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Analysis of ship voyage data based on Chow-Liu tree augmented Naïve Bayes-method to support biofouling management

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ABSTRACT

The Baltic Sea is a sensitive marine environment and a unique brackish water basin. In spite of environmental protection policies of its coastal states, the sea is still under unsustainable load. Environmental impact of shipping is one of the concerns, as the area is a major transport corridor for both passengers and cargo. Many restrictions and environmental regulations direct the shipowners actions. However, there is still issues yet too complicated to be regulated by laws. One such an issue is the spreading of harmful invasive species. In order to gather more data that the future regulations can be based on, the EU Interreg Baltic Sea Region programme funded a multinational research project called "COMPLETE". Ballast waters are well known pathways for invasive species, but migration by immersed hull structures is a lesser known vector. The role of the South-Eastern Finland University of Applied Sciences in the project is to conduct onboard measurements and data collection on ships' performance. The data is collected 2018. . . 2019 during normal operation of the ships, and consists of information extracted from voyage data; shaft power, fuel consumption, propeller pitches and rotation speeds, trim, draught, DWT, speed over ground, AIS data and weather conditions provided by coastal meteorological stations. The aim is to demonstrate on individual ship level the impact of biofouling on resistances and fuel consumption, and, in consequence, increase the shipowners' motivation to keep immersed hulls clean and thus save fuel, reduce gaseous emissions and prevent the spreading of invasive species. However, causation network of collected data includes powerful mixers such as weather conditions. The objective of this paper is to present experiences of utilizing Chow-Liu tree augmented Naïve Bayes formulation for analysing the voyage data. The method is computationally efficient and usually gives quite reliable results even if the collected data contains a lot of noise or inadequacies.

1. Introduction.

Through the ages, biofouling has produced additional challenges for seafarers when biofouled immersed hull structures increase the drag of ships. This problem has been identified early and a variety of methods has been applied to limit accumulation of organisms on ships' hulls [Lewis, 1988],[Tupper, 1996]. Copper-based immersed hull coatings are effective but toxic for marine environment [IMO, 2001]. As a result, treatment of hulls with copper-paints has reduced significantly in the Baltic Sea region and focused just on strategic locations, such as sea chests, where biofouling can cause serious problems and cleaning is often challenging [Oliveira, 2017]. During winter times, on the long-term average, the Gulfs of Bothnia, Finland and Riga, archipelagos of Estonia, Stockholm and south-west of Finland are covered by sea ice. Therefore, the immersed hull coatings must be resistant for heavy mechanical stress caused by operating in icy conditions and therefore many types of silicone based foul-release paintings are not usable at all.

Epoxy-based hard coats are suitable for operating in icy conditions. However, this kind of coating gets biofouled especially during summer season and, to avoid the increasing

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hydrodynamical resistances, immersed hulls are cleaned periodically [IMO, 2001],[Schultz, 2004]. At the latitudes of the Baltic Sea, the summertime temperatures of surface seawater can reach +20 ºC or sometimes even more [Laakso et al., 2018]. However, normal summertime temperature level stays around +15 ºC. Seawater temperature levels decrease rapidly in spring and in autumn, but this might be subjected to significant changes due to global warming in the future [Masson-Delmotte et al., 2018],[Pörtner et al., 2019]. The biggest change seems to occur during just these seasons.

The biofouling reaches noticeably levels monthly on surfaces treated with hard-coatings: The immersed hull sides near the water surface (0-2 meters) rate 0-20 mm long seaweed within the period of one month. If the summer season is warm and there is plenty of sunlight available, the length of the weeds can reach 30-50 mm, sometimes even 100 mm, and weeds can be found deeper also (4-5 meters from the water surface). Monthly aged weeds are usually soft and can be brushed off relatively easily, whereas two months old weeds are attached harder to the hull. After two months, other organisms such as barnacles, can typically be found. If the hull is heavily biofouled with hard-shelled varieties, only mechanical cleaning with metal brushes is a practicable method. However, this cleaning method usually damages the hull coating too. [Borenius et al., 2019]

Invasive species can be a major threat for the original ecosystem [Lehtiniemi et al., 2014]. Worldwide, numerous cases can be found where aggressive non-indigenous species have pushed native ones on the brink of extinction by causing changes in food chains. Often disadvantages have touched human activities too, for example, spreading of pathogens, impact on agriculture and fisheries and other harm to the economy. Ballast waters carried all around the world have been identified as a major vector for uncontrolled spreading. Therefore, international ballast water convention entered into force on 7th September 2017 [IMO, 2004] with the aim of limiting uncontrolled spreading of invasive alien species.

The "COMPLETE" is an international research project funded by the Interreg Baltic Sea Region Program of the European Union [IBSR, 2020],[Altarriba et al., 2019]. The project is ambitious: The aim is to generate new knowledge to support decision makers both in administrative and shipowner sectors to find more sustainable solutions to prevent spreading of invasive alien species both through ballast waters and biofouling of immersed hulls. One practical objective is to provide an evaluation tool for shipping companies and other operators to clarify different consequences of the biofouling issue and raise environmental awareness simultaneously.

The "COMPLETE" project is implemented during years 2017…2020. The responsible coordinator is Kotka Maritime Research Centre. The project partners are Universities of Helsinki, Tartu, Latvia, Klaipeda, Gdansk and Chalmers. The public authority representatives include Helsinki Commission HELCOM, Finnish Environment Institute and Federal Maritime and Hydrographic Agency of Germany, and the association sector is represented by Keep the Archipelago Tidy Association. The South-Eastern Finland University of Applied Sciences (Xamk) is one partner of the project. The main responsibility of Xamk is to execute data collection and onboard measurements in order to observe how biofouling effects a ship's voyage, fuel consumption and hydrodynamic drag. Validating the true impact is quite challenging in such cases where immersed hulls are constantly cleaned and heavy biofouling is not attained.

The effects of biofouling on ship speed and fuel consumption, published in several forums, are often observed cases where the immersed hulls are completely biofouled [Oliveira, 2017], [Watanabe et al., 1969],[Loeb et al., 1984]. Based on this knowledge, deciding the appropriate hull cleaning intervals is challenging. Shipowners rarely have resources to carefully analyse this issue: Using of rules of thumb and tacit knowledge of the crew often provides reasonable results to plan hull cleaning intervals – while acknowledging that biofouling is just a single element of the cost structure of the ship [Turan et al., 2016],[Schultz et al., 2011]. However, the level of experience among the vessel crews varies and attitudinal atmosphere differs between companies, even between separate ships. Contributing to the level of knowledge is therefore one aim of the project: In addition to the dissemination of the research results, sharing the gathered information with individuals is also essential.

2. Theoretical framework.

In this study, the collected voyage data contains several variables: Shaft power, fuel consumption, propeller pitches, rotation speeds, trim, draught, DWT and speed over ground are recorded from the ships' systems. In addition, based on AIS data provided by HELCOM, the ships' position and course were analysed. Weather data provided by coastal meteorological stations was utilized for taking into account the effect of changing weather conditions. Current estimations were provided by the Federal Maritime and

Hydrographic Agency of Germany (BSH), whereby comparability of different voyages can be assured. This research frame creates a typical mass data problem containing the following features:

- Voyage data is collected from several sources; time step, format and accuracy varies
- Voyage data gives primary or indirect information based on the source
- Voyage data is not intended to be used for analysing this research problem
- Voyage data collection is mainly an automatic process
- Voyage data includes all main features of mass data (volume, variety, velocity, value, veracity).

The collected voyage data contains a lot of information about the physical environment of the followed ship. In addition, the chosen approach enables the solving of this research problem by using options that are actually available for shipowners without investments to equipment. However, making reliable conclusions still needs an appropriate framework [Hilbert, 2016].

The Bayesian network probability theory provides a statistical approach for problem solving. In fact, this kind of mass data-based research problem basically leads statistical inference requirement: Interdependencies between various variables can be observed, but in all cases, the influence of numerous unknown variables is also involved to formed causation system [Woodward, 2004],[Hilbert & López, 2011]. Actually, this is not a surprising issue at all: Especially in human, social or medicine sciences, research is often faced with a similar problem and applications of causation models have been proven an effective method to reach reliable results.

In this case, the observed interactions in the causal network may be directly dependent on physical factors or dependencies can have a more indirect form. Interaction between thrust and hydrodynamic resistance is based directly on physics, but physical models that take into account all factors are very complex and, in any case, finding out real values for input variables is challenging [Tupper, 1996],[Molland et al., 2011]. Wind impact assessment is even more complicated: Drag can increase straightly, but wind can also increase drifting, in which case steering resistances increases synergistically. Wind also affects wave formation and surface currents and the winding profile over sea is turbulent [Lewis, 1988]. Also, ship's DWT and especially trim have an effect and with bulbous bow construction, interaction can be complex [Kracht, 1978].

Causation tree system based on Bayesian network is a functional and efficient approach to study a problem where variables contain lot of information about sub-variables [Lauritzen, 1995]. Naïve Bayes classifier [Firedman et al., 1997] is one machine learning method based on applying Bayes' theorem [Mitchell, 1997]. It is a simple model that has a strong independence assumption between all the features of the system. The real system rarely follows this assumption but, despite of this "naïve" approach, this classifier works quite reliably even if the research problem is complex and includes strong dependencies. The equation of Naïve Bayes classifier can be written as follows:

$$p(x_1, ..., x_n|C)p(C) = p(C)\Pi_{i=1}^{n} p(x_i|C) \tag{1}$$

where C is a chosen class and $x_1...x_n$ are independent variables of the system. Using this approach. a two-level Bayesian network can be formed. However, two-level network contains restrictions and due to this reason, method is often applied in a complemented form. Chow-Liu tree provides a computationally efficient method for expanding construction to second order level [26]. This is made by using joint probability distribution of variables minimized by Kullback-Leibner divergence. This leads to form:

$$p(C|x_1, ..., x_n) = p(C) \tag{2}$$

Achieved Chow-Liu tree augmented Naïve Bayes method can be applied as a classifier for large amounts of data. In this case, the chosen input variables are shaft power, DWT, trim, speed over ground, energy efficiency and computational efficiency. Shaft power is measured from torsion meters of the propeller shafts by using one-minute time interval. Same interval is used for trim data and speed over ground. Trim data contains bias depending of the system errors of the ship type. However, the trim trend is estimated to be sufficiently reliable. Speed over ground is GPS-speed and DWT is given by officers at the time of the departure. Energy efficiency contains relation of shaft power to DWT and sailed distance. Computational efficiency compares shaft power to calculated hydrodynamic resistance of the ship. Based on this framework, the following Naïve Bayes network is formed:

Efficiency is a factor that does not contain primary information about measurements but is based on the relationship between theoretical resistance and measured shaft power. Direct data of the drag is seldom available. However, estimations based on vessel main dimensions can be implemented quite straightforward and these methods have been comprehensively used in marine architecture before the era of computational fluid dynamics. In addition, with the research problem such this, the modelling accuracy of the hydrodynamics is actually not the most important issue: Selecting the routes the ship is cruising at constant speed as well as the observed difference between biofouled and clean hull are more essential than absolute accuracy. However, this approach gives more certainty as environmental conditions are comparable. This reduces the risk that biofouling effect is mixed with changes in the weather conditions.

The hydrodynamic drag of the ship [Lewis, 1988], [Tupper, 1996] can be observed by equation

$$F_{hydr} = \frac{1}{2}\rho S C_T v^2 \tag{3}$$

where ρ is density of water, S immersed hull area, C_T hydrodynamic coefficient and v speed of the ship. In this study, coefficient factor is formed as:

$$C_T = C_f + C_r + \Delta C_f + \Delta C_a + \Delta C_{bl} + \Delta C_l \tag{4}$$

including coefficients of viscotic (C_f) and wave resistances (C_r), roughness resistance factor (ΔC_f), scale factor (ΔC_a) and effects of bulbous bow (ΔC_{bl}) and steering (ΔC_l). Viscous resistances is defined by using Grigson's method [Grigson, 1993], [Grigson, 2000] based on Reynold's number of the ship

$$\begin{aligned} 10^3 C_f = {} & (1,032 + 0,02816(lgR_n - 8) \\ & -0,006273(lgR_n - 8)^2)\frac{0,075}{(lgR_n - 2)^2} \end{aligned} \tag{5}$$

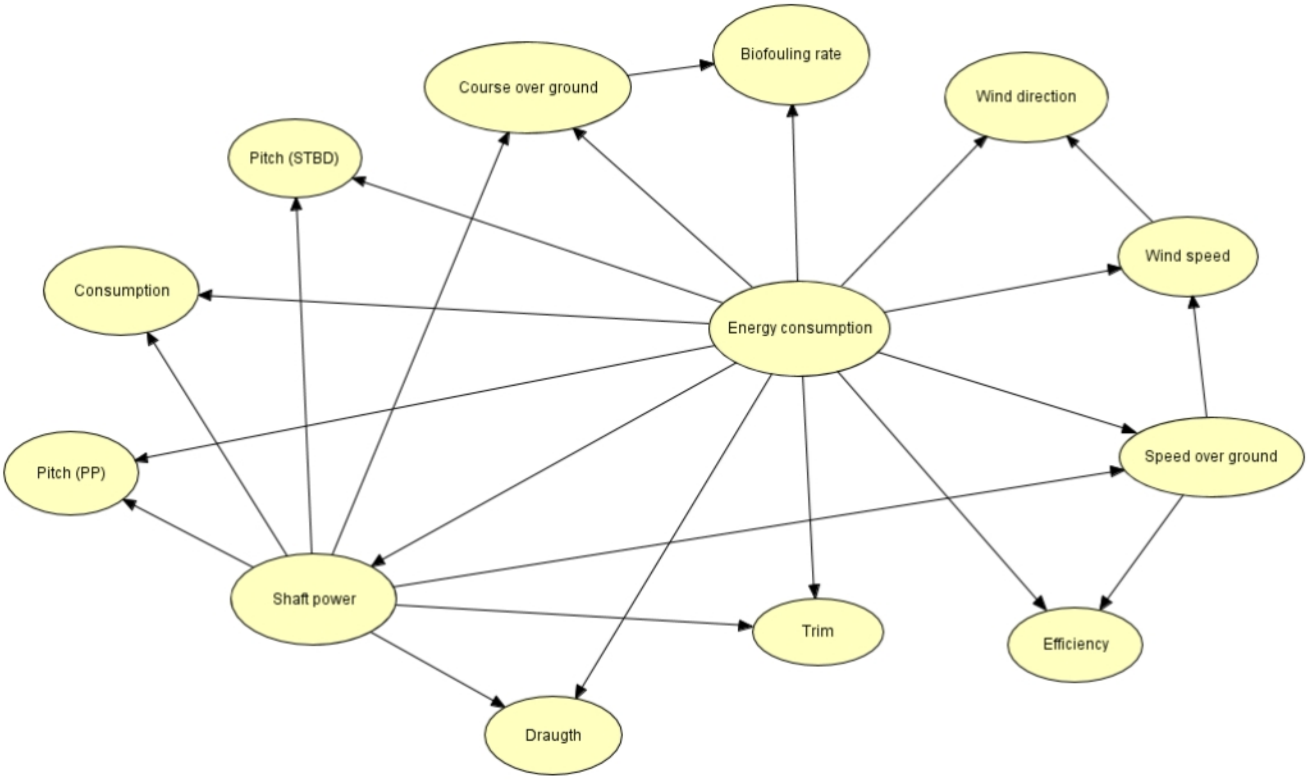
when $10^8 < R_n < 4 \cdot 10^9$,

Wave resistances are defined by using method presented by Harvald-Getler and TaylorGuldhammer [Harvald, 1983],[Guldhammer & Harvald, 1974]:

$$\begin{aligned} 10^3 C_r = {} & 1,2 \cdot 10^{-3}(10F_n - 0,8)^4(10C_p - 3,3)^2 \\ & (10^3 C_v + 4) + 0,05 \cdot 10^3 C_v + 0,2 + 0,17(\frac{B}{T} - 2,5), \end{aligned} \tag{6}$$

where F_n is Froude number, C_p prismatic coefficient, C_v displacement-length ratio, B beam and T draught. Bulbous bow factor [Kristensen & Lützen, 2013] is used for supplementing wave factor formulation

Figure 1: Formed Chow-Liu tree augmented Naïve Bayes network.



Source: Authors.

$$10^3 \Delta C_{bl} = -0,2 - 1,1 F_n, \quad (7)$$

and roughness resistance factor brings effect of surface roughness to hydrodynamic coefficient [Kristensen & Psaraftis, 2016]:

$$10^3 C_f = 0,044(\sqrt[3]{\frac{k_S}{L_{wl}}} - \frac{10}{\sqrt[3]{R_n}}) + 0,000125 \quad (8)$$

In this case, biofouling is understood physically for changes to immersed hull surface roughness giving this factor a significant role and scaling coefficient must be used along with this factor. Steering resistance is minimized by observing ships cruising in straightforward legs in good weather conditions. While environmental conditions remain comparable, the vessel is operated at constant speed and the ratio of computed hydrodynamic drag and thrust power remains in equal level. As wind conditions become rougher (or other changes occur, such as currents), this is reflected as difference in this computed efficiency. Comparing this to the data obtained from the coastal weather stations and current estimations, conditions prevailing in the area can be estimated reliably considering, as in this study, that the lanes are relatively close to the coast.

3. Results.

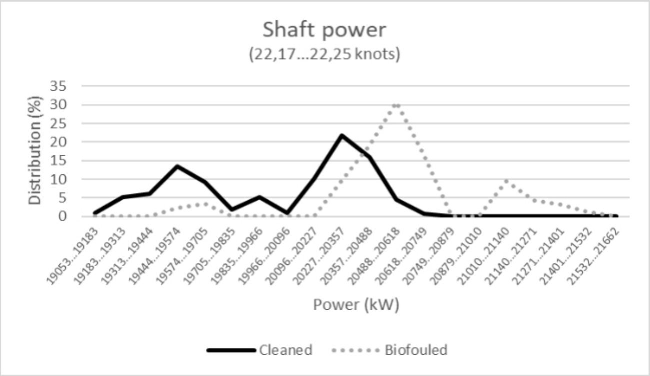
This study investigates two ship voyages, which took place in the Baltic Sea: one voyage from Germany to Finland on 24th July 2018 and second voyage from Finland to Germany on 28th…29th July 2018.

The data recorded onboard during the first voyage (24th July) contains a 12 hour set obtained during 11:00…23:00 UTC. On that period, the weather conditions were quite calm over the Baltic Sea region. The average wind speeds in the coastal weather stations were as follows: In Skillinge, the average wind speed was 3,8 m/s, and recorded wind range 1,0…6,6 m/s. In Utklippan, the corresponding values were 5,0 m/s and 2,2…7,5 m/s. In Ölands Södra Udde 3,8 m/s (1,6…5,5 m/s), in Hoburg 1,9 m/s (0,7…3,6 m/s), in Östergarnsholm 3,1 m/s (2,2…3,9 m/s) and in Gotska Sandön 2,2 m/s (0,7…2,8 m/s). On the second voyage, in 28th…29th July, the corresponding values were 2,0 m/s (3,4…5,6 m/s) in Gotska Sandön, 6,6 m/s (4,8…7,7 m/s) in Östergarnsholm, 3,7 m/s (1,2…4,9 m/s) in Hoburg, 2,2 m/s (1,2…4,9 m/s) in Ölands Södra Udde, 2,3 m/s (0,5…4,7 m/s) in Utklippan and 2,0 m/s (1,0…4,2 m/s) in Skillinge. Wind directions varied over all cardinal points. This is common when the wind conditions are calm.

During the studied voyages, the cargo and trimming conditions were quite comparable: On 24th July declared DWT was 7074 tons and 28th…29th July 7037 tons with a bow trim of 0,4…0,5 meters. The immersed hull was cleaned on the 25th July and the previous cleaning had been carried out on the 25th June. This means that, at the time of the first leg, the biofouling had accumulated about a month and the second leg was sailed with a freshly cleaned hull. During the intervening days, the ship had been in regular traffic but weather conditions had been windier and the loading condition varied between voyages.

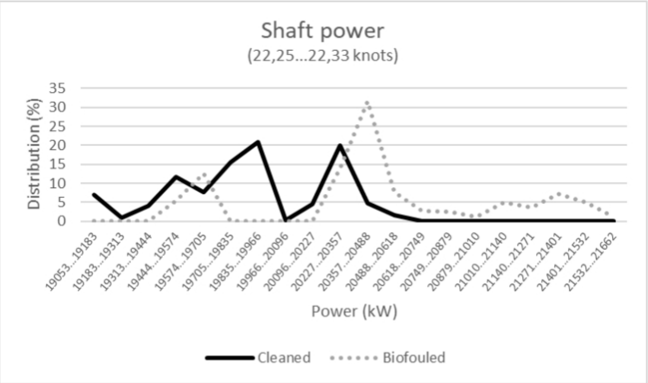
Because the wind conditions have a significant impact on the ship dynamics and therefore play an essential mixer in the system, the analysis is based only on data sets, during which wind conditions were discretized in class 1,00-2,34 m/s (wind conditions are discretized in 5 classes between range of 1,00-7,7 m/s). Increased accuracy is reached by choosing discretized speed classes of 22,17-22,25, 22,25-22,33 and 22,33-22,41 knots. With the selected ranges of the speed, the data is distributed between the voyages in the following proportions: 55,02/44,98%, 54,53/45,47% and 36,53/63,47%, correspondingly. Classificated curves of shaft power are illustrated in figures 2. . . 4.

Figure 2: Shaft power (speed range of 22,17-22,25 knots).



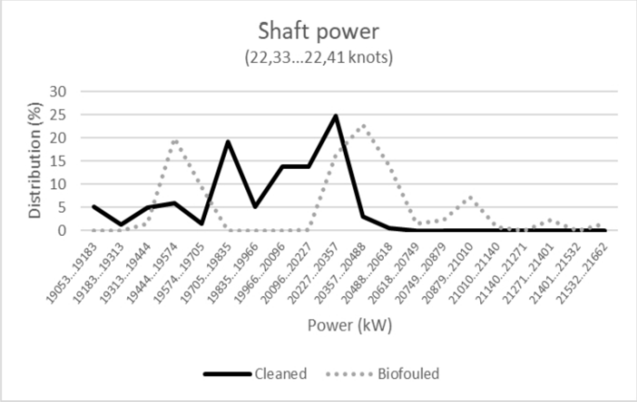
Source: Authors.

Figure 3: Shaft power (speed range of 22,25-22,33 knots).



Source: Authors.

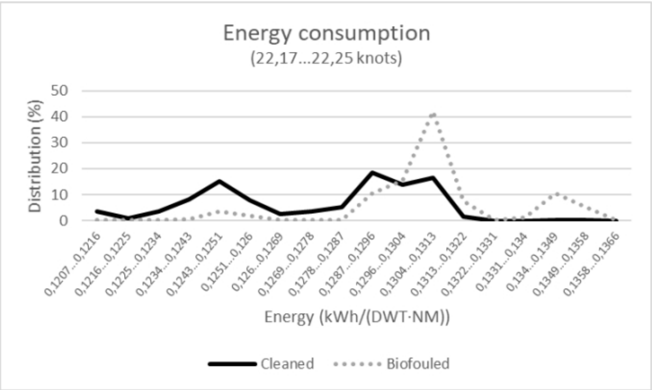
Figure 4: Shaft power (speed range of 22,33-22,41 knots).



Source: Authors.

Shift of emphasis can be noticed from the shaft power curves but doing conclusions based on visual observing is challenging. Expected values of the functions are giving a numerical evaluation of this issue. In the speed range of 22,17-22,25 knots the expected values are 19 879 kW for cleaned hull curve and 20 511 kW for a biofouled case. This leads to a 3,18% difference. In the range of 22,25-22,33 knots, the corresponding values are 19 785 kW, 20 411 kW and 3,16% and in the range of 22,33-22,41 knots 19 880 kW and 20 173 kW, where the difference is 1,47%. Although the speed class is already included in the power curves, more certainty is obtained by observing the energy consumption of the ship per ton-miles. For the corresponding speed classes, the energy consumption curves are illustrated in figures 5. . . 7.

Figure 5: Energy consumption (speed range of 22,17-22,25 knots).



Source: Authors.

Figure 7: Energy consumption (speed range of 22,33-22,41 knots).

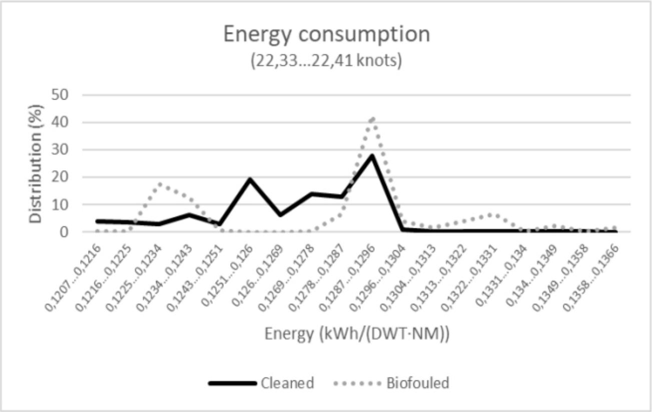


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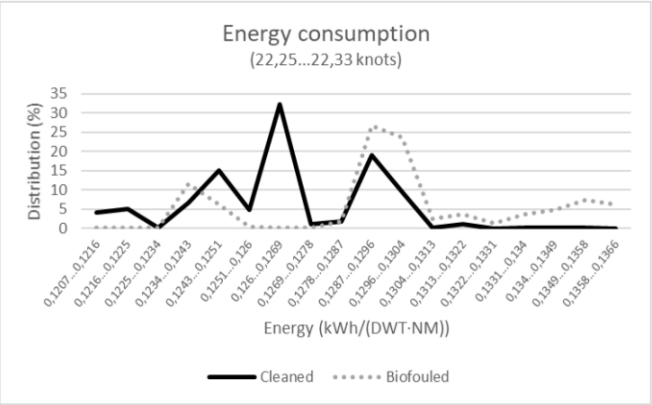
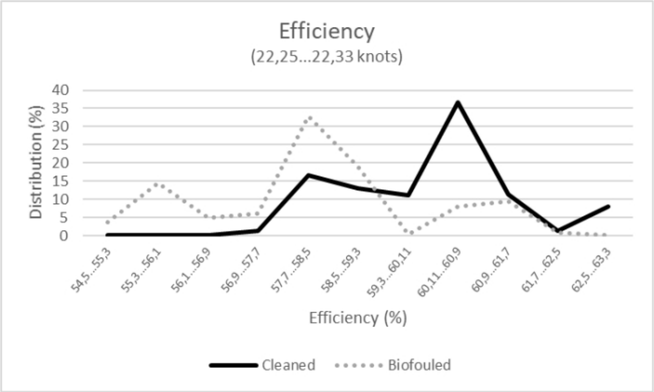
Figure 6: Energy consumption (speed range of 22,25-22,33 knots).



Source: Authors.

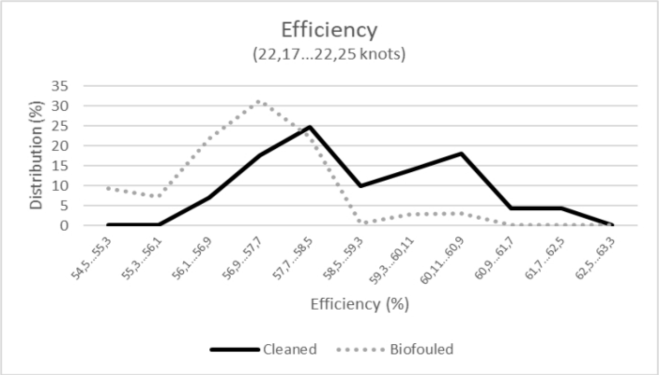
Trends of the energy consumption curves follow power curves, although the difference is slightly lesser. The energy consumption per ton-miles in the speed range of 22,17-22,25 knots is 0,1270 kWh/(DWT · NM) for cleaned and 0,1303 kWh/(DWT · NM) for biofouled hull and the difference is 2,57%. In the range of 22,25-22,33 knots, the values are 0,1260 kWh/(DWT · NM), 0,1295 kWh/(DWT · NM) and 2,72%. In the range of 22,33-22,41 knots, the corresponding values are 0,1263 kWh/(DWT·NM), 0,1274 kWh/(DWT · NM) and 0,89%. In figures 8. . . 10, the curves of theoretical efficiency are illustrated in the same speed classes as earlier.

Figure 9: Theoretical efficiency (speed range of 22,25-22,33 knots).



Source: Authors.

Figure 8: Theoretical efficiency (speed range of 22,17-22,25 knots).



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Computational efficiency curves expected values are, for the first speed range (figure 8), 58,47% and 56,70%, with the difference of -3,03%. Respectively, in the second case (figure 9), values are 59,65% and 57,78% including a difference of -3,13%. In the third case (figure 10), the values are 59,87% and 59,20%, and the difference is -1,11%. The negative change in computational efficiency follows the increasing scale of shaft power and energy consumption.

Conclusions.

Methods based on mass data analysis provide statistical approach for analysing complex problems. Chow-Liu tree augmented Naïve Bayes is computationally efficient and reliable framework for analysing mass data problems especially in cases that include incomplete information. This method has been used successfully in such a problems and, based on the research work carried out in the "COMPLETE" project, it seems that the method is applicable for analysing the effect of the biofouling on ship dynamics as well. The results presented in this paper show that there is noticeable change (about 3%) in shaft power data when sailing in the same speed range. This is also confirmed by the similar changes in energy consumption and computational efficiency curves. The magnitude of the change follows the expected rate of the biofouling effect on ship resistances using monthly cleaning interval during the summer time in the Baltic Sea region. However, results shown in this paper require more analysis in order to increase their reliability. "COMPLETE" project offers good opportunities to reach this aim as the mass data has been collected during long-term periods.

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