Hybrid Ship Fuel Consumption Prediction Through Operational Performance Simulation

Cristi Irimia
Siemens Industry Software
Brasov, Romania
cristi.irimia@siemens.com

Calin Husar
Siemens Industry Software
Brasov, Romania
calin.husar@siemens.com

Robert-Matei Szabo
Siemens Industry Software
Brasov, Romania
robert-matei.szabo@siemens.com

Mihail Grovu
Siemens Industry Software
Brasov, Romania
mihail.grovu.ext@siemens.com

Amine Touat
Compagnie du Ponant
Marseille, France
atouat@ponant.com

Mathieu Petiteau
Compagnie du Ponant
Marseille, France
mpetiteau@ponant.com

Abstract—The maritime industry's imperative to optimize fuel consumption and reduce environmental impact necessitates the development of advanced predictive models for ship operational performance. This paper presents an approach to address this challenge through the integration of hybrid modeling techniques and Siemens Simcenter Amesim software. The primary objective is to develop a hybrid ship functional model capable of accurately predicting fuel consumption across diverse seaway scenarios.

Keywords—maritime, ship hybridization, ship energy efficiency, operational measures, Simcenter Amesim simulation

1. INTRODUCTION

Reducing ship emissions and pollution is a mandatory requirement for ship-owners to meet stringent regulatory requirements, particularly those set forth by the International Maritime Organization (IMO) aimed at significant reductions in carbon emissions. Compliance with these regulations is paramount across the maritime industry[1-5].

The proposed study combines data acquired during the ship travel phases with multi-domain simulations [6,7] to capture the complex dynamics of ship operations.

Central to the developed hybrid model are the integration of ship propulsion systems, environmental conditions, operational parameters, and route characteristics. By incorporating historical real data feeds and weather forecasts [8], the model dynamically adapts to changing conditions, to ensure accurate and robust predictions of fuel consumption.

Extensive simulations are conducted across various seaway scenarios, encompassing calm seas, heavy waves, and adverse weather conditions[9-11], to validate the efficacy of our approach. Comparative analysis against empirical data prove the model's proficiency in accurately forecasting fuel consumption under diverse operational contexts.

The ramifications of our research extend beyond mere fuel efficiency improvements to encompass broader benefits such as emissions reduction, operational cost savings, and enhanced sustainability in maritime transportation. Additionally, the developed hybrid modeling framework serves as a versatile decision support tool for ship optimization and route planning [12-16].

During the simulation process, the constructive parameters of ‘Le Commandant Charcot’ ship, the pioneering hybrid polar exploration ship, were used with functional information acquired from the Ascenz Marorka platform during travel phases. Ship motion control is facilitated by the speed controller submodel, specialized in managing moving masses with dry viscous friction [17]. This model employs the "peak shaving" power management strategy, orchestrated by a statechart [18] that determines Gensets engines activation or deactivation based on requested power and battery SOC (State Of Charge). The battery acts as a power buffer between generated and consumed power, optimizing engines efficiency.

2. SHIP SIMULATION MODEL

The virtual ship model, developed during the EU NEMOSHIP project based on ‘Le Commandant Charcot’ data, presents a ship architecture for prediction of the fuel consumption and CO2 emissions along a user-defined sea route.

The virtual model architecture, presented in Figure 1, features a configuration where six internal combustion engines are connected to six electric machines functioning as electric generators. These generators supply the requisite power for the operation of two propulsion electric motors and manage the ship's energy allocation. A Power Management Controller is established to regulate the electric motors and to adhere to a user-defined mission profile for the ship.

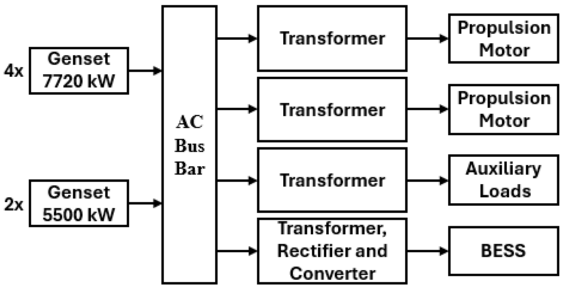


Figure 1 - Virtual model architecture

Energy allocation encompasses all electric consumption aboard the ship, with provisions for defining a constant generic load similar to a steady electric resistance. The two propulsion electric motors are linked via a gear ratio to two propellers responsible for powering the ship through water. The consumption strategy comprehensively assesses the power demands of the ship, determining the activation or deactivation of the six internal combustion engines based on operational requirements. The detailed sketch of the model implemented in Siemens Simcenter Amesim, depicting the interconnected components and control systems, is shown in Figure 2.

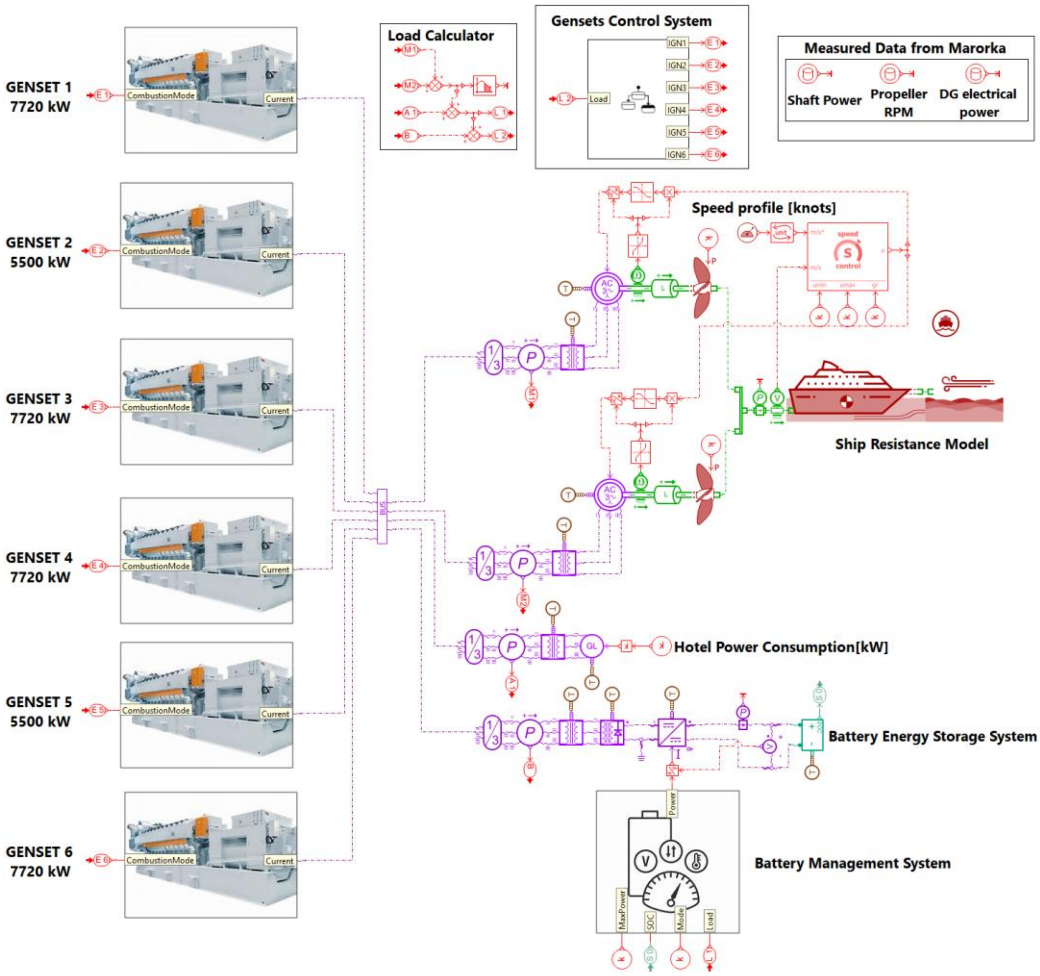


Figure 2 - Sketch of 'Le Commandant Charcot' model

In the virtual ship model, the primary structure comprises several key components:

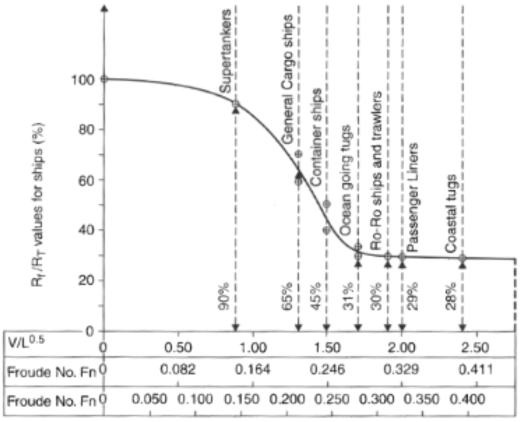
- Ship model: This encompasses the main body of the ship, accommodating the propulsion system and navigation equipment. It also includes features such as mass distribution and resistance to water flow.

- Propellers: Two propellers are responsible for generating thrust and propelling the ship forward or backward.
- Control algorithms, including statecharts, managing operational phases and navigation decisions.
- Battery model: Developed in Simcenter Amesim, the battery model powers the ship's propulsion system, providing the necessary energy for movement.
- Navigation systems: These systems incorporate maps, GPS, and other technologies to plot and follow sea routes effectively.
- Brake system, ensuring controlled deceleration and stopping when necessary.

Several methods can be used to calculate the forward resistance of the ship's hull in water, such as: Statistical Barrass, CFD import (resistance (N) = f (speed (knot)) and Holtrop Mennen algorithm.

The method used to simulate the ship`s hull resistance in this case was Statistical Barrass, which integrates various factors contributing to the overall resistance, including viscous drag, wave-making resistance, and additional resistance due to hull roughness and fouling.

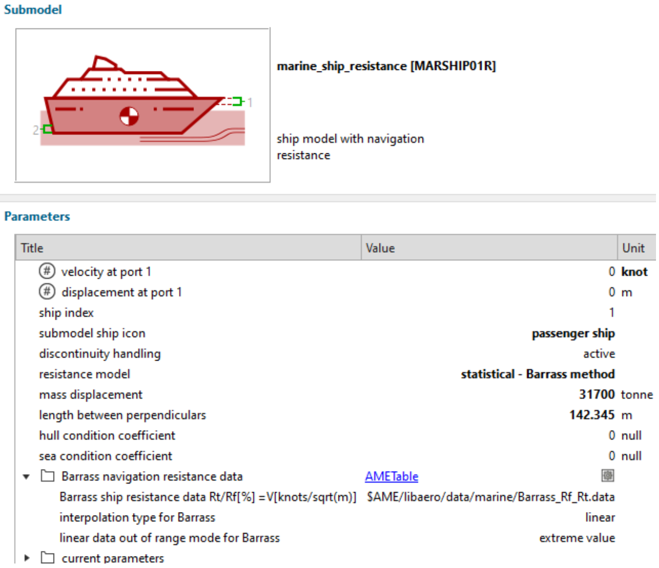
To compute the resistance force in Simcenter Amesim the following parameters have to be used as inputs: Length between perpendiculars, mass displacement, Barrass navigation resistance data [19], illustrated in Figure 3, and coefficients that increase the navigation resistance due to the wear of the hull and weather conditions.



For $V/L^{0.5}$; V in knots, L in metres
For Fn of $V/(gL)^{0.5}$; V (m/s), g = 9.806 m/s², L = LBP in metres
V = ship's speed

Figure 3 - Ratio between frictional resistance to total navigation resistance, based on Froude`s speed length law [20]

The ship parameters are represented in Figure 4 while the propeller parameters (the two propellers have the same parameters) in Figure 5.



Submodel

marine_ship_resistance [MARSHIP01R]

ship model with navigation resistance

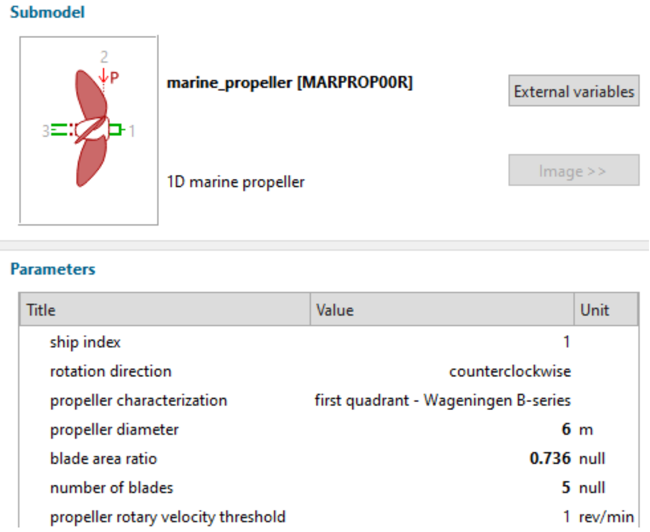
Parameters

Title	Value	Unit
velocity at port 1	0	**knot**
displacement at port 1	0	m
ship index	1	
submodel ship icon	**passenger ship**	
discontinuity handling	active	
resistance model	**statistical - Barrass method**	
mass displacement	**31700**	tonne
length between perpendiculars	**142.345**	m
hull condition coefficient	0	null
sea condition coefficient	0	null
Barrass navigation resistance data	AMETable	
Barrass ship resistance data Rt/Rf[%] =V[knots/sqrt(m)]	$AME/libaero/data/marine/Barrass_Rf_Rt.data	
interpolation type for Barrass	linear	
linear data out of range mode for Barrass	extreme value	
current parameters		

Figure 4 - Ship parameters and resistance modelling

Three different propellers models can be used: Wageningen B-series, *Kt/Kq* tables from CFD and Woodward method. The use of these submodels allows the optimal evaluation of the resistance to movement of the ship and the use of the results obtained from a CFD analysis.

The models work in different quadrants, depending on the direction of advance of the ship and the rotation of the propellers. Considering that predominantly a cruise ship operates in the first quadrant,when forward is the direction of advance and the propellers use ahead rotation, Wageningen B-series is used. This model provides a balance between accuracy, standardization, and ease of use. It helps simulate realistic propulsion performance and efficiency across varying operational conditions, making it ideal for projects focused on optimizing ship performance, fuel consumption, and environmental impact.



Submodel

marine_propeller [MARPROP00R]

1D marine propeller

Parameters

Title	Value	Unit
ship index	1	
rotation direction	counterclockwise	
propeller characterization	first quadrant - Wageningen B-series	
propeller diameter	**6**	m
blade area ratio	**0.736**	null
number of blades	**5**	null
propeller rotary velocity threshold	1	rev/min

Figure 5 - Propeller parameters

Using elements from marine library, the virtual model is capable of defining a sea route based on GPS coordinates. Attached to those coordinates, weather conditions are defined. The weather parameters used in the simulation, take into account data about wind, waves, water viscosity and density caused by the temperature and salinity.

In addition to these specialized marine models, the simulation model is constructed using components from the Aerospace and Marine, Electric Motors and Drive, IFP Drive, 1D Mechanical, Signal and Control, and Statechart Environment from Simcenter Amesim libraries. These libraries provide a comprehensive set of tools for modeling and simulating the ship's mechanical, electrical, and control systems.

Utilizing these components facilitates the modeling and observation of various dynamic parameters crucial in maritime operations, including velocity, displacement, force, rotational velocity, angle, and torque.

The Signal and Control library encompasses signal or "block" components, enabling the construction of block diagram models that visually represent the dynamics of physical systems pertinent to maritime navigation. One application of this library is the Load Calculator. By utilizing power sensors connected to electrical consumers, a comprehensive power budget for the ship can be established. The output from the Load Calculator is transmitted to the Battery Management System, that decides the battery power. Once the battery output is incorporated into the power budget, this information is relayed to the Genset Control System, which determines the number and type of gensets required for operation.

Both battery and genset control systems are developed using the Statechart Environment from Simcenter Amesim. The reason of this choice is that it offers a user-friendly graphical interface for creating, integrating, executing, and animating statecharts tailored to maritime scenarios, incorporating sequential decision logic based on state machines.

The Gensets` activation or deactivation is governed by the Combustion Mode signal, where a value of 0 signifies 'off' and 1 signifies 'on'. This signal also serves to control the opening or closing of a three-phase switch, responsible for connecting or disconnecting the electric generator from the ship's electrical grid.

The control system for the internal combustion engine operates on a Proportional-Integral-Derivative (PID) algorithm, regulating the rotational velocity based on a predetermined RPM (Revolutions Per Minute) target. Additionally, it evaluates a torque request received from the electric generator, comparing it against the maximum torque capacity of the engine. If the RPM target is deemed insufficient, the control signal undergoes adjustment to ensure the generation of the requested torque.

To initiate the internal combustion engine's startup process, a starting torque is generated when the Combustion Mode signal transitions from 0 to 1.

The three-phase electric generator is modeled as an ideal synchronous generator. The torque requested from the generator is calculated using a signal expression that factors in voltage and losses, with a constant efficiency set at 0.97.

The BESS (Battery Energy Storage System) used in the simulation process consists of 40 parallel connected *Orca Energy [20]* battery packs, provided by Corvus Energy. Each battery pack is a series strings of 20 battery modules. The number of modules in the pack determines the pack voltage. The module configuration consists of two cells in parallel and twelve such parallel-connected pairs in series. Figure 6 presents the complete specifications of a battery module.

***Orca Energy* battery module specifications**	
Chemistry	lithium ion NMC / graphite
Energy	5.65 kWh
Capacity	128 Ah
Dimensions	420 x 163 x 590 mm
Weight	60 kg
Maximum Voltage	50 VDC

Figure 6 - Battery module specification

The BESS has an overall configuration of 80 cells in parallel and 240 parallel-connected pairs in series with a total energy of 4520 kWh and a capacity of 5120 Ah. The voltage varies between 720 and 1000 VDC.

Connection of the gensets to the propulsion system, auxiliary loads and the BESS is done using a three-phase bus bar, that represents the electrical grid.

The primary objective of this study is to dynamically simulate the behavior of a ship's propulsion system. The input command for the ship corresponds to the designated route requested by the captain or chief engineer. This signal is relayed to the navigation system, which subsequently guides the ship through various operational phases.

The designated route for the ship, involves traversing from the departure port to a destination port. Throughout this voyage the weather conditions are variable and are translated into additional hull resistances.

The dynamic behavior of the ship is intricately linked to the evolution of its speed and acceleration as it navigates through different sea conditions. The ship's control system generates commands to adjust propulsion mechanism to ensure that the ship follows the intended route accurately. In the simulation model, these commands represent adjustments in electric motors power, consequently modifying the propellers thrust.

The functional parameters of the ship Le Commandant Charcot were recorded along a route from the south of South America, Figure 7.

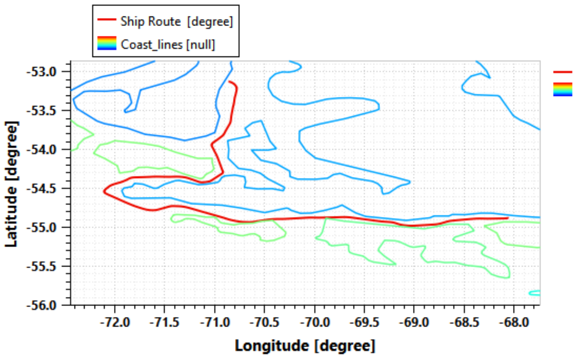


Figure 7 - Le Commandant Charcot route

Figure 8 presents the estimated total fuel consumption along the selected route under varying weather conditions (categorized as good, medium, and bad). These conditions are characterized by differences in wind speed and direction, wave height, period and direction, current speed and direction.

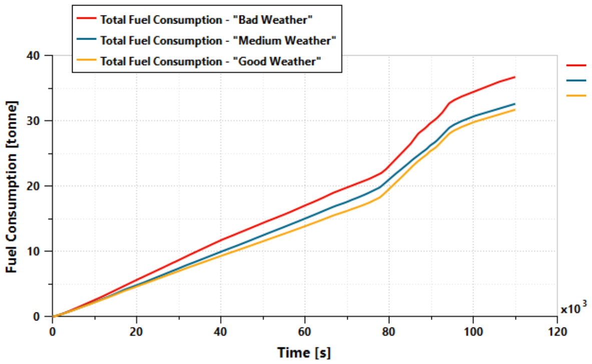


Figure 8 - Total fuel consumption in function of weather conditions

CO_2 emissions are directly related to fuel consumption and are calculated using a conversion factor (CF) that accounts for the carbon content of the fuel. In this simulation, Marine Diesel Oil (MDO) is the fuel used, with a conversion factor of 3.206, as reported by [22]. The CO_2 emissions are determined using equation (1), where E_{CO2} denotes the rate of CO_2 emissions in g_{CO2}/kWh, and SFOC represents the specific fuel oil consumption in g_{Fuel}/kWh.

$$E_{CO2} = SFOC \cdot CF \qquad (1)$$

Using this simulation approach, various weather conditions can be tested based on a predefined representative mission profile. Once a weather profile is established, operational adjustments can be simulated, enabling the ship to optimize its performance and operate at maximum efficiency.

3. VALIDATION MODEL ANALYSIS

The results obtained through simulation are compared with the measured ones from Ascenz Marorka platform. Both results are obtained from the same simulation and navigation conditions.

The input variable for the simulation is the ship's velocity during a selected voyage. The speed, shown in Figure 9, is incorporated into the simulation using GPS coordinates, each point being recorded at a 15-minute interval, as provided by Marorka.

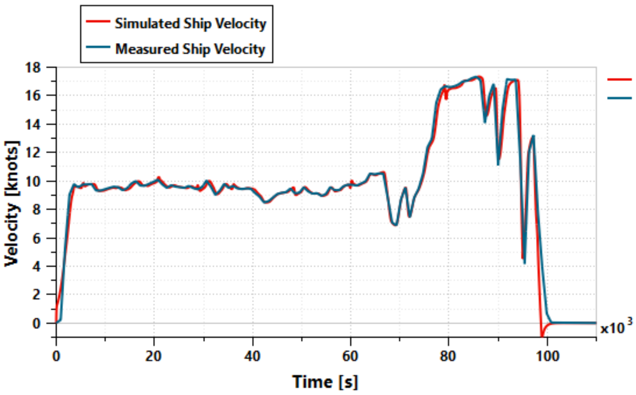


Figure 9 - Imposed and simulated ship speed profile

During the movement of the ship on the mentioned route, the propulsion power necessary to achieve the required travel speed was recorded. In Figure 10, a comparison between both simulated and measured propulsion power is shown.

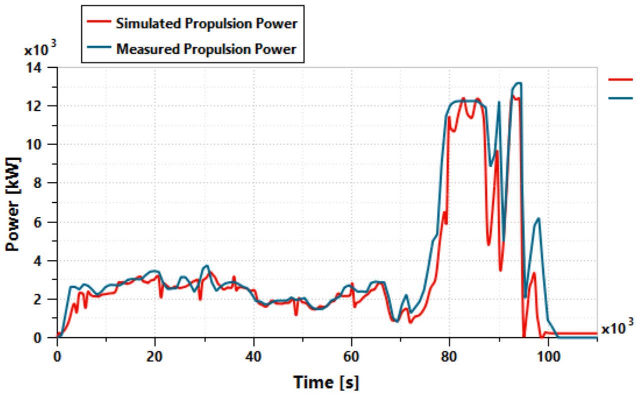


Figure 10 - Simulated and measured propulsion power

The propulsion power profiles are closely aligned during steady-state phases of the ship's operation. However, during transient phases, discrepancies increase due to factors such as the complex nature of the ship's dynamics and the input model used for speed the speed profile. Because the speed is inputted into the simulation as a function of latitude and longitude coordinates at an interval of 15 minutes, when the interpolation is done, and the speed is transformed in a function of time for the simulation process a lag can occur in the dynamic phases of the ship.

Despite these limitations, the curves remain sufficiently similar, to provide a meaningful representation of the electrical power consumption, and the optimization results can still offer valuable insights for the crew on board.

4. FUEL CONSUMPTION SCENARIOS

The PEMS (Power Energy Management System), composed of the Battery and Gensets Management System, has different settings that can be modified for a trip consisting in parameters such as:

- Genset Starting Sequence
- Genset Start/Stop Limit
- Peak Shaving Mode Activation
- Battery Operating SOC interval
- Peak Shaving/Charging Start Limit

Based on these settings, various scenarios can be defined to forecast the fuel consumption and identify the optimal settings for the PEMS. In this study, three specific scenarios were established and are presented below.

For the first scenario a genset starting sequence was defined by alternating between 5.5MW and 7.7MW Gensets, starting with the 5.5MW one. Peak Shaving mode was not active in this case, using only diesel generators to supply the demanded electrical power. This scenario represents the actual operating mode that was used for the particular trip, according to data collected by Marorka.

In the second scenario, the genset settings remained unchanged, but the peak shaving mode was activated. In this mode, the battery started to supply electrical power when gensets reached their upper threshold at 90% load, aiming to delay or even prevent starting an additional genset. When the power demand reached the lower threshold, at 40% load of the active gensets, the system charged the batteries to maintain the current number of operating gensets. This strategy helps keeping the diesel generators at optimal running load and prolong their lifespan which experience the highest wear due to friction in the start-up phase. The BESS operated in a state of charge range between 17 and 90%.

The Peak Shaving mechanism can be observed by analyzing the variation in power demand requested from the diesel generators. This comparison is illustrated in Figure 11, where also the battery power is shown.

When the battery power is negative, it indicates discharge, thereby supplying electrical energy to the grid. Conversely, when it is positive the battery is charging. It is visible that the battery does not have enough energy to avoid starting another genset, but it delays it. After the peak power demand is finished, the second genset remains operational allowing the BESS to charge when gensets are runnning under low load.

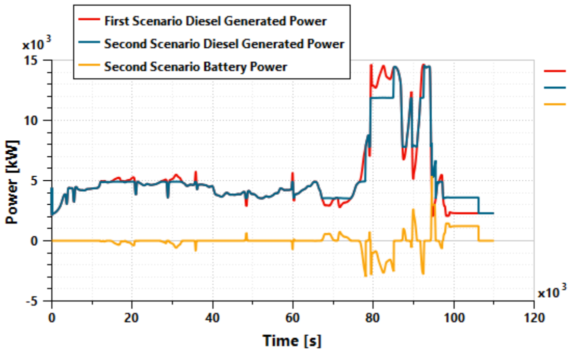


Figure 11 - Diesel Generated Power comparison

Figure 12 depicts the SOC evolution throughout the simulation, showing that it cannot surpass the SOC interval imposed at the start of the simulation.

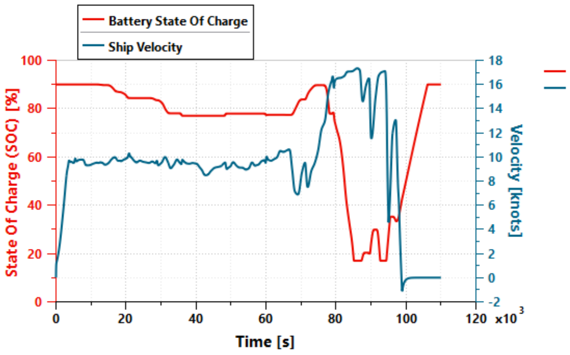


Figure 12 - SOC evolution compared to ship velocity

Using these operational settings a total of 1.3 tonnes which equivalates to 3.5% fuel saving was obtained, evolution of the fuel consumption being represented in Figure 13.

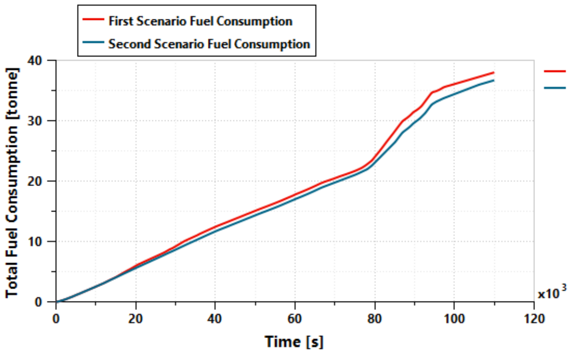


Figure 13 - Comparison of fuel consumed in first and second scenario

For the third scenario the same battery settings as in the second scenario were used, but with a different statechart. The changes made in this scenario targeted the genset settings such as the starting sequence. Starting first a 7.7 MW genset and then two 5.5 MW gensets allowed the Diesel engines to run at an optimal load, at around 65%. This lowers the fuel consumption and consequently the CO2 Emissions. In this case the battery was not used in the first part of the trip because of the higher power threshold of the different genset.

The total amount of fuel saved in this trip is 3.98 tonnes, which represents a 10.9% improvement.

An overview of the previously presented scenarios, the total fuel consumed is presented in Figure 14. The highest fuel consumption occurs in first scenario while the lowest is in the third. The difference between the two cases is 5.28 tonnes, equivalent to 14% fuel saved.

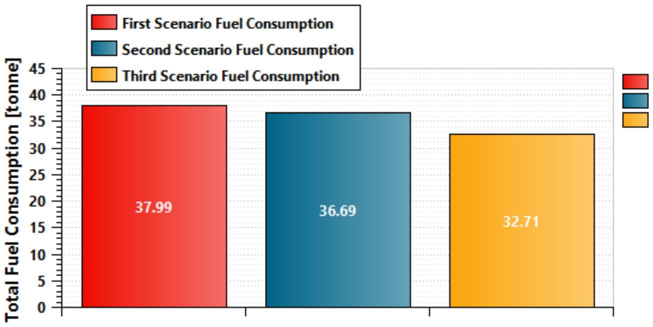


Figure 14 - Overview of fuel consumed on the simulated scenarios

Further simulations can be conducted to analyze how battery charging influences overall fuel consumption. This can be achieved either defining and testing different battery charging strategies using diesel generators when ship is working at steady loads or even when stationary, or from shore power, where such infrastructure is available.

5. CONCLUSIONS

This paper evaluates ship fuel consumption by analyzing a designated sea route and predetermined speed profiles. The proposed model is validated with real data and allows modifications of weather conditions against the ship performance.

In addition, after assessing the impact of weather conditions, the digital model enhance the exploration of different operational settings, enabling further experimentation to reduce fuel consumption for a selected route.

These findings assess how increasing cruising speed impacts fuel consumption and how sea conditions affect fuel usage and CO2 levels. By leveraging this data, it becomes feasible to optimize ship designs to minimize exploitation costs and polution while maintaining a specified cruising speed.

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