have accurate data which corresponds to the chosen methodology. Furthermore, the inaccuracy of the values is confirmed by the G-test (22):

$$Q_{calc} = \frac{|37{,}15 - 20{,}7\,|}{(37{,}15 - 0)} = 0{,}443 \qquad (22)$$

The number of samples in model (22) was taken 105, and accordingly is calculated $Q_{calc} > Q_{crit}$, we can reject accuracy and define that the value of consumption of 37,15 mt/day is an error. In that case, by rejecting values, new descriptive statistics calculations with the base of 103 samples is performed and shown in Tab. 9.

Table 8 Basic descriptive statistical analysis of fuel consumption and separated sludge during navigation for period 02/2020 – 08/2020 – M/V Vessel

	Sludge generation	Fuel Cons. HSHFO	Fuel Cons. LSMGO	Fuel Cons. Total
Mean	0,172	19,453	1,027	20,480
Standard Error	0,011	0,349	0,171	0,305
Median	0,140	20,100	0,600	20,800
Mode	0,140	20,000	0,600	20,000
Standard Deviation	0,109	3,574	1,753	3,121
Sample Variance	0,012	12,776	3,072	9,742
Kurtosis	19,198	12,082	26,281	22,476
Skewness	3,574	-0,746	4,886	-0,359
Range	0,900	35,700	12,900	37,000
Minimum	0,000	1,450	0,000	1,550
Maximum	0,900	37,150	12,900	38,550
Sum	18,080	2042,600	107,800	2150,400
Count	105,000	105,000	105,000	105,000
Largest (1)	0,900	37,150	12,900	38,550
Smallest (1)	0,000	1,450	0,000	1,550
Confidence Level (95,0%)	0,021	0,692	0,339	0,604

Source: Authors

Table 9 Revised descriptive statistical analysis of fuel consumption and separated sludge during navigation for period 02/2020 – 08/2020 – M/V Vessel

	Sludge generation	Fuel Cons. HSHFO	Fuel Cons. MGO	Fuel Cons. Total
Mean	0,173	19,456	1,032	20,488
Standard Error	0,011	0,257	0,174	0,177
Median	0,140	20,100	0,600	20,800
Mode	0,140	20,000	0,600	20,000
Standard Deviation	0,110	2,604	1,767	1,794
Sample Variance	0,012	6,778	3,123	3,218
Kurtosis	18,853	5,960	25,866	0,078
Skewness	3,539	-1,806	4,855	-0,414
Range	0,900	17,200	12,900	8,900
Minimum	0,000	6,700	0,000	15,800
Maximum	0,900	23,900	12,900	24,700
Sum	17,840	2004,000	106,300	2110,300
Count	103,000	103,000	103,000	103,000
Largest (1)	0,900	23,900	12,900	24,700
Smallest (1)	0,000	6,700	0,000	15,800
Confidence Level (95,0%)	0,022	0,509	0,345	0,351

Source: Authors

Number of distribution classes for sludge generation/ day for histogram during navigation is found to be 7 and is determined by a $2^k \geq n$ test, where n = 105 days and therefore reads:

$$2^k = 2^7 = 128 \geq 104 \tag{23}$$

Therefore, the amount of sludge generation per day during navigation is presented in histogram (Fig. 6) and distribution diagram (Fig. 7):

The overall dependence of the generated sludge quantity in relation to the total fuel consumption during navigation period, is shown in Fig. 8, where the data correlation is 0.0635 (Tab. 10), which is significantly less than when observing entire 192-day period.

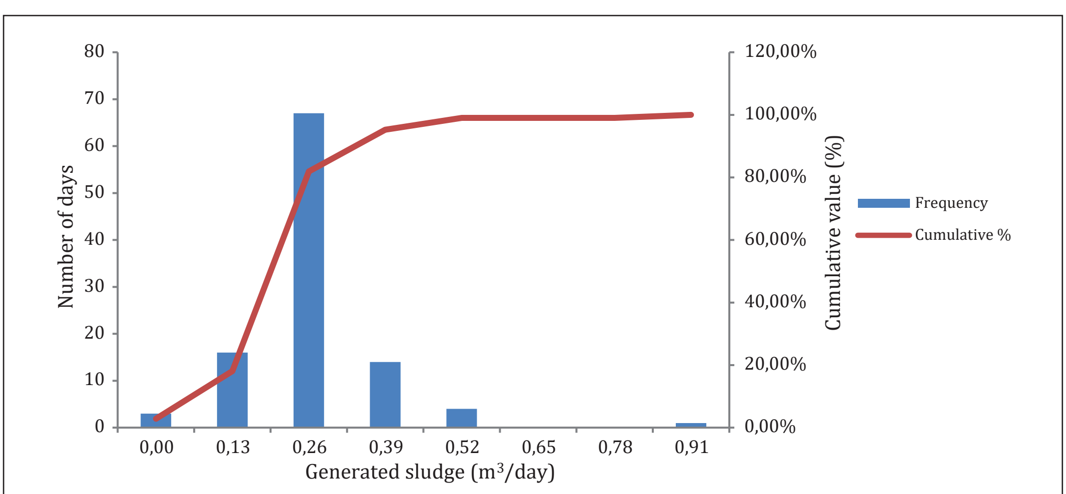

Figure 7 Histogram of the generated sludge per day from fuel during navigation during period 02/2020 – 08/2020 – M/V Vessel

Source: Authors

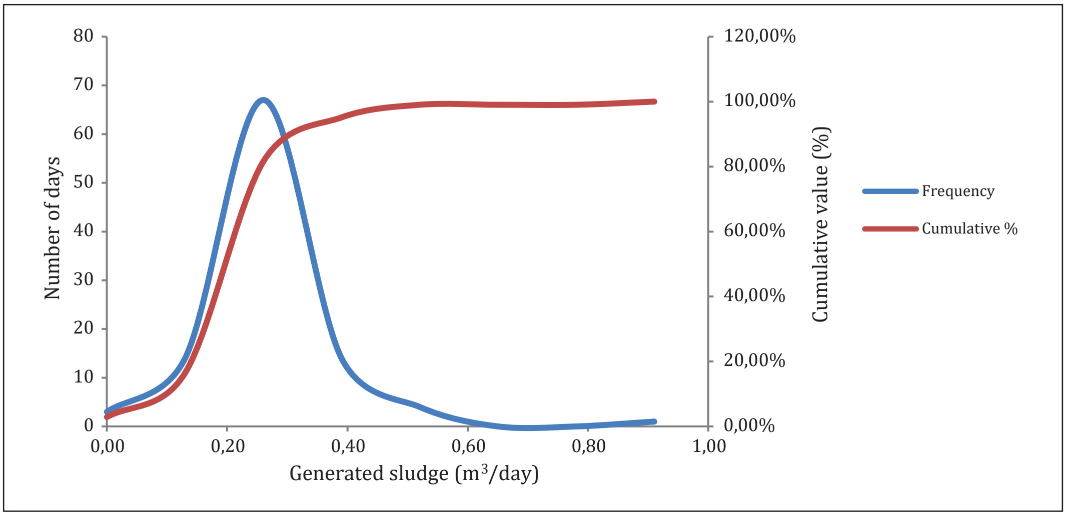

Figure 8 Distribution of the generated sludge per day from fuel during navigation during period 02/2020 – 08/2020 – M/V Vessel

Source: Authors

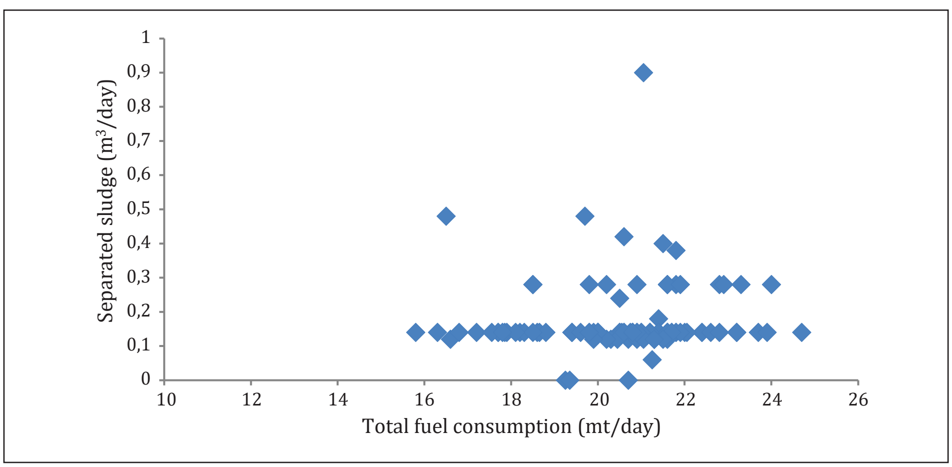

Figure 9 Dependence of the separated sludge to the total fuel consumption during navigation in period 02/2020 – 08/2020 – M/V Vessel

Source: Authors

Table 10 Data correlation of the separated sludge in relation to the total fuel consumption during navigation in period 02/2020 – 08/2020 – M/V Vessel

Correlation

	Sludge gen.	Cons. HSHFO	Cons. LSMGO	Total
Sludge gen.	1,0000			
Cons. HSHFO	0,1380	1,0000		
Cons. LSMGO	-0,1387	-0,7263	1,0000	
Total	0,0635	0,7359	-0,0690	1,0000

Source: Authors

From Tab. 10. is evident that the correlation between total fuel consumption during navigation and the sludge extraction from fuel is 0,063, which is less than when observing the entire period correlation of 0,23. The correlation between heavy fuel consumption and the separated sludge from fuel during the navigational period is 0,138, which is significantly lower than the observed correlation over the entire period of 0,29.

The dependence of separated sludge quantity to the total fuel consumption during navigation is described with linear regression formula (24):

$$y = 0{,}0039x + 0{,}0933 \qquad (24)$$

where R^2 = 0,0040. Calculated linear regression data are shown in Tab. 11.

Table 11 Calculation of linear regression for generated sludge in relation to the total fuel consumption during navigation in period 02/2020 – 08/2020 – M/V Vessel

Regression Statistics	
Multiple R	0,0635
R Square	0,0040
Adjusted R Square	-0,0058
Standard Error	0,1104
Observations	103,0000

ANOVA

	df	*SS*	*MS*	*F*	*Signif. F*
Regression	1,0000	0,0050	0,0050	0,4095	0,5237
Residual	101,0000	1,2307	0,0122		
Total	102,0000	1,2356			

	Coeff's	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95,0%*	*Upper 95,0%*
Intercept	0,0933	0,1253	0,7448	0,4581	-0,1552	0,3419	-0,1552	0,3419
Total fuel cons.	0,0039	0,0061	0,6399	0,5237	-0,0082	0,0160	-0,0082	0,0160

Source: Authors

In case of using logarithmic regression, model (25) is generated:

$$y = 0{,}0737\ \ln(x) - 0{,}0492 \quad (25)$$

where $R^2 = 0.0036$.

In the case of generating polynomial regression of the second order, model (26) is generated:

$$y = 0{,}011x^2 - 0{,}0423x + 0{,}554 \quad (26)$$

where $R^2 = 0.0061$.

In the case of generating polynomial regression of the 4th order, model (27) is generated:

$$y = -0{,}0001x^4 + 0{,}0078x^3 - 0{,}2065x^2 + 2{,}3329x - 9{,}2796 \quad (27)$$

where $R^2 = 0.0146$.

3.3.2 Analysis of the sludge separation from fuel during ship's anchorage stay

The basic descriptive statistics analysis of aggregated input data for fuel consumption (HSHFO and LSMGO) and

Table 12 Basic descriptive statistical analysis of fuel consumption and separated sludge during the ship's anchorage stay for the period 02/2020-08/2020

	Sludge generation	**Fuel Cons. HSHFO**	**Fuel Cons. MGO**	**Fuel Cons. Total**
Mean	0,0686	1,2643	3,3643	4,6286
Standard Error	0,0241	0,4157	0,3866	0,2819
Median	0,0000	0,0000	3,8000	4,3500
Mode	0,0000	0,0000	4,0000	4,0000
Standard Deviation	0,0900	1,5554	1,4467	1,0548
Sample Variance	0,0081	2,4194	2,0929	1,1126
Kurtosis	0,4177	-1,5849	-0,4225	4,8900
Skewness	1,0411	0,5290	0,2183	2,2503
Range	0,2800	4,1000	4,7500	4,0000
Minimum	0,0000	0,0000	1,6000	3,6000
Maximum	0,2800	4,1000	6,3500	7,6000
Sum	0,9600	17,7000	47,1000	64,8000
Count	14,0000	14,0000	14,0000	14,0000
Largest (1)	0,2800	4,1000	6,3500	7,6000
Smallest (1)	0,0000	0,0000	1,6000	3,6000
Confidence Level (95,0%)	0,0520	0,8981	0,8353	0,6090

Source: Authors

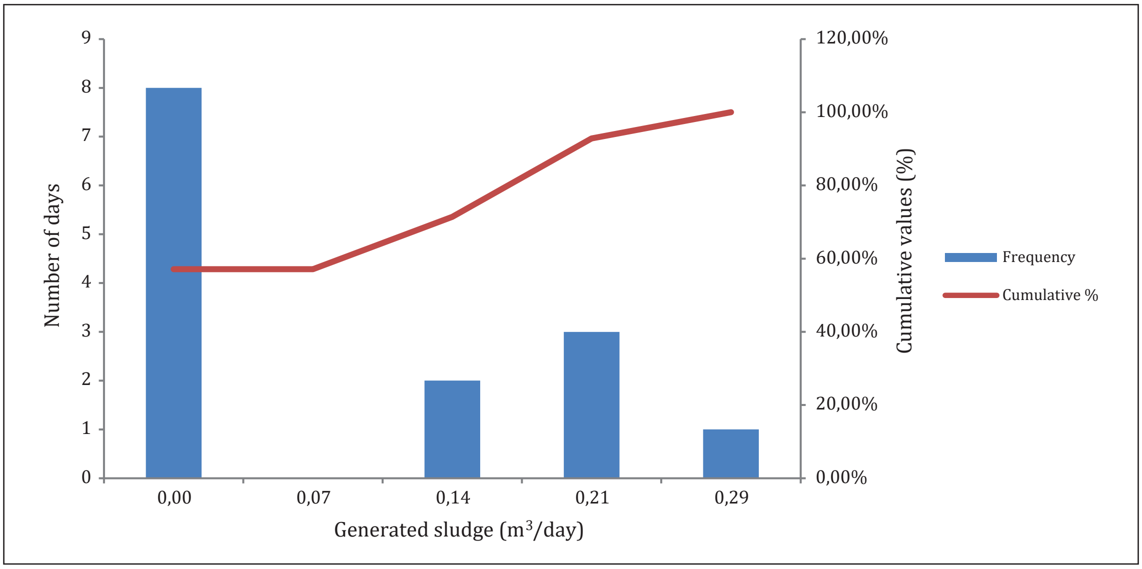

Figure 10 Histogram of the generated sludge per day from fuel during anchorage stay for period 02/2020 – 08/2020 – M/V Vessel

Source: Authors

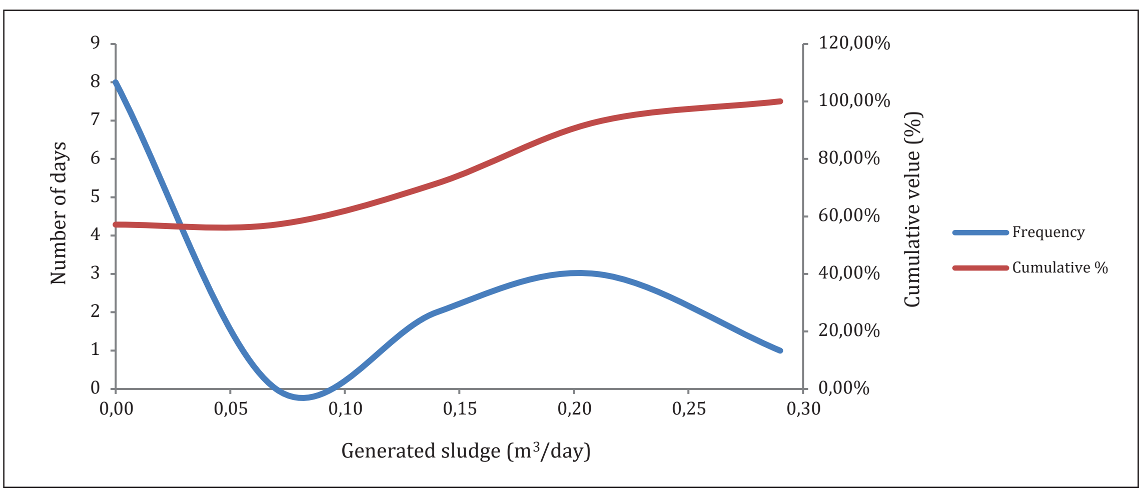

Figure 11 Distribution of the generated sludge per day from fuel during anchorage stay for 02/2020 – 08/2020 – M/V Vessel

Source: Authors

the separated sludge collected in the separator sludge tank during 14 full days while ship was at anchorage is shown in Tab. 12.

For the calculation of distribution classes number for sludge generation/full day for histogram generation is determined by a $2^k \geq n$ test (28), where n=14 days and therefore reads:

$$2^k = 2^4 = 16 \geq 14 \tag{28}$$

Accordingly, the class size is determined to be 0.07.

The overall dependence of the generated sludge quantity in relation to the total fuel consumption during anchorage stay, is shown in Fig. 11, where the data correlation is 0.0993 (Tab. 13), which is significantly less than when observing entire 192-day period (0,2345).

Table 13 Data correlation of the separated sludge in relation to the total fuel consumption during anchorage stay for period 02/2020 – 08/2020 – M/V Vessel

Correlation

	Sludge gen.	Cons. HSHFO	Cons. LSMGO	Total
Sludge gen.	1,0000			
Cons. HSHFO	0,2342	1,0000		
Cons. LSMGO	-0,1794	-0,7554	1,0000	
Total	0,0993	0,4386	0,2576	1,0000

Source: Authors

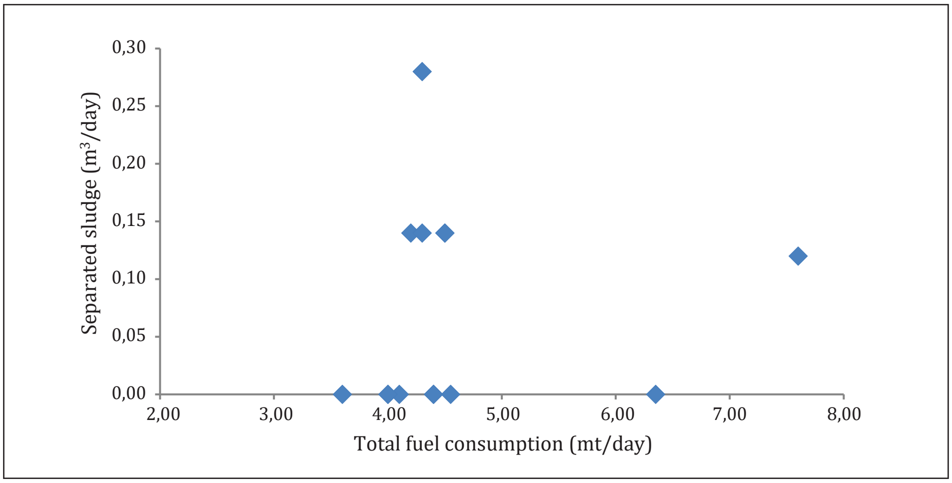

Figure 12 Dependence of the separated sludge to the total fuel consumption during anchorage stay for period 02/2020 – 08/2020 – M/V Vessel

Source: Authors

The correlation between heavy fuel consumption and the sludge generation from fuel during the anchorage stay is 0,2342, which is lower than observed correlation over the entire period of 0,29.

The regression formula for linear regression in this case is (29):

$$y = 0{,}0085x + 0{,}0293 \tag{29}$$

where $R^2 = 0{,}0099$. Calculated linear regression data are shown in Tab. 14.

In case of using logarithmic regression, a model (30) is obtained.

$$y = 0{,}0526 \ln(x) - 0{,}0111 \tag{30}$$

where $R^2 = 0.0128$.

In the case of generating polynomial regression of second order, model (31) is generated where $R^2 = 0.0177$.

$$y = 0{,}0078x^2 + 0{,}0971x - 0{,}2045 \tag{31}$$

In the case of generating polynomial regression of the third order, model (32) is generated where $R^2 = 0.187$.

$$y = 0{,}0282x^3 - 0{,}473x^2 + 2{,}5688x - 4{,}4585 \tag{32}$$

Table 14 Calculation of linear regression for generated sludge in relation to the total fuel consumption during anchorage stay for period 02/2020 – 08/2020 – M/V Vessel

Regression Statistics	
Multiple R	0,0993
R Square	0,0099
Adjusted R Square	-0,0727
Standard Error	0,0932
Observations	14,0000

ANOVA

	df	*SS*	*MS*	*F*	*Signif. F*
Regression	1,0000	0,0010	0,0010	0,1195	0,7356
Residual	12,0000	0,1043	0,0087		
Total	13,0000	0,1054			

	Coeff's	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95,0%*	*Upper 95,0%*
Intercept	0,0293	0,1162	0,2526	0,8049	-0,2238	0,2825	-0,2238	0,2825
Total fuel cons.	0,0085	0,0245	0,3456	0,7356	-0,0449	0,0619	-0,0449	0,0619

Source: Authors

3.3.3 Analysis of the sludge separation from fuel during mixed operations

Mixed ship operations in this view includes all operations for 24 hours periods (day) on whom vessel was not only in navigation or only at anchorage stay. In this group are the days spent during the port stay, manoeuvring, relocation, etc.

The basic descriptive statistics analysis of aggregated input data for fuel consumption (HSHFO and LSMGO) and the separated sludge collected in the purifier sludge tank during 74 full days while ship was under mixed operations is shown in Tab. 15.

Distribution of generated quantity of sludge per days for the vessel operating in mixed operations in presented in Fig. 13. The number of histogram classes is 7 and is determined by a $2^k \geq$ n test where it is n = 74 days, and therefore it reads:

$$2^k = 2^7 = 128 \geq 74 \quad (33)$$

Distribution of histogram cumulative functions shown in Fig. 14 layout.

Table 15 Basic descriptive statistical analysis of fuel consumption and separated sludge during the ship operating in mixed operations for the period 02/2020-08/2020

	Sludge generation	Fuel Cons. HSHFO	Fuel Cons. MGO	Fuel Cons. Total
Mean	0,1161	4,7405	5,4111	10,1516
Standard Error	0,0146	0,6528	0,4307	0,5294
Median	0,1400	3,1100	4,9250	10,3500
Mode	0,0000	0,0000	1,3000	15,4000
Standard Deviation	0,1257	5,6158	3,7048	4,5537
Sample Variance	0,0158	31,5374	13,7258	20,7362
Kurtosis	1,7459	-0,2269	-0,3083	-0,9237
Skewness	1,3674	0,9546	0,6722	0,2838
Range	0,4900	19,1500	14,7000	17,5000
Minimum	0,0000	0,0000	0,0000	2,3000
Maximum	0,4900	19,1500	14,7000	19,8000
Sum	8,5900	350,8000	400,4200	751,2200
Count	74,0000	74,0000	74,0000	74,0000
Largest (1)	0,4900	19,1500	14,7000	19,8000
Smallest (1)	0,0000	0,0000	0,0000	2,3000
Confidence Level (95,0%)	0,0291	1,3011	0,8583	1,0550

Source: Authors

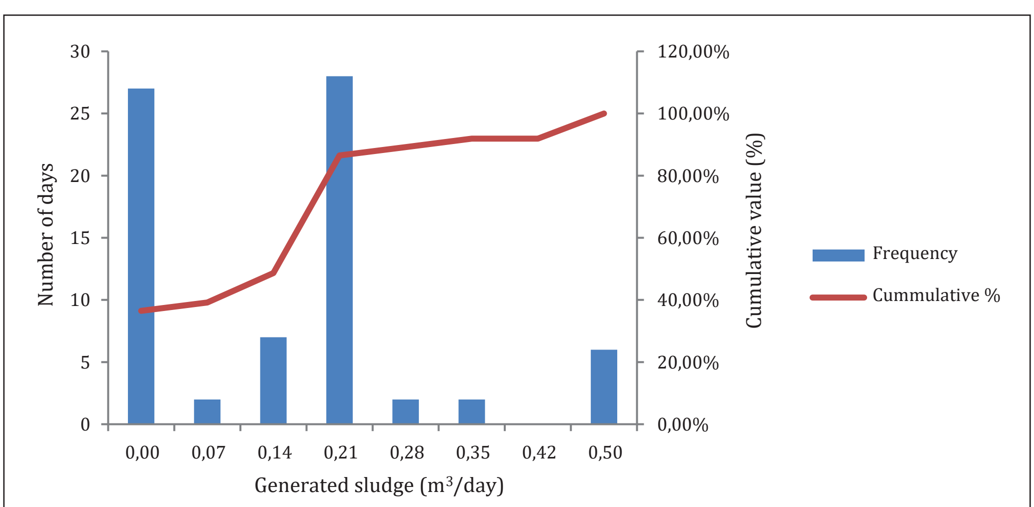

Figure 13 Histogram of the generated sludge per day from fuel during mixed operations for period 02/2020 – 08/2020 – M/V Vessel

Source: Authors

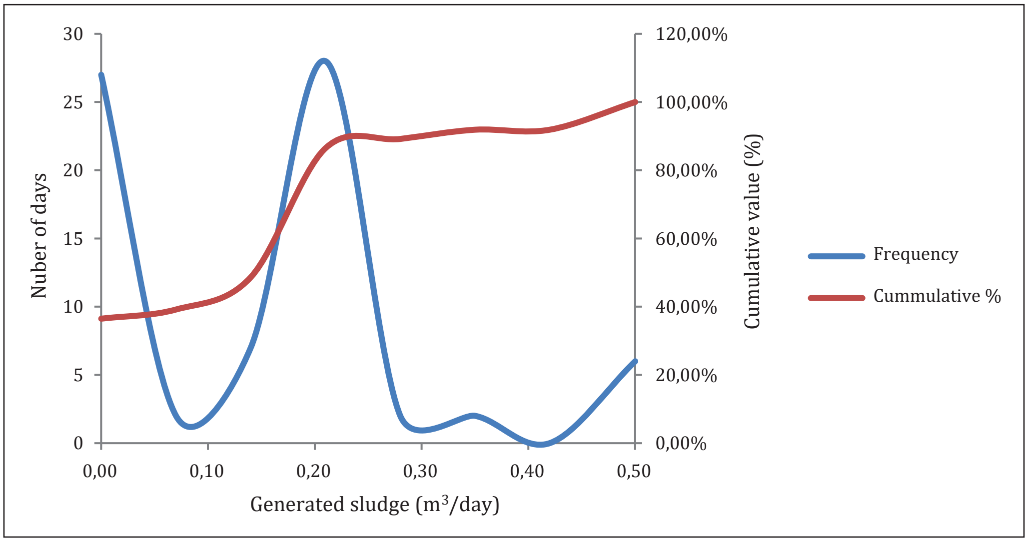

Figure 14 Distribution of the generated sludge per day from fuel during mixed operations for 02/2020 – 08/2020 – M/V Vessel

Source: Authors

Table 16 Data correlation of the separated sludge in relation to the total fuel consumption during mixed operations for period 02/2020 – 08/2020 – M/V Vessel

Correlation

	Sludge gen.	Cons. HSHFO	Cons. LSMGO	Total
Sludge gen.	1,0000			
Cons. HSHFO	0,1269	1,0000		
Cons. LSMGO	-0,2567	-0,5894	1,0000	
Total	-0,0523	0,7537	0,0867	1,0000

Source: Authors

The overall dependence of the generated sludge quantity in relation to the total fuel consumption during mixed vessel operations, is shown in Fig. 14, where the data correlation is -0.0523 (Tab. 16).

The regression formula of linear regression in this case is:

$$y = 0{,}0014x + 0{,}1307 \tag{34}$$

where R^2 = 0.0027. Values for linear regression are specified in Tab. 17.

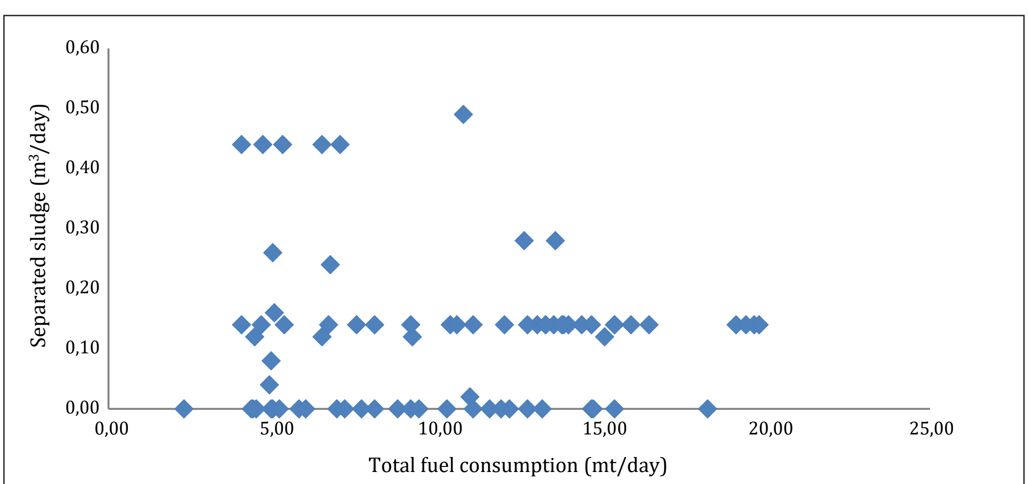

Figure 15 Dependence of the separated sludge to the total fuel consumption during mixed vessel operations for period 02/2020 – 08/2020 – M/V Vessel

Source: Authors

Table 17 Calculation of linear regression for generated sludge in relation to the total fuel consumption during mixed operations for period 02/2020 – 08/2020 – M/V Vessel

Regression Statistics	
Multiple R	0,0523
R Square	0,0027
Adjusted R Square	-0,0111
Standard Error	0,1264
Observations	74,0000

ANOVA

	df	*SS*	*MS*	*F*	*Signif. F*
Regression	1,0000	0,0031	0,0031	0,1972	0,6583
Residual	72,0000	1,1498	0,0160		
Total	73,0000	1,1530			

	Coeff's	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95,0%*	*Upper 95,0%*
Intercept	0,1307	0,0361	3,6214	0,0005	0,0588	0,2027	0,0588	0,2027
Total fuel cons.	-0,0014	0,0032	-0,4441	0,6583	-0,0079	0,0050	-0,0079	0,0050

Source: Authors

Therefore, in case of using logarithmic regression, a model (35) is obtained, where $R^2 = 0.0028$.

$$y = 0{,}013\ \ln(x) - 0{,}1456 \quad (35)$$

In the case of generating polynomial regression of the second order a model (36) is obtained where $R^2 = 0.0051$.

$$y = 0{,}003x^2 - 0{,}079x - 0{,}1593 \quad (36)$$

In case of using polynomial regression of the fourth order a model (37) is obtained where is $R^2 = 0{,}0146$.

$$y = 0{,}0005x^4 + 0{,}0012x^3 - 0{,}0197x^2 + 0{,}1242x - 0{,}1303 \quad (37)$$

Further comparison is made by dividing mixed ship operations that lasts one day (also 23-25 hours) into different specific operational profile as:

- The combination of navigation and vessel anchorage stay,
- The combination of navigation and vessel port stay,
- The combination of vessel anchorage stays and port stay,
- The combination of navigation, anchorage stay and port stay.

Different distributions of separated sludge quantities per day are generated and presented in Fig. 16 and Fig. 17.

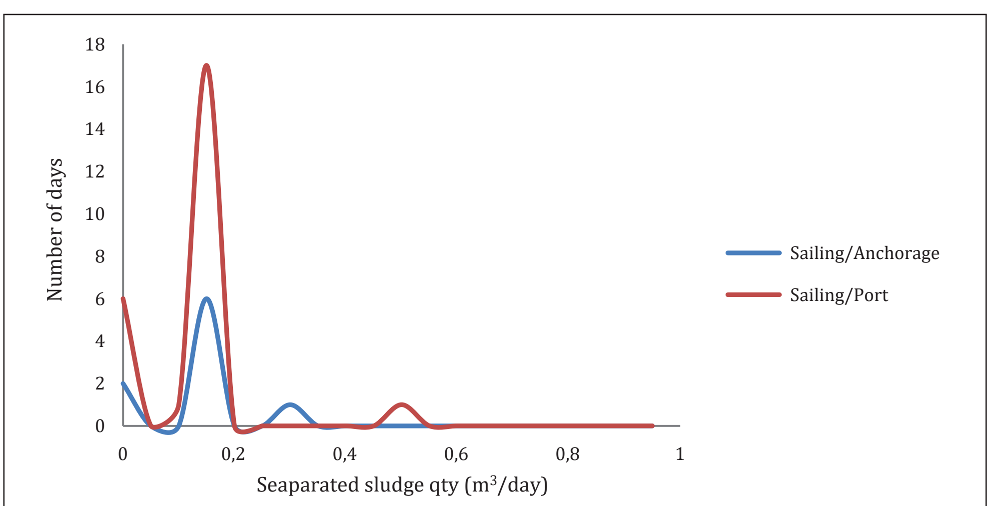

Figure 16 Distribution of separated fuel quantity from fuel per day during mixed operation different specific operational profile for the period 02/2020 -08/2020

Source: Authors

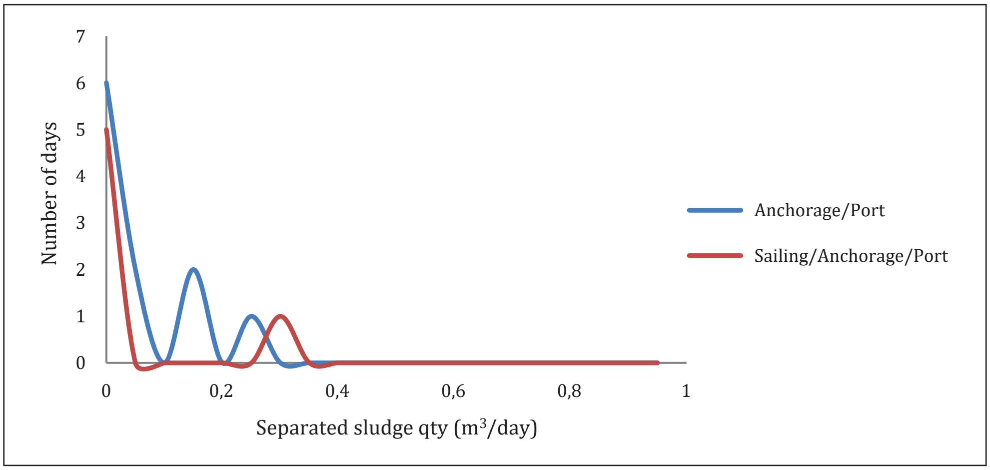

Figure 17 Distribution of separated fuel quantity from fuel per day during mixed operation different specific operational profile for the period 02/2020 -08/2020

Source: Authors

4 Hypotheses testing

4.1 Testing the difference in the separated sludge quantity from fuel in different ship's operation modes by means of T-test using an F-test

As the distribution of the separated sludge quantity per day from the fuel is not distributed acc. normal distribution, as previously proven by the formula (3). For proper testing of hypothesis whenever there is significant difference in separated quantity during different vessel operations a T-test with using of F-test is performed. In this case, the hypothesis is examined, whether there are differences in the separated sludge per day during navigation in comparison with mixed operations.

Set hypothesis are:

- Zero hypothesis (H_0): There is no strong statistical evidence that difference in separated sludge from fuel per day during navigation operations and during mixed operations is significant
- Alternative hypothesis (H_1): The resulting differences in the amount of separated sludge from fuel per day during navigation operations and per day in mixed operations are statistically significant.

With a T-test, testing of the significance of the difference between arithmetic means is performed. Considering that there are two different data sets available, first approach is to perform the variance test with an F-test where result are presented in (38) which is calculated as per model (14).

$$p = 0{,}215 \Longmapsto p > 0{,}05 \quad (38)$$

Therefore, with a reliability of more than 95%, it is accepted assumption that the samples have approximately equal variances and thereby a one-way homoscedastic T-test is further performed. The result obtained is indicated in the formula (39).[4]

$$p = 0{,}00079 \Longmapsto p < 0{,}01 \quad (39)$$

In case of using a two-way T-test the result is presented in model (40).

$$p = 0{,}00158 \Longmapsto p < 0{,}01 \quad (40)$$

Accordingly, with a level of significance p < 0.01 (i.e. with an accuracy of 99%) we can conclude that there is a significant statistical difference in the amount of separated sludge from the fuel per day during the navigational period versus during mixed ship operations. Therefore, alternative hypothesis (H_1) is accepted.

4.2 Testing of the differences in the amount of separated sludge in different ship operation modes by analysing variance with ANOVA test

4.2.1 Testing of the amount of separated sludge from fuel in relation to ship operation modes by single-factor analysis of variance

During different ship operations (in the case three data sets – navigation, anchorage, mixed operations) there are different sizes of data sets. By means of single-factor analysis of variance (ANOVA test) we are testing if there is a significant difference in arithmetic means? The data sets are grouped as mentioned before, according to the different ship operations mentioned in Tab. 2.

[4] Homoscedastic T-test – defined as a type 2 T-test with the existence of approximately equal variance

Table 18 Calculated single-factor ANOVA test for separated sludge quantity during different ship operations for the period 02/2020 – 08/2020 – M/V Vessel

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Navigation	103	17,84	0,173203883	0,012114144
Maneuvering/Port (Mix Oper.)	74	8,59	0,116081081	0,015794021
Anchorage	14	0,96	0,068571429	0,008105495

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0,225110298	2	0,112555149	8,484586012	0,000296561	3,043979683
Within Groups	2,493977661	188	0,013265839			
Total	2,719087958	190				

Source: Authors

Calculation presented in Tab. 18, a P-value is established and according to the formula (41) we get:

$$p = 0{,}0002965 \Longrightarrow p < 0{,}01 \quad (41)$$

Therefore, it can be concluded, with 99% accuracy, that there is present a statistically significant difference between the arithmetic means of the observed samples of the separated sludge quantity from fuel per day during various ship operations.

4.2.2 Testing the amount and type of consumed fuel in relation to ship operation modes by multi-factor analysis of variance

Considering that different type of fuel is consumed during different ship's operations, a multi-factor analysis of variance is performed to compare the impact of ship's operations mode (navigation and mixed operations) on the consumed fuel type quantity, as shown in Tab. 19.

Table 19 Calculated multi-factor ANOVA test to compare the impact of quantities and types of consumed fuel in relation to different types of ship operations for the period 02/2020 – 08/2020 – M/V Vessel

SUMMARY

Navigation	*Fuel consumption HSHFO*	*Fuel consumption LSMGO*	*Total*
Count	74	74	148
Sum	1451	64,55	1515,55
Average	19,60811	0,872297	10,2402
Variance	4,583906	1,491996	91,37193
Maneuvering/Port (Mix Oper.)			
Count	74	74	148
Sum	350,8	400,42	751,22
Average	4,740541	5,411081	5,075811
Variance	31,53743	13,72577	22,59081
Total			
Count	148	148	
Sum	1801,8	464,97	
Average	12,17432	3,141689	
Variance	73,57487	12,74229	

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Sample	1973,65	1	1973,65	153,7736	1,18E-28	3,873502
Columns	6037,549	1	6037,549	470,4056	8,31E-63	3,873502
Interaction	6967,22	1	6967,22	542,8393	1,42E-68	3,873502
Within	3747,754	292	12,83477			
Total	18726,17	295				

Source: Authors

To properly compare the impact of the consumed fuel quantity during different ship operation modes, each dataset size is reduced to the same number of samples which in this case is the 74. For the test purpose, three different hypotheses are set so that multi-factor ANOVA test can be performed:

– Hypothesis H_1: Is there a significant impact of the type of ship's operation mode on the fuel quantity consumed (ignoring the fuel type in use),
– Hypothesis H_2: Is there a significant impact of the fuel type on the fuel quantity consumed (ignoring the type of ship's operation mode),
– Hypothesis H_3: Is there a statistically significant influence between the type of ship's operation modes (navigation or mixed operation) and the fuel type consumed when influencing the fuel quantity consumed.

Calculated p-values, presented in Tab. 19 and based on set hypothesis, following conclusions were drawn out:

– Hypothesis H_1: P-value related to the impact of ship's operation mode type on fuel quantity consumed is 1.18 x 10^{-28}. Therefore, with a probability of >95%, it's confirmed that there is statistical significance on influence of ship's operation mode on the consumed fuel quantity (ignoring the type of fuel consumed). This claim can be supported by the fact that mixed ship operations represent fuel consumption while the ship was in port and/or anchorage, where the main engine was mainly stopped. Based on descriptive statistical analysis arithmetic means of the consumed fuel quantity during navigation is 10.24 mt/day, while for mixed operations is 5.07 mt/day.
– Hypothesis H_2: the calculated p-value is 8.31 x 10^{-63}, which confirms the hypothesis that with a probability >95%, there is present statistically significant influence of the fuel type in use on the amount of fuel consumed. This claim can be supported by the fact that LSMGO fuel is mainly consumed in port areas where fuel consumption is lower. The average consumption of HSHFO fuel is 12.17 mt/day while the consumption of LSMGO is 3.14 mt/day.
– Hypothesis H_3: the calculated p-value is 1.42 x 10^{-68}, and therefore confirms hypothesis, with a probability > 95%, that there is a significant statistical interaction between the fuel type consumed and ship operation modes on fuel quantity consumed. During navigation operations, the average consumption of HSHFO is 19.6 mt/day while LSMGO is 0.87 mt/day. During mixed operations, the average consumption of HSHFO is 4.74 mt/day while the LSMGO is 5.41 mt/day.

5 Discussion

Basic analysis of the ship operation modes shows that the ship spent 62.1% of the time in navigation, 7.8% of the time at the anchorage and 30.1% of the time in mixed operations consisting of port stay, manoeuvring, relocating, and anchorage stay. This is different from VLCC operation mode time distribution presented by Iordanidis et al. [16], where 70.2% of the time vessel spend in navigation. However, distribution of operational modes greatly depends of vessel type and area of vessel employment. Paper by Iordanidis et al. had review operational modes of a very large crude carrier (VLCC) while in this paper a product/chemical tanker has been monitored.

By means of basic descriptive statistics analysis several values has been calculated for separated sludge from fuel, heavy fuel consumption (HSHFO) and diesel fuel consumption (LSMGO) during entire observed period. Values for fuel consumption quantities and the separated sludge quantities were found dispersed in amounts from 0 mt/day to 0.9 mt/day for separated sludge quantity, from 0 mt/day to 23,9 mt/day for HSHFO consumption and from 0 mt/day to 12.9 mt/day for the LSMGO consumption. Therefore, it was calculated that on average 0.8% of fuel quantity has been removed from fuel during navigation. This quantity has to be deducted from bunkered fuel quantity if vessel generated emission from vessel is calculated using a "Top-Down" method. Separated components from fuel during anchor stay represents on average 1.2% of consumed fuel, while during mixed operations represent on average 1.0% of consumed fuel. Correlation between separated sludge and total fuel consumption is found to be 0.234, however it greatly varies when compares to different vessel operation modes (e.g. 0.099 during anchorage, 0.063 during navigation). Separated sludge figures present significant difference from the findings in Dujmović et al. [9], where during steaming was identified 0.15% and 0.26% of separated components from consumed quantity of fuel. However, the percentage of 0.8% to 1.2% are in line with guidelines from International Maritime Organization [24]. Correlation between separated sludge from fuel and consumed HFO quantity during complete period is found to be low, 0.23. This is mainly due to scattered quantities of both, fuel consumption quantity as well of separated sludge quantity. By testing those date by means of using different regression models, a very low R square values are obtained (from 0.0027 to 0.187) which is direct consequence of data scattering. Based on that it can be concluded that separated sludge form fuel is not directly influenced by consumed fuel quantity and another influencing factor should be investigated. This might present further research area in this field.

The resulting distribution of the separated sludge quantity per day during complete period is not normally distributed that is confirmed with Kolmogorov-Smirnov test. However, it is confirmed that quantity of separated components from fuel rise as total fuel consumption falls, that is confirmed also by means of one-way ANOVA test.

By means multifactorial variance analysis a several hypotheses were tested and confirmed with reliability of 95%; that there is present statistical significance impact of ship's operations type on total fuel quantity consumed. Furthermore, it was found statistical influence of fuel type in use on the fuel quantity consumed and influence of ship's operation mode on the type and quantity of fuel consumed. This finding corresponds to the fact that during port stay and anchorage fuel with lower sulphur content (LSMGO as recorded in Engine Log Book) is consumed to meet emission requirements. During navigation at open sea or outside special emission areas another type of fuel is used (HSHFO as recorded in Engine Log Book).

Main objective of paper is to present statistical quantitative analysis of consumed fuel and generated in real operating environment of product/chemical tanker example. It also presents quantitative analysis of separated components from fuel based on ship operation mode and fuel type in use. The values obtained for these can be used for more accurate emission estimation/calculation while using "Top-Down" method. Methodology used is adapted to appropriate use of data recorded in Engine Logbook and Daily Sounding Logs onboard a ship. This kind of analysis also represents potential approach to use daily recorded data from vessel crew.

Future research in this field would dismember fuel consumption according particular machinery/equipment. This would present additional view on distribution of consumed fuel and its usage during different operation modes. Potential further research area is to include further analyse of fuel stability and its influence on separated sludge quantity from long time storage.

6 Conclusion

A quantitative analysis of fuel consumption and sludge generation from fuel by means of centrifugal separation is performed based on engine logbook extracts for 29991 GT chemical/product tanker for period 22.02.2020 – 31.08.2020. Analysis is performed and adjusted based on technical characteristics of the ship's propulsion and auxiliary systems. Variables extracted from the engine logbook machine are: date and time of readings, ship operation type, level increase in fuel separator sludge and the consumption of each particular type of fuel for each individual fuel consumer since last recordings. Some of logbook records are recorded for different time duration and therefore are brought down to a time frame of one day regardless of its time duration. To accurately calculate the separated sludge level increase fuel separator sludge tank, the amount of separator process water consumed was subtracted form generated level based on the operational process parameters for fuel separator.

Basic analysis of the ship operation modes shows that the ship spent 62.1% of the time in navigation, 7.8% of the time at the anchorage and 30.1% of the time in mixed operations consisting of port stay, manoeuvring, relocating, and anchorage stay that lasted less than a one day.

Basic analysis obtains results of average values, minimums, maximums, standard deviations, and variations, median and mode, standard errors for separated sludge from fuel, heavy fuel consumption (HSHFO) and diesel fuel consumption (LSMGO) during entire observed period. Values for fuel consumption quantities and the separated sludge quantities were found dispersed in amounts from 0 mt/day to 0.9 mt/day for separated sludge quantity, from 0 mt/day to 20.9 mt/day for HSHFO consumption and from 0 mt/day to 12.9 mt/day for the LSMGO consumption. An average 0.8% of fuel quantity has been removed from fuel during navigation Separated components from fuel during anchor stay represents on average 1.2% of consumed fuel, while during mixed operations represent on average 1.0% of consumed fuel. The resulting distribution of the separated sludge quantity per day during complete period is not normally distributed that is confirmed with Kolmogorov-Smirnov test. However, it is confirmed that quantity of separated components from fuel rise as total fuel consumption falls

Further correlation analysis between the separated sludge quantity and fuel consumption of different types shows that correlates with the HSHFO consumption with a factor of 0.29 while with the LSMGO consumption with -0.29. The quantity of separated sludge in correlation to total fuel consumption is further expressed with different regression models; linear, logarithmic, and polynomial where R^2 ranges from 0.049 to 0.055. Low R^2 is a result of large data dispersal. This kind of analysis is performed for each type of ship operations: during the navigation, ship's anchorage stays and during mixed ship operation mode.

By means of F-test with a reliability of 99% it is concluded that there is a significant statistical difference in the separated sludge quantity from the fuel between navigational period and mixed operations. By means of one-way ANOVA test, with 99% reliability is proven statistically significant difference in the arithmetic means of separated sludge from fuel during various ship operations.

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