Power, propulsion and energy system co-design optimisation framework for future vessels

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Abstract. The maritime industry is in the process of shifting to more efficient and sustainable solutions with multiple technologies being researched towards this goal. The large variety of applications and requirements make the design of the Power, Propulsion and Energy (PPE) systems complex, and requires a systematic approach to reduce the uncertainties in the initial vessel design considering future proofing. Towards this objective, this paper proposes a multi-objective co-design approach for the optimization of the PPE design. The example of a mega-yacht is used to showcase the framework towards an initial vessel design with a retrofit at end of service utilizing alternate sustainable solutions such as fuel cells and dual fuel engines. Model Based Systems Engineering (MBSE) is used to extract specific requirements for the vessel design which function as constraints for the optimization. Models serve a key function in an MBSE approach, and the component models used are described with particular focus on the model confidence level. Furthermore, a scalable and configurable energy management strategy is developed to evaluate multiple architectures with the typical use-case of the mega-yacht such as Transatlantic and Mediterranean voyages serving as the basis for evaluation of the design.

Keywords: PPE · Co-design · MBSE · Energy Management

1 Introduction

The continued use of carbon intensive fuels contributes significantly to pollution and climate change. While maritime transport is among the most energy efficient means of transportation, it remains one of the few key sectors where the

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greenhouse gas (GHG) emissions are projected to increase [4]. To tackle this, key legislature has been enacted in the recent years by the International Maritime Organization (IMO) and the European Union (EU). These include ambitious targets to reduce the carbon intensity of international shipping by at least 40% by 2030, compared to 2008 levels [5]. At the EU level, starting January 2024 the Emissions Trading System (ETS) has been extended to cover GHG emissions from all large ships (greater than 5000 gross tonnage). Another driver for the de-carbonization of maritime transport is the FuelEU maritime regulation which promotes the use of renewable, low-carbon fuels alongside clean energy technologies. This regulation sets a target of 2% reduction in GHG intensity of fuels used in the sector by 2025 increasing to an 80% reduction by 2050 [2].

Volume, weight and cost are key factors involved in the design of vessels and these new regulations place an added challenge in the design of the Power, Propulsion and Energy (PPE) system of new vessels. Typical low- or zero- carbon fuels currently being investigated (such as, methanol, ammonia or hydrogen) do not have the same energy or volume density as conventional fuels like diesel and alternate technologies like battery packs and fuel cells are more expensive to manufacture and operate than internal combustion engines. While the performance and cost of the newer technologies is expected to improve in the coming years there are currently many unknowns, such as, which fuel and power system to consider, how to size battery packs, what battery chemistry to use, and how reliable are the new technologies. Therefore, conventional methods of design may not be sufficient.

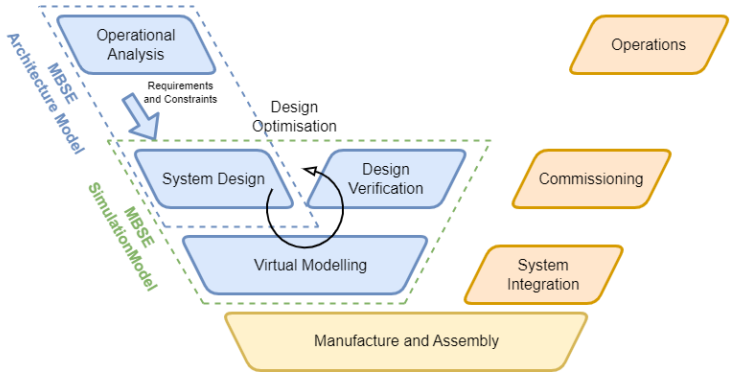


Fig. 1: Simplified representation of the V-model showing the integration of an MBSE architecture and simulation model.

Literature on MBSE in the maritime domain has usually focused on naval applications [15,20,24], however, recent studies have also looked at extending its use to the larger maritime domain [6]. This is especially important in the context of the energy transition. Brefort *et al.* presented a framework to study and identify interactions and interconnections between ship systems and the vessel

aiding the design of complex ships with distributed systems [8]. Poullis presented an approach to optimise the layout of the engine-room with a given design [21]. While the MBSE approach including the use of the V-cycle as depicted in figure 1 has been extensively used in the automotive domain, the use of models in the design process is in the early stages in the maritime domain. This paper incorporates the lessons learned from the automotive domain in addressing the model-based design of an engine room for future vessels. The design process described builds on the work presented in [27] by developing a multi-objective co-design framework and demonstrating the applicability of this approach for the initial design of a vessel considering a retrofit using alternate, cleaner technologies at end of first service life. A key component of this approach is MBSE where models serve as the basis for system requirements, design, and validation replacing the traditional document centric approach as represented in the V-model in Figure 1. This creates the necessary flexibility in investigating multiple design choices while ensuring performance criteria are achieved. The objective of this paper is to demonstrate the use of a design optimization framework in an MBSE approach for a maritime use-case.

This work is part of the Methanol as an Energy Step towards zero-emission Dutch shipping (MENENS) project which aims to make a significant impact on the Dutch shipping industry and reduce emissions by laying out the framework for equivalent safe use of methanol as a fuel in commercial shipping that is cost-effective and sustainable [19].

2 Co-Design Concept

The steps involved in the design process can be seen in Figure 2. The process starts with the definition of a Use Case and an operational analysis, this is the first step in an MBSE centered design approach. Here, the Arcadia method in Capella (Figure 3) is used for the MBSE architecture modeling for the chosen use-case. The operational analysis defines the context of the system independent of the solution. In this step, the stakeholder requirements and constraints for the system are captured, this includes the operational scenarios of the vessel and the operational profiles.

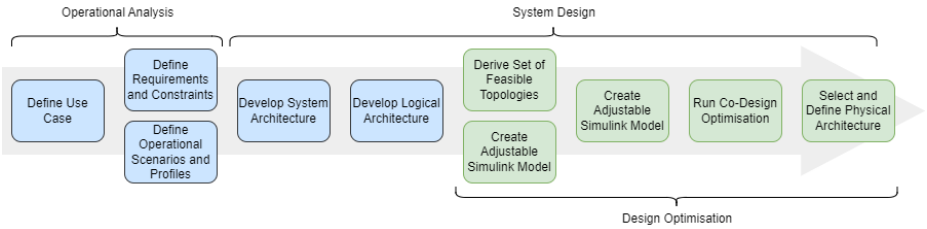


Fig. 2: Steps involved in the design process.

The system architecture defines the boundary of the system being designed, in this case the boundary was the PPE system and other aspects such as the hull and propeller were not considered in the design. Furthermore, the system architecture derives system requirements from the operational requirements. For example, it derives a PPE load power profile from the sailing profile. The logical architecture form the basis of the design optimization. It defines the basic architecture, refines requirements, and makes broad choices on technology and topology.

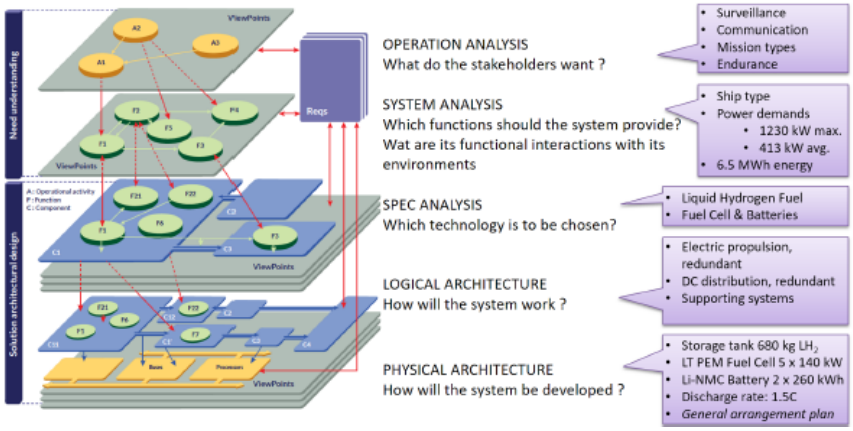


Fig. 3: The Arcadia Capella MBSE approach with an example. From [26].

Based on the broad architecture defined by the logical architecture, feasible topologies are generated for further investigation. Figure 4 shows the master topology, i.e., every feasible topology is a subset of this. Considering the number of components involved, the design space is very large. In order to showcase the applicability of the proposed design methodology certain assumptions are made to limit the design space.

- Only symmetric topologies are valid, i.e., the number of each component on starboard and port must be equal.
- Each topology can have a maximum of 1 battery pack per side.
- Each topology needs at least 2 power sources other than the battery for safety reasons (built-in redundancy).

The first assumption stems from the current model limitations. The DC bus implemented in the model is not scalable and needs to have a symmetric distribution of components numbers. The battery model used is based on a fixed chemistry and while the assumption of a maximum of 1 battery pack per side limits the number of topologies, the optimizer is free to choose a large capacity that could have in theory been stored across multiple batteries on a

side. Altogether, these assumptions limit the design space to 6 topologies. This is seen as sufficient to showcase the methods and future work is planned to expand on the number of topologies investigated.

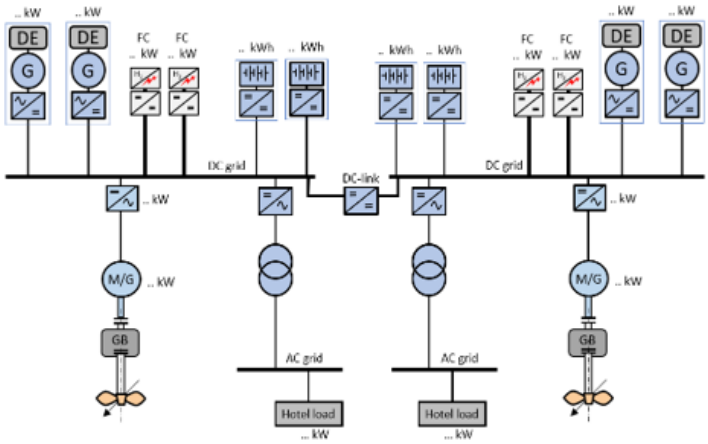


Fig. 4: Topology containing all possible topologies, i.e, the Master Topology.

The next key component in this design approach is developing a configurable and scalable simulation platform to be able to easily evaluate multiple topologies. The work involved in preparing the platform is described in another paper submitted to MOSES 2025 [11]. The details of the component models is explained in further detail in Section 3.

The final step in this design process is to perform a co-design optimization. Co-design is a methodology of combining the design of hardware of a system alongside its controls. The basis of the methodology used in this paper is describe in detail in [23]. The build-up and working of the framework is explained in detail in Section 4.

3 Use Case Description

The chosen use case to evaluate the design methodology mentioned in the earlier section is an 85 m, 2550 GT mega-yacht. This vessel type provides the challenge of needing high maximum power for achieving the top sailing speed for an extended period of time, high amount of energy on board to supply the auxiliary systems (these systems consume on average 10% of the total power of the vessel but over the course of a year this can account for up-to 50% of the total energy consumption) and redundancies in the PPE system in case of emergencies. Additionally since the vessel could be docked/close to the coast for a large period

of the year there is a strong need to have battery and/or fuel cell power available to comply with low and/or zero emission zone requirements.

The proposed design methodology is evaluated by considering an initial vessel design for 2028 and a retrofit in 2038. This timeline assumes that the cost of the new technologies such as battery packs and fuel cells are more expensive for the initial build but achieve cost comparability with conventional technologies like combustion engines by the retrofit. Additionally, the cost of alternate fuels such as methanol and hydrogen are assumed to be much more expensive than diesel for the initial build due to the limited supply but are expected to achieve cost parity by the retrofit timing.

Another consideration is that the newer technologies are expected to improve over the next decade. This is accounted for through improved efficiency maps of fuel cells, battery packs and alternate fuel combustion engines. The volumetric efficiency is also expected to improve which would enable the storage of a similar amount of energy as today's vessels without loss of sailing range.

3.1 Use Case Modeling

Models play a key role in the MBSE approach and therefore the results produced depend intrinsically on the models used. The models reported on in [11] are further enhanced by using scaling parameters to enable the investigation of different sizes for the involved components (generators, fuel cell, battery pack, and electric motor).

The component models used by the optimizer come from a library of components populated with component models that are validated using data (based either on open source, specification sheets or laboratory measurements). At this stage, this library of components is still under development due to challenges in obtaining data. Therefore scaled version of validated component models are used instead. The underlying model used is described in detail in [11] including details of the model approach, and model confidence level of the individual component models. The battery and fuel cell models are scaled by the number of cells (which is proportional to the power output). In the case of the electric motor, a torque scaling is applied to the continuous power output.

In the case of the generator, a base validated model is prepared for two different speed settings - a high speed and medium speed generator. The base model is fitted with data from specification sheets available online [1] for the purpose of this study. While there may be a loss of modeling accuracy in certain operating areas, the overall trends are expected to be maintained. Figure 5 shows the fitted full load curves of a base 380kW generator model to the full load curve of a Caterpillar C32 diesel generator. For the optimizer, the medium-speed generator is capped to a maximum power output of 895ekW and the high-speed generator is extended up-to 2000ekW for exploring a wide array of component sizes.

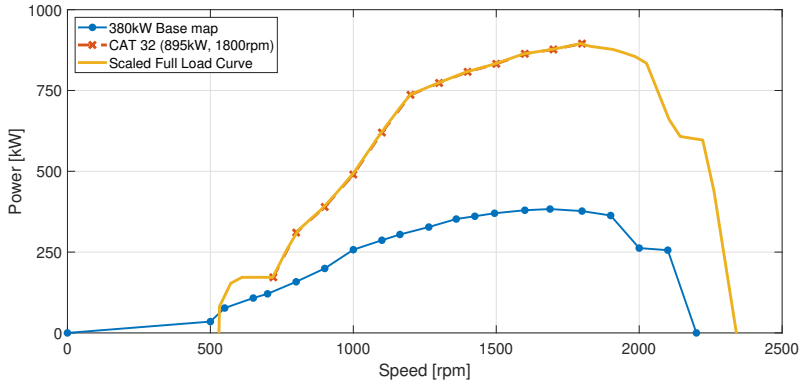


Fig. 5: Fitted model of CAT C32 Generator.

3.2 Energy Management Development

The co-design process involves the simultaneous optimization of both plant and controls. Considering the multiple technologies and topologies possible, having a modular and scalable Energy Management Strategy (EMS) is important. The EMS used for this research is the TNO Modular Energy Management Strategy (MEMS). This solution is based on work reported in [22], it uses a modified Equivalent Consumption Minimization Scheme (ECMS) approach to minimize the overall loses in the power delivered to the propulsion and auxiliary systems, thereby effectively minimizing the overall fuel consumption. The multiple energy vectors (electricity, diesel and methanol) involved are coupled through the use of co-state variables that equalize the consumption between the different energy sources.

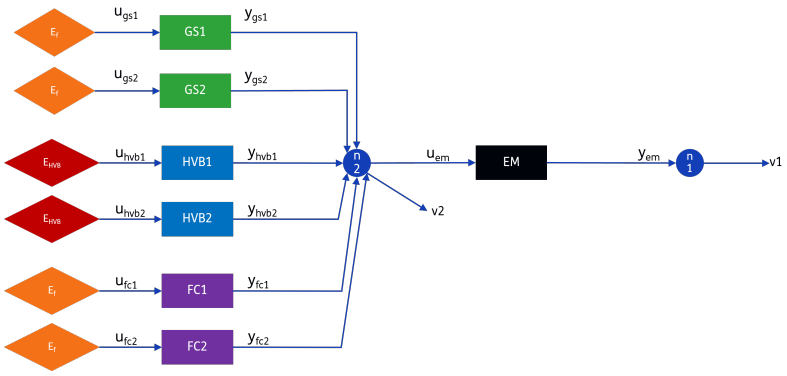


Fig. 6: Power balance representation for EMS.

Figure 6 shows the power balance representation for the master topology. The different energy sources (fuel and electricity) are shown at the left hand side of the image. The power balance equations represent the electric power demand (Eq. 2) and the propulsion power demand (Eq. 1). The electric power demand equation indicates the overall power consumption on the vessel through a combination of battery packs, fuel cells, generators and electric machine.

$$v1 = y_{em} \tag{1}$$

and

$$v2 = y_{hvb1} + y_{hvb2} + c_{gs1} * y_{gs1} + c_{gs2} * y_{gs2} + c_{fc1} * y_{fc1} + c_{fc2} * y_{fc2} - u_{em} \tag{2}$$

where, em stands for Electric Machine, hvb for High Voltage Battery, gs for generator, fc for Fuel Cell, v represents power output at node, u the input power to a component, y the output power from a component and c a switch to turn on/off a component.

To generate the EMS for a particular topology, the switches are used to disable the components that are not part of the topology. Considering that all the feasible topologies include a battery pack, the EMS is defined to have two modes, a 'regular' mode and a zero-emission mode where the required propulsion and auxiliary power is delivered only through the battery pack. These modes are automatically switched during the evaluation with the mode having the lower overall loss taking the preference. A penalty value is added to avoid rapid switching between the modes.

3.3 Operational profile

A 36 hour long short expedition voyage, depicted in Figure 7, is considered for evaluating the performance of the vessel design. The operational profile is focused

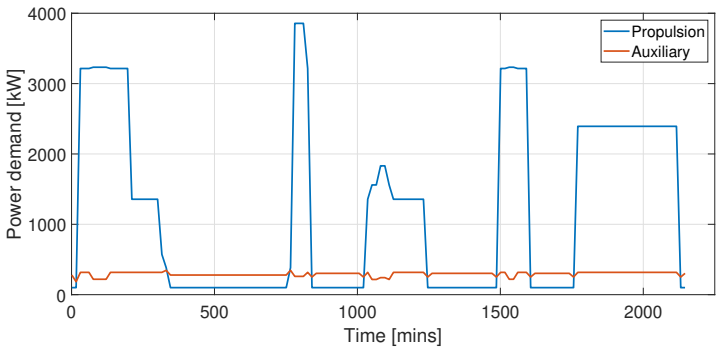


Fig. 7: Operational profile of a short expedition voyage.

on describing the vessel in the operation phase, thereby giving more emphasis

on the sailing events (approx. 50% of the profile). Over the course of a typical year, a yacht spends about 10% of the time sailing [3]. Therefore to calculate a representative operational cost over the lifetime of the vessel, this profile is scaled to represent a year (factor 243 for the 36 hours profile to equal 1 year) and then the average distribution of sailing/anchoring/harbor over a year are incorporated. The final evaluation of the proposed initial and retrofit solution is done using typical expeditions made by this type of vessel which includes the transatlantic crossing and island hopping trips in the Mediterranean. Figure 8 shows the operational profile for a transatlantic voyage. The journey is expected to take just under 14 days assuming nominal conditions.

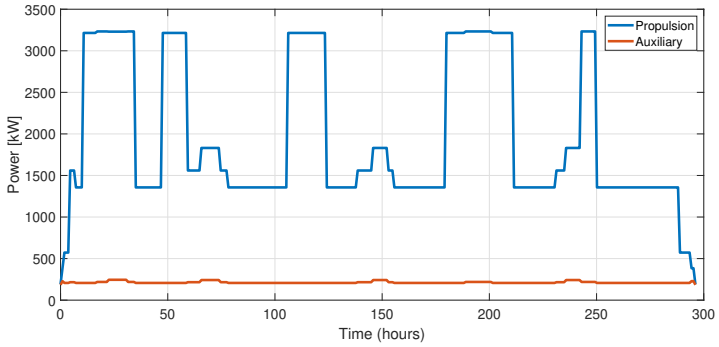


Fig. 8: Operational profile of a transatlantic voyage.

The average propulsion load demand on this profile is approximately 2000kW and average auxiliary demand is approximately 200kW. Assuming an average total system efficiency of 33% and a margin of 20% for the energy on-board, a total of almost 3000MWh is needed which translates to approximately 270 m^3 of diesel. This serves as one of the critical constraints in evaluating the optimized design of the vessel.

4 Co-design Framework Development

The optimization framework discussed in this paper applies a nested approach with three layers as depicted in Figure 9. The lowest layer of the nested approach applies the scalable simulation platform mentioned in Section 2 to evaluate operational cost and feasibility. This model is built in such a way that it facilitates all relevant topologies which are possible based on the master topology.

4.1 Connection Matrix

A connection matrix is used to adjust this platform to the respective topology. As mentioned in Section 2, the logical architecture is the baseline for the co-design

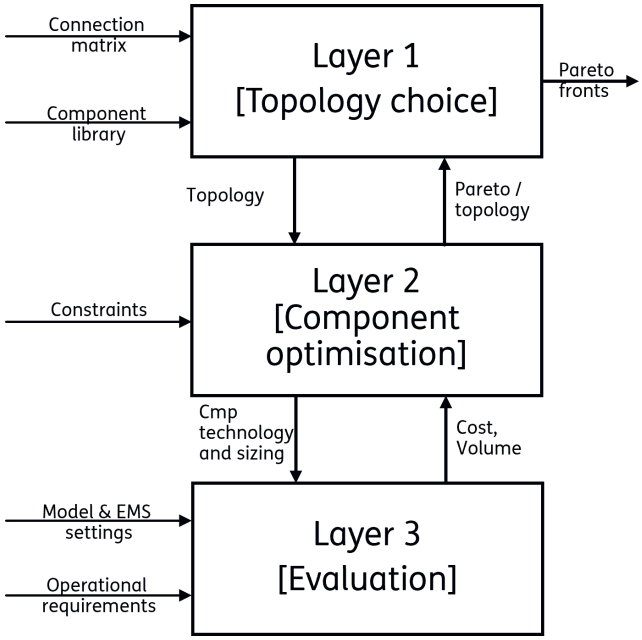


Fig. 9: Information exchange between layers.

optimization. A number of topologies have been defined which implement the functional blocks and connections defined by the logical architecture. Note that each of the functional blocks can be implemented by more than one component in the topology. Hence, the design space in terms of the number of components per side of the ship (i.e., starboard and port) is as follows:

- max. 2 Generators
- max. 2 Fuel cells
- max. 1 Battery
- 1 DC bus
- 1 Electric machine (main propulsion)
- 1 Gear box
- 1 Thruster
- Hotel load (shared by starboard and port)

Additionally, certain constraints are applied; for instance, there is no freedom in the number of electric machines, gearboxes, and thrusters, as they are determined by other parts of the ship design. In addition, each functional block in the logical architecture must be implemented by at least one component in the topology.

A component connection matrix is used in [7] to represent the topologies in a design optimization. It shows both, components that are included in a topology

and how they are connected with each other. In the co-design optimization described in this paper, connection matrices are additionally used as an interface via which the topologies can be communicated to the optimization framework.

	GS1	GS2	GS3	GS4	FC1	FC2	FC3	FC4	HVB1	HVB2	HVB3	HVB4	DC Bus1	DC Bus2	EM1	EM2
GS1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
GS2	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
GS3	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
GS4	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
FC1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
FC2	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
FC3	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
FC4	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
HVB1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
HVB2	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
HVB3	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
HVB4	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
DC Bus1	1	0	1	0	1	0	1	0	1	0	1	0	0	1	1	0
DC Bus2	0	1	0	1	0	1	0	1	0	1	0	1	1	0	0	1
EM1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
EM2	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0

Table 1: Connection matrix.

Table 1 shows the connection matrix of the master topology (Figure 4) used for the optimization framework. For readability, the components of the mechanical drive train behind the electric machines are not included. The connection matrix contains boolean operators representing a connection between components [7]. A connection between two components is represented by a logical "1" in the matrix. The connection matrix always contains fields for all components that are part of the master topology. If a topology only features a subset of these, only the components that are part of this topology have connections in the connection matrix. As the connection matrix defines how the components of a topology are connected with each other, it can be used to automatically generate a model of the topology, as demonstrated in [7] and [10]. However, automatic generation of models is not within the scope of this work. The use of the connection matrix is currently limited to interacting with the model by activating or deactivating components of the master topology. The automatic generation of models is considered for future work and the architecture of the optimization framework is designed to facilitate this step.

4.2 Optimizer

The optimization of technology choices and component sizing are part of layer 2 of the optimization framework. In previous works, several optimization strategies have been compared regarding their applicability in a similar co-design approach [10]. Among others, Particle Swarm Optimization (PSO) and Genetic Algorithms (GA) have both been applied for this kind of work, yet with a certain preference to one or the other depending on the type of problem. While

PSO is an optimization method for continuous problems, GA is also applicable to problems featuring both continuous and discrete variables [7], [10]. At the same time, literature does not allow for an apriori assessment which strategy can be expected to be more efficient computationally. Several comparative publications from other disciplines considering multi-objective variants of GA and PSO - namely NSGA-II and MOPSO - do not come to a unanimous result, e.g., [12], [13], while they show that the type of problem can have a large impact on computational performance.

The methodology described in this work is required to make choices between different technologies and may even choose between different component models based on the required sizing, hence the problem is not fully continuous. For this reason, GA has been chosen as optimization strategy. A comparison of several optimization strategies regarding their performance in this optimization problem is out of scope for this paper. However, this may be considered in future work. The architecture of the developed optimization framework has been designed to facilitate extensions in this regard.

This paper discusses a multi-objective optimization, providing Pareto-fronts as outputs. The optimization framework has been implemented in MATLAB [14], which offers a multi-objective GA optimizer based on NSGA-II (Non-Dominated Sorting Genetic Algorithm 2) as part of the Global Optimization Toolbox.

4.3 Preliminary Evaluation

It is the task of the optimization strategy to choose and "try" different configurations, i.e., component sizes and (if applicable) technologies. It does this following a method that eventually minimizes the costs as calculated by the cost functions. It might however happen that a configuration is not considered feasible from the perspective of ship design or operation, as it fails to fulfill important design or operational requirements. For example, the chosen component sizes might be too small to provide sufficient propulsion power, or the PPE system might turn out too large to stay within its predefined volume or mass limits. To avoid that the optimization suggests such designs as optimal, the following two steps have been performed:

1. Requirements have been detailed and formalized into clear operational constraints.
2. Operational constraints have been applied such that they impose a high cost on infeasible configurations.

The first step has been done based on available vessel requirements from the described use case. For the second step, after the model has been executed on layer 3 using the operational profile from Section 3 (Figure 7), the following constraints are checked:

- Performance constraints:
  - The vessel has enough propulsion power to sail at maximum speed
  - The vessel has enough emergency power available

  - The vessel has sufficient power available to follow the operational profile at all times
- Volume constraints:
  - The volume and mass of battery systems, generator and fuel cell systems combined are within defined design limits
  - The required bunker volume for fuel is within defined design limits

If operational constraints are violated, a penalty of 1e30 is applied to either or both CAPEX and OPEX at the end of the evaluation of layer 3. This indicates to the optimizer that the configuration is unfavorable in terms of costs, triggering it to avoid these configurations.

5 Results Analysis

The primary objective of the optimization study was to strike a balance among three critical design considerations: CAPEX, OPEX, and total system volume, while evaluating diverse engine-room topologies for two distinct implementation horizons (2028 and 2038). To streamline analysis and clearly visualize trade-offs, CAPEX and OPEX were aggregated into an *Annualized Total Cost* metric. This reduction from three objectives to two (Annualized Total Cost vs. Volume) significantly simplifies the interpretation of Pareto-optimal solutions, facilitating transparent and meaningful comparisons between configurations. Furthermore, it enables straightforward assessments of each topology's long-term viability and practicality within realistic operational and economic scenarios.

5.1 Overall Cost–Volume Trends

Figure 10 illustrates the combined optimization results, detailing how each configuration and topology balances annualized total costs against spatial constraints (volume). Solutions positioned nearer the lower-left quadrant of the chart generally represent more favorable outcomes, featuring reduced costs alongside smaller volumes. Conversely, points located toward the upper right reflect increasing compromises in either cost or volume. The hypothetical *Utopia Point* (yellow star) at approximately $100m^3$ and €9.0×10^6 total cost acts as an idealized reference to evaluate the proximity of real-world solutions. It becomes evident from the distribution of points that no single topology consistently optimizes both objectives simultaneously; instead, clear trade-offs must be managed.

Observations from Figure 10 indicate two distinct clusters of feasible solutions corresponding to the 2028 and 2038 technology scenarios. As anticipated, many 2038 configurations capitalize on technological advancements, such as improved engine efficiency, enhanced fuel storage systems, and cost reductions in alternative energy sources. These factors typically result in cost savings and moderate volume reductions. In contrast, the 2028 solutions demonstrate a moderate spatial footprint (approximately 110–130, m^3) but show significant variability in annualized total cost (ranging from €10.0×10^6 to €13.0×10^6). This variability

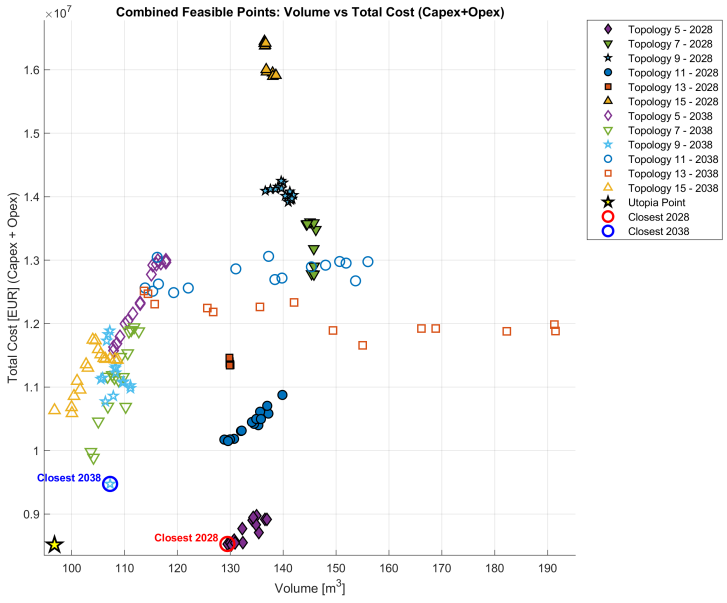
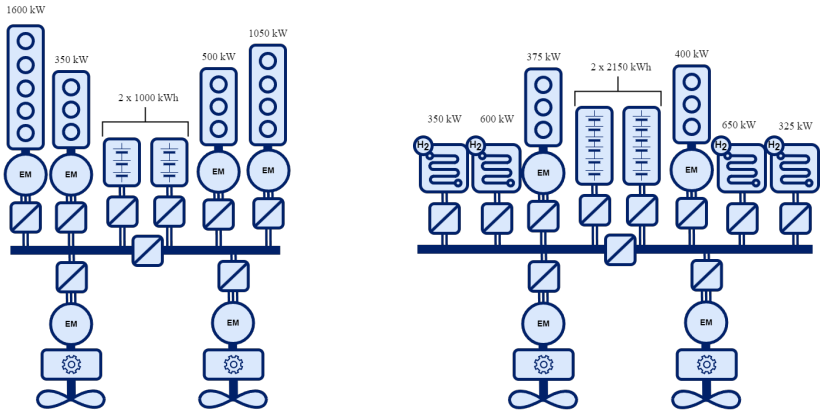


Fig. 10: Analysis of combined feasible solutions showing the trade-off between total annualized cost and system volume for all evaluated topologies in 2028 and 2038. The *Utopia Point* represents the ideal minimum-cost and minimum-volume solution. Points labeled as 'Closest 2028' and 'Closest 2038' indicate the feasible solutions nearest to the Utopia Point for each respective year.

highlights a particularly sensitive cost-volume trade-off region influenced significantly by the selected combination of propulsion and energy-storage components. Notably, specific topologies such as Topology 5 and 11 (2028 scenario) occupy a unique niche with moderate volumes and competitive costs, emphasizing their suitability for immediate implementation within restrictive volume constraints. However, these topologies demonstrate a substantial negative shift in annualized costs moving from the 2028 to the 2038 scenarios, suggesting decreased competitiveness under future technological and economic assumptions.

5.2 Notable Topologies and Cross-Scenario Analysis

To provide a clearer understanding of the shifts in optimal configurations due to technological advancements and changing economic conditions, this section compares in detail the top-performing feasible solutions from the 2028 and 2038 scenarios. The two solutions, Topology 5 (2028) and Topology 9 (2038), were identified based on their minimal Euclidean distance to the hypothetical *Utopia Point* within the normalized cost–volume objective space. Table 2 condenses the



(a) Closest 2028 Point Design. (b) Closest 2038 Point Design.

Fig. 11: Selected optimization solutions

Parameter	**Topology 5 (2028)**	**Topology 9 (2038)**
Dominant fuel	MGO (diesel)	H_2
Prime-mover tech	4 Diesel generators	4 PEM fuel-cell racks
Installed Generator Capacity [kW]	3500	775
Installed Fuel Cell Capacity [kW]	0	1925
Battery energy [kWh]	2000	4300
Number of Major Components	8	10

Table 2: Key configuration parameters of the two solutions.

essential technical attributes of the two leading solutions discussed throughout this section. Detailed schematics of the optimal configurations are presented in Figure 11.

In order to gauge how sensitive each design is to macro-economic uncertainty, we re-evaluated the 2028-optimal configuration (Topology 5) under 2038 fuel prices, efficiency factors and emission levies, and vice-versa. The four corner cases are summarized in Table 3. The comparative analysis across the four scenarios reveals the following significant trends:

1. In 2028, diesel-based Topology 5 offers the lowest system volume (129.4 m^3), thanks to its compact generator footprint and higher energy density fuels. However, by 2038, hydrogen-based Topology 9 achieves a smaller overall volume (107.3 m^3), demonstrating that maturing hydrogen storage and system integration technologies can eventually outperform traditional layouts in spatial efficiency.
2. Initially, diesel systems remain more affordable, with Topology 5 showing a much lower annualized total cost than Topology 9 in the 2028 context

Metric	Topo. 5		Topo. 9	
	2028	2038	2028	2038
Total System Volume [m^3]	129.4	117.4	145.85	107.3
Annualized Total Cost [€]	8.527×10^6	2.239×10^7	1.49×10^7	9.473×10^6
OPEX [€]	2.413×10^6	9.89×10^6	5.29×10^6	1.533×10^6
CAPEX [€]	6.114×10^6	1.25×10^7	9.57×10^6	7.94×10^6

Table 3: Comparative Metrics for Optimal and Cross-Scenario Solutions

(€8.53M vs. €14.9M). However, under 2038 conditions, fuel cells become more competitive. Topology 9's projected total cost (€9.47M) undercuts Topology 5's retrofitted cost (€12.24M) by nearly €3M—a shift driven largely by falling hydrogen fuel prices and OPEX improvements.

3. Diesel-dominated Topology 5 shows a heavy reliance on lower up-front costs (CAPEX = €6.11M in 2028) and correspondingly high OPEX. In contrast, Topology 9's 2038 version inverts this balance: CAPEX rises to €7.94M, but OPEX falls to just €1.53M, suggesting a fundamental shift toward capital-intensive, low-maintenance powertrains in the long run.

Assuming a linear trend between the annualized total costs of the diesel-based Topology 5 and the hydrogen-based Topology 9 reveals a critical economic inflection point around the year 2034. At this crossover, both configurations converge at a projected total cost of approximately €13.1 million. Prior to this point, diesel remains the more economically favorable option, offering lower upfront capital expenditure and manageable operational costs. However, beyond 2031, continued declines in hydrogen fuel prices and improvements in fuel cell system efficiency result in the hydrogen-based configuration becoming more cost-effective on a total cost basis. This transition reflects not only technological maturation but also a shift in the investment paradigm, moving from low CAPEX and high OPEX diesel systems toward capital-intensive but operationally efficient hydrogen solutions by the early 2030s.

5.3 General Outlook and Practical Considerations

The transition from conventional diesel-based PPE systems toward hydrogen-based fuel cell architectures, as modeled between 2028 and 2038, raises not only technical performance questions but also practical challenges related to feasibility, retrofit complexity, and investment risk. From a near-term implementation perspective, the 2028-optimal design (Topology 5) is fully compatible with existing shipyard workflows, using commercially available generators, battery packs, and a conventional electric propulsion layout. The electrical and thermal integration requirements align with class standards and current practice, implying a low technical risk. However, this configuration incurs the highest operational cost over the vessel's life cycle, driven by high fuel consumption and limited zero-emission capability. In contrast, the 2038-optimal design (Topology 9) incorporates emerging technologies such as high-capacity solid-state batteries and

Component/System Change	**Quantity**	**Mass Estimate [t]**
Removal of diesel generators	2.9 kg/kW x 2725 kW	−8
Addition of fuel-cell racks	2.0 kg/kW × 1925 kW	+4
Addition of battery storage	13 kg/kWh × 2,300	+30
Added HVAC and hydrogen piping systems	–	+5
Net additional mass	–	+31 **t**

Table 4: Estimated weight changes during retrofit from Topology 5 to 9.

fuel cells. While fuel cells in the 250–300kW range are approaching Technology Readiness Level 8 [18], scaling these systems to multi-megawatt capacities introduces integration challenges including hydrogen bunkering compatibility, storage system zoning (e.g., LOHC), ventilation requirements, and cold-start logistics. The increased number of major components, along with a more sophisticated EMS, further implies a higher commissioning workload and long-term maintenance complexity.

To assess the retrofit feasibility of transitioning from Topology 5 to Topology 9, a first-order estimation of both weight and cost impacts was carried out. The primary component-level changes are summarized in Table 4.

Using the simplified empirical expression for a large yacht light ship weight detailed in [9],

$$LSD = -377.98 + 1.8295\,(L \times B) \tag{3}$$

where LSD is the light ship displacement [tonnes], L is the overall length [m], and B is ship breadth [m]. A representative lightship displacement of approximately 1750 tonnes is obtained. Therefore, for the case-study mega-yacht, the retrofit adds approximately 1.8% in weight:

$$\frac{31\text{ t}}{1750\text{ t}} = 1.8\% \tag{4}$$

This aligns with literature reports, which place mid-life conversion impacts in the 2–6% range [25]. As such, from a stability and loading perspective, the impacts are likely manageable with minimal overall impacts. A first-order retrofit cost estimate [17] was also performed using:

$$\text{Retrofit Cost} \approx C_{\text{equip}} + \alpha \cdot C_{\text{equip}} + \beta \cdot D \tag{5}$$

where C_{equip} represents equipment costs, $\alpha = 0.5$ is an installation multiplier, $\beta = €20{,}000$ is daily yard cost, and $D = 25$ days. The assumed breakdown is:

- PEM fuel-cell system (2MW): €0.4M
- Battery upgrade (2,300kWh): €2.3M
- Hydrogen-compatible auxiliaries and EMS: €0.7M

Therefore the total expected cost is,

$$C_{\text{equip}} = €3.6 \times 10^6 \quad \Rightarrow \quad \text{Retrofit Cost} = 3.6 + 0.5 \cdot 3.6 + 0.5 = \boxed{€5.9 \times 10^6}$$

This estimate aligns with published benchmarks for mid-life hybrid or fuel conversion retrofits in commercial and high-end recreational vessels [4, 16]. While simplified, it offers a practical planning benchmark during early-phase evaluations. Therefore, the retrofit is technically feasible assuming modular framing and future-proofed switchboard layouts. The required structural allowances fall within conventional design margins.

However, challenges remain: shipyard hydrogen certification may be limited in 2038, and some owners may be unwilling to invest ∼€6M in retrofit CAPEX despite future OPEX benefits. Furthermore, while becoming more accessible, the current infrastructure of green hydrogen is not yet at a level of universal adoption. As such, availability will likely limit the initial possible operations.

In summary, while future PPE topologies offer clear gains in emissions, efficiency, and spatial performance, real-world implementation requires careful staging and lifecycle-aligned investment. Aligning design choices with shipyard readiness, technology maturity, and anticipated regulation is essential to secure both economic and operational value.

6 Conclusions and Outlook

A multi-objective co-design framework is developed and evaluated by designing the PPE system of a vessel with the consideration of a retrofit at the end of first service life. The framework uses MBSE principles in all phases of design starting from defining the operational requirements until the evaluation of the design. To achieve this, a flexible model in combination with a modular EMS is developed that connects to a multi-objective GA optimizer which determines the sizing of all relevant PPE components.

The use of Pareto fronts in this approach allows a designer to weigh out different objectives with each other, while also including practical aspects into the consideration. In case of the studied use case, the latter also refers to choices which can facilitate a more cost-effective retrofit. The initial design for a vessel build in 2028 favors conventional technologies while the balance shifts towards alternate technologies such as fuel cells for the retrofit. While these solutions are compared on the basis of technical feasibility, a more detailed look at the practical feasibility including a techno-economic assessment are planned as future work to enhance the confidence in the approach.

The developed model and EMS utilizes scalable component models fitted against online available data for large maritime engines and generators. A general challenge is noted in the requirement for component data to validate the results from this design process. Future work is planned to develop a library of validated component models to connect to the co-design framework.

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