Approaches to Economic Energy Management in Diesel-Electric Marine Vessels

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***Abstract*—Recently, the efficiency of diesel-electric marine vessels has been subject for discussion with focus on improving fuel efficiency, reducing the environmental footprint from emissions, as well as reducing running hours and maintenance costs. This work presents an analysis of load profiles extracted from three different vessels during operation; a ferry, a Platform Supply Vessel (PSV) and a seismic survey vessel. The analysis of the extracted data shows that the loadings of the diesel engines are typically quite low, and do not fall within the optimal loading range of diesel engines' Specific Fuel Oil Consumption (SFOC) curves. Furthermore, three different power plant configurations are proposed and compared, which include fixed speed (diesel engine generators), variable speed gensets and implementation of an Energy Storage System (ESS). Moreover, Energy Management System (EMS) algorithms based on Mixed Integer Linear Programming (MILP) are proposed as a suitable strategy for optimal unit commitment in the power generation. The results yielded from the MILP algorithms are compared to EMS algorithms based on logic such as if/else statements. The results indicate that optimal EMS algorithms in combination with a revised vessel configuration can increase the operational efficiency, in terms of fuel savings and reduction in genset running hours.**

***Index Terms*—Energy management, unit commitment, marine vessel power system, optimization, energy storage system**

I. Introduction

THE WORLD'S MARITIME FLEET, due to widespread use of fossil fuels, is currently an unnecessary large contributor to greenhouse gases and other emissions. Moreover, many marine vessels are not operated in an optimal way, where the fuel consumption is in line with the power demand. As up to 90% of a vessel's power generation capability may at some point be locked into the propulsion units [1], [2], and the fact that the propulsion demands tend to be highly dynamic for a wide range of different marine operations in varying weather conditions, often more diesel engine generators (gensets) than actually needed to supply the consumers are online. However, running more gensets than needed, i.e. the online power generation capability exceeds the power demand with remarkable margins, often causes the loading of each genset to be lowered with the effect of moving the Specific Fuel Oil Consumption (SFOC, $\frac{\text{g}}{\text{kWh}}$) away from its optimum [3], [4]. To run more gensets than needed (spinning reserve), often with open bus ties, is for some types of operation a redundancy requirement from stakeholders with the purpose of preventing partial or total loss of (vital) power in occurrences of faults and component failures. The remaining healthy power bus with its enabled gensets are supposed to, with no further delays, replace the power demand from the faulty power bus. Such requirements are particularly enforced for Dynamic Positioned (DP) operations during safety critical operations denoted as consequence class 2 according to regulations by the International Marine Organization (IMO) and national authorities [5], [6].

Loss of power can have severe consequences, which may not only cause severe material and environmental damage and put human lives at risk, but may also lead to economic penalties for the vessel's operational responsible, in terms of financial claims and exclusion from pending or future contracts. Stories from multiple vessels' crew indicate that non-optimal unit commitment, in the sense of having more gensets online than needed (exceeding required spinning reserves) with non-optimal loadings, is a widespread practice introduced by distrust of the Power Management System (PMS) and a risk of not being able to supply the vessel's, and thus the given operation's, required (and vital) load demands. Examples of such demands may be navigation and bridge systems as well as loads originating from propulsion units and winches during e.g. DP, heavy lifts and anchor handling operations. One can speculate that also lack of knowledge and incentives allows the crew in non-safety critical operations to operate with open bus ties with multiple gensets enabled, which cultivates non-optimal unit commitment, wasting fuel and increasing the emission of greenhouse gases.

The benefit of optimizing the power generation, and at the same time minimize fuel consumption by running gensets with optimal loadings relative their lowest SFOC, is not only limited to achieve cost-efficient operations. By minimizing the fuel consumption the emission of greenhouse gases is also reduced, which, due to the global goals of reducing environmental footprints, is an increasingly important requirement. January 1st 2015 IMO implemented Emission Controlled Areas (ECA), which specify stringent requirements for allowed emission of NO_x, SO_x and particle matter for selected areas [7]. In the near future, due to the stringent emission requirements near shore, it might also be expected that marine vessels are required to conduct emission-free approaches to harbor, which calls for energy storage and more advanced control algorithms, thus taking steps towards All Electric Ships

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(AES).

The use of ESS can enable emission-free approaches to harbor, but can also facilitate optimal power generation in terms of optimal loading of gensets. In situations where the online genests are running with low loading conditions, the ESS can be charged, which allows for an increase in generator loadings towards optimal SFOCs. With a fully charged ESS, one or multiple gensets may be shut down and their supply of power substituted by discharge of the ESS. There exist a range of different Energy Storage Systems (ESS), ranging from mechanical, thermal and chemical to electrical systems. Some examples are Battery Storage System (BESS), Pumped Hydro Storage (PHS), Compressed Air Energy Storage (CAES), Superconductive Magnetic Energy Storage (SMES), fuel-cells, flywheels and super-capacitors [8]–[12]. For a marine vessel it has also been proposed to use the DP system and the vessel's position as a short-term energy storage [13]. The differences between ESS technologies can be generalized and listed as capacity, charge and discharge rates, weight, cost (including maintenance) and expected lifetime. The type of ESS should be chosen relative to the application. For example, in peak-shaving applications high charge/discharge rates of the ESS may be more critical than high capacity, while high capacity might be more critical in situations where the ESS is substituting a genset. Implementation of ESS can take many forms and can be part of both AC and DC distribution systems [1], [14]. Even though the employment of ESS can be beneficial for overall efficiency, and adds to power redundancy and flexibility, the control of the ESS and the generator scheduling (also called unit commitment) is critical to achieve optimal power generation with reduced fuel consumption and emissions.

Examples of optimal control schemes that have been employed for power and energy management applications are Model Predictive Control (MPC) and Linear/Nonlinear Programming (LP/NLP) algorithms. In [15] an LP algorithm is applied to control the power balance in a vessel with diesel-electric power generation and batteries, where the efficiency of each diesel engine is regarded in the objective function. The output of the LP scheme dictates the amount of power delivered from each genset and the power flow to or from the battery. A Mixed Integer Nonlinear Programming (MINLP) approach for optimal sizing of ESS and economic dispatch of controllable units for a shipboard power system is explored in [16]. In [17] an MPC for real-time power management in a marine vessel with different power generation devices, including batteries, fuel-cells and gas turbines, is addressed. [18] includes a generator dispatching algorithm based on optimization (LP) in the EMS design for power sharing purposes. An optimal power management system strategy based on dynamic programming, which includes ESS and emission limitations, is addressed in [19]. Another approach, based on theoretical optimization, is addressed in [20], which optimizes the efficiency of AES with dc hybrid power system and ESS. Unlike optimal scheduling of gensets and control of ESS, also the demand-side can be controlled by adjusting the power consumption of the electric propulsion units. Such an approach, which is based on dynamic programming, is explored in [21]. Some of the applied optimal power management and optimal control strategies in the automotive industry might also be applicable for marine vessels [22]–[28]. It is also expected that further development of ESS for these industries will enable even more cost-effective solutions for the maritime industry as well. It should be mentioned that the energy management of the power plant of an advanced ship is a highly multi- and inter-disciplinary challenge, involving the fields of internal combustion engines, electric power generation and distribution, battery technology, control engineering, and maritime operations, safety, rules and regulations.

The main scientific contribution in this work is the analysis of experimental vessel data from normal operation to shed light on the potential for employing ESS and optimization-based unit commitment (generator scheduling). Moreover, three Mixed Integer Linear Programming (MILP) EMS algorithms are proposed for optimal scheduling of fixed-speed gensets, i) with ESS, ii) without ESS and iii) without ESS and substitution of one fixed-speed genset to a variable-speed genset. Furthermore, the algorithms are assessed on the load profiles extracted from the real vessel data and compared with logic-based EMS algorithms, that utilize if/else statements, with the same objectives. In this way, the impact of the ESS and EMS on the vehicle operation can be predicted.

The paper is organized as follows: Section II presents and discusses load profiles and power generation profiles extracted from three different vessels in operation. Section III presents three different power generation configurations along with corresponding EMS algorithms based on MILP. Section IV evaluates the proposed MILP algorithms, along with logic-based algorithms, on the data extracted from the three vessels to conduct a theoretical study exploring the differences between the three proposed configurations. Finally, section V concludes the paper.

II. Data Extracted from Vessels in Operation

Operational data from three different vessels, i) a ferry, ii) a Platform Supply Vessel (PSV) and iii) a seismic vessel, have been collected. The collected data are extracted using the vessels' Integrated Automation Systems (IAS), and include generator loadings and, except the data collected from the ferry, propulsion loads. All three vessels have diesel-electric propulsion systems, and as the emergency generators were not in use during the period the data were sampled, these have been omitted from the analysis. The loads from each propulsion unit, if available, have been added for each vessel for visualization purposes. The vessels' names are kept anonymous, as well as specific device and component names, which was a requirement set by the stakeholders owning the data used in this work. The sampling frequency used to log the experimental data is limited to ≤ 1 Hz. Hence, with this low sampling frequency, fast high-frequency dynamics such as harmonics and fast transients are not captured. It is not in the scope of this work to analyze such dynamics but to assess a long-time trending of the vessels' load profiles in the search of configurations and algorithms that cultivate fuel efficiency. For the collected operational data from the three vessels under investigation, the grid configuration relative to the different operational profiles the vessels exhibit, i.e. open or closed busties, is not known. In the following, the collected operational profiles from each vessel will be visualized and discussed.

A. Ferry

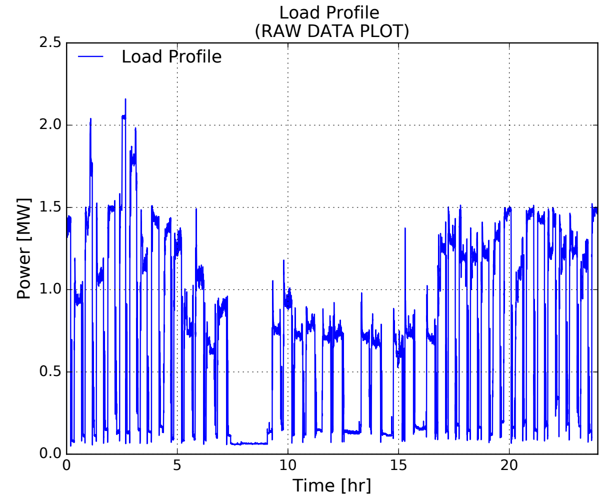
The first vessel under investigation is a ferry with power plant configuration given in Table I. As can be seen from the table, the vessel has two smaller gensets (G2 and G3) and two larger gensets (G1 and G4), and has two propulsion units, one at the stern and one at the bow. The sampling of the data set was started around 13:00 pm and stopped around the same time the following day, with sampling frequency of 1 Hz, spanning a 24 hour horizon. The vessel's load profile and generated power profiles from each genset are visualized in Fig. 1.

TABLE I
FERRY CONFIGURATION AND DATA SET INFORMATION.

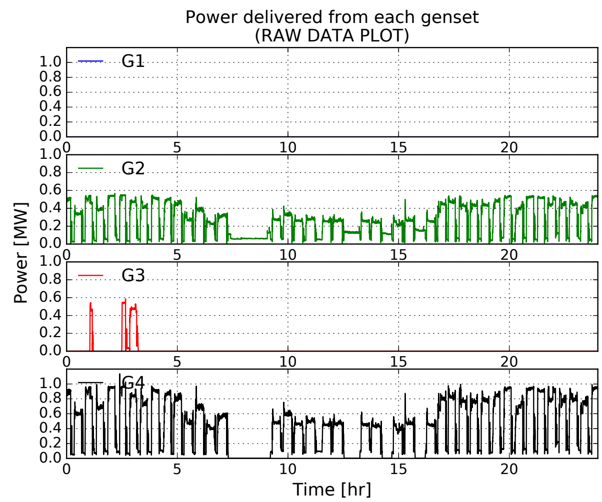
Parameter/Component	**Value/Rating** (each)
Machinery:	
2× Diesel engine	1200 kW
2× Diesel engine	640 kW
Propulsion system:	
2× (twin-propeller) rudder-propeller	1200 kW
Data set:	
Length	≈24 hr
Sampling frequency	1 Hz

The ferry uses, at minimum, about 25 minutes for each crossing, and conducts 40 crossings within the sampled 24 hour horizon. In this sense, the ferry exhibits two different operation profiles, i.e. transit (crossings) and docking. Fig. 1a, which portrays the vessel's load profile over the 24 hours horizon, shows quite varying load profiles for each crossing. In the start of the horizon, from about 1 to 3 hours, the ferry is a bit delayed, hence, does not slow down when approaching harbor. Instead, the ferry maintains speed as long as possible and reverses the propulsion units, with high Revolutions Per Minute (RPM), to slow down, which is clearly visible in the figure by the high power peaks stretching above 1.5 MW. In fact, this type of approach requires an additional genset to be started, which can be seen in Fig. 1b where genset 3 (G3) is brought online after 1 hour and after 2.5 hours into the sampled data horizon. This approach is not an economical approach, as an additional genset is started, and is only conducted when the ferry is delayed.

Furthermore, before starting the night crossings, the ferry takes a break with, among other things, a crew shift. This is visualized in Fig. 1a between approximately 7 and 9 hours into the data set. The night crossings are scheduled with more time between each crossings, hence the ferry can conduct the crossing with a slower pace. This is seen in Fig. 1a between approximately 9 and 15 hours, where the load profile is overall reduced, and is confirmed by the power delivered from each genset in Fig. 1b. After the night, the morning rush and the daytime scheduling of the crossings starts, around 17 hours, which requires the ferry to increase the pace of each crossing.



(a) Load profile.



(b) Power delivered from each genset.

Fig. 1. Measured data from ferry (approximately 25 minutes duration for each crossing): (a) shows the vessel's load profile while (b) shows the power generated by (and delivered from) each genset.

This is again confirmed by the load profile in Fig. 1a and the power delivered from each genset in Fig. 1b.

From Fig. 1b one can see that each genset, which is online, takes a range of different loadings. The smaller genset G2, which is online during the whole operational horizon, has in average a loading of 263 kW, which corresponds to approximately 42% of the genset's total rating. Moreover, during the break, only G2 is online, with a loading of approximately 60 kW (9.4%). The genset rating is even lower while in harbor between the crossings, with as low as 21 kW (3.3%). Also the larger G4 genset takes a range of different loadings, ranging from about 37 kW (3.1%) to 1136 kW (94.7%). A summary of the minimum, maximum and average loadings, calculated from the online gensets, are listed in Table II. A low rating of the gensets, in addition to have poor SFOCs, increase sooting of the prime movers and might lead to increased frequency of the engines' service (maintenance) intervals. Clearly, the ferry could benefit of an ESS to handle the low power demands while docking in harbor, and also keep the running gensets close to their optimal loading conditions by coordinating starting and stopping (scheduling) of gensets in accordance with the ESS' charge and discharge cycles. An ESS would also be able to supply additional power for fast approach to harbor if the ferry is delayed, thus, with the right power and capacity rating, eliminating the need for starting an additional genset.

TABLE II
FERRY: MAXIMUM, MINIMUM AND AVERAGE GENSET LOADINGS.

Genset	Min. power	Max. power	Avg. power
G1	0 kW (0.0%)	0 kW (0.0%)	0 kW (0.0%)
G2	21 kW (3.3%)	567 kW (88.6%)	263 kW (41.1%)
G3	40 kW (6.3%)	587 kW (91.7%)	355 kW (55.5%)
G4	37 kW (3.1%)	1136 kW (94.7%)	517 kW (43.1%)

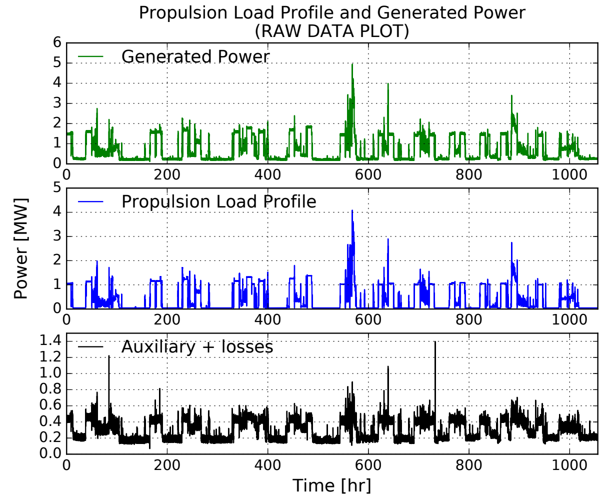
B. Platform Supply Vessel (PSV)

The next vessel under investigation is a Platform Supply Vessel (PSV). This vessel can be seen as a multi-purpose vessel that can conduct a range of different offshore operations. Such operations might for instance involve dynamic positioning (or station keeping) as well as winching and pumping operations, with highly dynamic load profiles. The power plant configuration of the PSV treated in this work is listed in Table III. Also this vessel has four gensets, two smaller (G2 and G3) and two larger (G1 and G4). The vessel has five propulsion units, ranging from azipull to bow- and azimuth thrusters. The data set spans a 1056 hours horizon (44 days), and is sampled with a frequency of 0.2 Hz. The vessel's total load profile, as well as the propulsion load profile and power delivered from each genset are portrayed in Fig. 2.

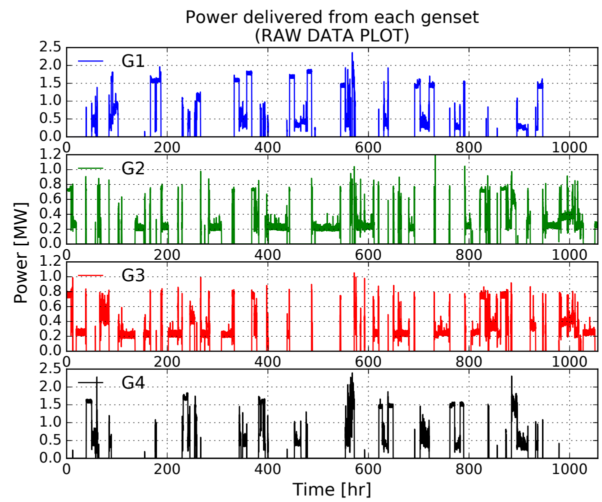
TABLE III
PSV CONFIGURATION AND DATA SET INFORMATION.

Parameter/Component	**Value/Rating** (each)
Machinery:	
2× Diesel engine	2350 kW
2× Diesel engine	994 kW
Propulsion system:	
2× Azipull	2200 kW
2× Bow thruster	880 kW
1× Bow azimuth (retractable)	880 kW
Data set:	
Length	≈1056 hr
Sampling frequency	0.2 Hz

The total load profile as well as the propulsion load profile is visualized in Fig. 2a. The difference between the total load profile and the propulsion load profile, which can be seen in the lower plot in Fig. 2a, constitutes the auxiliary load demands, as well as power losses related to power conversion and the distribution grid. Unlike the ferry discussed in the previous section, the characterization of the different operational profiles is not clear from the PSV's load profile. In fact, during the sampling of the data from the PSV, the different operations were not logged, and thus unknown for the data set presented in this work. However, from the load profile, one can clearly see some of the same behavior as



(a) Generated power and propulsion load profile.



(b) Power delivered from each genset.

Fig. 2. Measured data from PSV: (a) shows the vessel's generated power profile, propulsion load profile and the auxiliary load profile, while (b) shows the power generated by (and delivered from) each genset.

with the ferry's operational profile while in harbor, where the load demand is reduced. The PSV's data set also includes some peaks, especially around 570 hours into the data horizon, which is manifested in both the propulsion load profile and the auxiliary load profile in the lower plot in Fig. 2a. For the highest peak in the propulsion load profile, about 4138 kW is locked in the propulsion system, which corresponds to about 61.9% of the vessel's main power generation capacity. The total load demand at this time instance is about 4977 kW (74.4%), and only genset 1 and 4 (G1 and G4) are supplying the load demand, which can be seen in Fig. 2b.

Furthermore, the scheduling of the gensets, as well as the individual genset loadings, for the whole data set horizon, are presented in Fig. 2b. As can be seen from the figure, the loading of each genset is quite dynamic, and the gensets are scheduled (started and stopped) to fit the varying aggregated load demand. The main findings from Fig. 2b, which include maximum and minimum power, as well as average power, delivered from each genset while online, are listed in Table IV. As shown in the table, all gensets are at one point overloaded, exceeding 100% of rating. It is not known which kind of operation(s) caused the overloading of the gensets. The lowest genset loading is found for G4, with a loading of 5.2% relative to its rating. In addition, optimal SFCOs for diesel engines tend to be with loadings between 60-100% [29], thus the average delivered power from each genset, which are found to be below 40%, does not cultivate fuel efficiency. Hence, it is speculated that also this vessel would benefit of an ESS and a more advanced unit commitment strategy to keep the genset loadings close to the optimal loading dictated by each diesel engine's SFOC curve.

TABLE IV
PSV: MAXIMUM, MINIMUM AND AVERAGE GENSET LOADINGS.

Genset	Min. power	Max. power	Avg. power
G1	138 kW (5.9%)	2360 kW (100.4%)	892 kW (38.0%)
G2	77 kW (7.7%)	1198 kW (120.5%)	333 kW (33.5%)
G3	61 kW (6.1%)	1054 kW (106.0%)	346 kW (34.8%)
G4	123 kW (5.2%)	2394 kW (101.9%)	887 kW (37.7%)

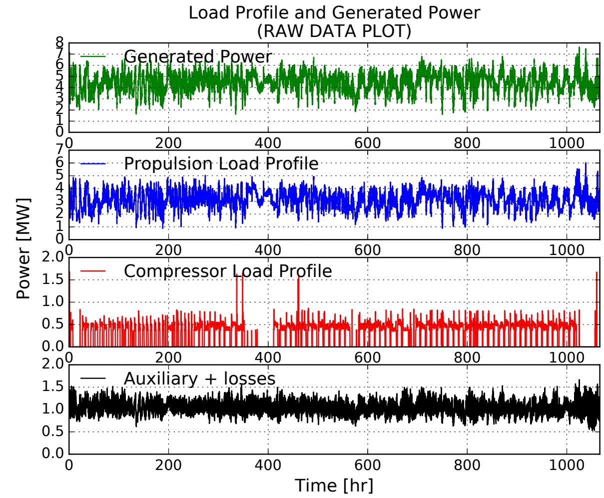
C. *Seismic survey vessel*

The last vessel under investigation is a seismic survey vessel. Such vessels usually tow enormous amounts of equipment, e.g. 8-12 streamer sets which can span up to 10 km each, while conducting offshore seismic survey operations. In addition, the canons used to generate sound waves for exploring the different layers of the geological formations use compressed air. Hence, high propulsion and compressor loads often constitute the main load demands in many of the seismic survey vessel's operational profiles. The seismic survey vessel treated in this work has four gensets of equal rating. The vessel's propulsion system consists of five propulsion units, including Controlled Pitch Propellers (CPP), bow and stern thrusters and a retractable azimut thruster. The data set is sampled during seismic operation, spans 1066 hours (44.4 days), and is sampled with a frequency of 0.2 Hz. The configuration of the vessel, as well as data set information, are listed in Table V. The vessel's total load profile, propulsion load profile, compressor load profile and power delivered from each genset are portrayed in Fig. 3.

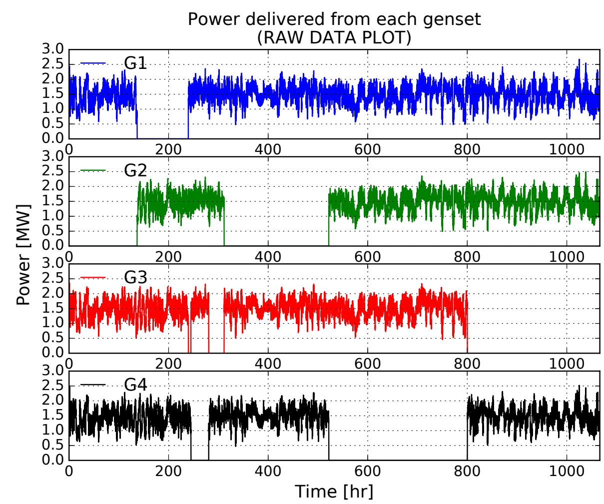
TABLE V
SEISMIC SURVEY VESSEL CONFIGURATION AND DATA SET INFORMATION.

Parameter/Component	**Value/Rating** (each)
Machinery:	
4× Diesel engine	3060 kW
Propulsion system:	
2× Controlled pitch propeller	4800 kW
1× Bow thruster	830 kW
1× Stern thruster	830 kW
1× Bow azimuth (retractable)	850 kW
Data set:	
Length	≈1066 hr
Sampling frequency	0.2 Hz

The total load profile, i.e. power delivered by the gensets, the propulsion load profile and the compressor load profile



(a) Generated power and propulsion load profile.



(b) Power delivered from each genset.

Fig. 3. Measured data from seismic survey vessel during seismic operation: (a) shows the vessel's generated power profile, propulsion load profile, compressor load profile and the auxiliary load profile, while (b) shows the power generated by (and delivered from) each genset.

are visualized in Fig. 3a. The lower plot in the figure is the difference between the power delivered by the generators and the sum of the propulsion and compressor load profile, and represents additional (auxiliary) loads, as well as power losses in components in the distribution system. From the figure one can see that the total load demand (generated power) is more stable than for the load profiles for the ferry and the PSV. Also the propulsion load profile is more stable, as the vessel performs a fixed low-speed towing operation of seismic equipment. The stable load profiles confirms that the seismic vessel exhibit few different operational profiles during the period the data were sampled. Even though the propulsion loads are the main contributors in the total load profile, the compressor load profile is significant. As shown in Fig. 3a, the compressor load has a distinct pattern, which shows that the vessel's compressors are started to fill tanks with compressed air, and stopped when the tanks are full. The number of compressors started determines the amplitude of the compressor load profile. The auxiliary power demand is also quite stable, and higher than the auxiliary load in the PSV. The high auxiliary load is expected due to power demand of the long tail of seismic measurement equipment the vessel is towing.

The individual generated power and scheduling of each genset are visualized in Fig. 3b. The figure confirms the stable load profiles in Fig. 3a. Also, compared to the PSV data set, the gensets are almost not scheduled at all (started and stopped). Gensets G1-G2 are scheduled two times each during the horizon, while the G3 and G4 gensets are scheduled three times. The low scheduling frequency is expected, due to the stable (and high) load profile. Table VI lists some of the main findings from Fig. 3b; the maximum, minimum and average loadings of each genset. As can be seen, the minimum loadings of each genset are higher than for both the ferry and the PSV. Moreover, the maximum loadings of the gensets are lower compared to the PSV. The average loadings are higher than for the PSV, meaning a more efficient fuel utilization, relative to the optimal SFOCs. However, with a suitable and proper dimensioned ESS, as well as more advanced Energy Management System (EMS) algorithms, it is speculated that the genset loadings could be kept closer to the optimal SFOC, thus cultivate more fuel-efficient operations.

TABLE VI
SEISMIC SURVEY VESSEL: MAXIMUM, MINIMUM AND AVERAGE GENSET LOADINGS.

Genset	Min. power	Max. power	Avg. power
G1	474 kW (15.5%)	2675 kW (87.4%)	1481 kW (48.4%)
G2	490 kW (16.0%)	2497 kW (81.6%)	1478 kW (48.3%)
G3	462 kW (15.1%)	2323 kW (75.9%)	1490 kW (48.7%)
G4	468 kW (15.3%)	2520 kW (82.4%)	1466 kW (47.9%)

III. EMS ALGORITHMS

The main difference between a PMS and an EMS is that a PMS controls the vessel's power plant at instantaneous time with the purpose of stabilizing voltage and frequency and meet load demands, while an EMS often considers events in past and present along with future predictions/estimates. An Energy Management System (EMS) is often considered as part of a Power Management System (PMS) that includes ESS and/or different types of power producers along with additional supervisory functionality. Some EMS/PMS today include decision support, however, scheduling of gensets is often considered a manual operation and conducted by the crew. As genset scheduling is a difficult task, where multiple aspects must be addressed, the way of manually scheduling the gensets often introduces human errors and poor decisions that do not support fuel efficiency and minimal environmental footprint through reduced emissions. With implementation of ESS, the complexity of the EMS/PMS increases, and with additional objectives, such as reducing and synchronizing the total number of running hours for all gensets, the process of scheduling the gensets manually in an optimal way becomes difficult for a human operator. This gives foundation for applying more advanced decision support tools and scheduling algorithms, where all important objectives and aspects are considered. In the following, the objectives of such algorithms are discussed and Mixed Integer Linear Programming (MILP) [30] is proposed as a viable option for EMS along with logic-based algorithms.

A. Objectives and models

The overall objective of an EMS/PMS it to supply the load demand, thus ensuring that all online consumers, and especially consumers that are critical for a given operation, experience a stable and reliable supply of power. With the implementation of an ESS also capacity and charge/discharge cycles must be supervised. Moreover, the system should cultivate fuel efficiency, thus reducing the fuel costs, and keep the emission of greenhouse gases to a minimum. Minimizing emission is especially important for maintaining a sustainable environment and for keeping the emissions below required levels set by the ECA zones introduced by IMO [7]. For the vessels treated in this work, service and maintenance of diesel engines are required after every 1000 running hours, which include, among other things, an expensive oil change. Thus, additional objectives could be to reduce the number of running hours for each genset and synchronizing the number of running hours so that service of multiple engines can be scheduled at a time - saving both maintenance costs and downtime.

Depending on the type of algorithm used in the EMS to handle all the objectives stated above, a model of the system must be developed. An MPC algorithm includes dynamic states, thus is able to capture dynamics in the systems, which are used to provide predictive abilities in the optimization scheme. Such dynamics may relate to starting and stopping of gensets, as well as ESS dynamics. Even though such a strategy provides an interesting aspect of control, many factors are unknown, or tend to unfold as stochastic distributions, which can prove challenging to implement in practice. In this work, a MILP strategy is adopted, which is based on optimization of linear algebraic models. The linear algebraic models used in this work are based on power- and energy balances. A power balance usually considers the instantaneous generated power relative to the load demand, while energy balance provides predictive abilities that consider e.g. the State Of Charge (SOC) of ESS. Three different MILP algorithms are proposed for energy management of a vessel with 4 gensets with following configurations:

1) 4 fixed speed gensets
2) 3 fixed speed gensets and 1 variable speed genset
3) 4 fixed speed gensets and an ESS

The fixed speed gensets are assumed to have optimal SFOC with a loading of 80% (relative to its rating). Furthermore, the variable speed genset has an operational range relative loadings of 10-90%. The ESS has a given maximum and minimum capacity (kWh), and also constraints for maximum charge and discharge rates (kW). Furthermore, dynamics related to starting and stopping delays of gensets are neglected. All EMS algorithms assumes closed bus-tie operations. The mathematical notation used to present the MILP algorithms is given in Table VII. In the following the MILP algorithms treated in this work, as well as logic-based algorithms constituting EMS/PMS, are discussed.

TABLE VII
MATHEMATICAL NOTATION AND DESCRIPTION.

Notation	Description
k	Discrete time step
$P_L(k)$	Load power demand at time k (kW)
$P_{g,i}^{\max}$	Maximum power capability for genset i (kW)
$P_{g,i}^{\min}$	Minimum power capability for genset i (kW)
$P_{g,i}^{\text{opt}}$	Optimal SFOC power loading of genset i (kW)
$P_{g,i}(k)$	Power capability for genset i at time k (kW)
$E_{g,i}^{\text{opt}}(k)$	Energy capability for genset i when online at time k, assuming optimal loading
$E_{ess}^{\max}$	Maximum energy capacity of ESS (kWh)
$E_{ess}^{\min}$	Minimum energy capacity of ESS (kWh)
$E_{ess}(k)$	ESS energy capacity at time k (kWh)
$P_{ess}^{\max}$	Maximum power rating (> 0) of ESS (kW) (Maximum discharge power)
$P_{ess}^{\min}$	Minimum power rating (< 0) of ESS (kW) (Maximum charge power)
$P_{ess}(k)$	ESS power at time k (kW)
$Q_{\text{fuel},i}(k)$	Fuel consumption for genset i at time k (kg)
$T_{g,i}(k)$	Number of running hours for genset i
$S_{g,i}(k)$	Number of starts/stops of genset i
Δt	Maximum time between every run of algorithm (s)
y_i	Integer decision variable for scheduling genset i
q_p, q_s, q_t	Objective weights for power balance, number of starts/stops and running hours, respectively
$J(k)$	Objective function for time k

B. Mixed Integer Linear Programming (MILP) Algorithms

A MILP algorithm is an LP algorithm, with an objective function, inequality and equality constraints, where some of the decision variables (manipulated variables) are integers [30], [31]. The MILP formulations uses the minimum number of starts/stops and running hours, considering all gensets, i.e.

$$\begin{aligned} T_g^{\min}(k) &= \min\{T_{g,i}(k)\}, \\ S_g^{\min}(k) &= \min\{S_{g,i}(k)\}. \end{aligned} \tag{1}$$

In the following, the three MILP formulations for the three configurations listed above are treated separately.

1) 4 fixed speed gensets:

$$\begin{aligned} \min_{y_i} \quad J(k) = {} & q_p \sum_i \left(P_{g,i}(k)\right) \\ & + q_t \sum_i \left(T_{g,i}(k) - T_g^{\min}(k)\right) \cdot y_i \\ & + q_s \sum_i \left(S_{g,i}(k) - S_g^{\min}(k)\right) \cdot y_i, \\ \text{subject to} \quad & \\ & P_{g,i}(k) = y_i \cdot P_{g,i}^{\text{opt}}, \\ & \sum_i \left(P_{g,i}(k)\right) \geq P_L(k), \\ & y_i \in \{0,1\}, \\ & i \in \{\text{gensets}\}, \end{aligned} \tag{2}$$

where y_i are the decision variables. The reason why $T_g^{\min}(k)$ and $S_g^{\min}(k)$ are subtracted from the gensets' running hours and number of starts/stops, respectively, is because minimizing the power production is the main objective, and should not be overshadowed by the accumulated running hours and number of starts/stops. In addition, the subtractions introduce equalization of running hours and number of starts/stops. $P_{g,i}^{\text{opt}}$ is used in the first set of equality constraints in (2) to enforce all running fixed speed gensets in the power calculation to have approximately optimal loading conditions as an approximation to schedule gensets.

2) 3 fixed speed gensets and 1 variable speed genset:

$$\begin{aligned} \min_{y_i, P_{g,j}(k)} \quad J(k) = {} & q_p \sum_i \left(P_{g,i}(k)\right) \\ & + q_t \sum_j \left(T_{g,j}(k) - T_g^{\min}(k)\right) \cdot y_j \\ & + q_s \sum_j \left(S_{g,j}(k) - S_g^{\min}(k)\right) \cdot y_j, \\ \text{subject to} \quad & \\ & P_{g,j}(k) = y_j \cdot P_{g,j}^{\text{opt}}, \\ & P_{g,l}(k) \leq P_{g,l}^{\max}, \\ & P_{g,l}(k) \geq 0, \\ & \sum_i \left(P_{g,i}(k)\right) \geq P_L(k), \\ & y_j \in \{0,1\}, \\ & i \in \{\text{gensets}\}, \\ & j \in \{\text{fixed speed gensets}\}, \\ & l \in \{\text{variable speed gensets}\}, \end{aligned} \tag{3}$$

where y_j and $P_{g,l}$ are the decision variables. Note that the minimum equality constraint for the variable speed gensets is set to 0. This is because if an additional integer variable is introduced to determine if the variable speed genset should run, i.e. $y_l \cdot P_{g,l}^{\min} \leq y_l \cdot P_{g,l} \leq P_{g,l}^{\max}$, the problem would become nonlinear, thus not supported by linear programming solvers. Thus the following evaluation of the results yielded from the MILP is adopted:

if $P_{g,l}(k) < P_{g,l}^{\min}$ **and** $P_{g,l}(k) > 0$**:**
  $P_{g,l}(k) = P_{g,l}^{\min}$
else: (4)
  use $P_{g,l}(k)$ from MILP
endif

3) 4 fixed speed gensets and an ESS: With the implementation of an ESS a mode variable is introduced to distinguish between charging and discharging of the ESS:

$$\begin{aligned}\min_{y_i, P_{ess}(k)} \quad J(k) &= q_p \sum_i \left(P_{g,i}(k)\right) \\ &+ q_t \sum_i \left(T_{g,i}(k) - T_g^{\min}(k)\right) \cdot y_i \\ &+ q_s \sum_i \left(S_{g,i}(k) - S_g^{\min}(k)\right) \cdot y_i,\end{aligned}$$

subject to

$$\begin{aligned}&\textbf{if } \text{mode == "charge"}\textbf{:} \\ &\quad P_{ess}(k) \leq 0 \\ &\quad P_{ess}(k) \geq P_{ess}^{\min} \\ &\textbf{else if } \text{mode == "discharge"}\textbf{:} \\ &\quad P_{ess}(k) \leq P_{ess}^{\max} \\ &\quad P_{ess}(k) \geq 0 \\ &\textbf{endif} \\ &P_{g,i}(k) = y_i \cdot P_{g,i}^{\text{opt}}, \\ &\sum_i \left(P_{g,i}(k)\right) + P_{ess}(k) \geq P_L(k), \\ &y_i \in \{0, 1\}, \\ &i \in \{\text{gensets}\},\end{aligned} \tag{5}$$

where y_i and $P_{ess}(k)$ are the decision variables. $P_{ess}(k) > 0$ is defined as positive power flow from the ESS (discharge), while $P_{ess}(k) < 0$ determines charging of the ESS. The introduced mode (charge and discharge) is determined by the caller of the algorithm, and is decided relative to the ESS' capacity, i.e.

$$\begin{aligned}&\textbf{if } E_{ess}(k-1) - P_{ess}^{\max} \cdot \frac{\Delta t}{3600} \leq E_{ess}^{\min}\textbf{:} \\ &\quad \text{mode = "charge"} \\ &\textbf{else if } E_{ess}(k-1) - P_{ess}^{\min} \cdot \frac{\Delta t}{3600} \geq E_{ess}^{\max}\textbf{:} \\ &\quad \text{mode = "discharge"} \\ &\textbf{endif}\end{aligned} \tag{6}$$

C. Logic Algorithms

Logic-based algorithms are often adopted in industry for control of various systems and processes. EMS/PMS is not an exception. Logic-based algorithms are usually intuitive, however, often requires a high number of nested logic statements to achieve the desired results. This makes logic-based algorithms complex, hard to construct and debug. For a genset scheduling algorithm, which uses the rating of each individual genset to construct logic with the objective of supplying the load demand with minimum number of gensets online, and with minimum online total power generation capability, the rating of the gensets are crucial to get the logic right. This can cause dependencies that may not be fulfilled if one or multiple gensets were to change rating. To account for such dependencies, the logic structure in the algorithm becomes even more complex, which increases the chance of failing to meet the desired objective. In this work three logic-based algorithms are implemented, relative to the three configurations presented earlier, with the objective of supplying the load demands with minimal online power generation capability. The logic-based algorithms use the gensets' optimal loading conditions to construct nested if-else statements relative the load profile, starting from the genset(s) with the lowest rating with optimal loading conditions. A small example of how the logic structure is implemented, with the configuration of 4 fixed speed gensets and genset ratings according to Table I, is given below in (7). $P_g^{\sum}(k)$ denotes the sum of the (intended) generated power (assuming optimal loading conditions) from selected gensets.

$$\begin{aligned}&\textbf{if } P_L(k) == 0 \textbf{ :} \\ &\quad P_g^{\sum}(k) = 0 \\ &\textbf{else if } P_L(k) \leq P_{g,2}^{\text{opt}} \textbf{ :} \\ &\quad P_g^{\sum}(k) = P_{g,2}^{\text{opt}} \\ &\textbf{else if } P_L(k) \leq P_{g,1}^{\text{opt}} \textbf{ :} \\ &\quad P_g^{\sum}(k) = P_{g,1}^{\text{opt}} \\ &\textbf{else if } P_L(k) \leq P_{g,2}^{\text{opt}} + P_{g,3}^{\text{opt}} \textbf{ :} \\ &\quad P_g^{\sum}(k) = P_{g,2}^{\text{opt}} + P_{g,3}^{\text{opt}} \\ &\qquad \vdots \\ &\textbf{else :} \\ &\quad P_g^{\sum}(k) = P_{g,1}^{\text{opt}} + P_{g,2}^{\text{opt}} + P_{g,3}^{\text{opt}} + P_{g,4}^{\text{opt}}\end{aligned} \tag{7}$$

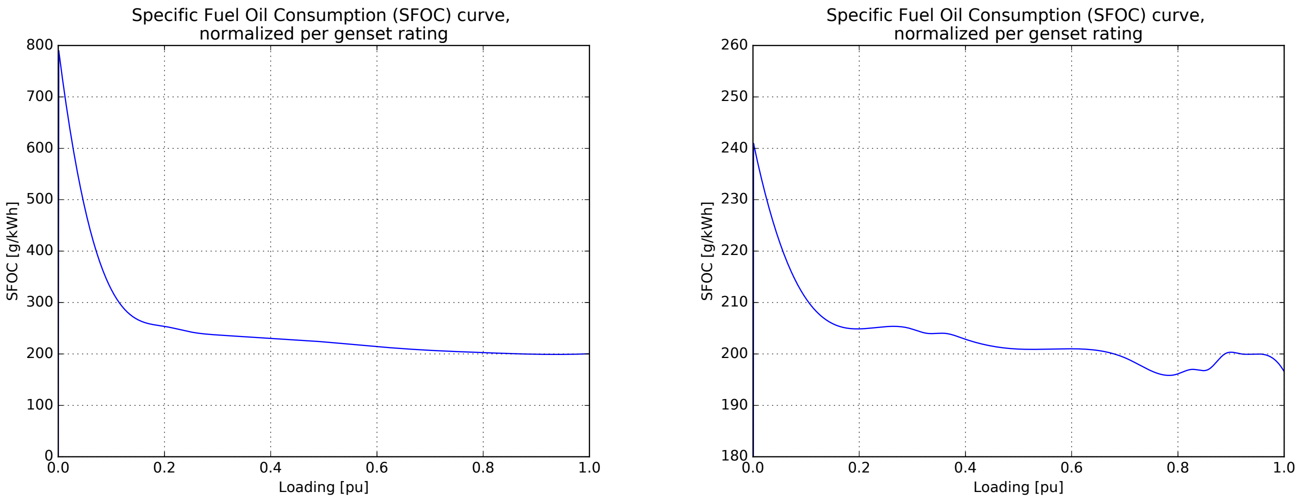
IV. Results

The proposed EMS algorithms, both MILP and logic-based, are in this section applied to the experimental data extracted from the three vessels to analyze the three proposed configurations and for various operational profiles. The MILP algorithms are implemented in Python using the Pulp framework that acts as an interface to solvers such as CPLEX. The rating of the gensets are kept the same as listed in Table I - V. For all the MILP algorithms the weights in the cost functions are chosen by trial and error according to

$$\begin{aligned}q_p &= 10^6 \\ q_t &= \begin{cases} 10, & \text{if } \max\{T_{g,i}\} - \min\{T_{g,i}\} \geq 50 \\ 0, & \text{otherwise} \end{cases} \\ q_{ss} &= \begin{cases} 10^3, & \text{if } \max\{S_{g,i}\} - \min\{S_{g,i}\} \geq 100 \\ 0, & \text{otherwise} \end{cases}\end{aligned} \tag{8}$$

The penalties related to running hours and number of starts/stops are not effectuated until the difference of the genset with lowest number and the genset with highest number exceeds a threshold. This is to avoid unnecessary scheduling in situations where the differences in number of running hours and starts/stops, considering all gensets, are marginal.

For all three vessels the second genset, G2, is chosen as variable speed genset for configuration 2, and marked as G2* in the following. The operation range of the variable speed gensets are set to loadings between 10% and 90%, and are assumed to follow the SFOC curve in Fig. 4b. The fixed speed gensets are assumed to follow the SFOC curve portrayed



(a) Normalized (brake) SFOC for fixed speed genset operation.

(b) Normalized (brake) SFOC for variable speed genset operation.

Fig. 4. (Brake) Specific Fuel Oil Consumption (SFOC) curves for fixed speed and variable speed genset operation adopted in this work, normalized relative to the per unit genset loading. The SFOC curves are based on acceptance and certification tests for fixed speed and variable speed operations of gensets and are provided by a leading genset supplier. Optimal loading for the fixed speed SFOC is about 90% with SFOC of 199 $\frac{\text{g}}{\text{kWh}}$, and the variable speed SFOC is about 80% with SFOC of 196 $\frac{\text{g}}{\text{kWh}}$.

in Fig. 4a, with optimal loading of about 90%. The EMS algorithms for all vessels will be run

- every 10 minutes,
- or if the load demand exceeds the online power supply capability,
- or if the ESS exceeds its capacity limits.

The ESS is assumed to have a capacity of C kWh and power constraints of $\pm C$ kW. The ESS capacities for the three different vessels treated in this work have been chosen relative the capacity of existing ESS applications in similar vessels. Furthermore, the ESS is assumed to have an operation range between 30% and 100% capacity. For a fair comparison of the three configurations, the start capacity of the ESS is set to 30%. The load demands to be met are, for each data set, calculated as the sum of the supplied power from each individual genset from the experimental data. To validate and compare the results from the three different configurations, with both MILP and logic-based EMS algorithms, three performance targets are used:

- Total fuel consumption throughout the data set horizon for all gensets: $\sum_i Q_{\text{fuel},i}$
- Running hours for all gensets: $\sum_i T_{g,i}$
- Number of starts/stops for all gensets: $\sum_i S_{g,i}$

The first item in the list above is especially important, as reducing the total fuel consumption, and thus minimizing the emissions, considering all gensets, is the main objective of the EMS. For comparison, the total fuel consumption and total number of running hours, as well as number of starts/stops, have been calculated from the operational data and listed in Table VIII. The results presented are affected by uncertainties, and the main uncertainties are considered to be the adopted SFOC curves and the accuracy of the sampled data from the three vessels. The SFOC curves used in this work have been constructed from a manufacturer's acceptance and certification tests of a single genset type for fixed speed and variable speed operation, and have been normalized (w.r.t. loading) to fit a range of different gensets with different ratings according to the three vessels' power plants treated in this work. The power measurements do also include uncertainties due to, among other things, measurement noise and sampling. The sampling frequencies used are small ($\leq$ 1Hz) due to the amount of logged data for long data collection horizons, and also due to limitations in the logging systems used. Such low sampling frequencies do also introduce uncertainties and do not account the fast dynamics in the power systems. Hence, the result presented in this section is regarded to be an indication of how alternative EMS/PMS strategies affect the performance targets listed above. In the following, each vessel with the three proposed configurations will be treated separately, and a load-sharing strategy with equal loading (% of relative individual genset ratings) of the running gensets are adopted.

TABLE VIII
PERFORMANCE TARGETS EXTRACTED FROM THE REAL VESSEL DATA.

		$T_{g,i}$ (hours)	$S_{g,i}$	$Q_{\text{fuel},i}$ (kg)
FERRY	G1	0.00	0	0.00
	G2	23.98	0	1405.98
	G3	0.88	2	83.71
	G4	20.48	5	2358.82
	$\sum$	45.34	7	3848.52
PSV	G1	266.11	34	53104.27
	G2	433.72	47	33084.15
	G3	433.87	38	34275.50
	G4	220.78	33	45783.06
	$\sum$	1354.49	152	166246.99
SEISMIC	G1	963.40	2	317683.71
	G2	719.33	2	236924.51
	G3	764.06	3	253209.37
	G4	752.10	3	246001.21
	$\sum$	3198.90	10	1053818.79

A. Ferry

The EMS configuration of the ferry is listed in Table IX. As can be seen, the maximum ESS capacity is set to 670 kWh. The total energy demand (E_L) throughout the ferry's data set is 17.24 MWh, thus the optimal genset scheduling (unit commitment) would yield $\sum_i E_{g,i}^{\text{opt}} = E_L$ MWh, where the online gensets have optimal loadings.

TABLE IX
EMS INFORMATION AND CONFIGURATION FOR THE FERRY.

Parameter	Value
Total load energy demand, E_L	17.24 MWh
Optimal loading, fixed speed gensets	90%
Load range, variable speed genset	10-90%
ESS max. capacity, $E_{ess}^{\max}$	670 kWh (100%)
ESS min. capacity, $E_{ess}^{\min}$	201 kWh (30%)
ESS start capacity, $E_{ess}(0)$	201 kWh (30%)
ESS discharge rating, $P_{ess}^{\max}$	670 kW (1C)
ESS charge rating, $P_{ess}^{\min}$	-670 kW (-1C)

TABLE X
FERRY: EMS RESULTS WITH RATING OF GENSETS ACCORDING TO TABLE I

		LOGIC			MILP		
		$T_{g,i}$ (hours)	$S_{g,i}$	$Q_{\text{fuel},i}$ (kg)	$T_{g,i}$ (hours)	$S_{g,i}$	$Q_{\text{fuel},i}$ (kg)
CONFIG 1	G1	9.57	63	1449.46	17.59	121	2500.29
	G2	24.00	1	1575.97	14.97	109	954.12
	G3	9.56	98	675.50	0.93	56	84.78
	G4	0.00	0	0.00	0.81	22	144.55
	$\sum$	43.13	162	3700.93	34.30	308	3683.74
CONFIG 2	G1	9.57	63	1776.34	2.97	44	579.80
	G2*	18.92	445	785.31	18.92	445	785.32
	G3	9.56	98	933.32	9.56	98	933.32
	G4	0.00	0	0.00	6.60	43	1196.59
	$\sum$	38.06	606	3494.96	38.06	630	3495.04
CONFIG 3	G1	2.57	23	513.09	10.66	86	2193.66
	G2	18.89	75	2117.60	11.29	100	1274.39
	G3	7.90	82	875.90	0.04	6	4.40
	G4	0.00	0	0.00	0.17	1	35.89
	$\sum$	29.36	180	3506.59	22.16	193	3508.35
	$\sum_{30\%}$	-	-	3457.37	-	-	3457.51

The EMS results using the three different configurations for the load demand extracted from the operational data are listed in Table X. As the ESS capacity in the end of the EMS analysis might be above minimum capacity, the added fuel consumption that has been used to charge the ESS beyond minimum capacity has to be subtracted from the total fuel consumption results to assure fair comparisons between the configuration. This has been done in the last row in Table X (denoted $\sum_{30\%}$), where $200\frac{\text{g}}{\text{kWh}}$ fuel has been subtracted from the total fuel consumptions to bring the ESS capacity down to 30%. Comparing the three different configurations, and the use of MILP and logic-based algorithms, the lowest total fuel consumption, $\sum_i Q_{\text{fuel},i}$, can be found for configuration 3 using the logic-based algorithm. The difference in total fuel consumption when comparing the MILP an the logic-based algorithm for this configuration is marginal, and both algorithms indicate fuel savings of 10.2% compared to the total fuel consumption calculated from the real vessel data in Table VIII. The highest total fuel consumption can be found for configuration 1 using the logic-based algorithm, which indicates fuel savings compared to Table VIII of 3.8%. The MILP algorithm for the same configuration indicates fuel savings of 4.3%, however, at the expense of increasing the number of starts/stops. The difference in total fuel consumptions for configuration 2, comparing the two algorithms, is also marginal, and both algorithms indicate fuel savings of 9.2%. Furthermore, configuration 3 with MILP results in the lowest number of total running hours, $\sum_i T_{g,i}$ (51.1% reduction compared to Table VIII), while the logic-based algorithms for configuration 1 results in the highest number of running hours (4.9% reduction compared to Table VIII). Configuration 2, which includes a variable speed genset, is the configuration with the highest number of starts/stops, $\sum_i S_{g,i}$. The highest number of starts/stops for a single generator is the variable speed generator, G2*, in configuration 2 for both algorithms, yielding 445 starts/stops for the whole horizon. This corresponds to an average of 18.54 starts/stops per hour, i.e. 3.24 minutes between each start/stop. The logic-based algorithm for configuration 2 has slightly lower number of total starts/stops, which is due to the MILP algorithm's objective of synchronizing running hours and number of starts/stops for all gensets.

The results presented in Table X indicate that it could be most beneficial to employ an ESS (configuration 3) to reduce the fuel consumption and the total number of running hours, where the lowest total number of running hours, $\sum_i T_{g,i}$, is obtained by the MILP algorithm. However, the number of starts/stops exceeds what is presented in Table VIII, which is expected due to minimizing the online power supply capability (spinning reserve).

It can be discussed whether high scheduling frequencies (i.e. high number of starts/stops) are beneficial, due to wear and tear of the gensets and increased fuel consumption during acceleration towards ideal working state. Assuming the cooling liquid from the running gensets flows through the engine blocks of the gensets that are not running, one prevents cold starts of the gensets. Furthermore, assuming an AC distribution network, the gensets are not exposed to any significant loadings before the gensets' voltages and frequencies match the distribution grid and the gensets are connected to the distribution bus, which will support fast acceleration of the genset to ideal states. For many gensets the acceleration phase will last for 20-30 seconds, and with no significant loads the fuel consumption during such a phase would be limited. The gensets' starters and starter relays would be subject for wear and tear with increased scheduling frequency. However, an assessment regarding how the scheduling frequency affects wear and tear of single components, and affects the fuel consumption of single gensets, lays outside the scope of this work.

B. Platform Supply Vessel (PSV)

The EMS configuration of the PSV is listed in Table XI. As can be seen, the maximum ESS capacity is in this case set to 1000 kWh, which is slightly higher than the ESS for the ferry. The total energy demand (E_L) throughout the PSV's data set is 728.49 MWh, which is calculated from the operational data's approximately 1056 hours long horizon. As earlier, the optimal genset scheduling (unit commitment) would yield $\sum_i E_{g,i}^{\text{opt}} = E_L$ MWh.

TABLE XI
EMS INFORMATION AND CONFIGURATION FOR THE PSV.

Parameter	Value
Total load energy demand, E_L	728.49 MWh
Optimal loading, fixed speed gensets	90%
Load range, variable speed genset	10-90%
ESS max. capacity, $E_{ess}^{\max}$	1000 kWh (100%)
ESS min. capacity, $E_{ess}^{\min}$	300 kWh (30%)
ESS start capacity, $E_{ess}(0)$	300 kWh (30%)
ESS discharge rating, $P_{ess}^{\max}$	1000 kW (1C)
ESS charge rating, $P_{ess}^{\min}$	-1000 kW (-1C)

TABLE XII
PSV: EMS RESULTS WITH RATING OF GENSETS ACCORDING TO TABLE III.

		LOGIC			MILP		
		$T_{g,i}$ (hours)	$S_{g,i}$	$Q_{\text{fuel},i}$ (kg)	$T_{g,i}$ (hours)	$S_{g,i}$	$Q_{\text{fuel},i}$ (kg)
CONFIG 1	G1	43.28	202	14688.83	37.28	142	12692.98
	G2	1029.67	251	98023.73	346.92	1134	45721.62
	G3	320.05	1156	43951.77	1002.79	285	96253.69
	G4	0.67	16	226.03	6.68	142	2222.03
	$\sum$	1393.67	1625	156890.36	1393.66	1703	156890.32
CONFIG 2	G1	43.28	202	16046.08	37.20	136	14009.72
	G2*	966.54	9533	74833.77	966.54	9533	74833.91
	G3	320.04	1156	55523.63	320.05	1156	55523.88
	G4	0.67	16	234.97	6.75	138	2271.35
	$\sum$	1330.54	10907	146638.45	1330.54	10963	146638.86
CONFIG 3	G1	27.23	178	11330.65	21.17	62	8868.53
	G2	558.77	1152	99477.98	428.42	1202	76352.20
	G3	194.13	774	34506.14	328.37	1204	58508.42
	G4	0.04	2	18.61	3.81	64	1576.91
	$\sum$	780.18	2106	145333.38	781.77	2532	145306.05
	$\sum_{30\%}$	-	-	145305.37	-	-	145293.80

The EMS results using the three different configurations for the load demand extracted from the operational data are listed in Table XII. Comparing the three different configurations, and the use of MILP and logic-based algorithms, the MILP algorithm for configuration 3 (with ESS) results in the lowest total fuel consumption, $\sum_i Q_{\text{fuel},i}$ (12.6% fuel savings compared to Table VIII), while configuration 1, with both MILP and logic-based algorithms, results in the highest fuel consumption (5.6% fuel savings compared to Table VIII). Both algorithms for configuration 2 indicate fuel savings, compared to Table VIII, of 11.8%. The main difference between the MILP and logic-based algorithms for configuration 1 and 2 relates to total number of starts/stops, $\sum_i S_{g,i}$, where the MILP algorithm has the highest number for both configurations compared to the logic-based algorithms. As discussed earlier, this is because the MILP algorithms synchronize the number of running hours and starts/stops for all gensets. The total number of running hours, $\sum_i T_{g,i}$, are about the same comparing the MILP algorithm and the logic-based algorithm in both configurations (1 and 2), indicating an increase of 2.9% for configuration 1 and a reduction of 1.8% for configuration 2 compared to Table VIII. For configuration 3, the logic-based algorithm has slightly lower total number of running hours compared to the MILP algorithm (reduction of 42.4% for the logic-based algorithm and a reduction of 42.3% for the MILP algorithm compared to Table VIII). The logic-based algorithm also results in a lower total number of starts/stops compared to the MILP algorithm.

Furthermore, the genset with the highest number of starts/stops is the variable speed genset, G2* for configuration 2 using both the MILP and logic-based algorithm, with 9533 starts/stops. This is approximately 9.03 starts/stops per hour, i.e. 6.65 minutes between each start/stop. Comparing the results in Table XII with the results extracted from the operational data presented in Table VIII, all proposed configurations with both MILP and logic-based algorithms results in lower total fuel consumption, however, for configuration 1 the total number of running hours exceeds the total number of running hours extracted from the operational data. As with the ferry, the numbers of starts/stops exceed what is presented in Table VIII, which is expected due to minimizing the online power supply capability.

The results in Table XII indicate that it would also for this vessel be beneficial to employ an ESS to reduce the fuel consumption. The MILP algorithm provides a slightly lower total fuel consumption, however, the logic-based algorithm for this configuration yields better results than the MILP algorithm considering running hours and total number of starts/stops. Even though the results indicate significant fuel savings, the reduced number of running hours for configuration 3 is also of interest from a maintenance/service perspective.

C. Seismic Survey Vessel

The EMS configuration of the seismic survey vessel is listed in Table XIII. As can be seen, the maximum ESS capacity is also in this case set to 1000 kWh. The total energy demand (E_L) is calculated from the operational data with horizon length of approximately 1066 hours and is 4731.17 MWh. As earlier, the optimal genset scheduling (unit commitment) would yield $\sum_i E_{g,i}^{\text{opt}} = E_L$ MWh.

TABLE XIII
EMS INFORMATION AND CONFIGURATION FOR THE SEISMIC SURVEY VESSEL.

Parameter	Value
Total load energy demand, E_L	4731.17 MWh
Optimal loading, fixed speed gensets	90%
Load range, variable speed genset	10-90%
ESS max. capacity, $E_{ess}^{\max}$	1000 kWh (100%)
ESS min. capacity, $E_{ess}^{\min}$	300 kWh (30%)
ESS start capacity, $E_{ess}(0)$	300 kWh (30%)
ESS discharge rating, $P_{ess}^{\max}$	1000 kW (1C)
ESS charge rating, $P_{ess}^{\min}$	-1000 kW (-1C)

The EMS results using the three different configurations for the load demand extracted from the operational data are listed in Table XIV. The EMS results from the seismic survey vessel show that configuration 2, with a variable speed genset installed, results in the lowest total fuel consumption, $\sum_i Q_{\text{fuel},i}$, 10.3% reduction compared to Table VIII for both algorithms. The total number of running hours for the same configuration is equal for both algorithms, indicating a reduction of 31.9% compared to Table VIII. The main difference between the algorithms for this configuration is related to number of starts/stops, where the MILP algorithm provides a higher number than the logic based algorithm. For configuration 3, the logic-based algorithm results in lower number of starts/stops, total fuel consumption and total running hours compared to the MILP algorithm, and it is speculated that the MILP algorithm uses too much effort to equalize the number of running hours and starts/stops, which impairs the results. For this configuration, the logic-based algorithm indicates an reduction in total running hours of 38.8% compared to Table VIII, while the MILP algorithm indicates a 37.7% reduction. For total fuel consumption, the logic-based algorithm indicates fuel savings of 8.9% compared to Table VIII, while the MILP algorithm indicates fuel savings of 8.6%. The configuration with the highest fuel consumption is configuration 1: The logic-based algorithm has slightly higher fuel consumption than the MILP algorithm (both algorithms indicate fuel savings of 6.4% compared to Table VIII). The total number of running hours are almost identical for both algorithms in configuration 1 (reduction of 29.2% compared to Table VIII), however, the number of starts/stops is higher for the MILP algorithm than for the logic-based algorithm. The genset with the highest number of starts/stops is the variable speed G2* genset in configuration 2 for both algorithms, with 16253 starts/stops. This corresponds to an average of 15.25 starts/stops per hour, i.e. about 3.94 minutes between each start/stop. As indicated from the results in Table XIV, all three configurations with both algorithms result in lower fuel consumptions and have lower numbers of running hours than what is stated in Table VIII, however, the total numbers of starts/stops are higher.

The load profile from the seismic survey vessel is quite different compared to the ferry and the PSV, with a more stable load profile without rapid power peaks of high magnitude. Thus, to investigate the benefit of the three different configurations further, the third genset, G3, is reduced to half of its rating to give more flexibility for the algorithms to utilize in the unit commitment. The results from this analysis are listed in Table XV.

TABLE XIV
SEISMIC SURVEY VESSEL: EMS RESULTS WITH RATING OF GENSETS ACCORDING TO TABLE V.

		LOGIC			MILP		
		$T_{g,i}$ (hours)	$S_{g,i}$	$Q_{\text{fuel},i}$ (kg)	$T_{g,i}$ (hours)	$S_{g,i}$	$Q_{\text{fuel},i}$ (kg)
CONFIG 1	G1	154.20	1278	60476.90	213.34	1940	89986.58
	G2	1066.34	1	467960.75	259.98	1940	108671.47
	G3	1044.77	175	457445.95	906.93	1303	397904.02
	G4	0.00	0	0.00	884.75	1497	389311.28
	$\sum$	2265.13	1454	985883.59	2265.01	6680	985873.36
CONFIG 2	G1	153.90	1280	81900.09	43.21	742	22823.31
	G2*	979.88	16253	293285.97	979.88	16253	293286.55
	G3	1044.77	177	570172.17	1043.28	183	569361.20
	G4	0.00	0	0.00	112.17	742	59888.51
	$\sum$	2178.55	17710	945358.23	2178.55	17920	945359.57
CONFIG 3	G1	3.95	136	1855.01	518.51	4003	249510.74
	G2	1066.34	1	527606.45	698.90	3433	337118.90
	G3	887.7	11715	430485.33	356.51	4004	172495.42
	G4	0.00	0	0.00	418.62	4004	204598.99
	$\sum$	1958.00	11852	959946.78	1992.54	15444	963724.05
	$\sum_{30\%}$	-	-	959806.78	-	-	963583.91

As can be seen from the results in Table XV, also in this case configuration 2 results in the lowest total fuel consumption, $\sum_i Q_{\text{fuel},i}$. The difference between the algorithms when comparing total number of running hours and total fuel consumption for this configuration is marginal, both algorithms indicate a reduction in total number of running hours of 29.2% and a reduction in total fuel consumption of 10.5% compared to Table VIII. However, the MILP algorithm results in a higher total number of starts/stops of gensets. As before, configuration 1 results in the highest fuel consumption, with approximately the same total fuel consumption for both algorithms, both indicating fuel savings of 8.1% compared to Table VIII. Also the total number of running hours for this configuration is approximately the same comparing both algorithms, indicating a reduction of 29.2%, the same as configuration 2, compared to Table VIII. For configuration 3, the logic-based algorithm results in lower total number of running hours and total fuel consumption compared to the MILP algorithm. Comparing the results from configuration 3 with Table VIII, both algorithms indicate fuel savings of 10.4%. For the total number of running hours, the logic-based algorithm results in a reduction of 37.3%, while the MILP algorithm results in a reduction of 37.1% compared to Table VIII. The difference between the algorithms for this configuration is related to total number of starts/stops, where the logic-based algorithm conducts more starts/stops of gensets compared to the MILP algorithm. Furthermore, all configurations with both algorithms result in lower fuel consumption compared to Table XIV. For configuration 2 and 3, the total number of running hours are higher than what is stated in Table XIV, while the total numbers of starts/stops are lower for configuration 2 using both algorithms with reduced rating of the G3 genset, and configuration 3 using the MILP algorithm. The genset with the highest number of starts/stops is now the G3 genset in configuration 3 using the logic-based algorithm, now with 11601 starts/stops. This corresponds to an average of 10.88 starts/stops per hour, i.e. about 5.51 minutes between each start/stop. Comparing the results in Table XV with the results extracted from the operational data presented in Table VIII, it is evident that all proposed configurations with both MILP and logic-based algorithms results in lower total fuel consumption and total number of running hours. As before, the number of starts/stops exceeds what is presented in Table VIII, which is

TABLE XV
SEISMIC SURVEY VESSEL: EMS RESULTS WITH RATING OF G3 SET TO 1530 KW.

		LOGIC			MILP		
		$T_{g,i}$ (hours)	$S_{g,i}$	$Q_{\text{fuel},i}$ (kg)	$T_{g,i}$ (hours)	$S_{g,i}$	$Q_{\text{fuel},i}$ (kg)
CONFIG 1	G1	788.03	1413	369825.75	1035.09	129	487750.64
	G2	1066.34	1	502360.39	459.85	3899	216103.81
	G3	410.16	2856	95786.14	410.05	2870	95762.11
	G4	0.60	14	243.98	360.02	3900	168594.68
	$\sum$	2265.13	4284	968216.26	2265.01	10798	968211.23
CONFIG 2	G1	788.02	1423	432667.83	344.22	4089	188989.64
	G2*	1065.46	217	397763.78	1065.46	217	397764.36
	G3	410.05	2870	112572.95	410.05	2870	112572.95
	G4	0.60	14	319.57	444.39	4088	243998.52
	$\sum$	2264.12	4524	943324.13	2264.12	11264	943325.47
CONFIG 3	G1	384.82	6218	209866.93	184.83	1926	99955.36
	G2	1066.34	1	582583.79	993.72	183	540386.38
	G3	554.23	11601	151611.34	549.78	2689	149667.19
	G4	0.02	2	8.36	284.91	1926	154807.74
	$\sum$	2005.42	17822	944070.43	2013.22	6724	944816.67
	$\sum_{30\%}$	-	-	943939.19	-	-	944685.43

expected due to minimizing the online power supply capability (spinning reserve), thus running the gensets with more optimal loadings which cultivate fuel savings.

The EMS results presented for the seismic vessel in Table XIV and Table XV indicate that for this kind of load profile the use of a variable speed genset could be more beneficial than the two other configurations when comparing fuel consumptions. However, the largest reduction in total number of running hours is indicated by configuration 3.

V. Conclusion

This work has presented three different load profiles extracted from three different marine vessels during operation, and the operational data have been presented and analysed in terms of genset loadings. To achieve a fuel-efficient operation, where the fuel consumption and the emission of greenhouse gases are in line with the load demand, the gensets should be running with optimal loadings, which is dictated by the diesel gensets' SFOC curves. To achieve optimal loadings of the gensets in the unit commitment, it is imperative that no more gensets than what is required to meet the load demand are running, meaning a minimal spinning reserve. In addition, with fixed speed gensets, the implementation of a variable speed genset or an ESS would further benefit the unit commitment by introducing flexibility in the power generation, and thus be able to further move the loadings of the fixed speed generators towards optimal loadings.

Three different configurations of the vessels were introduced; i) 4 fixed speed gensets, ii) 3 fixed speed gensets and 1 variables speed genset, and iii) 4 fixed speed gensets and one ESS. Both MILP-based and logic-based EMS algorithms were implemented and presented for the three different power plant configurations. The algorithms were run using the real load demands extracted from the three vessels during operation. The results of the EMS analysis showed that, with the load profiles presented in this work, the unit commitment would benefit most of the implementation of an ESS in terms of fuel savings and reduction in number of running hours for the ferry and the PSV. The seismic vessel would benefit most from a variable speed genset, seen from a fuel saving perspective, however, the lowest total number of running hours was obtained with the use of an ESS. A further implementation to improve the results obtained in configuration 3 could include optimal sizing of the ESS by including it in the EMS optimization algorithms objective function for offline analysis as treated in this work. If the ESS is based on battery packs, also optimizing the battery packs' lifetime, with higher C-ratings, by minimizing battery-cycling would make an interesting aspect for further work. The difference between the MILP-based and logic-based algorithms were also discussed. The MILP algorithms enable ease in implementation, and possibilities for multiple objectives, such as synchronization of running hours and number of starts/stops of gensets.

Even though the analysis presented in this work indicates that the efficiency of unit commitment can be improved by a configuration modification in the power plant and applying more advanced EMS algorithms, further research that includes genset dynamics must be conducted. Moreover, an assessment of the investment costs (CAPEX) related to installing an ESS, and the increased complexity of the total system, need further attention. In addition, even though unit commitment strategies, as presented and discussed in this work, indicate possibilities for further optimizing marine operations, the rules and requirements set by classification entities and vessels' employers might dictate stringent requirements related to spinning reserve (online power supply capability) and segregation of the vessel's power system assuring safety in error prone situations. Thus, additional work related to ensuring the safety of operations with a minimal online power supply capacity must be conducted, where rules and regulations are implemented in the EMS algorithms.

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