Model- Based Propulsion Layout Definition, Comparison and Selection

Nikolaos Sakellaridis *[1] , Erik-Jan Boonen [1] & Bastiaan Vink[1]

* Corresponding Author. Email: nikos.sakellaridis@damen.com
1 DAMEN Shipyards

Synopsis

The boundary conditions of ship propulsion layout definition are changing as a result of growing environmental concerns and tightening regulations, penetration and maturing of technologies rarely applied in the past such as hybrid/ full electric propulsion, battery technology. Simple sizing of main machinery according to specified sailing speed for a diesel- direct layout is no longer guaranteed to satisfy the considerations above in combination with ever- evolving customer requirements regarding vessel operation and performance.
The degrees of freedom opening up by electrification of propulsion systems need to be considered in co-dependency with the vessel intended operating conditions, so that propulsion layout definition follows a holistic optimization approach, namely choosing and sizing the propulsion system for the specific vessel and mission profile. Moreover, the suitability of technologies with lower readiness level such as fuel cells, alternative fuels etc. is difficult to evaluate due to limited experience and commercial availability. Towards this goal, in the paper will be presented a model- based methodology of propulsion layout definition using high- level subsystem models considering mechanical and electrical energy flows, using as inputs typical information available at initial project phase. The method is intended to be vessel- independent, applicable from large cargo vessels, naval ships to small scale passenger ships, but in this paper will be demonstrated a RoPax ferry application.
Following a description of the modelling framework and the various electrical and mechanical components, different propulsion layouts (mechanical, electrical and hybrid) are evaluated against environmental and operational performance criteria for the examined test case. Metrics such as fuel consumption and system operability are compared, sizing of equipment is performed and operating scenarios are evaluated, resulting in a clearer picture of the merits and demerits of the candidate propulsion configurations in an early stage.

Keywords: Hybrid Propulsion, Propulsion Layout, Ship Modelling, Energy Storage, Model- Based Design

Author's Biography

Nikolaos Sakellaridis completed his Mechanical Engineering studies up to PhD level in the National Technical University of Athens, Greece, on the topic of Marine Diesel Engine Simulation & Diagnosis. After working in the automotive field on 1-D/ 3-D simulations, joined Damen Research as Research Engineer. His interest include: Simulation of power/ propulsion systems, emissions reduction & energy saving technology & alternative fuels.

Erik-Jan Boonen is principal research engineer in the field of mechanics & systems at the R&D department of Damen Shipyards. He graduated in 2009 at Delft university of technology with a master's degree in mechanical engineering. After his graduation he worked as a researcher at the university and thereafter at Van Oord. Erik-Jan works for Damen since 2012 and has worked previously as a mechanical and R&D engineer. System integration, simulation and sustainability are the main themes through his career.

Bastiaan Vink is a naval architect working as Product Specialist Ferries in Damen for 5 years, leading the development of different electrical Ferry solutions in Europe and North America. He holds a master's degree in Ship Hydrodynamics from TU Delft. Before Damen he worked on digital monitoring of offshore equipment and Tug Hydrodynamics.

1. Introduction

In the effort towards decarbonization, the transport sector is subject to increased pressure, being responsible for 20.2% of global carbon emissions (IMO, 2014). Shipping emissions of 2018 amounted to a total of 2.89% of global carbon dioxide emissions (IMO, 2020). Although for some transport segments, such as passenger vehicles, decarbonization path appears to be quite straightforward though electrification, the large energy demands of shipping together with aviation complicates the situation.

While hybrid and electric propulsion in Naval ship applications is already established owing largely to flexibility in operation, design and noise signature, in the last years propulsion electrification combined with batteries has increased its share with short distance shipping, with the first electric ferries and tugboats in service, improving air quality in sensitive urban and port areas. For ships with longer autonomy requirements/ larger size, various options for sustainable operation are being proposed, such as hydrogen powered propulsion using fuel cells or internal combustion engines, alternative fuels such as methanol, ammonia, synthetic natural gas.

In the past, diesel direct propulsion was the default choice, with electric propulsion layout chosen upon request or for specific applications (Boonen et al, 2019). For diesel direct propulsion, vessel requirements (such as sailing speed/ sea margin, engine max speed and envelope, propeller cavitation considerations etc.) combined with the obvious need for fuel consumption minimization and constraints related to commercially available machinery components, provided a narrow design- space for propulsion machinery selection, making the preliminary design process quite straightforward.

As electrified propulsion technologies (batteries, e-drives) become more widespread in marine propulsion layouts, degrees of freedom increase regarding design choice increase. To complicate things more, requirements also become more complex, such as for example zero local emission sailing requirements or future technology readiness. For short routes where shore charging infrastructure is available, full electric sailing is an attractive option, with several full electric ferries already sailing mostly in urban environments or sensitive nature preserve areas (Sæther & Moe, 2021). An example can be shown in the figure below:

Figure 1: Hybrid Electric Ferry (Boonen et al, 2019).

Various degrees of hybridization are also possible, including synergies with energy storage systems. This allows, for example, fuel saving and noise signature reduction by propelling the vessel electrically under low-speed conditions, in which a combustion engine powered, traditional setup would be inefficient. It also allows covering propulsion and hotel (auxiliary) loads when the vessel is at berth or around populated areas, reducing the local environmental impact. Finally, shore power can be stored on board and contribute to vessel propulsion loads, thereby reducing the vessel's overall environmental footprint.

Decisions about the propulsion layout need to be made in an early stage of the design process. Different criteria come into play during this process (Boonen et al, 2019):

- CAPEX/ OPEX (Capital Expenditures/ Operating Expenditures): Cost of purchasing and operating the vessel is an important consideration, therefore comparative estimates of different options are valuable. Regarding operating costs, fuel is an important consideration, as well as equipment maintenance. In novel configurations, this includes also estimation of battery/ fuel cell lifetime, as well as electrical shore power additional infrastructure and consumption.
- Operability: System transient response, manoeuvrability and transition between different sailing modes (e.g., all electric/ direct drive in hybrid configurations), as well as simplicity of operation.
- Flexibility/ Adaptability: Capability of the system to perform different operating profiles (i.e., when switching route or capability to perform the same route under different conditions, for example variation in sailing speed, weather, different levels of available shore power etc.)
- Emissions: These can be categorized as greenhouse gas emissions (e.g., CO_2, CH_4 slip in natural gas powered vessels), and criteria pollutants such as NOx, Hydrocarbons, CO, particulate matter, sulphur

oxides etc. Noise emission, traditionally important criterion for Naval vessels, is nowadays an important consideration for commercial and passenger ships amidst growing environmental concerns. For Naval applications an additional emission of interest is infrared signature.
- Redundancy: Ability of the vessel to operate even under the effect of system failures.
- Future- proofing: Upgrade capabilities of the system for incorporating future state- of- the art technology. This is an important consideration since vessel lifetime can be in the order of 20-30 years combined with the evolving regulatory framework.

In the current work is presented and applied on a ferry test case a model- based framework allowing quantitative and qualitative analysis of the aforementioned criteria. Multiple candidate propulsion layouts can be easily simulated in a short time frame on the basis of the expected real- world operating profile, and insight in the performance and suitability of each propulsion layout can be gained.

The method is designed to be generally applicable, from Naval to commercial/ passenger applications, however the final decision is also driven by prioritization of the aforementioned criteria. In a naval application for example, redundancy/ flexibility/ operability may be prioritized, while in a commercial application CAPEX/ OPEX, emissions and future- proofing might have a more important role.

2. Test Case

The test case examined in the current work is a medium sized, RoPax ferry, performing 2 daily trips of less than 100 nautical miles in total per day. Cargo includes passengers, motor vehicles & substantial amount of goods leading to considerable auxiliary (hotel) electrical load.

2.1. Ship operating requirements

As shown in Table 1, the ship is required to be capable of zero- emission operation in the vicinity of the harbour, thus requiring some degree of zero emission sailing capability. During transit, which is the phase where most of energy is consumed and highest power demand, power is to be provided mainly by Internal Combustion Engine (ICE)/ Generator. Shore power is also available.

Table 1: Overview of operating profile requirements

Activity	Requirement
Start-up/ Loading	Zero Emission incl. Shore Power
Departure	Zero Emission
Transit	Engine/ Generator
Arrival	Zero Emission
Unloading/ Berth	Zero Emission incl. Shore Power
Departure	Zero Emission
Transit	Engine/ Generator
Arrival	Zero Emission
Unloading/ Overnight	Zero Emission incl. Shore Power

2.2. Evaluated propulsion layouts

A large number of candidate propulsion layouts can be proposed fulfilling the above requirements. Technologies for which experience is limited for the specific application are not considered in the current work (such as fuel cells for a ferry application), but instead focus is given on proven propulsion layout solutions. Electrified and hybrid propulsion layouts are considered in tandem with energy storage systems (ESS), to facilitate zero emission low speed manoeuvring, departure and arrival from/ to the harbour. Direct Current (DC) grid is considered, synergizing well with batteries as well as offering power stability and quality advantages (Kim et al., 2018).

Based on the above considerations, three propulsion layouts have been considered in the present study:

- Diesel Direct propulsion layout.
- Hybrid Propulsion (Diesel engine and electric motor/ generator in the propulsion train) including battery energy storage.
- Electric propulsion/ hybrid power supply (Diesel generators and battery energy storage).

More details on each of the considered layouts will be outlined below. In the following figures GB refers to gearbox, DE is diesel engine, either main or auxiliary (AUX), Energy Storage Systems (ESS) refer to the batteries, and EM is the electric motor.

2.2.1. Diesel Direct propulsion layout

Considering the operating requirements of the vessel, it can be concluded that this option cannot, in fact, satisfy a strict zero-emissions operation requirement near port. Nevertheless, modern aftertreatment systems in combination with renewable fuels can offer ultra-low emissions capability. This is the most straightforward, traditional arrangement and therefore has been considered in the study as the benchmark. The typical propeller-gearbox- engine setup is used for propulsion, split in two drive lines, while an AC grid is employed to cover electric loads, which is powered by diesel generators or shore power, when available.

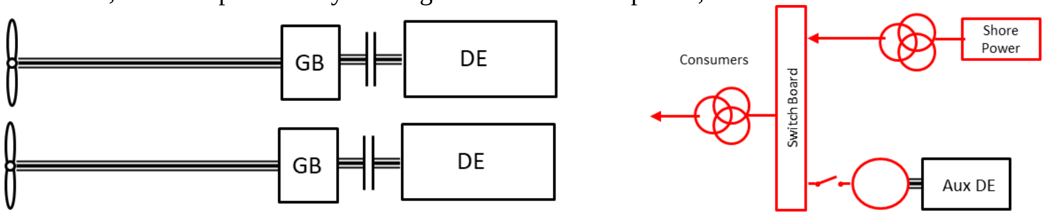


Figure 2: Diesel Direct propulsion lay-out

2.2.2. Hybrid Propulsion

In this propulsion layout, an electric motor provides low speed propulsion during arrival/ departure, enabling some degree of zero local emission sailing (Power- Take- In, PTI). During transit, the same electric machine is assumed to be able to generate electrical power to cover electric loads (Power- Take- Out, PTO). Electric power during low-speed manoeuvring/ zero emission sailing is provided by a battery pack, which is recharged both by shore power and during transit by the PTO function. Physical implementation of the layout is through a secondary input/ output shaft in the gearbox, used to connect the electrical motor/ generator (EM) with the propulsion shaft/ combustion engine. Following modes of operation are considered in the study:

1. PTI mode: Engine is declutched from the propulsion system and switched off. Electric motor, powered by the batteries, propels the vessel. Hotel loads and thrusters are also powered by the batteries.
2. PTO mode: During transit, the electric machine recharges the battery and produces electric power to cover ell electrical loads.

An auxiliary diesel generator is connected to the switchboard, which is usually turned off, since the required electric power is produced mostly by the PTO.

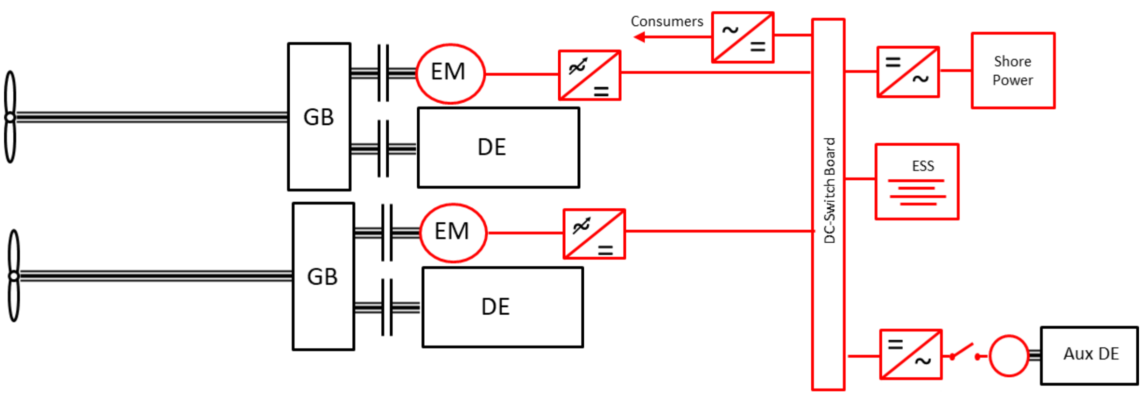


Figure 3: Hybrid propulsion layout.

2.2.3. Electric Propulsion/ Hybrid Power Supply

The last propulsion layout considered here is electric propulsion with hybrid power supply, i.e., Diesel generators and batteries. Generators are switched off at berth or during departure/ arrival and are switched on during transit to provide propulsion power and battery recharge. Basic layout is seen in Figure 4.

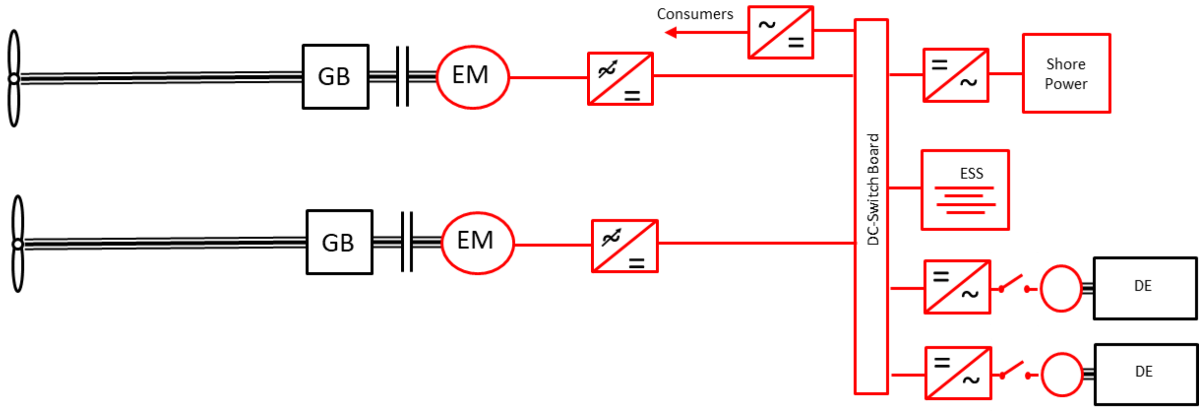


Figure 4: Electric propulsion/ Hybrid power supply

3. Model Description

The approach developed consists of a high- level systems modelling methodology, based on energy flow calculation. As a simplification, detailed system dynamics are neglected, since the intended purpose is a rapid back- to- back comparison of different options. A modular approach is developed, wherein component models are created and connected within MATLAB- Simulink to generate in limited time an entire propulsion layout similarly to the diagrams shown in Figure 2 to Figure 4, without requiring specialist knowledge. The philosophy and solution process adopted in the framework is summarized in Figure 5.

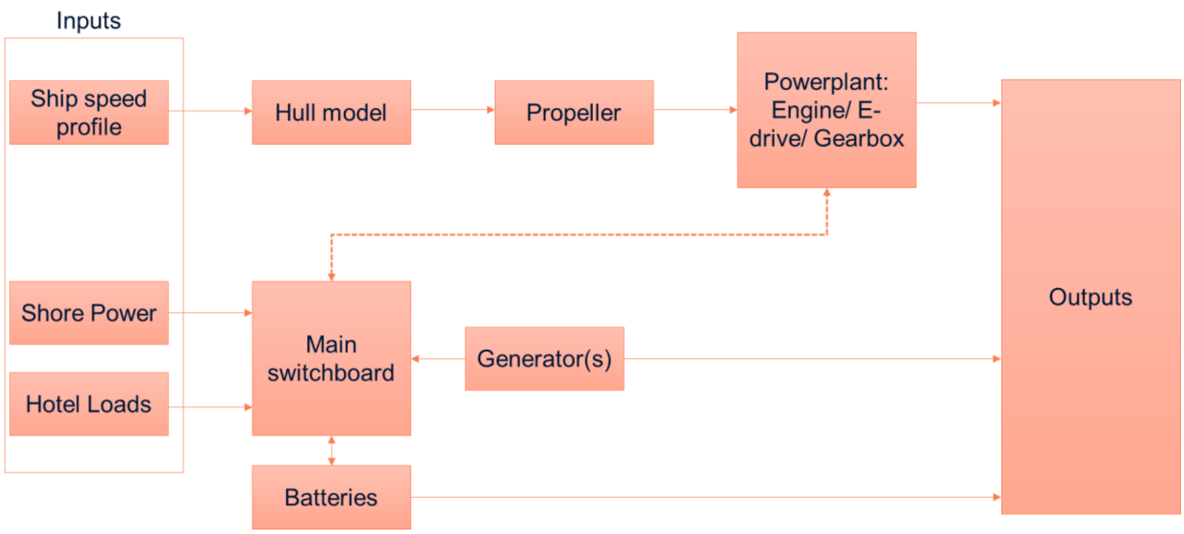


Figure 5: General structure of the simulation model.

3.1. Vessel

The vessel module calculates the ship resistance as function of vessel speed. 1-D lookup of ship resistance is used. This can be generated the initial project phase either by CFD, using empirical methods (Holtrop & Mennen, 1982) or by estimated using model tests/ trial measurements on similar vessels. Advance velocity v_a is also calculated and passed on to the propeller model, based on ship speed v and wake fraction w, the latter being defined experimentally or through simulation :

$$v_a = v(1 - w) \quad 3.1$$

3.2. Propeller

The propeller model uses open water measured data of standard propellers (Kuiper, 1992), also including 4 quadrant data when available. Inputs are the advance velocity from the hull model, as well as the resistance. Propeller thrust T is calculated from total ship resistance R using the following equation and neglecting dynamics:

$$R = T(1 - t) \quad 3.2$$

Thrust deduction coefficient t is also obtained either by CFD, trial or model test data in similar applications.

From the propeller thrust and advance velocity, the torque and speed can be calculated for a given propeller geometry (type, diameter, Pitch/ Diameter ratio), using the propeller thrust and torque coefficient. The relative-rotative efficiency n_0 is finally used to correct the propeller torque Q, after the torque Q_0 based on open water diagram has been defined:

$$Q = Q_o/n_0 \quad 3.3$$

3.3. Gearbox

The losses in the gearbox are estimated using a modified version of the model proposed in (Godjevac et al., 2016) and (Kalikantzarakis et al., 2018). Specifically, a correlation is made for the normalized value of loss torque, $M_{Loss}^{normalized}$ as a function of normalized Torque, $M_{input}^{normalized}$ and speed, $N_{input}^{normalized}$ (normalization performed by dividing by the corresponding full load performance parameter.

$$M_{Loss}^{normalized} = aM_{input}^{normalized} + bN_{input}^{normalized^2} + cN_{input}^{normalized} + d \quad 3.4$$

This is an empirical loss model, the coefficients *a ,b, c, d* of which are calibrated according to available data & in- house measurements for 3 often used gearbox configurations:

- Direct Diesel Drive: Single stage reduction connecting medium speed Diesel engine with the propeller shaft
- PTI gear stage: 2 stage reduction connecting electric motor with propeller shaft
- Z Drive: Azimuth thruster with 2 stage reduction

The model can be used to predict the losses in full as well as partial load condition, which is important when the operating profile includes significant part load operating conditions, such as in Patrol Vessels.

3.4. Electric Components

Models have been made for frequently applied electric components such as electric motors/ generators (synchronous, asynchronous and permanent magnet), Variable Frequency Drives, Transformers, Rectifiers, DC/DC converters etc.

Equipment power losses are calculated as function of load factor, using as input spec sheet values at different load factors (when available), or by using measured values on similar hardware. Polynomial interpolation is used between measured points to interpolate- extrapolate the performance curve.

3.5. Battery

The battery model consists of an integrator of the incoming/ outgoing power. Inputs are the initial capacity and State of Charge (SoC), as well as the instantaneous power. Outputs are the battery state of charge (and quantities that can derive from it, such as Depth of Discharge, Cycles, C-Rate etc.).

Fixed electrical efficiencies are applied during the charge- discharge phase, independent of the charging or discharging rate.

3.6. Internal Combustion Engine

The internal combustion engine is modelled as a 2-D lookup of Fuel Consumption vs engine speed and load (or 1-D in typical generator engine applications). According to the instantaneous load and speed, quasi- static lookup (not including any dynamics such as turbocharger etc.) provides the instantaneous fuel consumption. Integrating this can provide the overall consumption during an operating profile.

3.7. Power Management

Using as inputs the outputs of other subsystems (such as vessel speed, battery SoC etc.), logic can be programmed for the control of propulsion power. Of main interest at a high-level view is the control of main engine/ generator set operation points and battery charging/ discharging scheme, with typical options being (Boonen et al, 2019):

1. Battery leading strategy: Propulsion power comes from the battery, unless the state of charge falls below a predetermined threshold, in which case the generator starts in order to charge it back to a specified level.
2. Generator leading strategy: Generator operates at a specified load point, providing constant power, while the batteries are discharged when total load is larger than the generator power and charged when the generator produces surplus power.
3. Hybrid strategy, combining features of the above while adapting to load demand and battery state of charge.

In the current application, it is considered that all Diesel power is off at berth and near the harbor, and only operates during transit at a predetermined load to recharge the batteries and cover hotel loads, i.e., a type of generator leading strategy.

4. Results and Discussion

As mentioned in the introduction, purpose of the modelling tool is to provide guidance into the propulsion layout selection process. This can be done by defining specific Key Performance Indicators (KPI's),that are calculated and compared for the examined configurations.

In the table below are shown criteria for the selection of propulsion layout for a given application, and corresponding quantitative and qualitative measures to guide the selection process:

Table 2: Selection criteria for propulsion layout definition and corresponding insights from simulation

Criteria	KPI's/ Metrics for Comparison
Capex (% of Vessel)	Electric/ Mechanical Component Sizing
Operability	Propulsion machinery matching/ Margins
Operational Costs	Fuel Consumption/ Shore Power Consumption
Adaptability/ Flexibility	Scenario Setup & Evaluation, Check/ Optimise Controls (EMS)
Emissions	Emissions (local: GHG & Pollutants)
Footprint	System Weight & Volume
Redundancy	Simulation under failure mode
Future Proof	Impact of new technologies

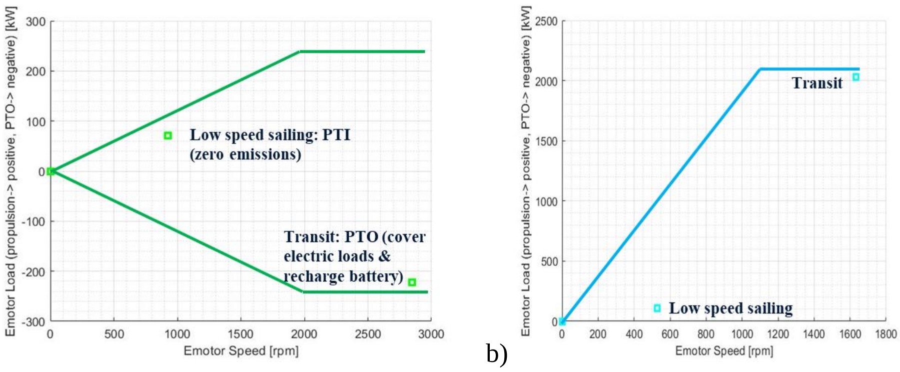
Using the developed model, insight can be gained regarding the above criteria. In the following paragraph the model is used to calculate performance of propulsion layouts described in 2.2 under the defined vessel operating profile.

For the electrified propulsion layouts, an assumption of charge sustaining operation has been made, i.e., the SoC of the battery at the start is set to equal the one at the end. Battery is charged during transit by the generators (in electric propulsion layout) or the e-drive of the hybrid propulsion layout working in PTO mode. It is assumed that electric power generation using ICE's only occurs during transit, while berthing, overnight, departure from and approaching the harbour is performed in zero emission mode (i.e., all ICEs switched off), propulsion load covered by batteries/ electric motors, while shore power is available at berth to cover hotel loads and recharge batteries. If shore power is not enough to cover all hotel/ overnight loads, batteries are used as an additional power source.

4.1. System sizing, footprint and cost considerations

An important criterion for propulsion layout choice is system cost. From simulation results the sizing of electrical/ mechanical components can be derived. To translate this directly into cost is challenging due to a multitude of parameters that come into play (supplier, machine type, price fluctuation etc), so this at the current stage constitutes an additional step to be performed.

The operating profile of the vessel examined is quite straightforward (fixed speed transit phases and low speed approach/ departure from harbour). For the hybrid configuration layout (Figure 6a), less than 100kW is needed in PTI mode while slightly higher than 200kW needs to be generated during transit to cover hotel loads and ensure charge sustaining operation. A preliminary e-drive envelope can be defined, while variation of gearbox ratios can be evaluated, within the model, to fine tune the selection and operating speeds once commercially available candidates are defined.

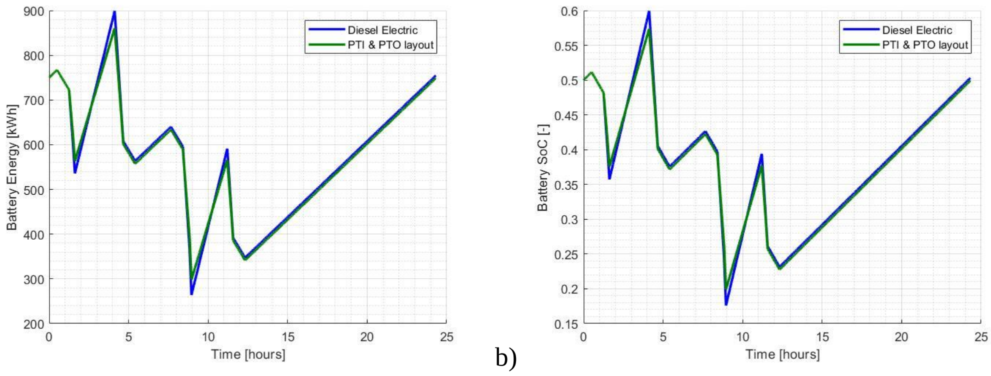


a) b)

Figure 6: Sizing of electric machinery for Hybrid (a) and Electric Propulsion (b) configuration

Model results can also guide battery sizing. First, battery energy is estimated for a daily operation. Together with the assumption of battery capacity and initial charge, the SoC throughout a day of operation can be defined as per Figure 7. Battery sizing needs to also consider lifetime, therefore, usually, battery energy profile can be used as input to suppliers in order to define battery capacity needed.

From the process presented above, the cost of the system, as well as the system footprint (weight/ volume) can be estimated based on commercial offerings.



a) b)

Figure 7: Battery Energy (a) and SoC (b) during vessel daily operation.

4.2. Operability

Operability is another important criterion, which is also hard to quantify into a single KPI through modelling. It consists static manoeuvrability considerations, i.e., ship's ability to achieve the determined operating profile, as well as dynamic considerations, acceleration potential, transition between operating modes of the machinery and how this affects the control over the ship's course during this critical time. As an example, using a Hybrid, PTI-PTO configuration, assuming departure is performed in full electric (PTI) mode, transition between several operating modes is necessary for switching from PTI mode to PTO & ICE operation both regarding the mechanical as well as electrical system.

A high-level model, aiming to be used in the preliminary project phase with limited input data, considering the steady state energy flows can, of course, not hope to capture the detailed system dynamics. Valuable insight can however be gained regarding propulsion machinery matching & margins (which gives an indirect indication of acceleration and manoeuvrability capabilities of the system, as well as high level system transitions, i.e., from PTI→ PTO and vice versa).

Interesting conclusions can be drawn regarding operability by overlaying the engine operation points in the engine envelope as per Figure 8. Same engine was considered for the Diesel Direct and Hybrid layout. The Electric propulsion/ hybrid power supply is not included in the graph, since there is no mechanical coupling (and thus high flexibility) between propulsion system and generators, with generator operation being defined by total power demand including propulsion and hotel loads, as well as ensuring battery charge sustaining operation.

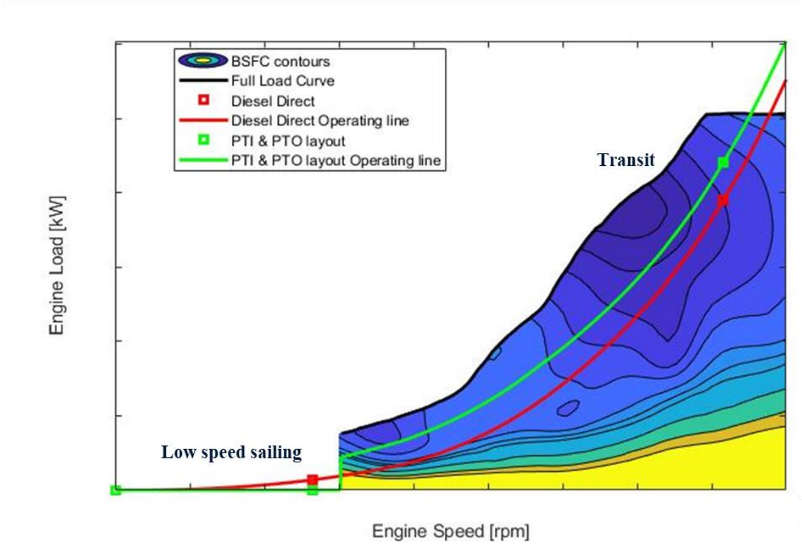


Figure 8: Engine envelope including operating points & propeller curve for Diesel Direct & Hybrid Layout.

It is seen that the low-speed sailing point for Diesel Direct layout falls outside of the engine operating range (lower speed than min. engine speed). Therefore, with the given gearbox ratio/ propeller geometry characteristics vessel speed will be higher that the defined value. Countermeasures such as gearbox ratio increase (and effect on high-speed transit point) or controllable Pitch Propeller (CPP) are to be evaluated using the model in a later stage.

The effect of necessary steady state PTO power causes a decrease in engine margin margins compared to Diesel Direct, as expected, together with a very slight increase in Brake Specific Fuel Consumption (BSFC) due to the shifting of the operating point to higher loads. It is not necessary however that high speed manoeuvrability is negatively impacted, since, due to the presence of batteries, PTO power can be reduced during an acceleration manoeuvre, and, depending on system design, even boosting can be employed to assist the acceleration.

4.3. Operational cost/ Fuel consumption

For a propulsion layout using an ICE, fuel costs are the most important operational cost. Daily fuel consumption for the three candidate propulsion layout concepts can be compared (Figure 9). It is shown that the Diesel Electric configuration has the highest fuel consumption figure, which is to be expected, since the entirety of the propulsion power, provided by the generators, is subjected to multiple conversions before reaching the propeller, with the associated losses. On the other hand, the PTI-PTO configuration does present a small benefit. This is due to two factors:

1. The efficiency of the main engine is generally higher than generators. Of course, the more complex gearbox does lead to some extra losses, which are accounted in the model developed.
2. Shore power is generally higher than the hotel load. In electrified propulsion layouts stored energy from shore power during berth can be used to offset fuel consumption for covering loads during sailing.

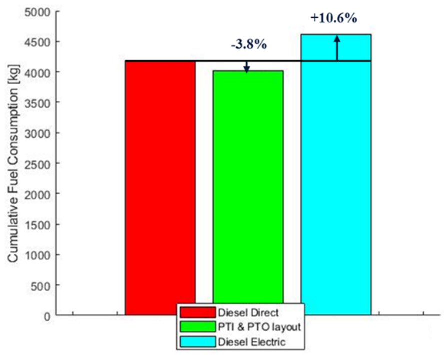


Figure 9: Fuel consumption (kg/day) for the examined propulsion layouts

It is important to note that the lookup table approach is quite simplistic, combined with the fact that there are no dynamics included in the model. In operations with highly transient profiles, it is expected that the model will under- estimate the fuel consumptions, since it does not consider the energy needed to increase the vessel kinetic energy, as well as possible increase in fuel consumption of the diesel engine in transient operating conditions. CO_2 and SOx emissions are directly linked to fuel consumption and fuel composition (considering that these substances constitute the majority of compounds formed by oxidation of fuel carbon and sulphur, which is a reasonable assumption)

Pollutants such as NOx/ Soot/ Hydrocarbons could also in principle be calculated using a similar method. In the present case, no pollutant information was available for the examined combustion engines.

4.4. Adaptability/ Flexibility

Often, a ship is designed with a specific route and operating conditions in mind, however it is desired that it be able to perform well in other operation conditions. For a ferry application as an example, design choices that are made with a specific route in mind can limit, or even prohibit, use of the vessel in other routes. Using the model, it is possible to simulate operating scenarios to define propulsion layout adaptability/ flexibility.

An example scenario, the sensitivity of fuel consumption to the availability of shore power is evaluated. Often the infrastructure for shore charging is not complete upon the delivery of a ship but is planned for the future. In this case, it is required that the ship can effectively perform its mission with and without shore power. If the vessel is designed to operate for most of its lifetime including shore power, it is of course desirable that the system is optimized for the corresponding design condition.

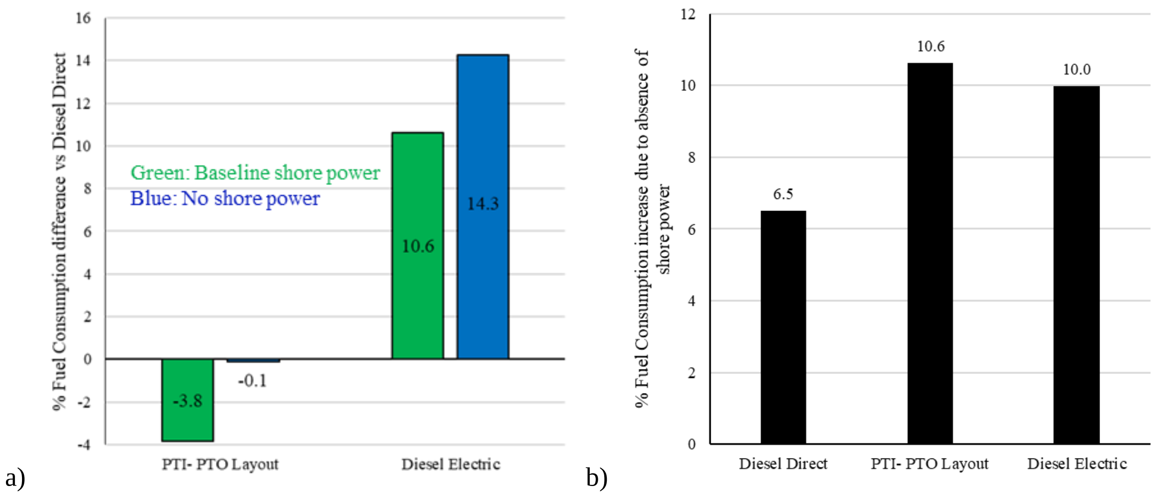


Figure 10: a) Comparison between Fuel consumption of Hybrid and Diesel Electric propulsion layouts with Diesel direct being the baseline for comparison and b) effect of shore power availability on the fuel consumption of different propulsion layouts.

In Figure 10a can be seen the fuel consumption difference of the 2 considered electrified propulsion layouts (as % variation vs the diesel direct layout), with and without shore power (green and blue bars, respectively). The benefit that was visible with the PTI- PTO hybrid propulsion configuration practically diminishes when no shore power is available. Increase of the penalty of the Diesel Electric configuration (shift magnitude is similar with PTI-PTO case) is also observed. Reason for this behaviour is that, due to the presence of batteries, leftover shore power is stored during berthing, being released later to cover propulsion and hotel loads, thus offsetting on-board use of fuel.

In Figure 10b can be seen the effect of absence of shore power on each propulsion layout separately. The diesel direct configuration, which does not benefit from energy storage system, has a moderate effect, since shore power just acts to replace/ unload the auxiliary generation for covering berth loads. The electrified propulsion layouts, as discussed, are penalized more heavily.

4.5. Future- Proofing and Redundancy Considerations

An important consideration is also future- proofing of the propulsion layout. This is quite difficult to quantify with simulation alone, experience and critical thought must also be employed. For example, in short routes, full electric sailing with shore charging has been demonstrated as a viable option for zero (local) emissions. The Diesel Electric propulsion layout, shown to be the least favourable based on fuel consumption alone, is very well suited for modification to full electric operation, removing diesel generator related systems and increasing battery capacity. Diesel electric is also suited for retrofitting for hydrogen propulsion either by dual fuel combustion engines or replacement of gensets with fuel cells. On the other hand, Diesel Direct or PTI- PTO propulsion layout can also be made future- fuel ready for zero (well- to- wake) CO_2 emission sailing.

Finally, redundancy of the propulsion layout can be quantified by running simulations under fault conditions and evaluating system performance (e.g., sailing speed & manoeuvrability considering fault of one or more ICE's). No such investigation will be presented in the current work, being outside of the scope.

5. Conclusions

A simulation framework for preliminary evaluation of propulsion layout has been presented in the current paper. The method consists of evaluation of energy flows in a 1-D fashion, including partload performance prediction for the propulsion layout components.

It has been applied in the case of a ferry application, in order to compare three candidate configurations, namely:

- Diesel Direct.
- Hybrid Propulsion/ Hybrid power supply
- Electric propulsion/ Hybrid power supply.

Using the model, the above cases are simulated using as input the intended vessel operating profile, and quantitative (KPI's) as well as qualitative measures are defined to define the most suitable. These are discussed in detail in chapter 4. Herein a summary of the results is presented in Table 3.

Table 3: Summary of candidate propulsion layout simulation

	Diesel Direct	PTI/ PTO	Electric Propulsion/ Hybrid Power Supply
Capex (% of Vessel)	(TBD based on sizing)	(TBD based on sizing)	(TBD based on sizing)
Operability	O	-	+
Operational Costs	O	O	-
Adaptability/ Flexibility	+	-	+
Emissions (0 emission near port)	-	+	+
Emissions (overall CO_2)	O	O	-
Future Proof	-	O	+

In the table above, + defines a favourable score, *o* a neutral one and – denotes a disadvantage. More specifically regarding the defined criteria:

- CAPEX is not directly calculated by the simulation model, however, the sizing of components can be defined as per 4.1, with a next step being the detailed cost estimation based on supplier input.
- Regarding the operability, having as baseline the traditional direct drive, the operating mode transitions that are necessary between full electric and hybrid mode penalize the PTI/ PTO layout, considering also the lower output of the electric/ motor generator compared to the main engine. Complete de- coupling of power generation and propulsion afforded by the electric propulsion layout is favorable in this regard.
- Regarding operating costs, the current study focuses on fuel consumption, with the multiple conversions needed in the electric propulsion layout amounting to an increase in fuel consumption for the same mission profile. The small benefit for the hybrid layout, as was demonstrated, is mostly related to the availability of shore power. It must be mentioned here that a complete calculation of operational costs should include also maintenance cost estimation, which currently is not included in the model. Future work in the model will include this cost estimation based on model outputs, namely operating hours evaluated together with engine loading, as well as engine stop/ start operations per day, that depend on propulsion layout and energy management strategy.
- As far as adaptability is concerned, limitations are considered (such as limited all- electric sailing speed and limitation of PTO output due to engine envelope in cases of increased hotel loads/ increased charging needs of the battery) for the hybrid layout.
- Emissions are split in 2 categories: Overall CO_2 , directly linked to fuel consumption as described in 4.3, and emissions near port. Zero emission capability near port is only available with PTI/ PTO and Electric propulsion configurations.
- Finally, some degree of future proofing is possible with every considered layout, if provisions are made. For example, readiness for future Zero-Carbom fuels can be designed into the diesel direct

layout, or usage of increasingly available shore power can be maximized with increase of battery capacity in the PTI- PTO layout (limited however by the lower output of the electric machine). The electric propulsion has the advantage of easily integrating a range of technologies due to flexibility in design and separation of propulsion and power generation system, for example fuel cell power sources or full electric operation.

The method presented herein is widely applicable to generate insight to guide the propulsion layout selection process, but, as shown above, in the last part of propulsion layout selection process the results need to be evaluated according to the application requirements (e.g naval vessel, transport, merchant etc).

The proposed method can be further developed by adding more component models such as fuel cells, heat exchangers, weight, volume and cost estimations etc, in order to be able to perform more complete system evaluation/ optimization.

The method presented constitutes a simple approach, to be implemented at initial phase of a project when limited data is available. However, despite its simplicity, as demonstrated, a comprehensive view of system performance can be gained, supporting the early decision-making process with quantitative and qualitative results and insights (KPI's), as well as traceability.

Acknowledgements

The views expressed in this paper are that of the authors and do not necessarily represent the views and opinions of Damen Shipyards

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