CIMAC CONGRESS 25
ZURICH, MAY 19 – 23, 2025

2025 | 284

Use Case: Layout and Control Optimization of a Hybrid Ship Power System in the Early Design Stage

System Integration & Hybridization

Oliver Klein, Hamburg University of Technology

Vincent Jarschel, TU Braunschweig
Peter Eilts, TU Braunschweig
Friedrich Wirz, Hamburg University of Technology

This paper has been presented and published at the 31st CIMAC World Congress 2025 in Zürich, Switzerland. The CIMAC Congress is held every three years, each time in a different member country. The Congress program centres around the presentation of Technical Papers on engine research and development, application engineering on the original equipment side and engine operation and maintenance on the end-user side. The themes of the 2025 event included Digitalization & Connectivity for different applications, System Integration & Hybridization, Electrification & Fuel Cells Development, Emission Reduction Technologies, Conventional and New Fuels, Dual Fuel Engines, Lubricants, Product Development of Gas and Diesel Engines, Components & Tribology, Turbochargers, Controls & Automation, Engine Thermondynamis, Simulation Technologies as well as Basic Research & Advanced Engineering. The copyright of this paper is with CIMAC. For further information please visit https://www.cimac.com.

ABSTRACT

With the trend in shipping industry to switch primary fuels to renewable low flash-point alternatives, the abilities of internal combustion engines of handling transient loads are reduced. This has a major impact on maneuverability of ships and is therefore crucial for regulatory, contractual and safety aspects. Hybridization of the power systems including energy storage and shaft alternators can compensate for disadvantages by providing additional degrees of freedom, making stable control of the power system essential. The decision for an appropriate power system and its control system needs to be made in early design stage to avoid increased project costs for late changes. Thus, fast and accurate simulations based on limited project data are required. The simulation tool HyProS depicts a software solution to estimate the performance of shipboard power systems for such use cases. Part of it is a generic mean-value model of medium- and high-speed engines, which is parameterized with e.g., project guide data. The focus of this work is on optimizing control strategies for a typical use case with respect to different objectives using HyProS. The power plant architecture envelopes hybrid power supply and hybrid propulsion. The influence of different control settings for major components on the system behavior is worked out and considered for designing the controllers for the objectives of high dynamic performance and overall efficiency. The results are highlighting two things: the capabilities of system hybridization for optimizing vessel operation for different objectives and the benefits of fast simulations in early project phases. The generic engine model allows for a fast simulation setup and provides an advanced understanding of engine limits and their influence on maneuverability compared with models with lower fidelity.

1 INTRODUCTION

Shipping industry pursues increasingly strict regulatory requirements to reduce its environmental impact. This includes the emission reduction of greenhouse gases and pollutants. Consequently, ship operators are switching primary fuels to renewable low flash-point alternatives. This leads to a reduced ability of internal combustion engines of handling transient loads and thus has a major impact on manoeuvrability of ships. Therefore, it is crucial for regulatory, contractual and safety aspects. Hybridization of the power system can compensate for disadvantages by providing additional degrees of freedom. The decision for an appropriate power system and its control system needs to be made in an early design stage to avoid increased project costs for late changes. Thus, fast and accurate simulations based on limited project data are required. The simulation tool HyProS (Hybrid Propulsion Simulation) depicts a software solution to estimate the performance of shipboard power systems for such use cases.

1.1 Hybrid Propulsion Simulation

The tool HyProS was developed by the department of marine engineering of Hamburg University of Technology, as part of the research project '*Gas Engine Performance'*. The project has been funded by the FVV e.V. HyProS is a co-simulation environment, combining three standalone simulation software solutions. MATLAB Simulink is used as central simulation tool. A set of generic blocks is available for simulations of hybrid power systems on ships. These include the co-simulation handling and data transfer, mechanic- and electric machinery and control functionalities. All blocks are pre-built solutions, which need to be parametrized by the user. Necessary data are typically publicly available. The HyProS-library is designed to enable users to substitute generic models by their own blocks, thus integrate and analyze specialized or proprietary modules [1].

Second part is the ship design data base E4, which is developed and supported by the Institute of Ship Design and Ship Safety of Hamburg University of Technology. It includes methods to calculate ships' behaviour and manoeuvrability in early design stage, when only limited data and design accuracy are available [2]. One strength of E4 is the calculation of sway and yaw motion in addition to surge, which enables fast simulation of full manoeuvres in all relevant degrees of freedom. This approach gives deeper insights into the behaviour of the ship and outperforms simple speed-power curve-based calculations. The HyProS-library and the E4-database are connected via a co-simulation server, which handles the data transfer during initialization and for each simulation step.

The third tool is GT POWER by Gamma Technologies, which is introduced later. The default step width for data exchange between all software solutions is Δt = 0.1 s.

1.2 Control Strategies

There are several optimization approaches for ship power systems from manual definition of power setpoints to sophisticated optimization algorithms. Classification into regular strategies, with rule-based (RB) and fuzzy-control and optimized strategies with real-time and global optimum control are usual [3], [4].

For rule-based control, different strategies can be selected based on predefined rules, e.g. load levelling and peak-shaving, which are described in literature [3], [5]. The main advantage is a simple definition and implementation of the control rules and that the system designer can check all possible configurations for accordance with regulatory and safety requirements in advance. Nevertheless, the plant will be operated optimally only within small operational limits and the quality highly depends on the knowledge and experience of the system designer. In this work fuzzy control will not be considered, since its quality depends strongly on engineers' knowledge, although its straight and easy implementation should be mentioned [6].

Real-time optimization needs fast solutions of an optimization problem. Roslan et. al. reviewed different optimization strategies and concluded, that equivalent consumption minimization strategies (ECMS) are leading to the highest system efficiency. It was neglected, that ECMS only suits to hybrid power supply systems including batteries. Multiple optimization algorithms were compared as well [4]. Algorithms which are applicable for real-time applications typically not guarantee the global optimum [4].

Therefore, global optimization strategies are necessary, which can lead to optimal solutions, but also to very high calculation times [3]. In fact, their application is limited to offline investigations on system performance and as reference and quality measure for above stated strategies. Investigations of Geertsma et. al. have shown the qualitative difference between RB-control and the global optimum for a given use case. Last leads to fuel savings of up to 17.4 %, compared to RB-strategies [7].

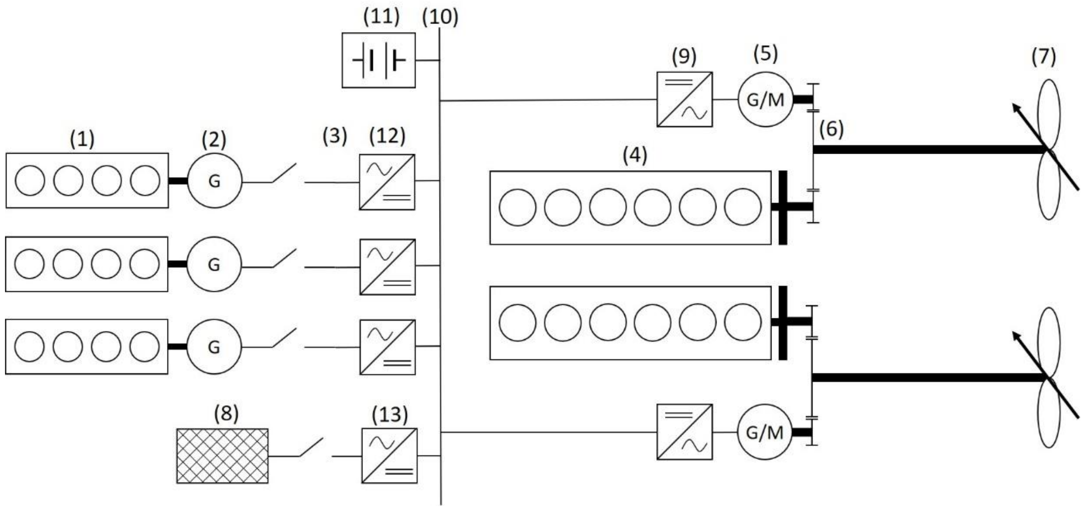

Figure 1. Hybrid ship power system of a typical RoRo-vessel, investigated in this work. The System includes a twin-shaft configuration with controllable pitch propellers (7), two main engines (4) and three GenSets (1 and 2).

1.3 Engine Model

One aim of the current project '*Hybrid Powertrains for Alternative Fuels'* is to specify the influence of engine operation on the manoeuvring behaviour of the ship. In particular, the difference between steady-state and transient operation is to be mapped. Engine load and speed are primarily determined by the fuel injection quantity and the propeller torque. A transition to a new operating point can occur within seconds. However, a change in the turbocharger speed is induced by the altered enthalpy flow in the exhaust gas. Notably, the inertia of the turbocharger's rotating assembly and the heat transfer in the exhaust piping are the limiting factors in transient operation and have a significant impact on the dynamic behaviour of the engine. The existing internal combustion engines of the HyProS-library are modelled with stationary limitation, based on engine performance maps, and dynamic limitation according to ramp-up limits, so that an adaptation to higher order models is necessary [1].

During system design it is important to analyze the behaviour of the power plant, in order to evaluate, if the interaction between all components is as desired, and if all regulatory and contractual requirements are fulfilled. Therefore, the software solution HyProS is extended to mean value engine models (MVEM). To depict the functionality scope, two simulations are carried out. One crash stop manoeuvre, since this is the highest dynamic performance requirement expected during ships' lifecycle, and an efficiency optimized one. In the following, the use-case vessel model of a RoRo-type ship is introduced as well as the mean value engine model. Afterwards, the energy management system is designed and both simulations are carried out. Finally, the introduced extensions of HyProS are discussed and topics for future works are proposed.

2 HYBRID PROPULSION SIMULATION

The modulation within HyProS is briefly described in following section.

2.1 Hybrid RoRo-Type Ship

The power plant of the RoRo vessel is depicted in figure 1. The twin shaft propulsion system envelopes two medium speed main engines (4), each acting on a gear (6) to reduce the speed level. Additionally, the gears enable the integration of shaft alternators (5) for power-take-out (PTO) and power-take-in (PTI), as well as power-take-home (PTH) option. The propulsors are controllable pitch propellers (CPP) (7). On the electric side, three generator sets (GenSet) (1 and 2) of variable speed type are supplying a direct current (DC) bus (10) through inverters (12). Electric consumers are fed through an inverter (13) as well as the shaft alternators. Additionally, a battery (11) is integrated to hybridize the power supply in order to increase operational flexibility.

2.2 System Model

The shaft line and the gears are modelled together, considering different speed levels and rotational inertia. The actual propeller speed n_{prop} is calculated by integration of the derivative of angular speed ω. The gears and all other rotational components are assumed to be stiff, thus torsional deformation is not considered in this work. The internal combustion engines will be described in following chapter 3. The CPP operation is simulated on a combinator curve or at constant speed. A selection can be made by the user. The electric power plant is based on a DC-Grid. All

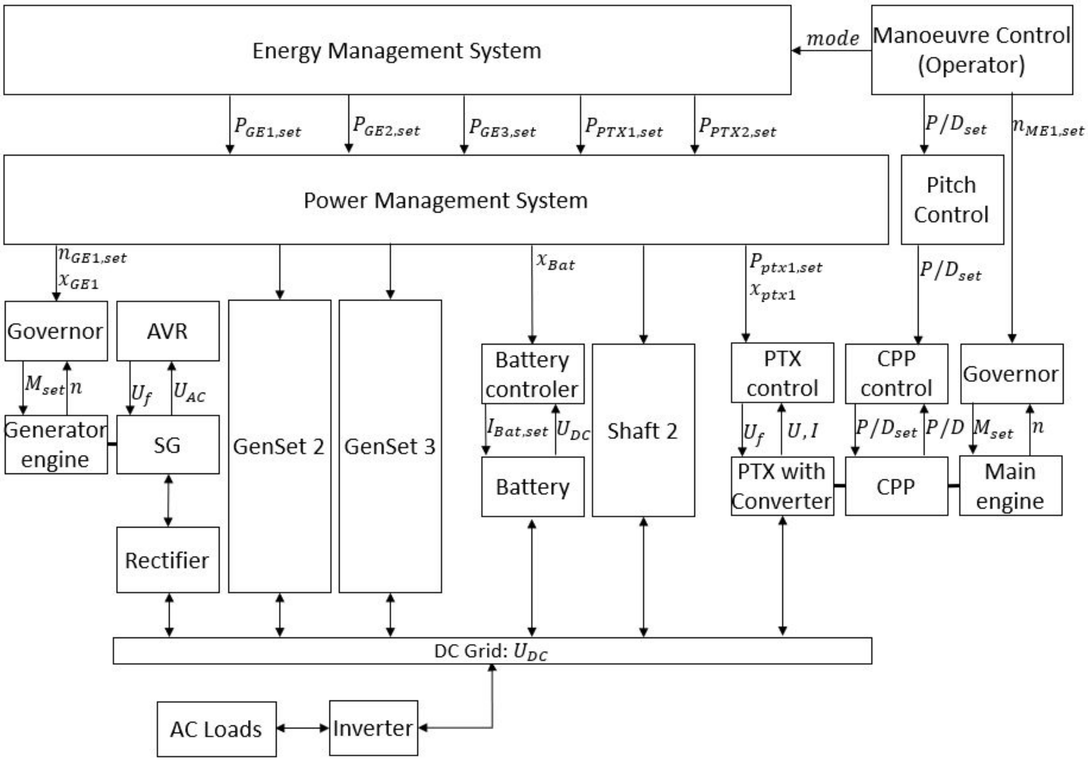

Figure 2. Control hierarchy of the power system of the RoRo-vessel, investigated in this work.

electric components are modelled with the Simscape Specialized Power Systems library. Further details can be found in the related documentation [8].

2.3 Power Management and Control

To guarantee that all necessary operational limits are not exceeded, a power management system (PMS) is implemented into HyProS. At this point, no detailed explanations are carried out, since it is not in the focus of this work. The control and automation components are modelled in a hierarchical structure of three layers, which is shown in figure 2. On primary control level, component-bound controllers are depicted, e.g. the governor and automatic voltage controllers (AVR) of the GenSets. The secondary control involves the power management and the tertiary level the energy management. Last is introduced in chapter 4. The user or operator is not directly part of the hierarchy, but considered in figure 2 within the block Manoeuvre Control. Additionally, figure 2 includes relevant setpoints states for the energy management system.

3 ENGINE MODELING

The tool HyProS is extended by engine models of higher fidelity. As third simulation part, GT-POWER by Gamma Technologies is used to build up and validate the mean value engine model.

3.1 GT-POWER and Full Engine Model

The full engine simulation is conducted using the software GT-POWER by Gamma Technologies. GT-POWER enables the modeling of the combustion engine, including the air path and turbocharging, as a 0D/1D simulation. The air path piping can be discretized into segments of a specific length. The state and process variables in the cylinder are calculated using a zero-dimensional approach. The gas exchange process is implemented using the filling-and-emptying method. Heat input from combustion is considered by the Vibe function [9]. The variation of the Vibe parameters is based on the approach of Woschni and Anisits [10]. Heat losses to the cylinder walls are calculated using a model adapted by GT, based on Woschni's original formulation [11].

The engine model consists of the cylinders, each with two intake and two exhaust valves, their respective ducts and the crank mechanism. Additionally, the model includes intake and exhaust manifolds, a charge air cooler and a turbocharger. To avoid surging of the compressor at low speeds, an engine bypass is installed, which is opened during part-load operation in propeller or combinator mode. Through this valve uncooled charge air is directed into the exhaust upstream of the turbine.

3.2 Mean Value Model

In order to reduce the computational effort of the engine models and increase the simulation speed, the engine is implemented as a mean value model. Specifically, the working process is no longer resolved over the crank angle. Instead, a cycle-averaged approach is employed. The calculations are simplified to the airflow rate and the distribution of the fuel energy. Furthermore, gas-dynamic effects in the piping are omitted by averaging the values over the engine cycle. This ensures the real-time capability of the model while maintaining high result accuracy.

In the mean value model, the engine's target variables - indicated mean effective pressure *IMEP*, exhaust gas temperature, volumetric efficiency λ_A, and trapping ratio - are predicted based on a large set of data points obtained through Design of Experiments (DOE) using the full engine model. For this purpose, key parameters influencing engine behaviour are systematically varied. These parameters include the pressures upstream and downstream of the cylinder, intake air charge temperature, fuel injection quantity and timing as well as engine temperature. The variation of parameters in the DOE is carried out using Latin Hypercube Sampling. This method randomly selects parameter values within predefined boundaries for each individual experiment. The resulting dataset is particularly well suited for training neural networks. To ensure accurate predictions across the entire operating range of the engine in the mean value model, the DOE parameters are extended beyond the operating boundaries. Simultaneously, it is essential to align certain parameters within specific ranges to ensure that all operating points represent a meaningful operational domain. For instance, instead of directly specifying the fuel injection quantity, the air-fuel equivalence ratio in the cylinder can be prescribed or the pressures can be adjusted in relation to one another.

The mean value cylinder represents the target variables based on the predictions of the neural networks. These variables allow the characterization of the engine's behaviour as a function of its current operating point. While the exhaust gas temperature quantifies the enthalpy contained in the exhaust gas, the *IMEP* is a measure of the conversion of fuel energy into mechanical work. Given the known friction mean effective pressure *FMEP*, the engine power of a four-stroke engine can be calculated as a function of the *IMEP*:

$$P = (IMEP - FMEP) \cdot V_H \cdot n \cdot 0.5 \qquad (3.1)$$

Here, V_H represents the engine's displacement volume, and n denotes the engine speed. From the volumetric efficiency, the corresponding air mass flow rate can be determined as:

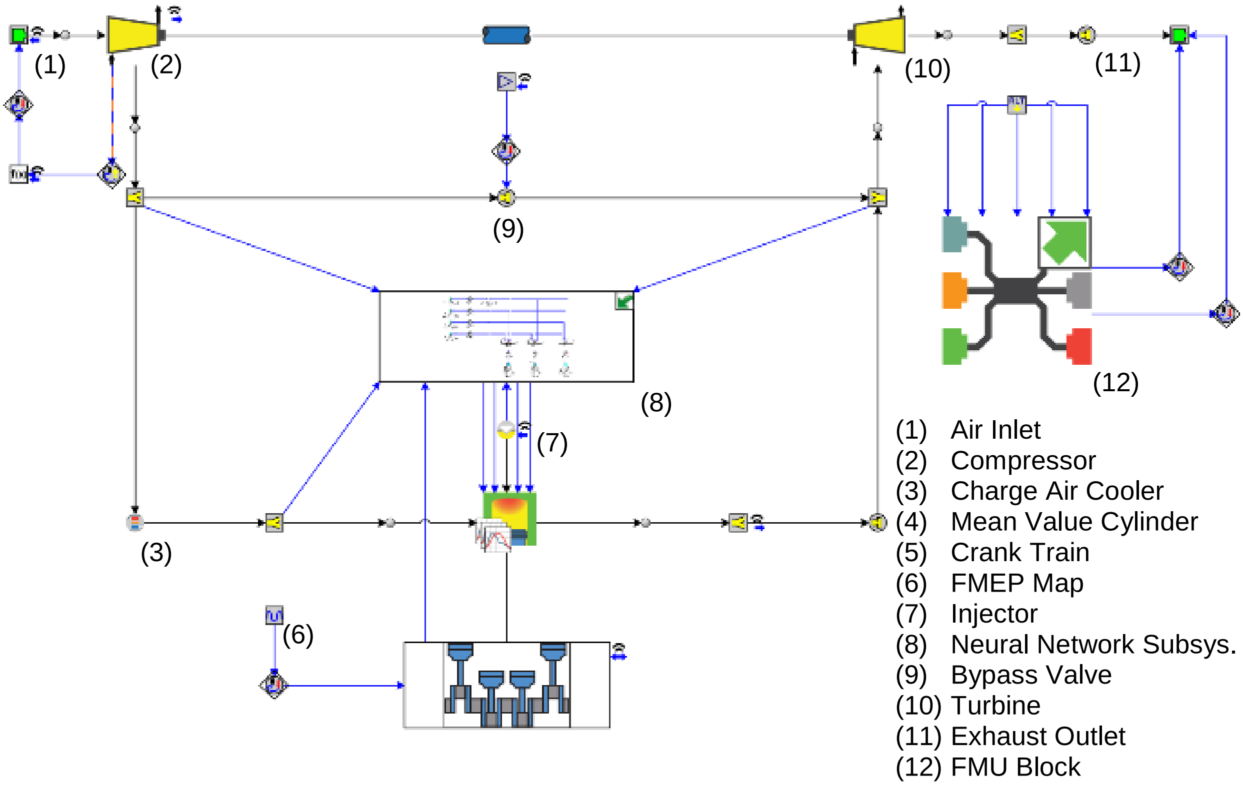

Figure 3. GT-POWER GUI: Mean Value Model containing Neural Network Subsystem and FMU Block

$$\dot{m} = \lambda_A \cdot \rho_{inlet} \cdot V_H \cdot n \cdot 0.5 \quad (3.2)$$

using the density ρ_{inlet} upstream of the cylinder.

Marine engine operation features positive scavenging gradients across a wide operating range. As a result, a certain fraction of the intake air directly flows into the exhaust during valve overlap and does not participate in combustion. Therefore, it is necessary to consider the trapping ratio. It describes the ratio of the air mass retained in the cylinder to the total air mass that passed through the intake valves during the intake process.

In the mean value model, shown in figure 3, the piping systems are further simplified and represented as containers, rather than being divided into discrete segments. Furthermore, air pulsation within the system is no longer modeled. This simplification affects the pressure and enthalpy losses within the piping as well as the behaviour of the turbocharger. For engines with constant pressure charging, the deviations are small. However, to account for all effects, the model requires calibration based on a known operating point.

3.3 Integration in HyProS

The integration of the mean value engine model into HyProS is accomplished via a standardized interface called Functional Mockup Unit (FMU). GT-POWER provides a predefined block for this purpose in which the signals, exchanged between HyProS and GT-POWER, are specified. For instance, the torque generated by the engine is transmitted to HyProS, where the speed calculation is performed. The resulting speed is then passed back to GT-POWER and applied to the cranktrain. The default step width for data exchange is $\Delta t = 0.1$ s as well. Beyond signal exchange, the FMU in GT-POWER allows the selection of parameters that can be defined in Simulink and transferred to GT-POWER during initialization. Given the project's goal of enabling the engine model to simulate engines of varying sizes, this functionality is of critical importance. These parameters include the geometric data of the engine, turbocharger and containers as well as their initial wall temperatures. The initial wall temperatures are calculated manually based on user input prior to running the simulation.

4 ENERGY MANAGEMENT SYSTEM

Part of this work is the introduction of an energy management system (EMS) for the considered vessel. Core of this EMS is an optimization algorithm which calculates the optimal reference power setpoint for each degree of freedom (DoF) of the plant. The available degrees of freedom are the operation points of each main engine, the shaft alternators and the GenSets, as well as the Battery. The reference operation points are then transferred via the PMS to the controllers on component level according to figure 2. The optimization algorithm is continuously estimating the fuel consumption of all prime movers and is minimising the total fuel consumption $\dot{m}_f$.

$$\dot{m}_f = \sum_{i=1}^{2} \dot{m}_{f,ME,i} + \sum_{j=1}^{3} \dot{m}_{f,GE,j} + \dot{m}_{f,eq,BAT} \quad (4.1)$$

$\dot{m}_{f,ME}$ is the estimated fuel mass flow of the main engines and $\dot{m}_{f,GE}$ the one of the generator engines. Since no fuel mass flow can be directly assigned to battery usage, an equivalent fuel consumption is used to consider the fuel demand for recharging. It is calculated from equation 4.2 with the actual battery power P_{BAT}, an equivalent consumption $b_{e,eq}$ and a penalty factor μ.

$$\dot{m}_{f,eq,BAT} = P_{BAT} \cdot b_{e,eq} \cdot \mu \quad (4.2)$$

The equivalent consumption is selected to be $b_{e,eq} = 215\ \frac{\text{g}}{\text{kWh}}$, considering the fuel consumption map of the GenSets. The value leads to operational areas, in which a usage of the GenSets will be cheaper and others, where it is virtually more expensive than Battery usage. The penalty factor μ is calculated with the piecewise-defined equation 4.3.

$$\mu = \begin{cases} 1 - \left(\frac{SOC - 0.3}{0.2}\right)^3, & SOC < 0.3 \\ 1, & 0.3 \leq SOC \leq 0.7 \\ 1 - \left(\frac{SOC - 0.7}{0.2}\right)^3, & SOC > 0.7 \end{cases} \quad (4.3)$$

In the area of $0.3 \leq SOC \leq 0.7$, the penalty factor does not influence equation 4.2. But when becoming deeply drained, μ increases and thus the equivalent fuel consumption of the battery. High states of charge are leading to increased usage of battery respectively. Three energy-balances are formulated as constraints to the optimization with one for each shaft and one for the electric power system. The shaft power balance is redundant for port and starboard and depicted with equation 4.4. It ensures the power balance at the propeller hub by considering relevant efficiencies between each component and the hub.

$$P_{prop} = \eta_{shaft} \cdot (P_{ME} \cdot \eta_{gear} + P_{PTX} \cdot \eta_{gear} \cdot \eta_{PTX}) \quad (4.4)$$

To keep the calculation effort within limits, it is assumed that the efficiencies η_{gear} and η_{shaft} are constant. Nevertheless, this does not affect the accuracy of the power system simulation, since it is only relevant for the EMS. The energy balance for the electric grid is given with equation 4.5 and ensures the power balance in the DC-Bus.

$$\frac{P_{cons}}{\eta_{inv}} + \frac{\Sigma P_{PTX}}{\eta_{con}} = \sum_i P_{GE,i} \cdot \eta_{GE,i} \cdot \eta_{rec} + P_{BAT} \quad (4.5)$$

On producer side, each GenSet power and respective efficiencies of the synchronous generator η_{GE} and the rectifier η_{rec} are considered. The power demand of the electric consumers P_{con} are defined to be positive and the electric power demand of the shaft alternator is defined to be positive in motor operation. Last, the batterie's efficiency is assumed to be constant with a selected roundtrip efficiency of $\eta_{BAT,rt}$ = 0.85. The signs of P_{PTX} and P_{BAT} need to considered, since power flows in both directions are allowed. Beyond the three constraints stated above, additional constraints for each component are necessary to limit minimal and maximal available power in the next optimization time-step *t+1*. The procedure is depicted in equation 4.6 for the minimal main engine power $P_{ME,t+1,min}$, but adopts for all degrees of freedom.

$$P_{ME,t+1,min} = \max(P_{ME,t} - \frac{dP_{ME,min}}{\Delta t_{opt}}, 0) \quad (4.6)$$

$dP_{ME,min}$ is the maximal negative slope of load ramps for each engine according to manufacturer's data. This assumption neglects relevant dynamic characteristics of internal combustion engines, e.g. detailed turbocharger dynamics. Again, this only influences the optimization result and not the accuracy of the power system simulation, but yields much faster calculations than higher sophisticated approaches.

To solve the optimization problem, the MATLAB-Optimization toolbox is used and integrated into HyProS [12]. The interior-point algorithm is selected as optimization algorithm and above stated constraints and boundary conditions are formulated. A vector with starting values x_0 is necessary for each optimization step. It is assumed, that the result will be found close to the previous result, if the procedure is carried out within a small interval. Therefore, the optimization is carried out in intervals of Δt_{opt} = 10 s. This value depicts a trade-off between fast calculations and considerations for x_0 as stated above.

5 SIMULATION RESULTS

5.1 Simulation Setup

Two simulations are carried out. One transient and one efficiency-optimized. First, a crash stop manoeuvre is carried out and the advance *x* is used as measure to check for accordance with IMO-requirements, according to equation 5.1 [13].

$$x(v = 0) < 15 \cdot L_{pp} = 2996 \text{ m} \quad (5.1)$$

The resulting dynamic behaviour of the power system is shown by plotting relevant data over time. Second, a notional operation profile of the RoRo-vessel is simulated with the introduced energy management system. The profile envelopes four operation points (OP) and is summarized in table 1. The command lever setpoint ranges from -10 to 10

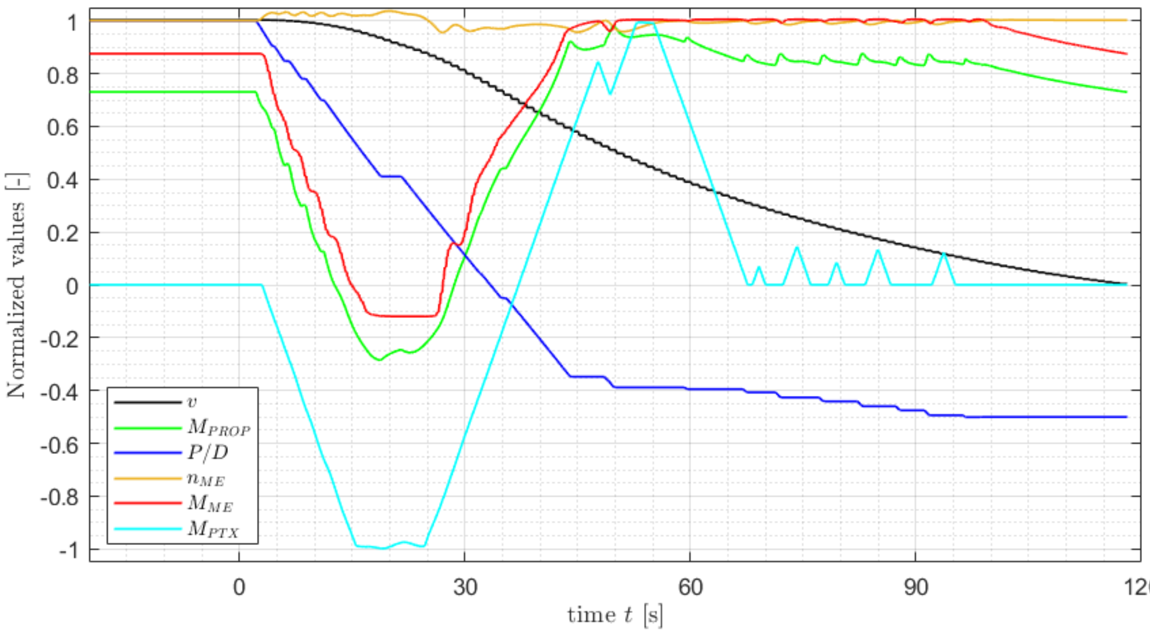

Figure 4. Power train data for crash stop manoeuvre. At *t* = 0 s the command lever is set to full astern.

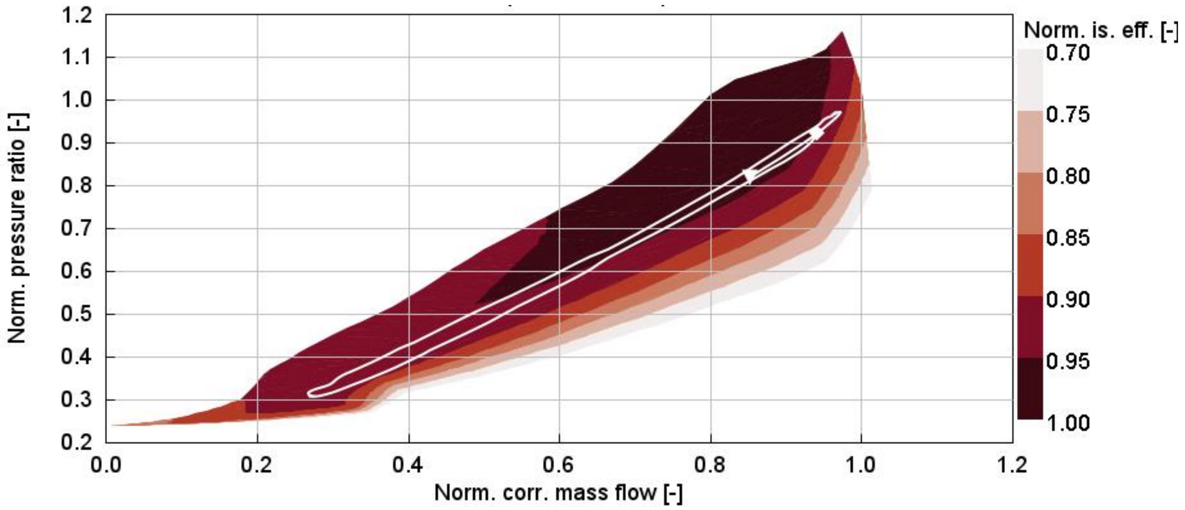

Figure 5. Operation point of the compressor during the crash stop manoeuvre.

and is used to interpolate the setpoints for the shaft speed and the propeller pitch in the combinator curve. Relevant data is plotted as well. For simplicity, the results are presented for only one shaft line. Since both manoeuvres are simulated without changes in heading, a symmetric behaviour can be assumed.

5.2 Crash Stop Manoeuvre

Figure 4 shows the crash stop manoeuvre behaviour for the RoRo-vessel in HyProS. At $t = 0$ s the command for full astern is given. The figure displays the manoeuvre until the vessel speed (black) is decreased to $v = 0$ kn. Since the shaft speed setpoint is $n_{set} = 1$ for full astern and full ahead, only the propeller pitch (blue) is adjusted. The steps result from the action of the pitch control, in order to avoid overspeed and overload operation. The normalized engine speed (yellow) depicts the shaft line and shaft alternator speed as well, since they are coupled through the gear box. Engine (red) and propeller torque (green) are shown additionally.

Between $t = 12$ s and $t = 28$ s the propeller torque is negative, thus windmilling occurs. Here, the engine torque is negative as well, which is a result of the friction. After $t = 25$ s the engine torque rises to its nominal value. The propeller torque behaves similar, but does not reach a stationary level. Instead, a sequence of ripples, which overlay with the propeller pitch steps, occurs. The difference between the engine torque and the propeller torque rises, as the shaft alternators' load is reduced. After about $t = 95$ s the propeller torque and engine torque as well decreases until the simulation is stopped at $t = 118$ s, when the vessel speed reaches $v_{vessel} = 0$ kn. The advance x at $t = 115$ s is $x = 604$ m. The limit according to the IMO depends on the ship length between perpendiculars L_{pp} and is given for the use case vessel in equation 5.1 [13].

Since a mean value engine model is used, additional engine data are available for further studies of the simulated power plant. For example, the compressor map is depicted in figure 5. It shows the normalized pressure ratio over the normalized and corrected mass flow rate. The map includes the normalized efficiency, neglecting values below $\eta_{norm} = 0.7$. The compressor state at the beginning of the crash stop manoeuvre is highlighted by the white diamond. The path, which the compressor operation point follows during the manoeuvre, is shown as white line. The final operation point at the end of the simulation is highlighted by the white triangle. The operation point first moves in the direction of the origin, until the pressure ratio and the corrected mass flow rate raises again.

Table 1. Notional sequence of an operation profile for the RoRo-vessel with four operation points (OP)

OP	Start time	Command Lever	Apparent power electric grid
	[min]		[kVA]
1	0	8	408
2	5	6	921
3	10	6	1188
4	15	9	2968

5.3 Efficiency Simulation

The simulation results for the efficiency simulation is shown in figure 6. Relevant data for one shaft line and the electric grid is selected. For simplicity the second shaft line is not show. Additionally, the fuel consumption of each prime mover is given.

Starting with figure 6a, the biggest changes occur at $t = 5$ min and $t = 15$ min, when the command lever is changed from *8* to *6* and *6* to *9* respectively. The influence of the energy management system can be seen in all operation points by focusing on the main engine torque (red), the propeller torque (green) and the shaft alternator torque (cyan). After short stabilizing phases, the main engine torque is at a constant level, although the propeller torque is still changing. This is only possible because of the support of the shaft alternator. Negative values depict PTO-modes and positive PTI-modes. The resulting impact on the electric grid can be seen in figure 6b, where the battery (blue) and the first GenSet (magenta) are necessary, to fulfill the energy balance.

Load sharing, based on the ECMS-strategy can be highlighted at about $t = 9$ min. The electric hotel load and the PTI-mode of the shaft alternator require energy from the grid. The battery is discharged at a low C-rate and no GenSet is running. The slope of P_{PTX} leads to increased energy demand. As soon as an efficient operation of GenSet 1 is possible, it starts and takes over the load. The fuel consumption of all prime movers is shown in figure 6c.

The result of $P_{GE,1}$ shows fast transients between $t = 11$ min and $t = 15$ min. The same behaviour occurs for the battery power P_{BAT} and the fuel consumption $\dot{m}_{GE,1}$.

5.4 Simulation Performance

A relevant measure for the practical usage of the tool HyProS, is the calculation time of each simulation. The duration for both simulations, including initialization and settling, is shown in table 2. Equation 5.2 shows the calculation of the

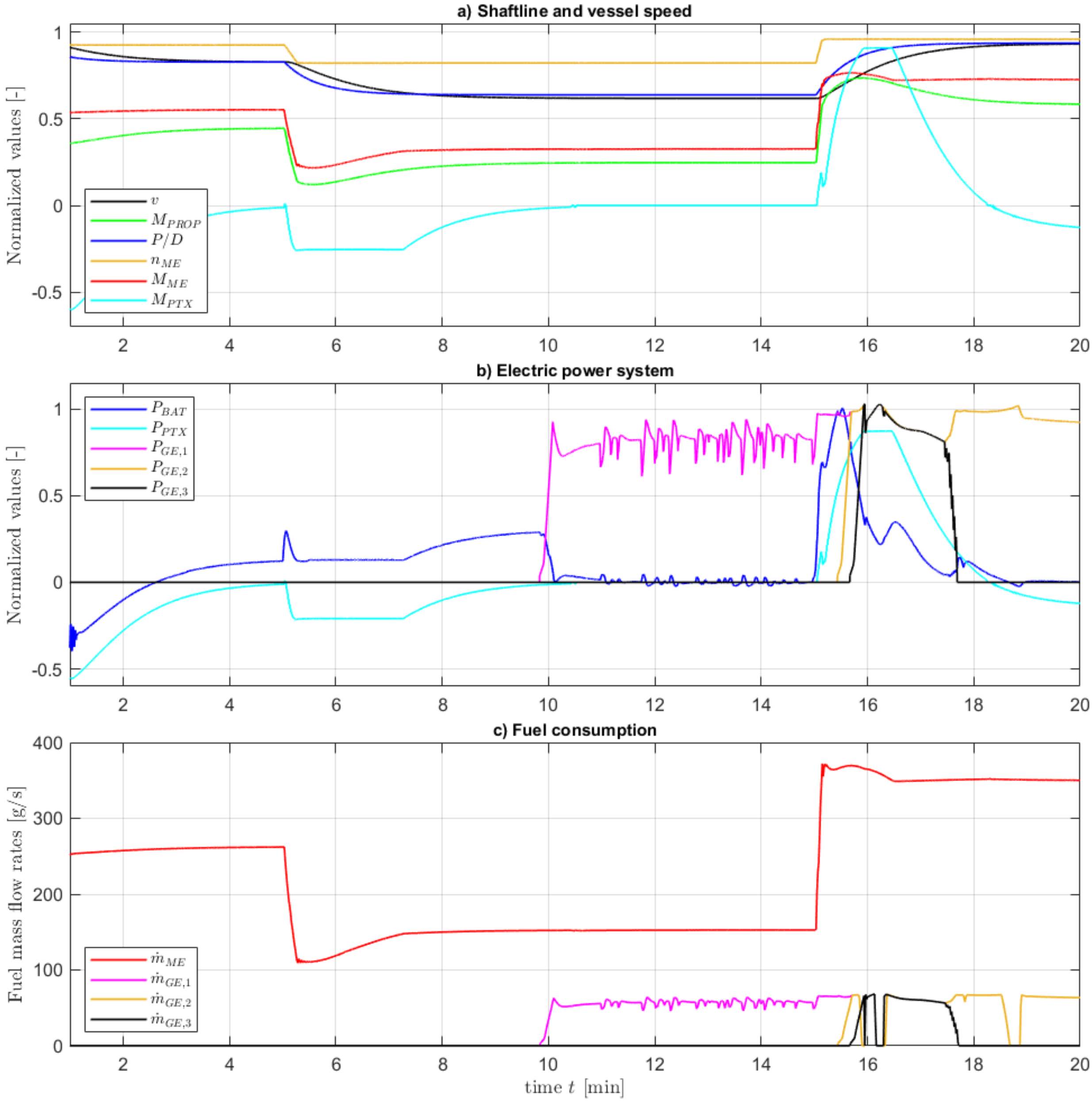

Figure 6. Results of the efficiency simulation for the operation points from table 2.

real-time factor *RTF* with the duration of the calculation t_{calc} and the simulation duration t_{sim}.

$$RTF = \frac{t_{sim}}{t_{calc}} \quad (5.2)$$

Table 2. Simulation performance for both manoeuvres with calculated real-time factor.

Simulation	Simulated time	Calculation time	Real-time factor
Unit	[s]	[s]	[-]
Crash stop	800	1859	0.43
Efficiency sim.	1200	2324	0.52

6 DISCUSSION

Two simulations were carried out to investigate the functionality of the hybrid ship power system simulation in an early design phase. On the one hand, the crash stop manoeuvre was simulated. Since this use case represents the highest dynamic requirements expected during ship operation, it is used as dynamic reference. On the other hand, the efficiency optimized use case for a notional operating profile is taken as efficiency reference, where the burden is not a high fidelity of engine models, but a sophisticated energy and power management, which needs to be considered in an early design stage already. Both manoeuvre simulations allow deep insights on the behaviour of the power plant for their specific use case.

The ability of the power plant to change operation points very fast is crucial during a crash stop manoeuvre. With the presented tool including the engine model, it is possible to zoom into relevant components and parts of the engine model, in order to investigate their behaviour. With only showing the resulting main engine torque, figure 4 depicts the results on a bigger scale. If the information is not sufficient for optimization of the plant, the presented mean value engine model allows to analyse the behaviour of relevant parts of the engine more detailed. This was shown for the operation point within the compressor map, for instance. The same procedure is available for other parts of the engine. Nevertheless, the simulation performance is still acceptable with $RTF = 0.43$.

The efficiency-optimized simulation shows the performance of the EMS in all four operation points. Starting with the first OP, the main engine is set to a higher load than required for propulsion, which leads to a lower specific fuel consumption. The excess energy is used to charge the battery. Although the optimization is carried out every t_{opt} = 10 s, the real time factor of RTF = 0.52 makes the tool suitable for fundamental decisions during early ship design. For the example use case in this work, this means, that the predefined power plant with the selected components is operable in an efficient way and a preliminary design of a suitable EMS is possible.

This information, together with the investigation opportunities of the MVEM, is necessary in an early design stage, in order to choose the best configuration and control strategy. Based on the simulation with HyProS, the power plant architecture can be further investigated with higher fidelity simulation models, next.

An abnormality in the result of $P_{GE,1}$ occurs, as shown in figure 6b. A reason for these fast transients might be an interaction between the controllers of the GenSet on the one hand and the battery controller on the other. An investigation of this effect will be part of future works.

7 OUTLOOK

In the following course of the project, the simulation tool will be continuously developed further, based on the status quo presented in this work. The focus is to be set on the control system and the engine models. The presented EMS already shows the potential of such analysis for the given use case. A deeper interaction between the control system and all relevant components might allow further optimization and efficiency improvements. Additionally, there are multiple other objectives beyond fuel consumption, e.g. emissions, the system could be designed for. Regarding the engine simulation, gas engines will also be modelled and implemented in addition to diesel engines. The corresponding operating limits will be considered in the engine control system. Furthermore, the control unit will be expanded. For example, the engine will receive an explicit signal when the emergency mode is activated or when operating in an Emission Control Area.

8 CONCLUSIONS

In this work, extensions to the simulation tool HyProS are introduced to increase its functionality scope to support system designers in early project phases. Therefore, a scalable mean value engine model is designed from a full engine model and integrated in the simulation environment. The model enables fast simulations of the dynamic behaviour, in order to check different configurations for requirement fulfilment. For instance, a crash stop manoeuvre is simulated for a RoRo-vessel and the behaviour of the power plant is depicted. Beyond the resulting engine torque, the mean value engine model allows a deep view into the behaviour of relevant components of the engine. This is shown for the turbocharger compressor. To increase the functionality of the simulation tool in respect to control system design and higher-level control functions, an energy management system is designed and evaluated for a notional operation profile, based on four operating points. The functionality of the EMS is highlighted for selected regions of the profile. For both simulations, the real time factors are in the range of $RTF = 0.5$. Combining the resulting real time factors, the fidelity of the results and the necessary data for the parametrization, the tool allows users to design and investigate the power plant architecture and interaction between different components prior to detailed design decisions.

9 DEFINITIONS, ACRONYMS, ABBREVIATIONS

9.1 Abbreviations

AVR	Automatic Voltage Controller
CPP	Controllable Pitch Propeller
DC	Direct current
DOE	Design of experiment
DoF	Degree of freedom
DYN	Dynamic mode
ECMS	Equivalent consumption minimization strategy
EMS	Energy Management System
FMU	Functional Mock-up Unit
GenSet	Generator Set
GUI	Graphical user interface
HyProS	Hybrid Propulsion Simulation
MVEM	Mean value engine model
OP	Operation point
PMS	Power management system
PTH	Power take home
PTI	Power take in
PTO	Power take out
RB	Rule-based
RoRo	Roll-on Roll-off vessel

9.2 Symbols

Symbol	Unit	Description
b_e	[g/kWh]	Specific fuel consumption
FMEP	[bar]	Friction mean effective pressure
IMEP	[bar]	Indicated mean effective pressure
J	[kg*m^2]	Rotational inertia
L_{pp}	[m]	Length between perpendiculars
$\dot{m}$	[kg/s]	Mass flow rate
n	[1/s]	Rotational speed
P	[W]	Power
SOC	[-]	State of charge
t	[s]	Time
Δt	[s]	Time step
v	[kn]	velocity
V_H	[m^3]	Displacement volume
x	[m]	Track reach
η	[-]	efficiency
λ_A	[-]	Volumetric efficiency
μ	[-]	Penalty factor
ρ	[kg/m^3]	Density
ω	[rad/s]	Angular speed

9.3 Indices

Index	Description
BAT	Battery
cons	Consumer
eq	Equivalent
f	Fuel
GE	Generator engine
gear	Gear
inv	Inverter
ME	Main engine
min	Minimal
opt	Optimization
prop	Propeller
PTX	Shaft alternator (PTI/PTO)
rec	Rectifier
rt	Round trip

10 ACKNOWLEDGMENTS

This paper is part of the research project '*Hybrid Powertrains for Alternative Fuels'*, performed by the Department of Marine Engineering of TUHH, the Institute of Ship Design and Ship Safety (TUHH) and the Institute of Internal Combustion Engines and Fuel Cells (TUBS). The project is organised by the FVV and financed by the Federal Ministry for Economic Affairs and Climate Action (BMWK). The authors gratefully acknowledge the support received from the FVV, the BMWK and from all those involved in the project.

11 REFERENCES AND BIBLIOGRAPHY

[1] Jannsen, L. 2020. Gas Engine Performance: Optimization of transient performance of gas-driven ship propulsion plants (Final report), FVV, Frankfurt am Main.
[2] Haack, T., Krüger, S. 2005. A new concept for the simulation of extreme manoeuvres in an early design stage. *Hydronav-Manoeuvering*, Gdańsk.
[3] Tian, L., Chen, H., Yang, X. 2023. A Review of Control Strategies for Hybrid Ships Energy Management Systems, Proceedings of 2023 *International Conference on Marine Equipment & Technology and Sustainable Development*, Springer, Singapore: 791 – 807.
[4] Roslan, S.B., Konovessis, D., Tay, Z.Y. 2022. Sustainable Hybrid Marine Power Systems for Power Management Optimisation: A Review. *Energies*, 15, 9622
[5] Balestra, L., Schjølberg, I. 2021. Energy management strategies for a zero-emission hybrid domestic ferry, International Journal of hydrogen Energy, 46, 38490-38503

[6] Yuan, Y., Zhang, T., Shen, B., Yan, X., Long, T. 2018. A Fuzzy Logic Energy Management Strategy for a Photovoltaic/Diesel/Battery Hybrid Ship Based on Experimental Database, *Energies*, 11, 2211.
[7] Geertsma R. 2019. Autonomous control for adaptive ships: with hybrid propulsion and power generation. Dissertation, Delft University of Technology.
[8] The MathWorks Inc. (2025). Simscape Electrical: Users Guide (Specialized Power Systems) (r2024b).
[9] Vibe, I. I. *Brennverlauf und Kreisprozess von Verbrennungsmotoren*. VEB Verlag Technik, Berlin, 1970.
[10] Woschni, G., Anisits, F. Eine Methode zur Vorausberechnung der Änderung des Brennverlaufes mittelschnelllaufender Dieselmotoren bei geänderten Betriebsbedingungen. *MTZ* 34, Nr. 4, 1973.
[11] Woschni, G. Die Berechnung der Wandverluste und der thermischen Belastung der Bauteile von Dieselmotoren. *MTZ* 31, Nr. 12, Vieweg Verlag, Stuttgart, 1970.
[12] The MathWorks Inc. (2025). Optimization Toolbox: Users Guide (r2024b).
[13] International Maritime Organisation, 2002, Resolution MSC.137(76): Standards for ship maneuverability.

12 CONTACT

Oliver Klein, M.Sc., Hamburg University of Technology, o.klein@tuhh.de

Dipl.-Ing. Vincent Jarschel, TU Braunschweig, vincent.jarschel@tu-braunschweig.de

Prof. Dr.-Ing. Peter Eilts, TU Braunschweig, p.eilts@tu-braunschweig.de

Prof. Dr.-Ing. Friedrich Wirz, Hamburg University of Technology, wirz@tuhh.de