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Research paper

Sustainable yacht refits: Structural solutions in methanol-powered conversion

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ABSTRACT

In the pursuit of sustainable solutions to reduce carbon emissions, the maritime industry is increasingly focusing on transitioning from fossil fuels to alternative fuels. Methanol offers significant environmental benefits, including Well-to-Wake greenhouse gas emission reductions of 95% with synthetic methanol and 89% with green methanol. Gray methanol can increase emissions by 20% compared to marine diesel oil. Methanol reduces sulfur oxides by 99%, nitrogen oxides by 60%, and particulate matter by 95%. However, its lower energy density requires 75% larger storage volumes to maintain comparable ranges. This study explores retrofitting a 60-meter yacht for methanol propulsion, addressing structural, spatial, and safety challenges associated with converting existing vessels into more environmentally sustainable ships. Key innovations include compact cofferdams, reduced from 800 *mm* to 100 *mm*, and corrugated bulkheads, improving tank efficiency from 0.32 to 0.83 while preserving safety. A Finite Element Model validated the structural integrity of these solutions, confirming their ability to withstand operational stresses while meeting stringent safety standards. Methanol propulsion provides a 23% range reduction compared to diesel, a trade-off balanced by its environmental advantages. This work highlights the interplay between structural modifications, onboard capacity enhancements, and alternative fuels in maritime decarbonization, contributing to more sustainable and responsible yacht transportation.

1. Introduction

Climate change and environmental protection are some of the most debated issues for the future. One significant problem is air pollution caused by greenhouse gas (GHG) emissions. Human activities have caused a global temperature rise of 1 °C since the beginning of the industrial era, with a per-decade increase of 0.2 °C. To avoid reaching a 2 °C increase over the pre-industrial era, reducing greenhouse gas emissions through clean energy production is the challenge of the millennium and can deeply impact our lifestyle (IMO, 2020). With a fleet almost entirely powered by fossil fuels, the shipping sector is responsible for about 3% of total annual human-produced greenhouse gas emissions (Jägerbrand et al., 2019), particularly carbon dioxide (CO_2) (Altosole et al., 2023). With current trends, emissions will increase by 150–250% by 2050, while global trade will triplicate. In contrast, the European Union has set a goal of achieving net zero CO_2 emissions by 2050 to limit global temperature rise to 1.5 °C.

The pleasure craft sector is less significant than the merchant ship sector in terms of number of units, tonnage, and sailing time. However, it hugely influences local pollution, significantly impacting marine protected areas and small water cities. Chartered yachts are increasing their market; therefore, the demand for greener solutions is increasing, primarily due to their specific operating profile. In the future, most ships approaching sensitive coastal areas should be designed to operate in zero/low emission mode.

Over the years, increasingly restrictive International Maritime Organization (IMO) regulations have been enacted to reduce polluting emissions and combat global warming. The regulatory framework is committed to reducing environmental pollution by implementing sustainable industry strategies. Indeed, the massive and steady reduction of GHG emissions is one of the main thrusts of the International Maritime Organization in issuing regulations. Consequently, the industry's approach rapidly changes, focusing on developing low-impact propulsive configurations (Livanos et al., 2014).

In 2015, the Paris Agreement set ambitious and challenging targets to limit greenhouse gas emissions and the rise in the global average

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Abbreviations

$BSEC$	Brake Specific Energy Consumption
FEA	Finite Element Analysis
GHG	Greenhouse gas
IMO	International Maritime Organization
LHV	Lower Heating Value
LNG	Liquefied Natural Gas
MDO	Marine Diesel Oil
$SFOC$	Specific Fuel Oil Consumption
SMC	Specific Methanol Consumption

temperature. In 2018, the International Maritime Organization developed and adopted an Initial Strategy that provides targets, tools, and principles for reducing greenhouse gas emissions from shipping, making decarbonization one of the most urgent issues in a sector strongly linked to fossil fuels.

In 2023, the strategy has been revised with more ambitious goals for decarbonization and zero greenhouse gas emission maritime transport. The European Commission's FuelEU Maritime initiative presents a Well-to-Wake approach to decarbonization. This part of the Fit for 55 package focuses on reducing the GHG intensity of fuels, imposing increasingly restrictive limits and penalties, supporting the adoption of renewable fuels and energy, especially of non-organic origin, and using the onshore power supply (Tadros et al., 2023).

Increasing attention to environmental impact and challenging limits on greenhouse gas emissions requires a radical transformation. The maritime industry and research cooperate to find sustainable and environmentally friendly solutions.

Adopting innovative technologies, transitioning to cleaner fuels, and implementing effective policies can improve the industry's energy efficiency and reduce its environmental impact. Collaboration among all stakeholders is critical to ensure that shipping facilitates global trade in an environmentally responsible manner. Given the complexity and extent of the problem, there is no one-size-fits-all solution. Instead, there is a wide range of possible solutions with different impacts on emission reduction. The impact of battery-powered electric propulsion on reducing GHG emissions is significant. However, the applicability of this type of solution is limited to short navigation, such as might be in inland waters or marine protected areas (Maloberti et al., 2022).

Hybrid systems, in which the battery system is recharged through the generators while sailing, are needed to use batteries in longer-range applications (Al-Falahi et al., 2018; Kanellos, 2013; Belvisi et al., 2024; Maloberti and Zaccone, 2025; Maloberti et al., 2025). Such systems, including those optimized for load management in military applications, provide the flexibility to adapt to different energy mixes. This system is adaptable to different energy mixes, integrating devices such as fuel cells, or employing alternative fuels such as methanol (Maloberti et al., 2024). These configurations aim not to achieve zero emissions but to significantly reduce them.

Due to its unique characteristics, methanol, a widely traded chemical commodity, has recently garnered interest as an alternative marine fuel. Its liquid state in atmospheric conditions offers a significant advantage, making transportation and storage more convenient. However, it is essential to note that methanol has some drawbacks. Its calorific value is about half that of conventional marine fuels, necessitating twice the volume and weight to store the same chemical energy on board. It is also a volatile, colorless gas with a low flash point (12 °C) and is toxic for humans (Ellis and Tanneberger, 2015). Methanol's characteristics allow it to be used in conventional internal combustion engines with some modifications related to the injection and fuel system, and it uses a small amount of pilot fuel. The dual-fuel methanol–diesel technology with methanol injection in the intake has proven to be a promising retrofit solution for vessels (Dierickx et al., 2021). Recent studies highlight the potential of methanol as a sustainable alternative fuel for internal combustion engines (Verhelst et al., 2019), offering benefits such as high efficiency, reduced emissions, and compatibility with renewable production methods (Korberg et al., 2021), with minor economic barriers that can be overcome by strengthening environmental targets or increasing fuel oil prices (Svanberg et al., 2018). Emissions from fuel use can be evaluated by adopting two different approaches. The Tank-to-Wake approach, used by IMO to set limits to the atmospheric emissions of pollutant gases, considers only the emissions produced locally, neglecting everything that occurred before. In contrast, another approach, the so-called Well-to-Wake approach, considers the entire toolchain, from raw material extraction to onboard use. Methanol can be produced from various sources, including fossil products, agricultural waste, biomass, municipal waste, and other environmentally friendly feedstocks. The feedstock used in methanol production is crucial for emission assessment, especially when adopting the Well-to-Wake approach. Methanol is classified based on its feedstock, using a color code: gray methanol when the feedstock is natural gas, brown methanol produced from coal, blue methanol if produced from both fossil and biological feedstocks, and green methanol obtained exclusively from green sources. This category also includes e-methanol from carbon capture. This distinction is significant as the environmental impact varies among different production pathways. The use of green feedstock methanol offers the most significant reduction in GHG emissions, providing a hopeful outlook for the future of marine fuel. The final product from the different feedstocks and production toolchains is identical, so the Tank-to-Wake emissions are the same for everyone.

Considering GHG emissions, if a Tank-to-Wake approach is used, there is a reduction if methanol is used as a fuel. However, if a Well-to-Wake approach is taken, one no longer has this clear distinction. Fossil-based methanol produces similar emissions as marine diesel oil, while methanol produced from coal is even much more impactful. The only option that reduces the carbon footprint is using methanol from green feedstock (Methanol Institute, 2023). Considering emissions of other pollutants, using methanol, a sulfur-free chemical, eliminates 99% of sulfur oxides (SO_x) emissions compared to fossil fuels. This significant reduction in SO_x emissions with methanol use should encourage the audience about its potential for cleaner marine operations. As for nitrogen oxides (NO_x), emissions are still present but reduced by about 60% compared to conventional fuels, and straightforward solutions exist to meet Tier III regulations. Particulate emissions are reduced by about 95% compared to Heavy Fuel Oil. A multi-parametric methodology for assessing the feasibility of alternative-fueled ships has highlighted methanol as a promising alternative, significantly impacting ship design and market strategies and reducing GHG emissions (Adami and Figari, 2024). Recent studies on chemical precooling cycles have explored advanced thermodynamic applications, including the use of methanol as a fuel to improve engine efficiency and reduce emissions (Wang et al., 2021, 2022a,b).

To significantly reduce emissions in the maritime sector, it is crucial to design new ships with reduced emissions and consider converting existing units. Retrofitting offers a viable solution, enabling operating ships to adapt to more sustainable technologies without requiring new construction. This study focuses on retrofitting, essential for making the existing fleet more sustainable and complementing efforts in building new vessels. As of July 2024, there were 5932 superyachts over 30 m, with 63% measuring between 30 and 40 m, and all 5039 motor yachts relying on polluting diesel propulsion (Super Yacht 24 Editorial Desk, 2025). Transitioning these yachts to methanol propulsion requires substantial structural modifications. The study examines structural modifications and range assessment, as no methanol-powered engine currently meets the power requirements for these units. The methodology for calculating the vessel's range involves converting a traditional MDO engine to methanol, assuming the same specific energy consumption for both fuels.

Refitting a yacht from diesel to methanol propulsion necessitates several structural modifications. Firstly, the fuel storage system must be altered to accommodate methanol, which has different properties and storage requirements compared to diesel. This includes the installation of new fuel tanks that are resistant to methanol's corrosive nature and compliant with safety regulations. Additionally, the fuel delivery system, including pumps, filters, and injectors, needs to be replaced or adapted to handle methanol's lower energy density and higher flow rates. The engine itself may require significant modifications or complete replacement with an engine designed for methanol combustion. Safety systems, such as gas detection and ventilation, must also be upgraded due to methanol's higher flammability. Moreover, adjustments to the yacht's control systems and possibly the onboard power management may be needed to ensure optimal performance and integration of the new propulsion system.

This paper explores the structural modifications necessary for refitting a 60-m yacht to methanol propulsion. The study was prompted by a risk assessment conducted in collaboration with classification societies, which highlighted the need for a cofferdam solution with corrugated bulkhead tanks. This design choice aims to minimize the space taken from accommodations and streamline the welding and installation processes of tank bulkheads.

This work presents a significant advancement in sustainable maritime engineering by retrofitting a 60-m yacht to utilize full green methanol propulsion - a notable departure from conventional uses of green fuels limited to generator sets or bi-fuel engines. The retrofit includes innovative solutions like compact, safety-enhanced methanol storage systems and structural modifications to address the challenges of energy density and operational range, highlighting its pioneering role in adapting yachts for comprehensive decarbonization while preserving performance and luxury features. The research focuses on the dimensioning of the bulkhead plating and the gap of the cofferdam. Given the specific requirements of the risk assessment, it was crucial to develop a finite element numerical model to validate the proposed solution. This model provides a detailed analysis of the structural integrity and safety of the design, ensuring compliance with industry standards and performance under various operational conditions.

The paper further discusses the engineering considerations involved in the transition from diesel to methanol propulsion. Methanol's different properties necessitate changes in fuel storage, delivery systems, and engine modifications or replacements. The cofferdam solution addresses the challenges posed by methanol's corrosive nature and higher flammability, incorporating enhanced safety measures such as improved gas detection and ventilation systems.

This comprehensive examination provides valuable insights and a robust framework for future yacht refitting projects aimed at adopting methanol propulsion, highlighting the critical engineering processes and validation methods necessary for successful implementation.

The paper is organized as follows: Section 2 discusses the modifications required for the retrofit, focusing on the design and adaptation of the fuel storage system, including calculating the minimum fuel volume needed to ensure a range of 5000 nautical miles, equivalent to an Atlantic crossing, which would enable the vessel to operate in the Mediterranean Sea during the summer and travel to warmer destinations, such as the Caribbean, in the winter. Section 3 explores the differences in regulations between methanol and diesel propulsion systems, highlighting the regulatory challenges in the maritime industry. Section 4 presents a case study of the yacht retrofit, evaluating the feasibility and performance in terms of fuel consumption and range. Section 5 addresses the scantling of tank plates, ensuring structural integrity and safety in the modified fuel storage system. Section 6 presents the finite element analysis (FEA) used to evaluate the structural design and validate the modifications. Eventually, Section 7 concludes the paper by summarizing the findings, discussing limitations, and suggesting future research directions.

2. Methodology

The ship's range must be considered when converting a diesel-powered vessel to an alternative methanol fuel supply. This is because methanol has a much lower calorific value than diesel fuel, which means that in order to transport the same energy, much more fuel needs to be transported. As a result, it is necessary to reconsider the shipboard layout, increasing the volumes allocated to fuel storage. As highlighted in Section 1, no engines currently utilize methanol as the single fuel or operate with only minimal reliance on pilot fuel. Developing a new yacht project designed exclusively for methanol propulsion would require approximately 5–7 years of lead time. Consequently, retrofitting existing vessels emerges as the only feasible short-term approach to reduce emissions, as detailed further in Section 4 significantly. From a naval architecture standpoint, aside from the necessary replacement of the primary propulsion engine and auxiliary generators, the differences between a methanol-powered system and a conventional propulsion system for high-speed recreational vessels (typically employing fast 4-stroke diesel engines) are relatively minor. The primary design challenge lies in methanol storage due to its corrosive nature, which can compromise fuel tanks and associated systems if not adequately treated. Furthermore, methanol cannot be stored directly with the hull structure to mitigate potential environmental risks during grounding or collision. The criterion adopted in determining the space to be allocated for fuel was to ensure sufficient range to make the Atlantic crossing, i.e. 5000 nm, in order to make it possible to spend the summer in the Mediterranean Sea and move to warmer waters, such as the Caribbean Sea, during the winter. The specific consumption of the methanol-fueled engine has been derived by considering the typical energy consumption of a 4t diesel engine. The energy consumption of the engine was calculated according to the following equation:

$$BSEC = SFOC_{MGO}\ LHV_{MGO} \tag{1}$$

where $BSEC$ represent the Brake Specific Energy Consumption of the engine, $SFOC_{MGO}$ represent the specific MGO consumption, and LHV_{MGO} is the Lower Heating Value of the marine diesel oil. The specific consumption of methanol is then obtained from the following equation:

$$SMC = \frac{BSEC}{LHV_m} \tag{2}$$

where SMC and LHV_m represents the specific methanol consumption, and its lower heating value respectively. To ensure a 5000 nautical miles range, the minimum volume required for the fuel tanks is determined using the following equation:

$$V_{min} = \dot{m}_m\ \rho_m\ t \tag{3}$$

where ρ is the methanol density, t represents the time required to travel 5000 nm at cruising speed, and $\dot{m}_m$ is the methanol mass flow rate, calculated according to the following equation:

$$\dot{m}_m = P_{req}\ SMC \tag{4}$$

where P_{req} is the power required to cruise at the cruising speed, including hotel loads, and SMC is the specific methanol consumption, as determined using Eq. (2).

Well-to-wake GHG emissions are assessed using the following equation:

$$m_{CO_{2\,eq}} = EF_X\ m_X \tag{5}$$

where $m_{CO_{2\,eq}}$ represent the mass of CO_2 equivalent emitted using the generic fuel X, EF_X is the emission factor of the Equivalent CO_2 generated using the generic fuel X, and m_X is the generic fuel X consumption. Emissions assessment is performed for different fuels, and the impacts produced are compared with each other. In particular, it has been evaluated how the impact varies depending on whether Marine Diesel Oil (MDO) or methanol is used, considering different raw materials.

3. Differences in regulations compared to diesel

The design of a yacht using methanol as fuel requires several specific considerations that differ from those of conventional diesel-powered yachts. These include the need for cofferdams around tanks, nitrogen-inerted tanks, and double-walled pipes. Furthermore, to maintain approximately the same range, it will be necessary to enlarge the fuel storage tanks, considering that the lower heating value (LHV) of methanol is slightly less than half that of diesel fuel.

There are already regulations addressing safety standards for low flashpoint fuels such as methanol: The International Code of the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code), International Code of Safety for Ship Using Gases or Other Low-flashpoint Fuels (IGF Code), Lloyd's Register 'Classification of Ships using Gases or other Low-flashpoint Fuels' (Lloyd's Register, 2019) and China Register 'Guidelines for Ships using Methanol and Ethanol Fuels' (China Register, 2022) among others. Generally, these standards regulate the layout of areas and spaces, gas-fueled engines and systems, storage and bunkering arrangements, piping systems, ventilation systems, control systems, electrical equipment, gas detection systems, and the tests or trials required to validate such installations. To date, these regulations are optimized for a certain type of vessel (such as chemical tankers) with very different sizes, purposes, and needs than a recreational yacht. Therefore, it will be necessary to adapt these existing standards to the size of a yacht.

Cofferdams are a safety feature required by current rules and regulations, as explained in the IMO CCC6 guidelines (IMO, 2019): a cofferdam is a structural space surrounding a fuel tank that provides an added layer of protection against external fire, toxic and flammable vapors, and ensures gas and liquid tightness between the fuel tank and other areas of the ship.

In the context of a yacht using methanol as fuel, the cofferdam performs a fundamental function. Its main responsibility is to act as a secondary barrier, ensuring impermeability to gases and liquids, and separating the methanol storage tank from other areas of the yacht. This way, any methanol leakage from the tank is prevented, and gases are kept from spreading into spaces not suitable to safely contain them. Additionally, the cofferdam plays a crucial role in protecting the tank from any fire hazards that might arise in other parts of the yacht and spread toward it, with potentially disastrous consequences. The presence of the cofferdam is mandatory when the methanol storage tank is in contact with other areas of the yacht, except where the tank encounters side or bottom plating panels below the lowest water line and areas dedicated to fuel preparation as shown in Fig. 1.

The size of the cofferdam is determined by its accessibility, as it must be inspectable by a person. The IMO CCC6 guidelines (IMO, 2019) state: for safe access, horizontal hatches, or openings to or within fuel tanks or surrounding cofferdams should have a minimum clear opening of 600 mm × 600 mm that also facilitates the hoisting of an injured person from the bottom of the tank/cofferdam. For access through vertical openings providing main passage through the length and breadth within fuel tanks and cofferdams, the minimum clear opening should not be less than 600 mm × 800 mm at a height of not more than 600 mm from bottom plating unless gratings or footholds are provided. Smaller openings may be accepted, provided the evacuation of an injured person from the bottom of the tank/cofferdam can be demonstrated.

According to IMO regulations, the double bottom is not a suitable area for storing methanol. The presence of the cofferdam is required between the methanol storage tank and other areas of the yacht. This means the cofferdam must be positioned both inside and above the tank, resulting in a loss of space inside the double bottom for its construction. Consequently, the double bottom is not only impractical from a construction point of view (as it would be difficult to weld in those areas) but also inefficient from a volumetric perspective. As evidenced by the above regulations, there are many provisions focused on detecting and containing any methanol leaks, whether in liquid or gaseous form. This containment is of utmost importance since methanol vapors tend to 'float' in the air, making it difficult to confine them in a safe place that does not pose a risk to persons on board. The presence of the cofferdam provides additional security as a secondary barrier around the methanol storage tanks; however, valuable space within the yacht must be utilized.

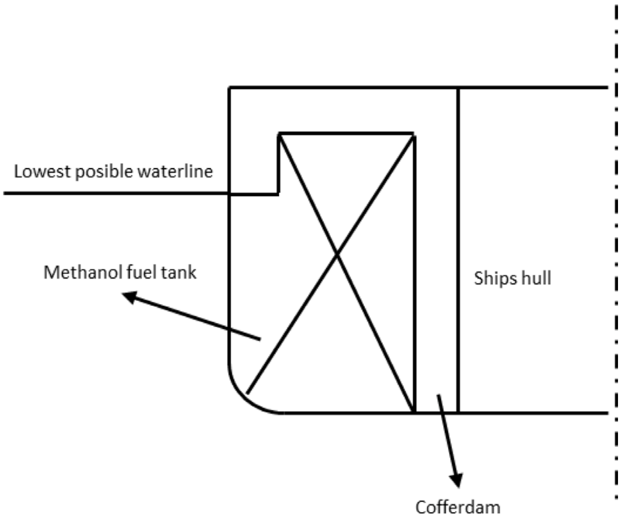


Fig. 1. Placement of the cofferdam.

4. Case study

Spaces on board a pleasure vessel are extremely valuable, especially in luxury areas, as these are what guests desire and are willing to pay for. Each additional space dedicated to storage or energy conversion leads to an increase in the technical area, which in turn reduces the space available for guests. Therefore, the spaces and volumes available for fuel storage are limited. In the case of methanol as fuel, the volume available for fuel is the net capacity of the tanks, excluding the volume occupied by the cofferdams. The yacht examined for this paper is a 64-m yacht with a steel hull and aluminium superstructure and a volume of 1500 GT.

It is powered by two diesel engines, pushing it up to 16 knots. The capacity of the diesel tanks is 175 m^3. It was necessary to carefully analyze the spaces on board to identify areas that could be converted into tanks as shown in Fig. 2.

As previously discussed, current rules and regulations require the presence of a cofferdam around methanol tanks, with a current size of 800 mm according to Lloyd's Register guidelines for methanol-fueled ships. However, this arrangement can be problematic on a pleasure yacht, especially in the case of retrofit solutions. While on large commercial vessels the size of the cofferdam is relatively small compared to the overall size of the ship, on a pleasure yacht, especially a medium-sized one, the size of the cofferdam can be considerable, taking up space that could otherwise be allocated to accommodation or luxury areas. In this context, an alternative to the traditional cofferdam is a significant aid in the design of a methanol-powered yacht, allowing optimized use of interior spaces.

For projects that deviate from existing rules and regulations, or for innovative design solutions for which no precise guidelines yet exist, a design approach based on risk analysis must be adopted. This methodology requires a thorough assessment of the associated risks. Through this analysis, safe and efficient design solutions can be developed, while ensuring compliance with relevant safety standards and reducing the impact of the cofferdam on the yacht's interior layout. The designer must prove that the proposed solution guarantees a level of safety equivalent to standard rules and regulations.

Although a detailed risk analysis is not the primary focus of this paper, it is essential to consider how alternatives to the traditional cofferdam could influence yacht design. The size of the cofferdam is currently limited by the requirement that it must be accessible for internal inspection by a person. If a solution could be devised to remove this accessibility requirement, the cofferdam size could be significantly reduced, allowing for more efficient use of space. Lloyd's Register's Rules and Regulations for the Classification of Ships Using Gases or Other Low Flashpoint Fuels provide an interesting point of Ref. Lloyd's Register (2020). These regulations specify that LNG-fueled vessels with independent Type C tanks do not require secondary barriers such as cofferdams. This provision is based on the robust containment capabilities of these tanks and highlights how, under certain circumstances, alternative solutions can ensure safety and compliance without negatively impacting interior space. Applying these principles to methanol tanks provides a pathway for innovative and practical design adaptations. The rationale for these design changes is supported by a risk analysis that focuses on key considerations such as safety, space optimization, and compliance with classification standards. This paper are interesting for understanding the design process concerning LNG tank regulations and risk analysis methodologies in maritime contexts (Margulies, 1982; Peng et al., 2022; Wang et al., 2024).

While this paper does not delve into the full details of the risk assessment, the analysis evaluated scenarios including fuel leaks, fire hazards, and the structural integrity of the containment system under extreme conditions. To address these risks, the proposed alternative cofferdam incorporates a monitoring system with sensors strategically positioned between the inner and outer walls. This approach ensures real-time safety monitoring, drawing on the practices established for LNG tanks, while adapting them to methanol's unique properties. Methanol tanks do not require cryogenic containment and have a higher flashpoint than LNG, which makes them less hazardous. As a result, adopting a design approach similar to LNG tanks is feasible and advantageous. The alternative cofferdam is also designed to meet Lloyd's Register's requirement for A-60 fire protection, which specifies that the system must withstand fire exposure for at least 60 min. This can be achieved by using sufficient thermal insulation and enclosing connections and valves within a protective box. These measures allow the cofferdam to be smaller and more compact, significantly reducing its impact on the yacht's interior layout while maintaining safety and compliance. By leveraging the insights provided by LNG tank regulations and incorporating findings from the risk analysis, this approach demonstrates how innovative design solutions can balance safety, regulatory compliance, and spatial efficiency.

The structural feasibility of a smaller cofferdam is crucial. An option would be to build the cofferdam first and then the methanol tank from the inside, using more generous space to facilitate processing. The size of the alternative cofferdam, chosen as a reasonable value of 100 mm, is crucial to the correct development of the design, as it directly influences the tank volumes and range of the yacht.

Considering the cofferdam that would have to be implemented according to Lloyd's standards, the overall usage factor would be 0.32, while considering the alternative cofferdam solution (i.e., 100 mm instead of 800 mm) the usage factor rises to 0.83, thus significantly increasing the efficiency of the tank deck. Certainly, working on a boat that has already been designed and built poses very big challenges, and it may not be economically worthwhile to make such changes. Designing from scratch a boat that will be powered by methanol is perhaps less complex as it will be the result of a careful and targeted design, aimed at reducing the number of tanks as much as possible, to minimize interruptions, pipes, valves, and filters. To complete the analysis related to onboard volumes that will be occupied by methanol, a comparison of autonomies was conducted considering the original layout (with MDO) and our proposed layout (with methanol). The reference power values were provided by the shipyard for two speeds: the ship's typical cruising speed, i.e., 12 knots, and a reduced speed, called economic transfer speed, of 9 knots. For prime mover power, a 20% sea margin was considered, while for hotel power, an electrical efficiency of 0.98 was assumed. The methodology detailed in Section 2 has been employed to assess the expected autonomy range for the new configuration. The specific fuel consumptions of the prime mover and generators have been assumed constant. Table 1 present the specific consumptions for the prime mover and generators using methanol as fuel. Tables 2 and 3 display the volumes and range achieved for the two propulsion configurations: conventional and methanol-powered. When using methanol, the range in nautical miles is reduced by approximately 23%, while the fuel tank volume increases by about 75% (from 175 m^3 to 306 m^3). To meet the typical operational requirements of this ship category, a substantial increase in fuel tank capacity is necessary to maintain an acceptable range.

Table 1

Main engine(ME) and generator sets (G) specific consumption.

LHV_{MGO} [MJ/kg]	LHV_m [MJ/kg]	$SFOC_{MGO,ME}$ [g/kWh]	SMC_{ME} [g/kWh]	$SFOC_{MGO,G}$ [g/kWh]	SMC_G [g/kWh]
42.6	19.7	235	508	240	519

To compare the impact due to the use of different fuels, marine diesel oil and three different types of methanol have been considered:

- Gray methanol refers to methanol produced by steam methane reforming;
- Green methanol indicates methanol produced using the steam reforming process of bio-methane (Steam bio-methane reforming SBR);
- E-methanol indicates synthetic methanol produced using renewable energy.

The emission factors of the different fuels are shown in the Table 4.

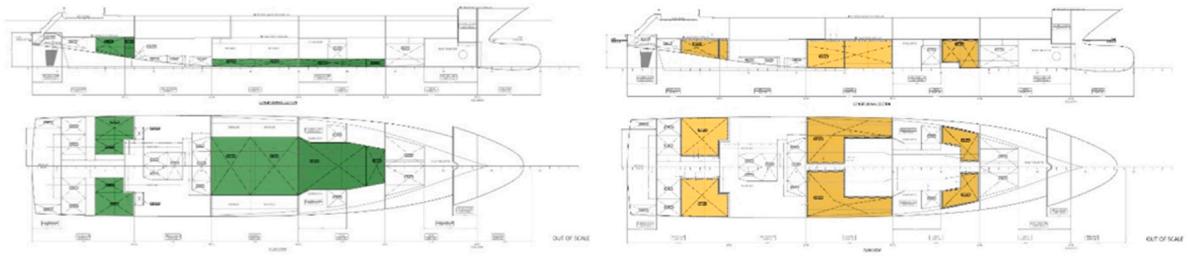
Fig. 3 shows the results obtained considering the ocean crossing of 5000 nm on which the fuel tank has been sized at 12 knots. Emissions produced using the three types of methanol considered are represented as a percentage variation from emissions produced using MDO. Fuel consumption is calculated using one of the following equation, depending on the considered fuel:

$$\begin{aligned} m_{MDO} &= \int_{t=0}^{T} (P_B^{ME}\ SFOC_{ME} + P_B^{G}\ SFOC_G)\, dt \\ m_{methanol} &= \int_{t=0}^{T} (P_B^{ME}\ SMC_{ME} + P_B^{G}\ SMC_G)\, dt \end{aligned} \tag{6}$$

where $t = 0$ is the initial time-instant and T is the final time-instant. The Equivalent CO_2 emissions are calculated using Eq. (5).

The most significant reduction is achieved by using synthetic methanol (−95%). A significant reduction of 89% is similarly obtained using methanol produced by steam bio-methane reforming. In contrast, due to the impactful production process, using methanol produced by steam methane reforming results in an increase in emissions of about 20%.

Considering the significant changes made to the vessel's capacity plan, it was appropriate to conduct a preliminary stability and trim verification. These changes in capacity plan were made with the aim of maintaining, as far as possible, the original ranges of the diesel-powered vessel. This approach provides an initial assessment of the stability and trim of the vessel. Although it cannot provide absolute accuracy, it does delivers preliminary and useful information on the preservation of good stability and trim of the vessel after modifications are made. It has been necessary to develop a hydrostatic curves table, which provides useful geometric values of the hull as the draught changes, in this case considering immersion ranges from 0 to 4.1 [m] with 0.1-m increment. Once the stability of the boat in calm water was assessed, the trim was evaluated considering the vessel with the new capacity



(a) Original layout (b) Alternative layout

Fig. 2. Case-study ship tank layout.

Table 2
Ranges considering MGO.

	Main engines		Generators							
V_s [Kn]	$P_{B\,tot}$ [kW]	$SFOC$ [g/kWh]	$P_{B\,tot}$ [kW]	$SFOC$ [g/kWh]	$C.P.H.$ [kg/h]	ρ [kg/m^3]	$C.P.H.$ [l/h]	V_{tanks} [m^3]	$H.R.$ [h]	$M.R.$ [nm]
9	360	235	193.9	240	131.1	850	154.3	175.11	1032.7	9294.2
12	840	230	234.7	240	249.5	850	293.6	175.11	542.7	6512.4

Table 3
Ranges considering methanol.

	Main engines		Generators							
V_s [Kn]	$P_{B\,tot}$ [kW]	$SFOC$ [g/kWh]	$P_{B\,tot}$ [kW]	$SFOC$ [g/kWh]	$C.P.H.$ [kg/h]	ρ [kg/m^3]	$C.P.H.$ [l/h]	V_{tanks} [m^3]	$H.R.$ [h]	$M.R.$ [nm]
9	360	512	193.9	521	285.3	790	361.2	306.2	805.4	7248.5
12	840	508	234.7	519	548.7	790	694.5	306.2	418.8	5026.1

Table 4
Well-to-Wake emission factors.

Short name	Technology	WtW - EF
MDO	–	3.87
Gray Methanol	SMR	11.7
Green Methanol	SBR	0.2
E-methanol	Synthetic	0.09

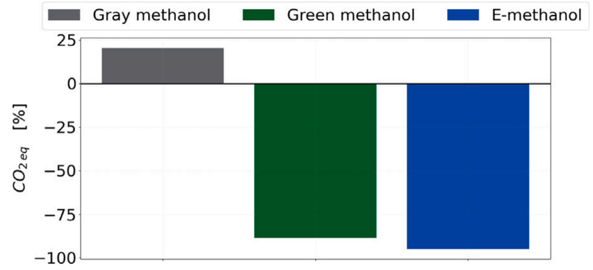


Fig. 3. GHG emissions variation compared to MDO.

plan and more than three hundred cubic meters of methanol embarked. Both longitudinal trim angle and transverse metacentric height (GM T, Table 5) were evaluated. After trim verifications, a study of the ship's stability behavior in response to potential heeling moments was undertaken. These phenomena may result from factors such as wind or wave action, the presence of a hanging load, or a high-speed turn. To assess the stability behavior, the value of the stability arm and the area subtended by its curve, known as the ship's stability reserve, are studied. The difference between the two stability arm curves turns out to be minimal, an indication that this variation in the capacity plane does not substantially affect the stability of the ship, at least in first analysis. Although the huge change in the capacity plan, the stability characteristic of the vessel, both in departure, mid-range and arrival loading conditions, have not suffered a significant variation.

Table 5
GM_T [m] evaluation.

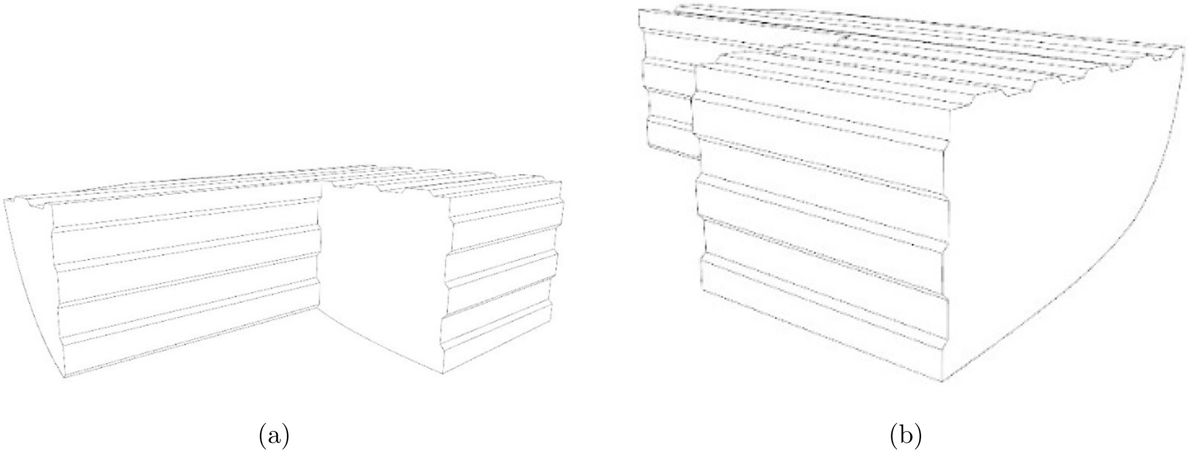
	Departure	Mid-range	Arrival
MGO-powered	1.65	1.49	1.34
Methanol-powered	1.70	1.39	1.35

5. Scantling of tank plates

Once the layout of the cofferdams has been assumed, direct scantling calculations must be performed both on bulkheads that form the cofferdam itself and on the plates of the tanks with the material AH36 steel, before moving on to finite element analysis. The methanol containment system utilizes structural cofferdams that extend the full height of the under lower deck and, in some areas, extend in width to the middle of the ship, leaving a central space of about 800 mm to install a passageway. Unlike traditional diesel containment tanks, which are typically located within the double bottom, these tanks extend much higher as the double bottom alone is not feasible for the reasons previously discussed.

Corrugated sheets have been chosen over traditional flat sheets due to practical design considerations and lightweight (Aguiari et al., 2022). The tank is protected by a cofferdam placed at 100 mm in every direction, making it impossible to weld any vertical reinforcements from the inside of the cofferdam. Therefore, the traditional flat reinforced sheet is replaced with a corrugated sheet, whose shape eliminates the need for vertical reinforcements as shown in Fig. 4. Consequently, the tank is composed mostly of corrugated sheets, which are welded to the bottom panels using asymmetrical corner welds. These welds require an X-ray check to verify penetration. Depending on the specific case, the use of a backing plate and performing a double weld could be considered.

The scantling of the corrugated sheets was conducted in accordance with IACS standards (IACS standard, 2004) and compared with a direct calculation using a triangular acting load. From these calculations, the



(a) (b)

Fig. 4. Mid methanol tank.

Table 6
Corrugated bulkhead scantling comparison.

Triangular-shaped load	IACS prescription	Adopted
W_{min} [cm^3]	W_{min} [cm^3]	W_{min} [cm^3]
89.9	56.2	136.8

minimum section modulus value of the steel plate, as well as the minimum thickness value, were determined. The calculations considered the worst-case scenario: a water head of 3.4 m, corresponding to the maximum height of the tank, rather than methanol. Since water is heavier than methanol, the worst-case scenario for the ship would involve the breaking of the sidewall around the tanks, resulting in methanol spilling into the sea and a progressive filling of salt water. In the scantling of tank plates section, it is noted that the plates are subject to worst-case load scenarios (Gaiotti and Rizzo, 2012; Brush et al., 1975; IACS, 2023) including pressures due to water and methanol, which could induce bending and compressive stresses. A buckling analysis could strengthen the justification for the structural design, particularly when considering the efficiency of corrugated plates in resisting such stresses. Specifically, such an analysis could validate the plates' ability to prevent buckling under combined loads, ensuring that they meet safety and performance standards. The comparison revealed that the section modulus evaluated using direct sizing with a triangular acting load is higher than that prescribed by IACS standards. The difference in the calculation of the minimum section modulus lies in the different evaluations of the bending moment acting at the end of the beam, as shown in Table 6. In the case of the triangular load, the standard formula of structural mechanics is used. In contrast, the IACS method evaluates the bending moment by considering the force acting on the corrugation due to the sea water head.

The minimum required thickness is 2.75 mm. However, to ensure a robust safety margin, the thickness was increased to 5 mm, providing additional resilience against uncertainties such as dynamic fuel sloshing or accidental impacts. This thickness also facilitates better weldability, as thinner plates could pose challenges during welding, potentially compromising the structural integrity and seal of the tanks. Moreover, using 5 mm plates accommodates worst-case scenarios, such as saltwater ingress in the event of a tank breach, by withstanding the associated higher pressures. The uniform thickness simplifies manufacturing, inspection, and assembly, ensuring consistent performance across the tank. Additionally, given methanol's corrosive nature, the thicker plates enhance durability and extend the service life of the system, reducing the need for frequent maintenance. Not all plate can be corrugated because it would complicate welding the connection areas between horizontal and vertical sheets (Poggi et al., 2019), as shown in Fig. 4.

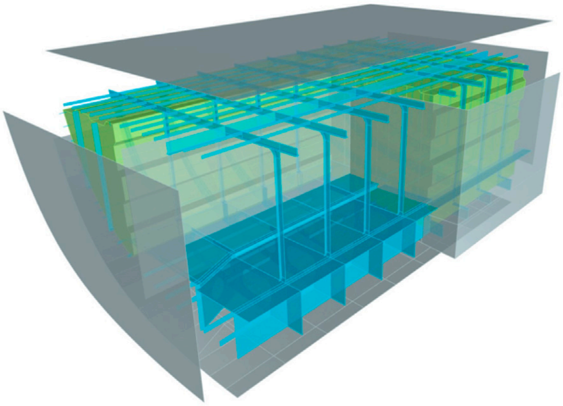
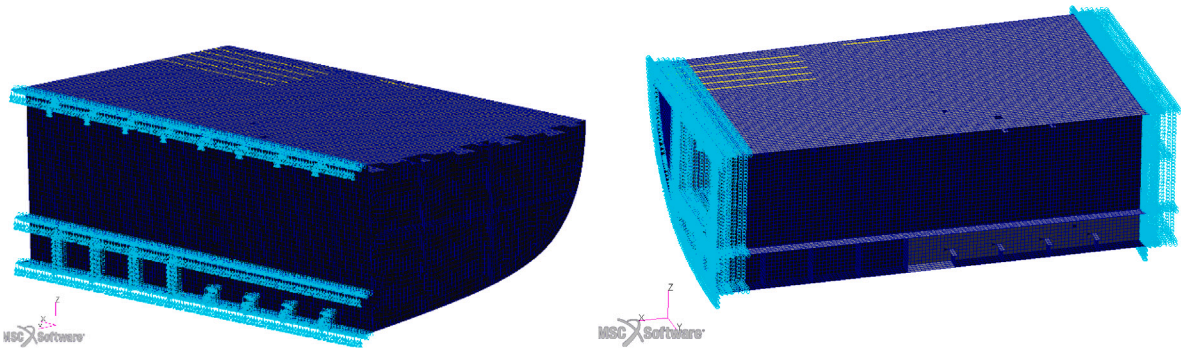


Fig. 5. Amidship tank and surrounding cofferdam.

Therefore, corrugated plates have been selected for those that primarily extend horizontally and vertically, while traditional flat sheets are used to 'close' the tank transversely.

The compartmentalization of the vessel's cargo area is achieved using watertight bulkheads reinforced with vertical profiles. These structural elements are not subject to global loads as they are transverse structures, allowing their dimensioning to be evaluated considering only local loads. Structural dimensioning was performed using the simply supported beam model. The concept of structural hierarchy was employed to define loads and constraints for each beam, as the ship structures are designed as grids with beams of various sizes and functions. For the plating panels, it is assumed that the secondary beams provide a constraining function, so the panel is embedded on the long side in the longitudinal direction of the secondary weighted structural area and element. The dimensioning of the panels is independent from the width of the weighted area and focuses on defining the thickness. The minimum thickness t required to ensure that the acting stress does not exceed the maximum permissible stress of the material σ_{adm} is assessed. The dimensioning of beams involves determining the minimum section modulus so that the maximum acting stress does not exceed the permissible stress. The effective width must also be considered in the resistance section. Certain sheets must necessarily be flat to facilitate installation without resorting to complex construction methods that can lead to errors and malfunctions. For example, the sizing for one of the flat sheets of the tanks located amidships is shown. In this case, the sheet is reinforced with three primary vertical stiffeners and four secondary vertical stiffeners, resulting in eight plating panels as shown in Fig. 4.



(a) Simmetry boundary condition (b) Bulkhead constraint

Fig. 6. Boundary conditions.

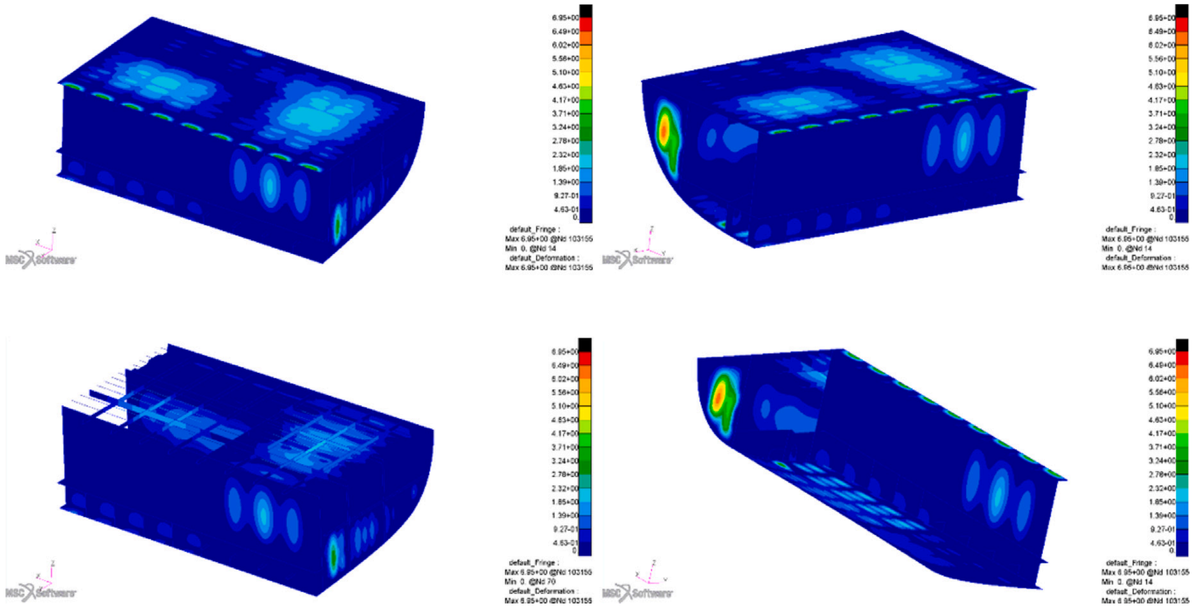


Fig. 7. Displacements: Translational results.

As a result of the scantling, the thickness of all plates, both flat and corrugated, will be 5 mm. Flat plates are provided with appropriately dimensioned reinforcements, whereas corrugated plates do not require them. Additionally, the vessel was originally fitted with a longitudinal bulkhead consisting of primary and secondary vertical stiffeners, likely dimensioned to withstand a high-water head in the event of damage.

Modifications have been made due to the tank's non-constant width, necessitating the installation of additional partial bulkheads to create a cofferdam that encloses the tank. These modifications were essential to achieve a shell that entirely covers the tank, except for the side and bottom areas where the plating panels are in contact with seawater as shown in Fig. 5. This additional safety layer comprises various structural components: the lower deck, the existing longitudinal bulkhead, the newly added bulkheads, and the two transverse watertight bulkheads.

The modifications are designed so that the reinforcements lie perfectly within 100 mm of the width/height of the cofferdam, or 200 mm in the corrugation areas, with the corrugation height being 100 mm. From a practical standpoint, the assembly process involves installing the tank plate by plate once the lower deck with its reinforcements and the longitudinal bulkhead with its vertical stiffeners are already in place. This allows for working from the inside of the tank, which is very large and facilitates riveting, welding, or both, the tank sheets to the vertical stiffeners' flange and deck girders' flange, which are external to the tank but inside the cofferdam. After conducting direct calculations to assess the structural integrity, a finite element analysis (FEA) was required to verify that the dimensioning is appropriate. This analysis ensures that the global stresses remain below permissible levels and that deformations stay within acceptable thresholds.

6. Finite element analysis

The numerical model of the tanks with the portion of the hull between two watertight bulkhead is performed as shown in Fig. 6. The plate and the reinforced beam are modeled by shell element instead the common stiffener by beam element. The applied loads are water head acting on the side and bottom structures and plating panel, methanol head acting on the same structures but with opposite direction. Then there is one-meter water head acting constantly on the lower deck panels and structure, to simulate a crowd on the deck, or a leakage; then a 0.5-m water head acting on the top part of the tanks has been accounted, simulating fuel sloshing phenomenon. Regarding the boundary conditions, a symmetry boundary condition with respect to the y-axis is applied to all elements, as illustrated in Fig. 6(a). Additionally, all degrees of freedom of the nodes corresponding to the bulkhead are fixed, as shown in Fig. 6(b).

The results are promising as both the deformation (Fig. 7) and the Von Mises stress levels (Fig. 8) are acceptable. The maximum

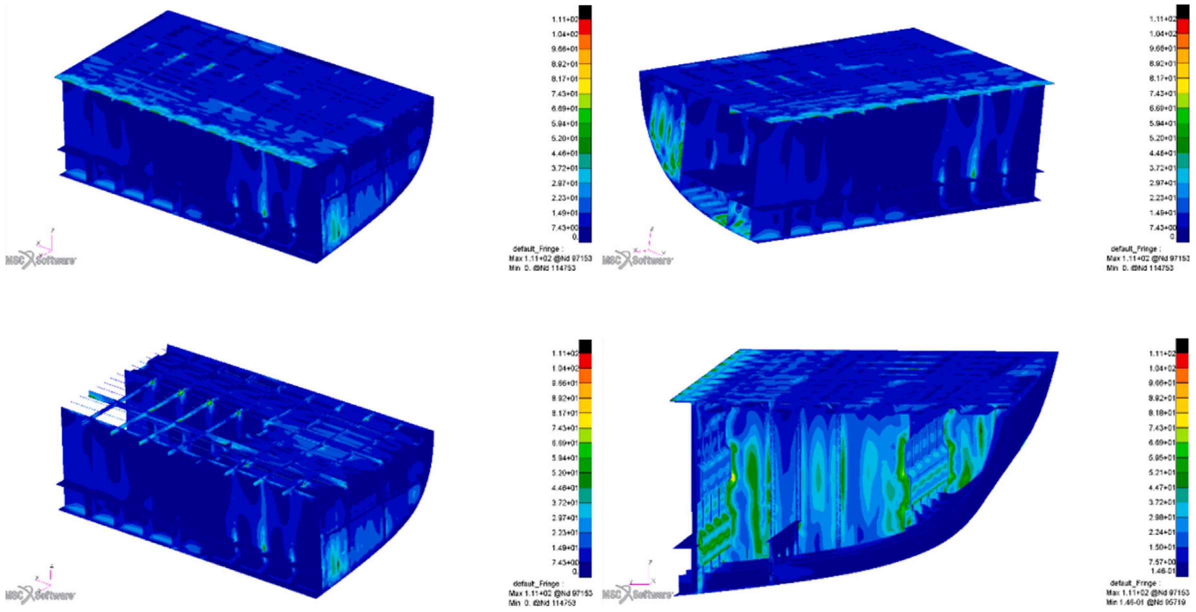


Fig. 8. Stress tensor, Von Mises.

displacements, in the order of approximately 7 mm, occurs at the two partial transverse sheets that has been introduced. The displacements of the side and bottom plating panels are also in line with what was expected, with a maximum intensity in the order of 3 mm at the ship's bottom panels.

The maximum equivalent stress value is around 111 MPa, which is well below the permissible stress limit, which has been considered the 75% of the yield stress of AH36 steel, which is approximately 265 MPa.

7. Conclusions

Methanol can be used in internal combustion engines and fuel cells. Although it poses significant risks to human health, its complete miscibility in water is a notable advantage. Currently, the majority of methanol produced is derived from fossil fuels such as coal and natural gas, which does not contribute to CO_2 reduction. The IMO's target to reduce CO_2 emissions by 50% by 2050 compared to 2008 levels necessitates the large-scale production of green methanol. Without this shift, the use of gray methanol will continue to generate considerable greenhouse gases.

In considering the decarbonization process, it is essential to evaluate both the energy converter's emissions and the fuel's production methods. If large-scale production of green methanol, particularly through CO_2 capture, becomes feasible, it could serve as a low-environmental-impact fuel. However, stakeholders need incentives to adopt this currently expensive and scarcely available fuel. The conversion of bunkering plants to methanol is feasible with minor modifications, as methanol is a liquid at ambient temperature and pressure, similar to MGO.

This study demonstrates the feasibility of retrofitting a 60-m yacht for methanol propulsion, highlighting the trade-offs between environmental benefits and operational constraints.

Methanol propulsion results in a 23% reduction in range compared to diesel, while the required fuel tank volume increases by approximately 75% (from 175 m^3 to 306 m^3). While adopting methanol as fuel reduces the vessel's range, the ship can still complete the Atlantic crossing, representing one of the study's key objectives. The design modifications implemented have effectively ensured that the vessel can meet this requirement despite the reduced range. However, innovations such as the adoption of a compact cofferdam (100 mm instead of the standard 800 mm) significantly improve tank efficiency, increasing the usage factor from 0.32 to 0.83. Finite Element Analysis confirms the structural integrity of the design, with maximum deformations of 7 mm and stresses well within safety limits (111 MPa compared to a permissible limit of 265 MPa). The environmental benefits vary significantly depending on the type of methanol used. Using green methanol (e.g., from bio-methane reforming) can reduce well-to-wake greenhouse gas emissions by up to 89%, while synthetic methanol (e-methanol) offers the most substantial reduction, reaching 95%. Conversely, gray methanol, derived from steam methane reforming, results in a 20% increase in emissions compared to marine diesel oil, highlighting the importance of sustainable feedstock choices in maximizing the benefits of methanol propulsion.

While this paper focuses on structural aspects, other considerations such as auxiliary systems, fire-fighting systems, management and control systems, and issues related to damaged ships require further investigation. Additionally, dynamic analyses are needed due to changes in mass and weight distribution, which affect the ship's natural frequencies. New analyses of vibrations and on-board comfort will also be necessary. Regulations require the cofferdam to be ventilated with a specified number of air changes per hour or saturated with nitrogen under light pressure. Currently, pressurized nitrogen is preferred to avoid methanol vapors and internal condensation. Nitrogen flow rate into the tanks will match the methanol consumption rate by the engines, maintaining a light pressure to prevent contact between methanol vapors and oxygen. A comprehensive risk assessment must be submitted to the Register for certification of the structures and auxiliary equipment. Based on the performed work and achieved results, the design of a methanol-powered boat is structurally feasible. This is particularly true for new vessels, as retrofitting existing vessels with larger tanks may disrupt existing accommodations and prove commercially unviable for recreational vessels.

Further research is needed to explore the potential, capability, and willingness of large companies to produce and market green methanol at a profitable price. Additionally, collaboration between Classification Societies and shipyards is expected in the coming years to establish precise regulations tailored to the needs of recreational vessels, distinct from those for merchant ships.

CRediT authorship contribution statement

Federico Basciu: Writing – original draft, Software, Methodology, Conceptualization. **Giorgio Casali:** Writing – original draft, Software,

Methodology, Conceptualization. **Luca Maloberti:** Writing – original draft, Methodology, Data curation, Conceptualization. **Tatiana Pais:** Writing – review & editing, Supervision, Software, Project administration, Methodology, Data curation, Conceptualization. **Gianmarco Vergassola:** Writing – review & editing, Supervision, Software, Project administration, Methodology, Formal analysis, Conceptualization. **Raphael Zaccone:** Writing – review & editing, Supervision, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Adami, G., Figari, M., 2024. Multi-parametric methodology for the feasibility assessment of alternative-fuelled ships. J. Mar. Sci. Eng. 12 (6), 905.

Aguiari, M., Gaiotti, M., Rizzo, C., 2022. Ship weight reduction by parametric design of hull scantling. Ocean Eng. 263, 112370.

Al-Falahi, M.D., Nimma, K.S., Jayasinghe, S.D., Enshaei, H., Guerrero, J.M., 2018. Power management optimization of hybrid power systems in electric ferries. Energy Convers. Manage. 172, 50–66.

Altosole, M., Balsamo, F., Mocerino, L., Scamardella, F., 2023. Methanol fuelled hybrid propulsion system for a charter yacht. In: 2023 International Conference on Clean Electrical Power. ICCEP, IEEE, pp. 810–817.

Belvisi, D., Maloberti, L., Zaccone, R., Figari, M., 2024. Battery energy storage system sizing strategy for naval vessels through multi-objective optimisation. Proc. Int. Ship Control Syst. Symp. 2024, http://dx.doi.org/10.24868/11140.

Brush, D.O., Almroth, B.O., Hutchinson, J., 1975. Buckling of bars, plates, and shells.

China Register, 2022. Guidelines for Ships using Methanol and Ethanol Fuels. Technical Report.

Dierickx, J., Verbiest, J., Janvier, T., Peeters, J., Sileghem, L., Verhelst, S., 2021. Retrofitting a high-speed marine engine to dual-fuel methanol-diesel operation: A comparison of multiple and single point methanol port injection. Fuel Commun. 7, 100010.

Ellis, J., Tanneberger, K., 2015. Study on the use of ethyl and methyl alcohol as alternative fuels in shipping. Eur. Marit. Saf. Agency 46, 1–38.

Gaiotti, M., Rizzo, C.M., 2012. An analytical/numerical study on buckling behaviour of typical composite top hat stiffened panels. Ships Offshore Struct. 7 (2), 151–164.

IACS, 2023. Buckling Strength Assessment of Ship Structural Elements. Technical Report, URL: https://www.classnk.or.jp/hp/pdf/info_service/iacs_ur_and_ui/ur_s35_new_feb_2023.pdf.

IACS standard, 2004. Evaluation of Scantlings of Corrugated Transverse Watertight Bulkheads in Bulk Carriers Considering Hold Flooding. Technical Report.

IMO, 2019. Draft Interim Guidelines for the Safety of Ships Using Methyl/ethyl Alcohol as Fuel. Technical Report.

IMO, F.I., 2020. Greenhouse gas study. Exec. Summ. Final. Rep..

Jägerbrand, A.K., Brutemark, A., Sveden, J.B., Gren, M., 2019. A review on the environmental impacts of shipping on aquatic and nearshore ecosystems. Sci. Total Environ. 695, 133637.

Kanellos, F., 2013. Optimal power management with GHG emissions limitation in all-electric ship power systems comprising energy storage systems. IEEE Trans. Power Syst. 29 (1), 330–339.

Korberg, A.D., Brynolf, S., Grahn, M., Skov, I.R., 2021. Techno-economic assessment of advanced fuels and propulsion systems in future fossil-free ships. Renew. Sustain. Energy Rev. 142, 110861.

Livanos, G.A., Theotokatos, G., Pagonis, D.-N., 2014. Techno-economic investigation of alternative propulsion plants for Ferries and RoRo ships. Energy Convers. Manage. 79, 640–651.

Lloyd’s Register, 2019. Rules for the Classification of Methanol Fuelled Ships. Technical Report.

Lloyd’s Register, 2020. Rules and Regulations for the Classification of Ships using Gases or other Lowflashpoint Fuels. Technical Report.

Maloberti, L., Adami, G., Figari, M., Zaccone, R., 2024. Evaluating alternative fuels and power systems for marine hybrid propulsion. Adv. Marit. Technol. Eng., Vol. 2 45 – 53. http://dx.doi.org/10.1201/9781003508779-5.

Maloberti, L., Zaccone, R., 2025. An environmentally sustainable energy management strategy for marine hybrid propulsion. Energy 316, http://dx.doi.org/10.1016/j.energy.2025.134517.

Maloberti, L., Zaccone, R., De Gaetano, J., Campora, U., 2025. A comparison among innovative hybrid propulsion systems to reduce the environmental impact of a small passenger ship. Sustain. Energy Technol. Assess. 75, http://dx.doi.org/10.1016/j.seta.2025.104194.

Maloberti, L., Zaccone, R., Gualeni, P., Mazzucchelli, P., 2022. A Zero-Emission Ferry for Inland Waterways. Prog. Mar. Sci. Technol. 6, 162–169. http://dx.doi.org/10.3233/PMST220021.

Margulies, T.S., 1982. Risk analysis of liquefied natural gas transport. Energy 3, 4.

Methanol Institute, 2023. Marine Methanol: Future-Proof Shipping Fuel. Technical Report.

Peng, S., Zhou, D., Xie, B., 2022. Analysis of LNG storage tank safety: a comprehensive model approach with ANP and normal cloud. Appl. Sci. 12 (23), 11941.

Poggi, L., Gaggero, T., Gaiotti, M., Ravina, E., Rizzo, C.M., 2019. Robotic Inspection of Ship Structures: How to fill the gap between available technologies and current survey practices? In: Proc. IMEKO TC-9 International Workshop on Metrology for the Sea.

Super Yacht 24 Editorial Desk, 2025. Super Yacht 24 accelerates with over 433,000 page views and 201,000 users in 2024. SuperYacht24 URL: https://www.superyacht24.it/2025/01/08/super-yacht-24-accelerates-with-over-433000-page-views-and-201000-users-in-2024/.

Svanberg, M., Ellis, J., Lundgren, J., Landälv, I., 2018. Renewable methanol as a fuel for the shipping industry. Renew. Sustain. Energy Rev. 94, 1217–1228.

Tadros, M., Ventura, M., Soares, C.G., 2023. Review of current regulations, available technologies, and future trends in the green shipping industry. Ocean Eng. 280, 114670.

Verhelst, S., Turner, J.W., Sileghem, L., Vancoillie, J., 2019. Methanol as a fuel for internal combustion engines. Prog. Energy Combust. Sci. 70, 43–88.

Wang, Y., Cha, Z., Liang, G., Zhang, X., Li, K., Guan, G., 2024. Risk assessment of LNG bunkering vessel operation based on formal safety assessment method. Process. Saf. Prog..

Wang, C., Cheng, K., Qin, J., Shao, J., Huang, H., 2022a. Performance comparison of three chemical precooled turbine engine cycles using methanol and n-decane as the precooling fuels. Energy 249, 123606.

Wang, C., Dang, C., Ha, C., Qin, J., Huang, H., 2022b. Thermodynamic analysis for a novel steam Rankine cycle based indirect chemical precooled engine used for supersonic flight. Fuel 321, 123956.

Wang, C., Ha, C., Pan, X., Qin, J., Huang, H., 2021. Thermodynamic analysis of chemical precooled turbine combined engine cycle. Energy Convers. Manage. 239, 114184.