Assessing the impact of sustainable fuels for Large Surface Combatants

A comparison between sustainable methanol and diesel for the Future Air Defender of the Royal Netherlands Navy

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Abstract

Progressing targets on GHG emission reduction urge the the Netherlands Ministry of Defense (NL MoD) to reduce the use of fossil fuels, as they announced to contribute to the Paris agreement by reducing its dependency on fossil fuels by at least 70% by the year 2050. However, without sacrificing striking power, because future naval combatants need to perform their operations on the highest end of the violence spectrum and need to have sufficient autonomy to perform their operations at sea independent of logistic supply lines. The Royal Netherlands Navy (RNLN) is investigating the replacement of the Air Defense and Command Frigate (*LCF*) between 2030 and 2040 by a Large Surface Combatant. As it will be impossible to achieve substantial reduction of GHG emissions through energy-saving technologies, sustainable fuels need to be implemented in the design. In this thesis, the impact of sustainable fuel choice on the design of Large Surface Combatants with a displacement of around 6000 tonnes is assessed. In particular, the current and future developments of sustainable methanol and diesel have been reviewed from existing literature and are examined on the replacement Large Surface Combatant: specifically their advantages, disadvantages, production routes, future production cost estimates and availability to give an understanding which pathways can help the NL MoD to achieve their stated GHG emissions reduction goals. Furthermore, three different design concepts are presented with respect to fuel composition from which the impact of the established fuels is quantitatively examined. First, sustainable diesel is a drop-in fuel, which makes blending of sustainable diesel with fossil diesel possible in the existing infrastructure allowing a gradual transfer from fossil diesel to sustainable diesel. However, the production is less efficient in a well-to-wake approach and the cost of Bio-diesel and E-diesel is 5% to 30% more expensive with a mean estimated additional cost of 6 €/GJ compared to methanol. Secondly, operating on methanol has a significant impact on the design of a large surface combatant: the specific energy of methanol is more than twice as low as diesel and the ship needs a longer machinery space to allow for a diesel engine propulsion configuration. This results in a increase in displacement of 20%. Finally, navies could consider a two-fuel strategy: sail on methanol during operations with limited autonomy, typically in peace time, and operate on diesel during operations with high autonomy, during war time operations. In this case the design needs to include both diesel and methanol fuel systems and additional space for methanol safety measures. This results in a increase in displacement of 4%. However, the range when operating on methanol is reduced to 2187 nm compared to a 5000 nm baseline range. Assessing the impact of sustainable methanol and diesel for Large Surface Combatants at this level of detail and considering a two-fuel strategy is novel for the field. The results can be used by the Royal Netherlands Navy to compare the different concepts and serve as an indicative substantiation in the acquisition of a new Large Surface Combatant. Moreover, it can help in forming the strategy to migrate future naval combatants from current fossil fuels to future sustainable fuels.

Preface

By completing this thesis, I also conclude my time as a student. After finishing my bachelor'a degree as a Maritime Officer on Terschelling, I was driven to learn more about the theory of everything I had studied. I came to Delft to start a masters degree, which started out as quite a challenge. Gradually I got used to the academic level and found where my interests were.

Miranti Steijger brought me in contact with DMO, and I was instantly enthusiastic about the company and the challenges they faced. I am thankful for DMO that I was able to work on such a relevant project. Throughout my graduation internship I have had excellent contact with all colleagues there. I would especially like to thank Jeroen Reurings for his dedicated mentoring. You made me feel at home at DMO and were always available for questions and support.

From the TU Delft I would like to thank Peter de Vos and Rinze Geertsma. When searching for a graduation position, Peter supported me in making the right considerations between different projects. Afterwards you became an excellent chair to my project by asking the right critical questions. Rinze, you were there for me through every step of my graduation. You helped me grow tremendously in academic skills and with your guidance my work has found another level. With your encouragement I had the chance to present my work at the International Naval Engineering conference, one of the highlights of my academic achievements. Thank you for your endless support and always being open to talk.

Finally I would like to thank my support system: my parents, who encouraged me to continue studying and have always rooted for me; my friends and roommates, for proof-reading my thesis and the good time I had studying in Delft; and finally special thanks to my girlfriend Ariëla, I don't know how I could have managed without you.

I aspire to continue my career at DMO and I look forward to continue working to support the safety of our country in this way.

Maarten R. J. Pothaar
Rotterdam, December 2022

Contents

1 Introduction

The most recent estimates in the Fourth International Maritime Organization (IMO) Greenhouse Gas (GHG) Study 2020 show that GHG emissions of shipping have increased by 9.6% between 2012 and 2018 (IMO, 2021), while the IMO strives to reduce CO_2 emissions by at least 40% by 2030, pursuing efforts towards 70% by 2050, compared to 2008 (IMO, 2018). At the same time, the Netherlands Ministry of Defense (NL MoD) strongly depends on energy, and the access to energy is crucial for the Royal Netherlands Navy (RNLN) to perform its operations at sea. Currently, this energy requirement is mainly met by fossil fuels. That should change, as the MoD announced to contribute to the Paris agreement by reducing its dependency on fossil fuels by at least 20% by the year 2030 and 70% by the year 2050, compared to 2010, in its Operational Energy Strategy (OES) (Netherlands MoD, 2015; Bijleveld-Schouten and Visser, 2019). Whilst further improvements of power and propulsion systems can significantly contribute to the reduction of GHG emissions (Roskilly et al., 2015), it will be impossible to achieve the 2050 IMO's and MoD's ambitions just through energy-saving technologies (IMO, 2021). Therefore, under all projected scenarios, a large share of the total amount of GHG emission reduction and use of fossil fuels will have to come from the use of sustainable fuels (Lloyd's Register and UMAS, 2019b; DNV GL, 2019).

In the recent Defence whitepaper, the NL MoD has confirmed the replacement of its Air Defense and Command Frigates (LCF), *De Zeven Provinciën* class frigates, between 2030 and 2040 (Netherlands Ministry of Defense, 2022; Ministerie van Defensie, 2021). One of the most likely options for this replacement is a Large Surface Combatant (Ministerie van Defensie, 2021), which should be designed to operate at the high end of the violence spectrum NATO (2004). Therefore, the operational requirements are of the highest level and should be able to deal with developing Air Defence capabilities, such as hyper-sonic missiles, swarm threats and the high energy demand of modern weapon systems. Moreover, limiting the susceptibility to these threats is most important. Therefore, both the Radar and Infrared Signatures, and thus ship size and power need to be minimised. The planned lifespan of the future surface combatant is expected to be 30 years. Consequently, the IMO initial strategy and the OES must be taken into account.

The main pathways to reach IMO's low carbon-shipping goals are: (1) battery-electric propulsion with sustainable electricity , (2) zero carbon fuels like sustainable hydrogen or ammonia , (3) sustainable E-fuels or Bio-fuels, or (4) sails and wind. Despite the accumulation of literature, there is a lack of guidance on which pathway is suitable for different shipping segments, although literature agrees that the required range and autonomy are key drivers (van Biert et al., 2016). Especially for a Large Surface Combatant, with typical autonomy requirements of 30 days at sea, a range of 5000 nm at 18kn and maximum speed of 29kn, energy density, specific energy, fuel weight and volume are particularly important factors in the design, as ship volume and displacement are decisive design parameters for its size, cost and signatures. With a typical fuel capacity of 600 m^3 or 530 *tonne* for a Large Surface Combatant, replacing diesel oil with lower density hydrogen or methanol fuels directly adds 1200 or 600 *tonne* displacement, respectively, as shown in Figure 1.1 (Van Kranenburg et al., 2020). For low density power sources, such as sails, batteries, hydrogen and ammonia, this would lead to increased ship displacement, propulsion power requirement, increased signatures, and unaffordable cost increase. To limit the size and power increase of the vessel to acceptable proportions, the most energy dense alternative fuels that can be produced sustainably are considered: sustainable methanol and sustainable diesel.

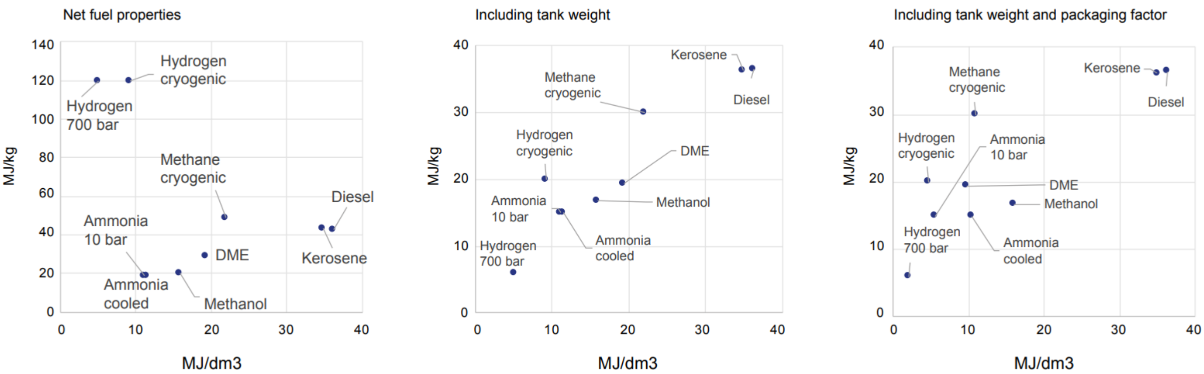

Figure 1.1: Energy density and specific energy of fuels with and without the tank weight and volume Van Kranenburg et al. (2020)

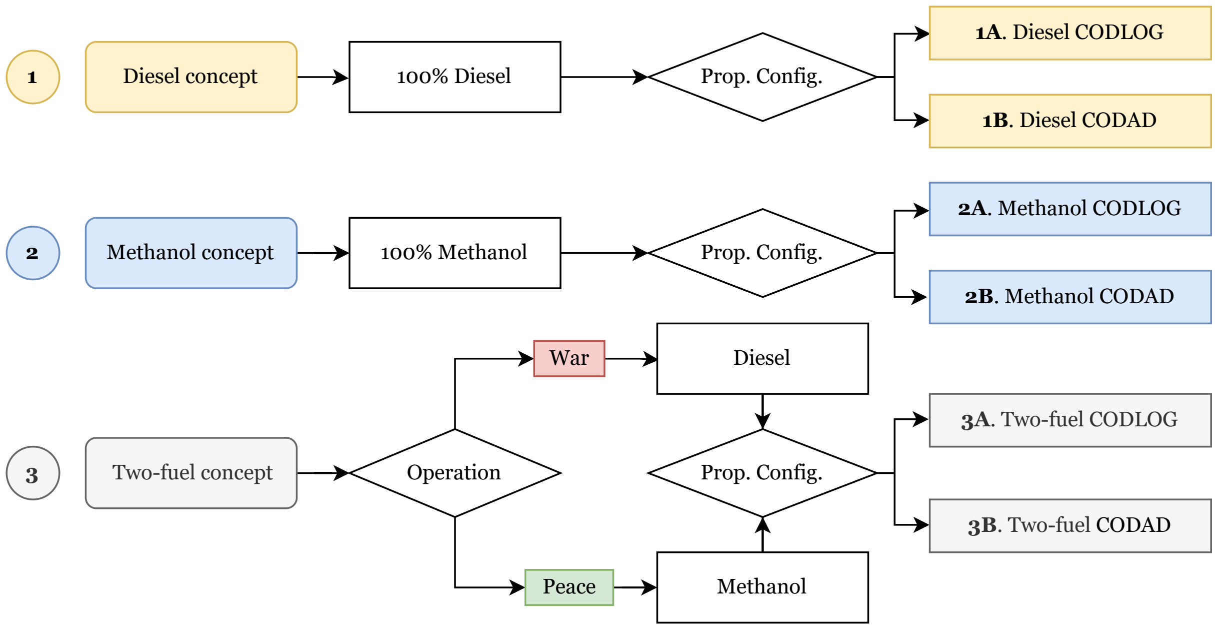

Figure 1.2: Different design concepts with respect to fuel composition and propulsion architecture

Given the challenges of implementing sustainable fuel on Large Surface Combatants as elaborated in the introduction, the aim in this thesis is:

To assess the impact of sustainable methanol and diesel for Large Surface Combatants.

The impact is presented for three different design concepts with respect to fuel composition: In concept one the vessels always uses sustainable diesel, in concept two the vessel always sails on sustainable methanol with the same autonomy and range, and in concept three the vessel sails on methanol in peacetime operations with a reduced autonomy and range, but sails on sustainable diesel during actual operations that require the typical autonomy of 30 days at sea with a range of 5000 nm, as visualised in a schematic shown in Figure 1.2.

The objectives to achieve the research aim are:

- To establish an overview from literature of the qualitative impact of the choice of alternative carbon based fuels for future naval vessels. This encompasses the production process, future availability, cost estimates and the impact on design.
- To quantify the impact of the fuel choice in a concept design iteration. To generate comparable concept designs, an iterative conceptual design model is used. This is novel to the field, as previous research stalled at parametric and qualitative level (Astley et al., 2020; Streng, 2021; Harmsen, 2021).
- To generalise the conclusions based on the design study and literature review. The results can be used by navies to compare different concepts and make decisions for future naval combatants.

The thesis is organised as follows: the quantitative impact based on literature is presented in Section 2; in Section 3, a typical Large Surface Combatant with its energy system layout is described; in Section 4, I describe the methodology used to establish comparable concept designs; in Section 5, I present the results and evaluate and compare the impact of each concept design; finally, I present the main conclusions and recommendations for future work in Section 7.

2 Literature review

In this literature review, an overview is established of the qualitative impact of the choice of alternative carbon based fuels for future naval vessels on the size, displacement, propulsion power, machinery space layout, fuel consumption, well-to-wake emissions and ultimately procurement and life cycle cost. Thus, the literature review examines the effect of short- and long-carbon chain sustainable fuels, sustainable methanol and sustainable diesel, respectively, on the replacement Large Surface Combatant. Specifically, it examines their advantages, disadvantages and production routes to give an understanding which pathways can help achieve the IMO and NL MoD sustainability goals. To assess the feasibility of the proposed fuel, I compare future production cost estimates and availability. Moreover, the impact on the design of the chosen fuels will be examined including the effect of difference in energy density; the possibilities in the power and propulsion plant concepts and related characteristics; and the impact on auxiliary systems, such as the fuel system. Finally, I present the impact for three different design concepts with respect to fuel composition. These concepts are the foundation for the design iteration that follows after the literature review.

2.1 Fuels

For the Large Surface Combatant, short- and long-carbon chain alternative fuels, sustainable methanol and sustainable diesel, are considered in this work. This section provides an overview on sustainable methanol and sustainable diesel, and examines their advantages and disadvantages. Table 2.1 provides the chemical properties of marine diesel oil (F-76) and methanol.

Table 2.1: Fuel properties: F-76 and Methanol

Parameter	**F-76**	**Methanol**	**Unit**
Lower heating value	42.8	19.9	[$MJkg^{-1}$]
Lower heating value	36.6	15.8	[$MJdm^{-3}$]
Hydrogen content	13.1	12.5	[wt.%]
Carbon content	86.6	37.5	[wt.%]
Sulfur content	0.05	0	[wt.%]
Oxygen content	0	50	[wt.%]
Density	847.4	790	[kgm^{-3}]
Flash point	69.65	11.15	[$C°$]
Boiling temperature	463.15-553.15	64.85	[$C°$]
Autoignition temperature	254.15	464.15	[$C°$]

2.1.1 Methanol

Methanol, a widely available and traded product, is seen as one of the favored contenders to decarbonise the shipping industry (Ellis and Tanneberger, 2015; Andersson and Márquez, 2015). Methanol does not have cryogenic complexity, since it is in liquid phase at room temperature and ambient pressure and it is easier to handle than gaseous fuels such as hydrogen and ammonia (International Renewable Energy Agency and Methanol Institute, 2021). This offers the possibility to store methanol in almost any tank shape (Skov, 2015), which means no additional ship volume is lost due to inefficient tank designs. Since the methanol infrastructure for the chemical industry worldwide is already there and available in more than hundred ports globally (Ellis and Tanneberger, 2015; DNV, 2021), minimal modifications are needed to provide methanol as a fuel, in particular in comparison to the implementation of gaseous alternative fuels (Andersson and Márquez, 2015). In the early stages of implementation, truck-to-ship bunkering would be a feasible method (Van Lieshout et al., 2020).

Methanol has the highest hydrogen-to-carbon ratio of any liquid fuel. This relationship can already reduce tank-to-wake (TTW) emissions by up to 10% compared to diesel. Furthermore, methanol combusts cleanly in primarily CO2 and water, and combustion produces fewer air pollutants compared to the combustion of diesel. Due to a lower peak cylinder temperature, there is typically 60% less NO_x formation during combustion. Since methanol contains zero sulphur and has no carbon- to carbon-bonds, it emits 99% less SOX and 95-99% less particulate matter, depending on the combustion principle (Balcombe et al., 2019). In the event of a spill, it is less hazardous to the environment than heavy fuel oil or diesel, since it biodegrades rapidly in water (DNV GL, 2016). These characteristics make methanol a potential replacement to meet the policy requirements set by the IMO.

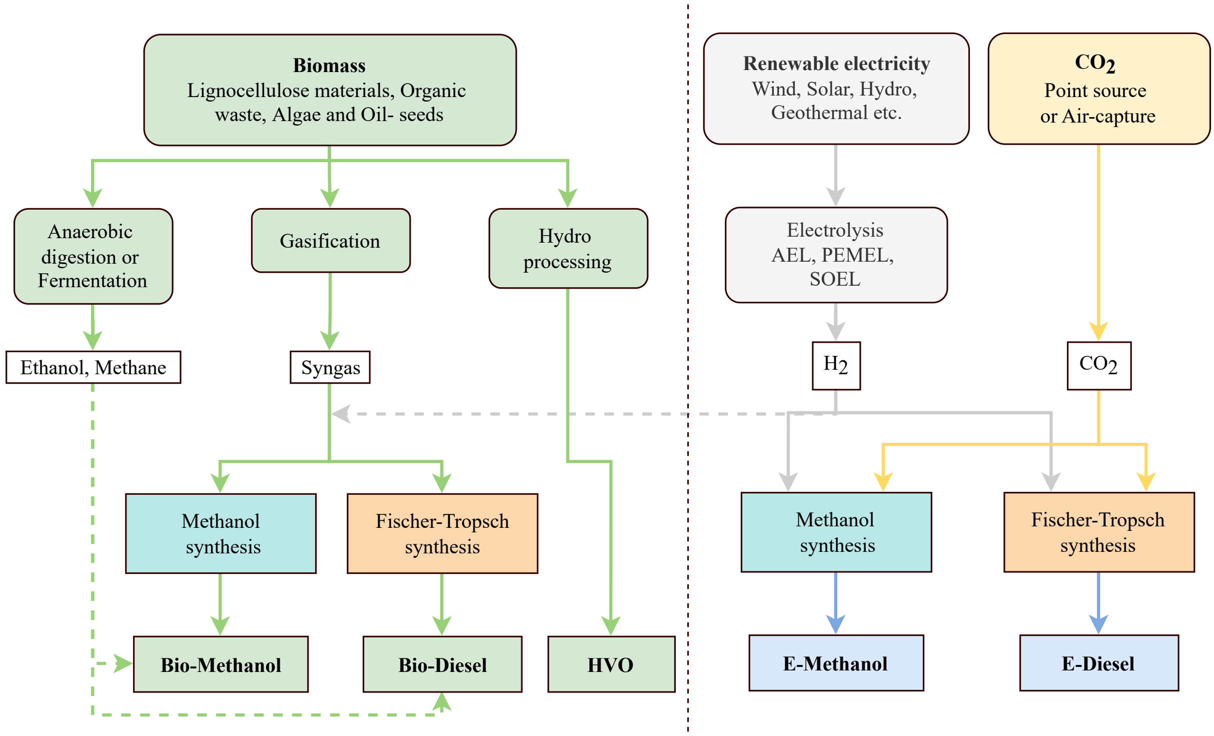

Figure 2.1: Simplified overview of the two main fuel production pathways

2.1.2 Diesel

Diesel is traditionally manufactured by refining fossil crude oil. Nowadays, sustainable diesel can be and is produced via several other alternative and sustainable production pathways, such as Fatty Acid Methyl Esters (FAME) from vegetable oils; Hydrotreated Vegatable Oil (HVO) from waste oil; and Fischer-Tropsch (FT) diesel, which can be produced from various bio-feedstocks or renewable electricity and captured CO_2 (Andersson et al., 2020). Sustainable diesel is attractive for a number of reasons. Most importantly, many of the sustainable diesel variants, HVO and FT-diesel for example, are backward-compatible with existing ships, distribution and infrastructure (Brynolf et al., 2022). Therefore, fossil diesel can be phased out step-by-step by blending sustainable diesel while leveraging on the existing fuel supply chain infrastructure and the well developed internal combustion engines (Zang et al., 2021). However, the additional production effort of sustainable diesel leads to a lower life cycle efficiency of sustainable diesel over methanol (Brynolf et al., 2022), which justifies investigating the trade-off.

2.2 Production and cost of sustainable fuels

2.2.1 Production process

The main two reasons to implement sustainable fuels are to reduce the environmental impact and dependency on fossil fuels. It is important to not just consider the impact during combustion of sustainable fuels, as they emit GHG in the same amount as conventionally produced fuels. Instead, the entire life cycle, in the shipping industry often referred to as well-to-wake (WTW), should be considered, as for sustainable hydrocarbons the difference is made in the production process. Therefore, it is essential to distinguish the different production pathways, their energy usage and efficiencies to be able to assess their viability.

In this thesis, diesel and methanol are considered sustainable when produced from sustainable feedstock, which can be a combination of sustainably obtained biomass, renewable electricity and captured CO_2. Sustainable methanol and diesel can be categorised in two production pathways: Bio-fuels and E-fuels, as shown in Figure 2.1. For Bio-fuels, that use biomass as the only feedstock, the prefix “Bio-” is used. For E-fuels, that combine captured CO_2 with H_2, the prefix “E-“ is given.

Bio-fuels can be produced through various production processes. The process depends on the desired fuel and the available biomass. Organic waste from food processing or crops are typically used for anaerobic processes such as fermentation or digestion, resulting in ethanol and Bio-gas (consisting mainly of CH_4 and CO_2), respectively. Lignocellulose feedstocks are considered suitable for gasification. This is a process that converts biomass by reacting it endothermically without combustion to synthesis gas, consisting of H_2, CO, CO_2, H_2O and CH_4. If desirable, the resulting products, ethanol, methane and synthesis gas, can be further synthesised into other fuels. Vegetable oils are commonly used to produce FAME Bio-diesel and HVO Bio-diesel through transesterification

Table 2.2: Overview of the production process, feedstock, limitations and production efficiency for Bio-methanol, Bio-diesel, E-methanol and E-diesel.

Fuel type	Production procces	Feedstock	Dependancy/limitations	%[1]
Bio-methanol	Anaerobic digestion (Bio-gas to methanol)	Manure, food waste and sewage sludge	Biofuel feedstock can compete both direct and indirect with the world food demand.	54
	Gasification (syngas to methanol)	Biomass and municipal waste	There is insufficient biomass available to supply the total energy demand.	
	Anaerobic fermentation (ethanol - methanol)	Energy crop		
Bio-diesel	Hydroprocessing or Transesterification	Vegetable oils		51
	Anaerobic digestion (Bio-gas to diesel)	Manure, food waste and sewage sludge		
	Gasification (syngas to diesel)	Biomass and municipal waste		
	Anaerobic fermentation (ethanol to diesel)	Energy crop		
E-methanol	Methanol synthesis	CO2, hydrogen and electricity	Limited availability of renewable energy and therefore H2 and DAC. PSCC could become unavailable. Biomass can not supply sufficient CO2 for large scale production.	41-72
E-diesel	FT-synthesis	CO2, hydrogen and electricity		37-64

1. Overall production efficiency

and catalytic hydroprocessing, respectively. To increase the production yields of biomass, H_2 can be added to the excess CO and CO_2 generated in the biomass to fuel conversion process. This will generate additional fuel without the need for energy intensive carbon capture. Huang and Zhang (2011) estimated the biomass-to-fuel efficiency for Bio-methanol around 54% and around 51% for Bio-diesel, by dividing the energy in the resulting fuel and the energy content in the biomass, without significant inputs or outputs of other energy.

Methanol synthesis can be achieved in a one or two step hydrogenation, during which synthesis gas consisting mainly of CO or CO_2 and H_2 is processed to generate methanol. Synthesis gas can be obtained by gasification of biomass or via combination of CO_2 and H_2. The composition CO:H_2 ratio of the synthesis gas can be tuned via the water-gas shift reaction. To increase the ratio, CO_2 can be added or reduced by adding more or less steam to the reactor. If desirable, methanol can further react to produce diesel. The reported synthesis efficiency of synthesis gas to methanol varies between 69%-89% (Brynolf et al., 2018; Lester et al., 2020) and the overall production efficiency between 41%-72% Grahn et al. (2022).

Diesel can be produced either with synthesis gas from biomass or with captured CO_2 and hydrogen via Fischer-Tropsch synthesis, during which synthesis gas reacts to form synthetic crude. The chain growth of the synthetic crude depends on the catalysts used in the Fischer-Tropsch synthesis and the syngas stoichiometry, as well as temperature and reactor pressure. The reported efficiency of the Fischer-Tropsch synthesis at process-level ranges between 59%-78% (Blanco et al., 2018; Hänggi et al., 2019; Lester et al., 2020). And the overall production efficiency between 37%-64% Grahn et al. (2022).

Renewable CO_2 can come from Direct Air Capture (DAC), Point Source Carbon Capture (PSCC) or biomass. DAC is an energy intensive process and is not yet available on industrial scale. CO_2 from biomass is widely available and more affordable (Daniel et al., 2022). However, biomass alone can not supply sufficient CO_2 in the future for large scale production of carbon based E-fuels. Currently, CO_2 from biomass can be supplemented by

PSCC, as long as significant CO_2 emission from industry is available. In the long term however, CO_2 from industry will become less. For example, the sustainable pathway for iron and steel industry could be CO_2 free. Therefore, upscaling of DAC will most likely be required. With different studies carried out on DAC developments, the range of cost estimations is wide and strongly depends on the energy price. However, DAC is expected to become more cost efficient in the future (Fasihi et al., 2019).

For the production of H_2 there are three leading technologies: Alkaline Electrolysis (AEL), Polymer Electrolyte Membrane Electrolysis (PEMEL), and Solid Oxide Electrolysis (SOEL). Electrolysis uses electricity to separate water into hydrogen and oxygen by current between two electrodes that are separated and immersed in an electrolyte to raise ionic conductivity. The efficiency of these electrolysis methods ranges between 63-71% for AEL, 58-71% for PEMEL and 75-83% for SOEL (Grahn et al., 2022). For the production of e-fuels in general, large amounts of hydrogen are required. As a result, the efficiency of the electrolysis primarily determines the total E-fuel production efficiency.

Summarising, Table 2.2 provides an overview of the production process, feedstock, limitations and production efficiency for Bio-methanol, Bio-diesel, E-methanol and E-diesel. While the production efficiency for the various fuels depends on the details of the production process and the potential to efficiently combine various required feedstocks, the general trend is that production of diesel is 5% to 15% less efficient than the production of methanol.

2.2.2 Future availability

Methanol is a readily worldwide available product, with a production of around 100Mt per annum. The majority of the produced methanol originates from the fossil sources, natural gas and coal (Methanol institute, 2021). However, methanol originating from fossil sources leads to more GHG emission than diesel in a life-cycle analysis under current circumstances Balcombe et al. (2019). The availability of sustainable methanol is limited, currently the production capacity is below 1% of the total produced methanol volume yearly. For future availability of sustainable methanol production, the Methanol Institute analysed the market development of sustainable methanol production facilities (International Renewable Energy Agency and Methanol Institute, 2021). In Figure 2.2 locations are marked where Bio- and E-methanol production facilities are projected or in operation.

Bio-Methanol provides the largest contribution to the total sustainable projected production capacity of methanol for 2025, which is around 3.1 Mt per annum versus 1.7Mt per annum of E-Methanol. A disadvantage of Bio-methanol, especially when produced from agricultural biomass, is that it competes with the world food demand. Furthermore, there is insufficient biomass available to supply the total energy demand of the shipping sector in Bio-fuels (Concawe Review, 2019). The disadvantage for E-methanol is that it requires large amounts of renewable energy, if E-fuels will be fully deployed in shipping, it might double or even triple the maritime sector's energy consumption on a well-to-wake basis, due to the inherent thermodynamic conversion inefficiency that occurs when

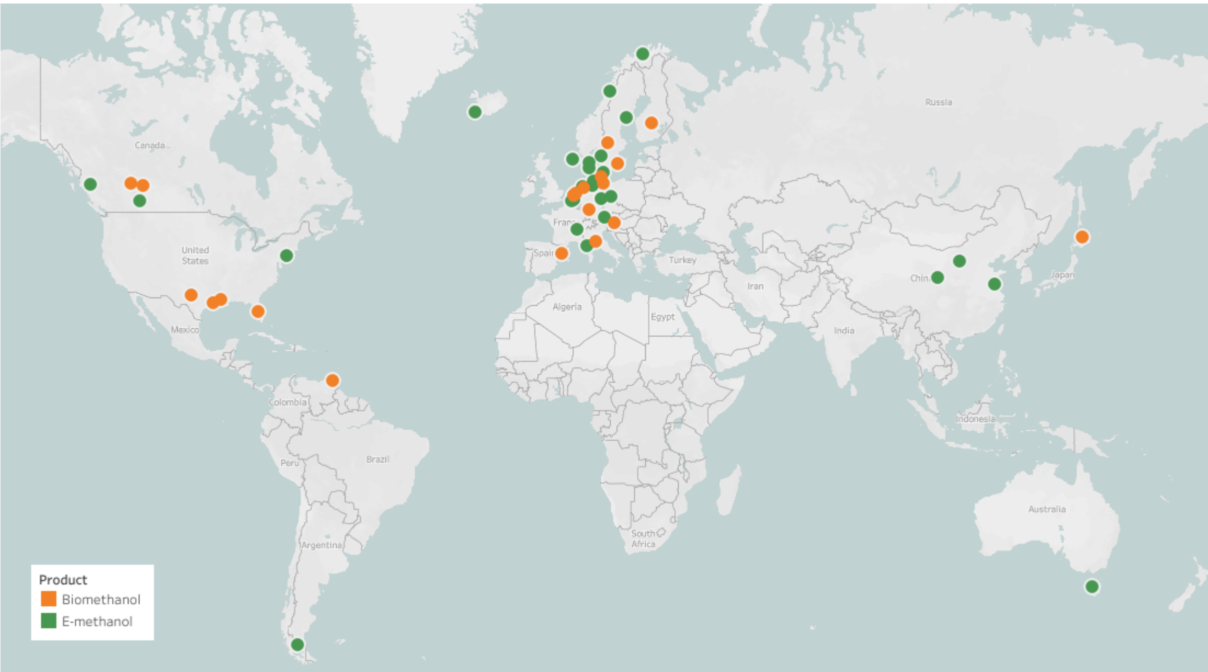

Figure 2.2: Renewable and Biomethanol Projects 2021 International Renewable Energy Agency and Methanol Institute (2021)

producing E-fuels Lindstad et al. (2021). Therefore, the feedstock for future production of sustainable fuels for shipping should consist of a combination of sustainably obtained biomass supplemented with sustainably produced hydrogen and CO_2.

For the future availability of E-diesel for maritime use, there are no concrete plans yet for large scale production facilities. However, aviation is dependent on sustainable aviation fuels (SAFs) for making aviation more sustainable US Department of Energy; Sustainable Aviation. SAFs are longer chain sustainable fuels, such as E-kerosene and Bio-kerosine. The production process of SAFs has many similarities with the production process of sustainable diesel and its upscaling could therefore play a crucial role in the pathway to sustainable diesel for maritime use.

2.2.3 Fuel production cost estimates and assumptions

Decarbonising of the shipping industry is strongly driven by cost evolution of sustainable fuels. Production, supply and storage costs are important elements. Table 2.3 provides an overview of studies into fuel production cost of sustainable diesel end methanol.

Figure 2.3 and Table 2.3 provide an overview of cost estimates from various studies that have been performed over the past years. (Brynolf et al., 2018; Lloyd's Register and UMAS, 2019b; Verbeek, 2020; van Kranenburg et al., 2021). At first glance it seems to indicate a huge uncertainty and disagreement in cost estimates, which is caused by different assumptions and is a confirmation of the volatility of the fuel market. This is confirmed by the most scientific study of Brynolf et al. (2018), which clearly provides a large uncertainty range indicated by the error bars in Figure 2.3. In this study, the author reviewed literature to analyse the factors affecting production costs of the E-fuels, and collected production costs and efficiencies associated with E-fuel synthesis. Then, he established the total production cost of the E-fuels in a consistent manner. Most other studies do seem to fit in the uncertainty range provided by Brynolf et al. (2018), except the study from Lloyd's Register and UMAS (2019b), which has taken very positive assumptions. However, the study of Lloyd's Register and UMAS (2019b) does provide a useful trend for the development of the cost of various fuels which is solidly justified in Lloyd's Register and UMAS (2019a), but does not address uncertainty. All studies agree that the difference between Bio-diesel and Bio-methanol and between E-diesel and E-methanol is only a limited percentage of the estimated cost of the fuels, in the range of 5% to 30% depending on the assumptions of the cost of sustainable electricity and feedstock, due

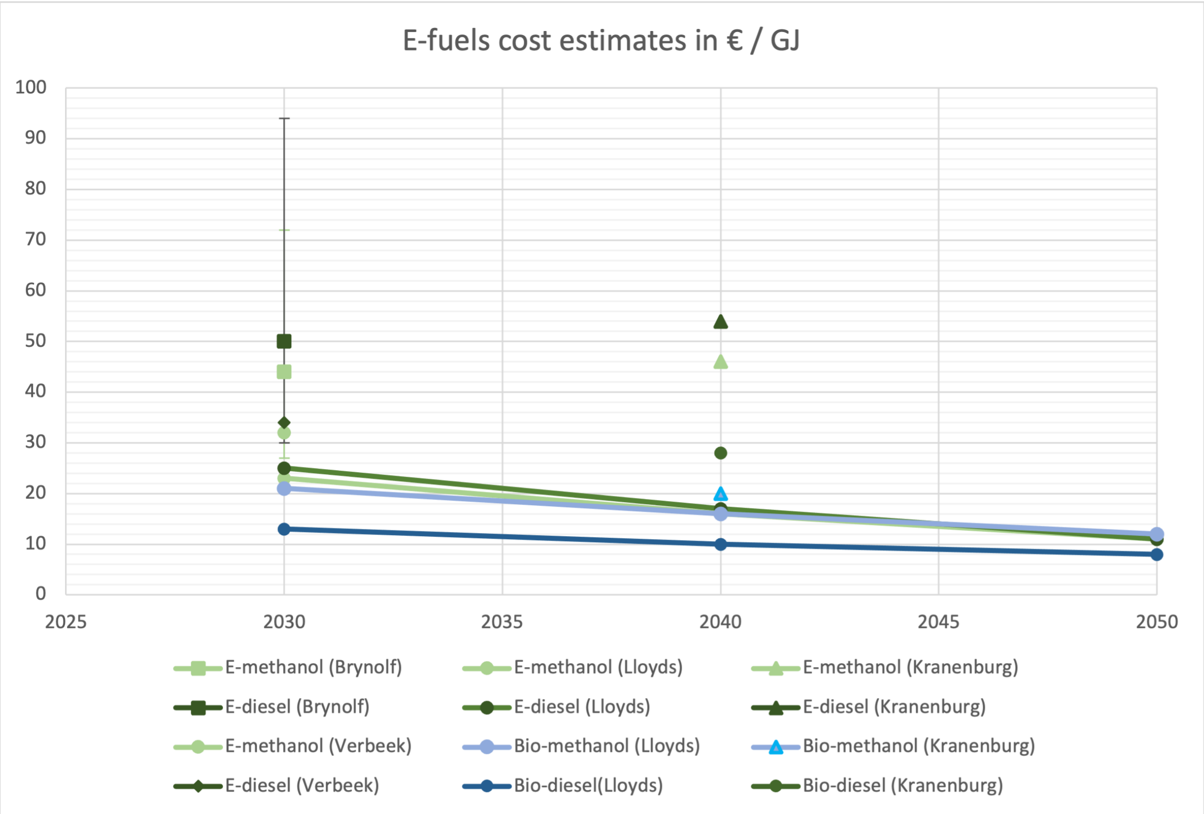

Figure 2.3: E-fuel cost estimates (Brynolf et al., 2018; Lloyd's Register and UMAS, 2019b; Verbeek, 2020; van Kranenburg et al., 2021)

Table 2.3: Overview of studies into fuel production cost of sustainable diesel and methanol

Author/Article	Year	Time Horizon	Fuels Assessed	Assumptions	Cost range [€/GJ]
Brynolf et al.	2018	2030	E-methanol E-diesel	Production cost including investment, operation and maintenance, electricity, water, CO2 and selling excess O2 and heat.	27-44-72[1] 30-50-94[1]
Lloyds-register and UMAS	2019	2030, 2040, 2050	Bio-methanol Bio-diesel E-methanol E-diesel	The costs composed of: total production costs, transportation, bunkering and vessel storage.	21, 16, 12 13, 10, 8 23, 16 , 11 25, 17, 11
Verbeek (TNO)	2020	2030	E-methanol E-diesel	Production cost levels are based on costs of H2, CO2, electricity and CAPEX.	25-39[2] 27-41[2]
van Kranenburg et al. (TNO)	2021	2040	Bio-methanol Bio-diesel E-methanol E-diesel	Production costs in this study are calculated with the Supply Chain Model[3].	20[4] 28[4] 36-57[5] 42-66[5]

1. Three cases: base, low and high where calculated. In the low and high cases, the most optimistic and pessimistic values were used and for the base case, the average data is used from literature.
2. Estimations are done for two assumptions of LCoE and €/tonne CO2, €30/MWh, €40/tonne and €50/MWh, €30/tonne.
3. TNO's Supply Chain Model is an economic model that calculates complete supply chain costs for import of green hydrogen and hydrogen based carriers from different countries and compares these to local production in the Netherlands. Costs are based on expected CAPEX levels for 2030.
4. The expected price development of Bio-fuels were based on extensive research done by the International Energy Agency and the U.S. Energy Information Administration. International Energy Agency (2021a,b); Brown et al. (2020); US EIA (2019).
5. Estimations are done for two assumptions of LCoE, €30/MWh and €70/MWh.

to the lower efficiency of the production process of Bio- or E-diesel, again with the study of Lloyd's Register and UMAS (2019b) providing a significant outlier. Concluding, the studies agree on a 5% to 30% increase in price from Bio- or E-methanol to Bio- or E-diesel and a reducing trend in cost of sustainable fuels as production capacity and technological readiness increases.

2.3 Impact on design

Leading parameters in the design of large surface combatant are volume and displacement. Sensor, Weapon and Command (SEWACO) systems, the power and propulsion plant, accommodation, fuel storage, and auxiliary systems all compete for volume, displacement and position on board the vessel (Van Oers et al., 2018). Consequently, the available volume and displacement determine the amount of fuel and the installed power that can be carried on board. Therefore, a direct relation between the displacement and the operational profile and autonomy of a vessel arises. This makes the energy density of a fuel a critical parameter for its applicability. Furthermore, the additional requirements and complications that come with the use of a certain fuel can be crucial for its compatibility in the design. For this thesis, the author assumed a Future Air Defence Frigate (FuAD) with a displacement of 6000 tonnes and propulsion configurations similar to the ones presented in Geertsma et al. (2017). The key parameters are presented in Table 2.4 and a 3-D render plot is shown in Figure 2.4

2.3.1 Ship/platform

According to interim guidelines from IMO (IMO, 2020), methanol tanks should be surrounded by protective cofferdams, except on those surfaces bound by shell plating below the lowest possible waterline, other fuel tanks containing methanol, or fuel preparation spaces. Cofferdams are a structural space surrounding a fuel tank which provides an added layer of gas and liquid tightness protection against external fire and leakage of toxic and flammable vapours between the fuel tank and other areas of the ship. Alternatively, diesel tanks do not have

Parameter	Notional FuAD	Unit
Displacement	6000	[tonne]
Top speed	29	[kts]
Propulsion power	36	[MW]
Range at 18kts	5000	[nm]
Diesel volume	600	[m^3]

Table 2.4: Key parameters of a potential concept design for a notional Future Air Defence Frigate

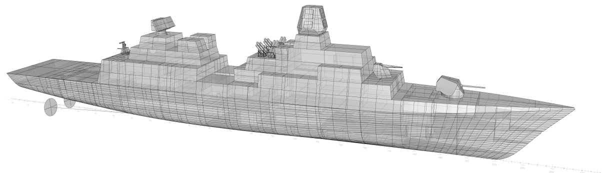

Figure 2.4: 3-D render plot of a potential concept design for a notional Future Air Defence Frigate

this arrangement complexity. However, alternative protection against spread of fire and leakage of methanol are investigated in various Dutch and European research projects. An equivalent safety compared to current diesel configurations needs to be demonstrated before alternative measures with less volumetric impact on the design can be accepted.

Methanol has a specific energy of 19.7 MJ/kg (16.6 MJ/L), which is a factor 2.3 lower than that of diesel, which is around 45.6 MJ/kg (38.6 MJ/L). One of the main challenges is not designing an engine to run on methanol, but finding the space to store methanol on board (Nysjö et al., 2022). While methanol has a lower energy density than diesel, its energy density and ease of storage are great advantages over other sustainable fuels, since it is liquid at ambient temperature and pressure. Two other sustainable fuels that are considered by the maritime sector, ammonia and hydrogen, have an even lower energy density and need to be stored under pressure or cryogenically, often requiring cylindrical tanks. However, for the same energy content as diesel, taking into account the extra measures required for safe storage, methanol requires up to 2.5 times more storage volume than diesel (Andersson and Márquez, 2015; Ellis and Tanneberger, 2015). On the other hand, sustainable diesel is compatible with conventional diesel, it has comparable energy density, it can be mixed with conventional diesel and it can be transported in the existing diesel infrastructure. Figure 1.1 shows the relative tank capacity required for different fuel options to store the same amount of energy. Concluding, the required volume for methanol storage is estimated at 1300 m^3 to 1500 m^3 compared to a typical diesel storage of 600 m^3.

2.3.2 Power and propulsion plant

Methanol tests in marine engines have already been performed for a long time demonstrating good engine power and fuel consumption, and showing lower harmful emissions (Song et al., 2008). The novelty with using methanol as a fuel mainly lies in the fuel system and injection technology. Engine manufacturers have shown compatibility with several combustion principles. This concerns both spark-ignition (Otto-cycle) and compression-ignition (Diesel-cycle) engines. At the moment, MAN Energy Solutions is developing methanol retrofit solutions for its four-stroke customers which will be sales-ready from 2022 onwards, with retrofits starting in 2024 (MAN Energy Solutions). This will be a dual-fuel compression-ignition concept to provide greater flexibility. Also, Wärtsilä announced their first modern, methanol-fuelled engine, the Wärtsilä 32 Methanol (Nysjö et al., 2022). For robust operation, this engine is equipped with a full diesel and methanol fuel system. Therefore, 8% pilot fuel (diesel) is required at 85% MCR when the engine is running on methanol, allowing a seamless switch to diesel as a back-up or for a switch during operations that require longer autonomy. In conclusion, methanol engines emerge, with dual-fuel variants in the high power four stroke range, enabling methanol to become one of the main fuels available to decarbonise shipping and as a serious option for future naval vessels.

The marine gas turbine market is small and highly dependent on developments in the aerospace industry. Methanol has three characteristics that make turbine modifications necessary (GE Power, 2001): its lower heating value results in higher fuel flow rate; the poor lubricating effect of methanol requires changes in the main fuel pump and flow divider system; and due to the low flash point of methanol, precautions to eliminate possible sources of ignition and therefore, explosion proof components are required. Rolls Royce indicates that the energy transition pathway and their solution direction is uncertain (Rolls Royce, 2022). In the development of aviation gas turbines, the focus is currently on SAFs, thus maritime gas turbines will most likely not be developed for methanol in the near future.

Therefore, a methanol fuelled vessel with gas turbine propulsion is unlikely. However, for sufficient energy density, internal combustion engines at speeds of 1000 rpm or higher are required; these are available up to 10 MW. For a future air defence frigate with top speed requirements of 30 kts or higher, four of these engines would

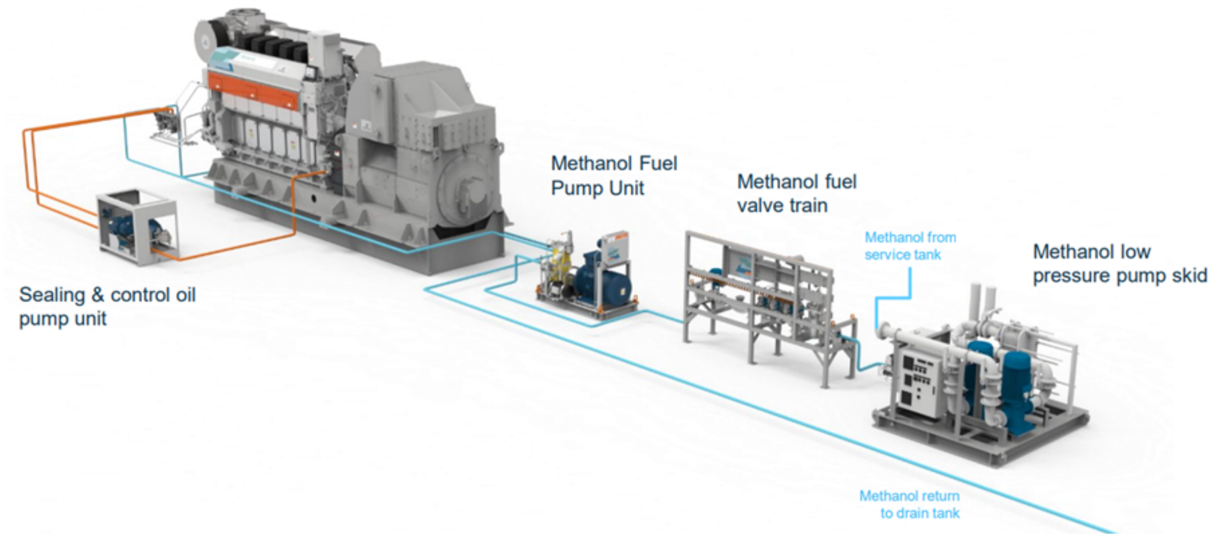

Figure 2.5: Wärtsilä W32 methanol engine system overview Wärtsilä (2022)

be required. Compared to a vessel with gas turbine propulsion, this would lead to an increased length, weight and cost. This length might also provide space for the extra required methanol. To establish the full impact, a concept design needs to be performed.

2.3.3 *Vulnerability*

A Large Surface Combatant is designed to operate at the highest end of the violence spectrum (NATO, 2004). Thus, it is important to maintain the ability to accomplish the mission by avoiding or withstanding weapon effects. The vulnerability of a vessel concerns the damage that will be done by an impact or the sensitivity to impact. This damage comes in two forms, often referred to as primary and secondary damage (Habben Jansen, 2020). The first is the sensitivity of the system to primary damage. If a system is very sensitive to damage, weapon impact may easily disrupt the operation, leaving the vessel dead in the water and possibly without weapons, sensors, communication systems and propulsion. The second aspect is the possible propagation of damage if sensitive fuel systems are compromised. Fuels with higher flammability may be prone to explosion and will magnify the damage already done. Due to the lower flash point and toxicity of methanol with respect to diesel, safety measures need to be taken into account in the design. On the other hand, the lower heating value of the fuel and its good miscibility with water might ease fire suppression and fire fighting. For now, however, Lloyd's Register Lloyd's Register (2021) and the IMO introduced interim guidelines for the classification of methanol-fuelled ships and guidelines for the safety of ships using alcohol as fuel IMO (2020).

According to these guidelines, methanol fuel tanks must be filled with an inert gas to prevent an explosive gas mixture forming in the tank. To make the above possible, the tanks must be provided with a controllable pressure vacuum system. For the fuel supply system, fuel pipes must be constructed double-walled. Leak detection must be present in this double wall and it must be possible to ventilate the hollow spaces and fill them with inert gas. In the event of a leak detection, the fuel supply must be stopped and a back-up fuel supply system is necessary to maintain (minimum) propulsion and energy generation in accordance with the PSMR classification (Lloyd's Register, 2022). In the fuel supply system, that pumps methanol in the first stage at approximate 15 bar and feeds it to the high pressure pump of the common rail system, the surplus of methanol is fed back to the tank, but must be cooled to prevent heating up of the fuel tank. In the final stage, the methanol is pressurised in the common rail system up to 600 bar. An overview of the fuel systems from Wärtsilä (2022) is presented in Figure 2.5.

2.4 *Discussion*

In Table 2.5 an overview is presented on the qualitative impact of the fuel choice on the design of a future air defence frigate.

While the implementation of methanol as a fuel for high-end naval vessels does appear technically feasible for propulsion systems based on diesel engines alone, its impact on the size of the vessel is large and its top speed might be limited unless the ship is stretched. The size increase starts with 800 m^3 extra tank space, extra fuel pump and safety system space and extra length for additional engines. To establish the full impact, including the effect of the propulsion power increase, the concept design of such vessels needs to be established and compared. To reduce the impact, navies could consider operating the vessel on a two-fuel strategy, on methanol during operations with

Table 2.5: Qualitative impact of the fuel choice on the design concepts of a future air defence frigate

Design concept	Characteristic	Size	Cost	Emissions
1A. Diesel fuel with gasturbine hybrid propulsion	High top speed with 36 MW propulsion	Most compact design	6 Eur /GJ extra fuel cost	Increased hazardous emission
1B. Diesel fuel with diesel engine propulsion	Limited top speed with up to 30 MW propulsion	Extra lenght for additional engines	6 Eur /GJ extra fuel cost	Increased hazardous emission
2A. Methanol fuel with gasturbine hybrid propulsion	Not feasible or very expensive	900 m3 extra tank space, extra fuel pump and safety system space and	Reduced fuel cost, but uncertain extra power requirement	Reduced hazardous emissions
2B. Methanol fuel with diesel hybrid propulsion	Feasible but extra ship length	900 m3 extra tank space, extra fuel pump and safety system space and extra length for additional engines	Reduced fuel cost, but uncertain extra power requirement	Reduced hazardous emissions
3A. two-fuel strategy with gasturbine hybrid propulsion	Not feasible or very expensive	Extra fuel pump and safety system space	Reduced fuel cost, but uncertain extra power requirement	Reduced hazardous emissions.
3B. two-fuel strategy with diesel hybrid propulsion	Feasible but extra systems and some ship lenght	Extra fuel pump and safety system space and extra length for additional engines	Reduced fuel cost, but uncertain extra power requirement	Reduced hazardous emissions.

limited autonomy, typically in peace time, and on diesel during operations with high autonomy, during (certain) war time operations. The compatibility of the specific tank coatings suitable for methanol with long term storage of diesel would need to be investigated. Finally, navies could consider preparing for investment in production of Bio-diesel or E-diesel. The main limitation will be the availability of feedstock and the up-scaling of the required production facilities to reduce the long term cost of these fuels. The development in aviation towards SAF might be a crucial enabler for this strategy.

2.5 Conclusions and further research

In this literature review the current and future developments of sustainable methanol and diesel are reviewed. The adoption of these fuels for a Large Surface Combatant is a multi-dimensional challenge, because of the uncertainty in the development of their production process, future availability, fuel production cost and their impact on design. The production capacity of Bio-methanol and E-methanol is growing rapidly as illustrated in Figure 2.2. Bio-diesel is becoming more available as well, but availability of E-diesel is lagging behind. The development of SAF production facilities for aviation might prove an enabler for future availability of E-diesel for maritime use.

Currently, the scarcely available proposed sustainable fuels are significantly more expensive than conventional fuels. The production cost of sustainable fuels is mostly led by renewable feedstock costs. It is expected that, due to stimulating government policies, the prices of the proposed fuels will become equal and eventually lower than conventional fuel prices, while the availability will become higher. In summary, the production cost of Bio-diesel and E-diesel is 5% to 30% more expensive with a mean estimated additional cost of 6 €/GJ compared to methanol.

Operating on methanol has a significant impact on the design of a Large Surface Combatant. The specific energy of methanol is more than twice as low as diesel and therefore the endurance of the ship is more than halved or the tank capacity has to be increased by 700 to 900 m^3, which directly adds 10% to 15% to the displacement and similar cost and signatures. Gas turbines are unlikely to become available, and therefore the ship might need a longer machinery space to allow for more propulsion engines to compensate for the increased power requirement.

The required auxiliary and safety systems add further volume area to the engine room. Moreover, the safety measures make the ship design larger and less flexible, due to segregation requirements. To more exactly quantify the impact of methanol on the design, a concept design iteration is required, which the author will undertake in this thesis.

Sustainable diesel is a drop-in fuel, which makes blending of sustainable diesel with fossil diesel possible in the existing infrastructure allowing a gradual transfer from fossil diesel to sustainable diesel. The main uncertainty in the feasibility of this option is the future availability of sustainable fuels, as production facilities have not yet been planned as much as sustainable methanol production facilities. Moreover, more hazardous emissions, such as particulate matter and NO_x might remain, but these could be mitigated by after treatment. During the lifetime, however, the navies should take additional cost of sustainable diesel compared to sustainable methanol into account. Whether this cost is higher than including methanol in the design will be determined with an economic trade-off after the comparable concept designs have been established.

Finally, navies could consider a two-fuel strategy, on methanol during operations with limited autonomy, typically in peace time, and on diesel during operations with high autonomy, during (certain) war time operations. In this case the design needs to include both diesel and methanol fuel systems and additional space for methanol safety measures. The feasibility of this option depends on how much this impacts the design, which shall again be established through a concept design. Moreover, the compatibility of the same tanks for two-fuels needs to be further investigated, but ultimately the limitation on flexibility of the navy to change operations in a short time might prove the factor that blocks this option for naval commanders.

3 System description

First the primary, secondary and other typical tasks of a Large Surface Combatant are described with the necessary requirements to perform typical operations. Then, multiple power plant configurations are described and two are selected. Finally, the requirements for the placement of fuel tanks are shown both for diesel and methanol.

3.1 Large Surface Combatants

Large Surface Combatants eligible for the replacement of the *De Zeven Provinciënklasse* frigate are primarily ships with air defense capabilities for naval task forces at short and medium range, which should be designed to operate at the high end of the violence spectrum NATO (2004). Therefore, the operational requirements are of the highest level and should be able to deal with developing Air Defence capabilities, such as hyper-sonic missiles, swarm threats and the high energy demand of modern weapon systems. For this purpose, the current Air Defence Frigates of the RNLN are optimized for Area Missile Defence. The SMART-L radar provides an overview of the airspace at great distances (200+ nm). The APAR has a shorter range, but gives a full 360 degree view around the ship and is able to track more than 100 air targets simultaneously. The Sirius infrared detection system also provides an aerial image in radar silence. Approximately 30 targets can be intercepted simultaneously. Secondarily, Air Defence Frigates are intended to operate in a taskforce. For this reason, extra accommodation is available for a taskforce commander and his staff. Other typical tasks are maritime security operations, maritime assistance operations and maritime combat operations.

During typical operations, a Large Surface Combatant needs to have high mobility with a top speed of 29 knots as well as good acceleration, deceleration and maneuvering capabilities. Next to mobility requirements, the vessel has to be able to sail 5000 nm at transit speed of 18 knots. One of the aspects by which naval combatants are distinguished from ordinary sea going vessels is survivability, which is important when operating on the highest end of the violence spectrum. The main three aspects of survivability are susceptibility, vulnerability and recoverability. To limit the susceptibility to air threats, both the radar and infrared signatures, and thus ship size and power, need to be minimised. The vulnerability of a vessel concerns the damage that will be done by an impact or the sensitivity to impact. It is important to maintain the ability to accomplish the mission by withstanding weapon effects. Low flash-point fuels with high flammability may be prone to explosion and will magnify the damage already done by impact. The recoverability is determined by the redundancy of crucial systems. Energy systems that the vessel is dependent on need to be set up redundantly. The requirements for Air Defence Frigates to perform typical operations are reflected in the ship parameters shown in table 3.1.

Table 3.1: Requirements for Air Defence Friages to meet typical tasks reflected in ship parameters

Parameter	**Value**	**Unit**
Displacement	6000	[tonnes]
Top speed	29	[kts]
Transit speed	18	[kts]
Installed power	50	[MW]
Propulsion power	36	[MW]
Range at 18kts	5000	[nm]
Diesel volume	650	[m^3]
Endurance	30	[days]
Operational days	200	[days per year]
Design life	30	[years]

3.2 Power plant configuration

The sailing profile of a Large Surface Combatant has widely varying ship speeds in combination with poor performance of propulsion machinery in part load, especially in terms of fuel consumption. Hybrid propulsion architectures are therefore found on almost any frigate. With a hybrid propulsion architecture, it is possible to compensate for the weaknesses of one system with the strengths of another system. Furthermore, choosing for a hybrid propulsion architecture adds redundancy to the design.

When looking at the overview of selected frigates shown in Table 3.2, it becomes apparent many frigates operate on gas turbines to reach high top speeds. To operate on cruise speed, either diesel or diesel electric propulsion systems are used. The propulsion concepts proposed in this thesis are based on the power plant configurations of

Table 3.2: Overview of a selection of designs of CODLOG and CODAD hybrid propulsion architectures of frigates

Navy	Vessel	Power plant	Speed [kts]	Length [m]	Δ [tonne]	Year[1]
Royal Navy	Type 23 frigate	2x Spey, 4x MTU12v4000, 2EM (3kW each)	28	133	4900	1987
Royal Navy	Type 26 frigate	MT30, 4x MTU20v4000, 2EM	26	150	6900	2025
US Navy	Constellation-class	LM2500, 4x DG, 2x EM	27	150	7400	2026
German Navy	F125	LM2500, 4x MTU12v4000, 2x EM	28	149	7200	2019
Italian Navy	FREMM-class	LM2500, 4x MTU16v4000 , 2x EM	30	142	6000	2012
Royal Danish Navy	Iver Huitfeldt-class	4x MTU20v8000, 4x DG	30	139	6645	2012
Royal Navy	Type 31	4x MTU20v8000, 4x MTU16V2000	28	139	5700	2027

1. In commission

these selected frigates. Since the likelihood that a gas turbine for methanol will be developed is low, a concept needs to be chosen without a gas turbine as well. Currently, frigates without a gas turbine have large diesel engines on board to reach the necessary propulsion power. Possible configurations for operating on methanol would be a diesel electric and diesel or a diesel and diesel propulsion configuration. Disadvantageous to diesel electric are the losses due to electric conversion in the propulsion train. Therefore, the propulsion concepts chosen to compare in this thesis are a gas turbine hybrid system (CODLOG) and a diesel and diesel system (CODAD) based on the Iver Huitfeldt and Type 31 class as shown in Appendix A .

The energy generation for the CODAD and CODLOG propulsion systems works differently at top and cruise speed. At top speed in a CODLOG propulsion configuration, the auxiliary power of 1 MW is provided by the DG-sets and the propulsion power of around 36 MW is provided by the gas turbine (GT). For the CODAD propulsion configuration, four diesel engines (DE) can be combined to provide the required propulsion power. At cruise speed in a CODLOG propulsion configuration, the auxiliary power is provided by the DG-sets and the propulsion power is provided by the electric motors (EM). For the CODAD propulsion configuration, one or two diesel engines can be used to provide the required propulsion power.

3.3 Fuel tanks

It is important to consider how different spaces interact with each other and how fuel tanks are placed on board of a Large Surface Combatant. This section will discuss how fuel tanks are conventionally placed on frigates and what the differences are when implementing methanol as a fuel.

For Large Surface Combatants operating on diesel, the fuel storage tanks are conventionallly placed in the lower hull amidships, inside the double bottom below the engine room. Advantages to this placement are that this space cannot be used for other purposes, it is suitable to be compartmentalised which adds redundancy and it is close to the engine room. The service tanks are usually placed on the same level of the engine room. For every engine room there are separate service tanks. By placing fuel storage inside the double bottom there is no arrangement complexity. Both the storage and service tanks are placed in structural hull tanks and therefore there are little packaging losses.

When operating on methanol, additional requirements for the tanks are in place. As methanol is a low flash-point and toxic fuel, protective cofferdams around the tanks are necessary which need to be large enough for inspection with openings of 600x600 mm (Lloyd's Register, 2021). This translates to a minimum height of 800 mm to allow for enough construction around the openings. Cofferdams are not necessary around surfaces bound by shell plating below the lowest possible waterline, other fuel tanks containing methanol, or methanol fuel preparation spaces.

4 Methodology

In this section, the methodology to establish comparable results for Large Surface Combatants of around 6000 tonnes is presented. First, three different design methods are described with their typical properties. Secondly, the ship synthesis model is presented which is used to establish the comparable design concepts. Thirdly, the methodology influencing the ship synthesis model is further elaborated , with respect to sizing of the design, power requirement, power and propulsion configuration, floodable length and energy consumption. Finally, a procurement cost model is presented to establish the difference and impact of the fuel choice on the procurement costs.

4.1 Design methods

Ship design is a process that brings together a wide range of disciplines and methods of analysis. During the design process, the designer is able to change the input variables to create a complete ship design. Despite the difference in terminology used in literature concerning ship design to distinguish the different design phases, a distinction is often made between three different phases: preliminary, contract and detailed design.

This thesis will primarily focus on the preliminary design phase. The aim of the preliminary phase is to present one or multiple designs that represent a feasible and economical implementation of the established requirements of the future owner. At the end of this phase, the main characteristics of the design are established. Commonly, this phase starts with a study of existing ships that meet the operational requirements and this is used as starting point in the preliminary design process. Thereafter, a host of combinations can be made with different hull types, machinery equipment and parameters dictating its size.

For generating numerous design iterations, computer models have been developed to obtain alternative designs, with each of the designs meeting the operational requirements. Different levels of detail can be distinguished between the developed computer models and design stages within the preliminary phase. Which model is most suitable within the preliminary design phase depends on how far along the design is, which implies the level of detail of the available input data. In the early stage of the preliminary phase, the aim is to rapidly explore and evaluate different designs. This generally favors a set-based approach.

A first step in the preliminary phase can be to create parametric design variations. An example of a computer model for creating parametric designs is the Ship Power & Energy Concept (SPEC) tool developed by Maritime Research Institute Netherlands (MARIN). This tool has already been used in studies performed at DMO before (Astley et al., 2020; Streng, 2021). The SPEC tool allows to make variations of specific design parameters to generate many different parametric designs, which gives insight in the influence of basic design parameters on the design in a short time span. However, the parametric design approach is uncritical toward nuances and implanting detail into the design. Furthermore, the results are often based on linearised sizing, which may not be correct, while actual sizing occurs in discrete steps.

A second step often executed in the preliminary design phase is concept exploration. A well-known and used ship synthesis model at DMO for rapidly exploring a large set of alternative concept designs is named PACKING (van Oers, 2011; Duchateau, 2014). This synthesis model generates alternative designs on a conceptual level. It uses a three-dimensional model to generate and change the aspects of the ship's arrangement. The PACKING model results in a large set (10^4) of ship concepts that comply with the operational requirements. This set can then be explored in detail in a trade-off analysis. However, this requires extensive knowledge in ship design to understand the effect of minor features, without them actually being in the design, and judge their usability. Furthermore, the PACKING model is a complex tool, time would be spent to get familiar and understand the workflow of the tool. It is recommended for future research to explore a broad range of the design possibilities to cover a large area of the design space. In doing so, different possibilities can be compared and the uncertainty in the design and the impact of the design drivers can be investigated.

Another concept design synthesis model, with more focus on detail instead on exploration, is the Functional Integrated Design Exploration of Ships (FIDES model) (Van Oers et al., 2018). This tool primarily facilitates the preliminary concept design process, using historical data from comparable ships. It uses functional building blocks for a complete spatial description of the ship. These functional building blocks are chosen from a predefined set of types. Each block type determines properties such as weight, size, density or surface-weight. After modeling the building blocks in the FIDES concept design tool, programmed as Rhinoceros plugin tool running on Python, the blocks are visualised in the 3D-CAD environment of Rhinoceros. The numerical block definition in FIDES, together with the representation in Rhino, describe the ship concept. By analysing the FIDES concept design, the Naval Architect is able to predict the basic naval architectural performances, i.e., weight, centre of gravity and the required input parameters for ship stability calculations and for ship resistance and propulsion power estimates, whether the required speed and range are attainable with the proposed machinery and energy concept. Due to the possibility to generate designs at conceptual level, FIDES is considered suitable to establish comparable concept designs as proposed in Figure1.2.

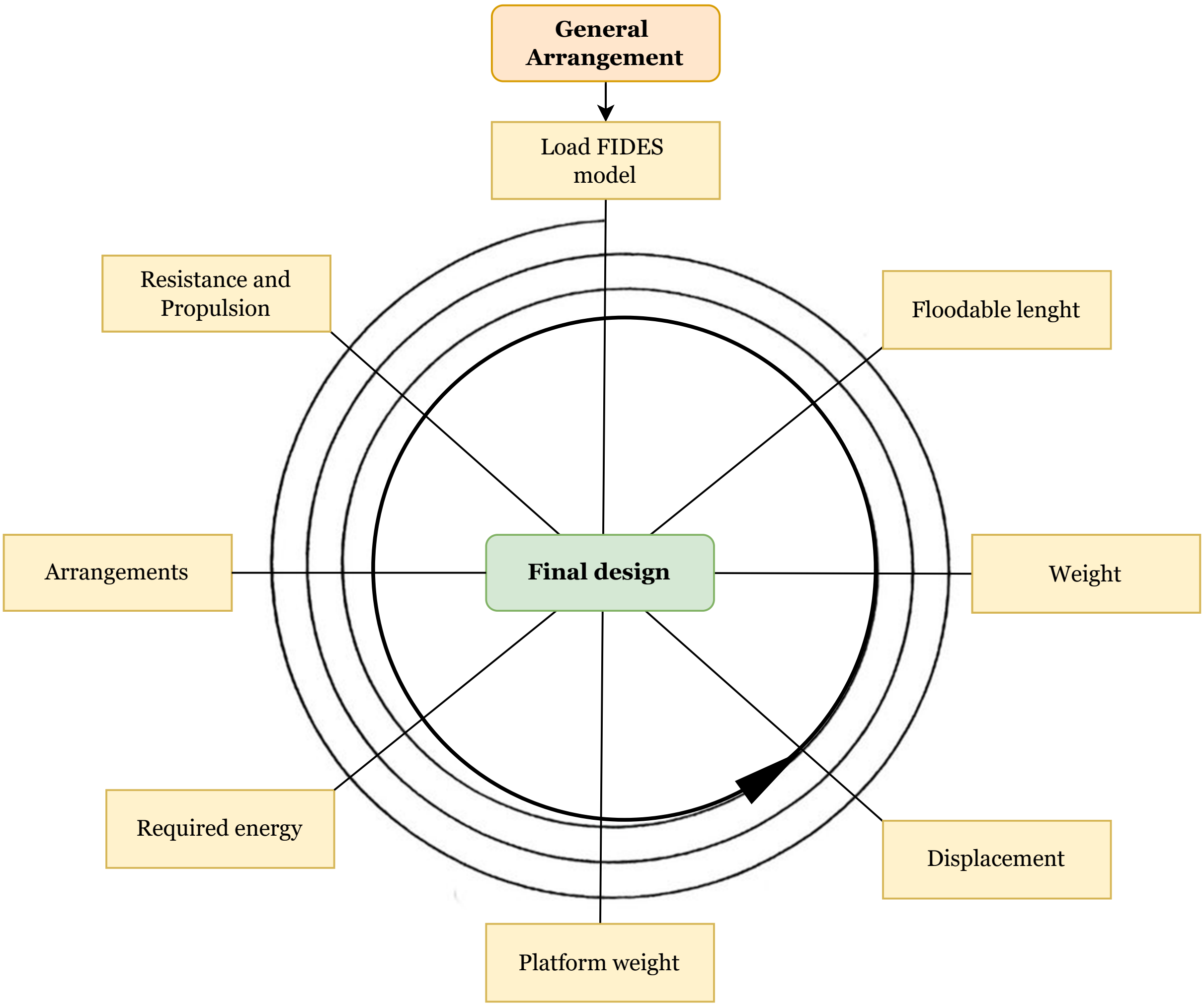

Figure 4.1: A graphical illustration of the schematic design iteration process

4.2 Ship synthesis model

The aim of this part of the thesis is to investigate the impact of fuel choice on the design of Large Surface Combatants with a displacement of around 6000 tonnes. These results cover an overview of the impact of the proposed concept designs, illustrated in Figure 1.2. In this overview, the main design parameters that dictate the size are presented, from which the parametric fuel cost, OPEX and procurement costs can be derived. This overview enables to compare the final designs and draw conclusions as a result of the different design choices.

To do so, it would be ideal to make a general arrangement plan, to divide the available space on a detailed level and examine how differed spaces interact to establish the impact in the most precise way. This is an extensive design process, and it would take years to refine and crystallise the research and therefore this is not reachable in the time duration of this graduation thesis. Furthermore, this level of detail is not necessary to establish the quantitative impact on the proposed concept designs.

However, to establish an overview of the impact of the proposed concepts , a certain level of detail needs to be established in the design. This includes varying the energy systems for the design concept, as illustrated in Figure 1.2, and to maintain all other variables of the design constant. The design concept of the methanol energy systems requires additional tank space, additional fuel and safety systems, additional engines and possibly additional displacement due to the extra required weight and volume of the additional systems and engines. This impacts the weight and thus displacement of the design and therefore the design needs to be sized accordingly. In this work the hull form is kept constant during the sizing process, as well as the ships width and draft, to maintain the same intact static transverse stability and to avoid unwanted layout issues. Therefore, lengthening of the vessel is chosen to increase its displacement and to comply with the weight displacement balance. Subsequently, to ensure the actual flooded length due to a damage length percentage does not exceed the floodable length curve due to lengthening the design, a floodable length analysis is required, as floodable length is a critical design and iteration step in warship design. To implement this level of detail into the design, the Naval Architect needs to be

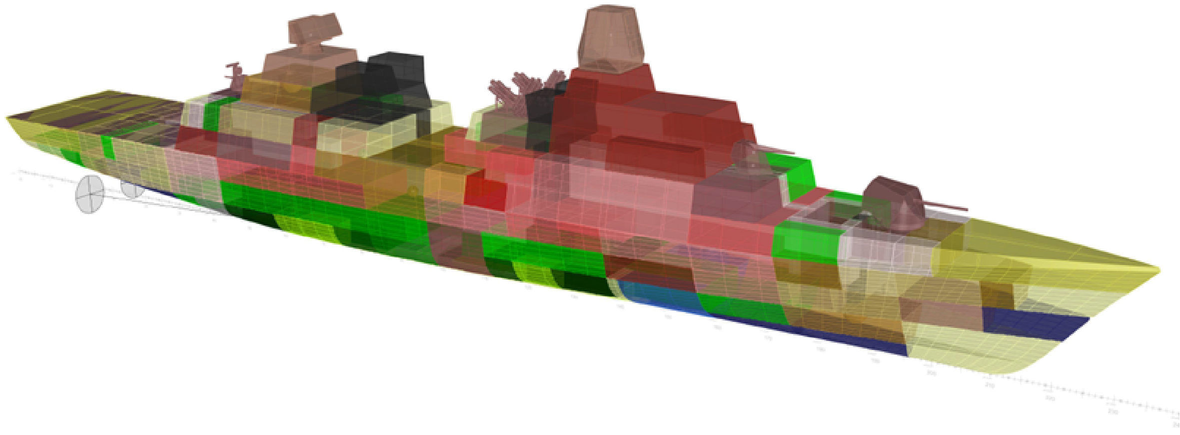

Figure 4.2: 3-D render plot of the case study concept design for a notional Large Surface Combatant

critical towards nuances. Therefore, the proposed designs need to be designed on conceptual level.

To establish comparable concept designs and to implement the required level of detail, a conceptual design model is presented in a schematic overview shown in Figure 4.1 This displays a process of ship design in a iterative way, using the conceptual design tool FIDES. This preliminary ship design model is based on the design spiral established by Evans (1959). This process of iterative exploration of feasible designs is known as point-based or sequential exploration. Requirements at this stage include a detailed list of spaces and systems layout, frame-table, hull form and weight estimates. The first step within the proposed design process as well as in the design spiral of Evans (1959) is the initial configuration of the general arrangement.

The initial general arrangement of the Large Surface Combatant is presented in Figure 4.2, which is used as case study in this thesis. This is a complete design issued by DMO simplified to a FIDES concept design resulting in a notional frigate. It can be assumed that the initial design is a thought-out and well elaborated design in terms of stability, strength, weight, displacement and the subdivision of its available volume, weight and area.

The weights of the concept designs are subdivided into the Ship Work Breakdown System (SWBS) for navy ships and are used to monitor the changes in weight between the different concept designs. An overview of the SWBS codes is presented in Table D.1 in Appendix D. Each type of building block that is used to describe the spatial description of the design is subdivided into the SWBS codes. This enables to determine the impact on the design due to sizing and changing the layout of the design per building block.

4.3 Concept description

With the ship synthesis model presented in section 4.2, in total 6 different concepts designs will be established. It will also be used to determine the physical dimensions and design parameters. This includes the basic naval architectural performances, i.e., weight, centre of gravity and the required input parameters for ship stability calculations and for ship resistance and propulsion power estimates, whether the required speed and range are attainable with the proposed propulsion configuration and available energy storage. This design process requires various iterations before converging on the final dimensions of the design. This process will simultaneously verify the qualitative impact on the designs stated in Section 2. The physical dimensions and design parameters are then used to determine the parametric fuel cost and procurement costs. The results will cover the following concepts as previously introduced in Section 1:

- 1A: Diesel CODLOG
- 1B: Diesel CODAD
- 2A: Methanol CODLOG
- 2B: Methanol CODAD
- 3A: Two-fuel CODLOG
- 3B: Two-fuel CODAD

Diesel fuel in combination with a combined diesel electric or gas turbine propulsion configuration (1A: Diesel CODLOG) is used as baseline in this work. This is chosen as starting point, since this configuration corresponds to the complete design issued by DMO, which is used as case study in this thesis. Subsequently, this concept has been lengthened to accommodate additional engines for a combined diesel and diesel (CODAD) propulsion configuration resulting in concept 1B: Diesel CODAD. Based on both concept 1A: Diesel CODLOG and concept 1B: Diesel CODAD the other two-fuel variations (2 and 3) with each two propulsion configurations (2A, 2B, 3A and 3B) are derived. In the following subsections, the methodology influencing the design spiral is further elaborated on with respect to sizing of the design, power requirement, power and propulsion configuration, floodable length and energy consumption.

4.4 Power requirement

Ship speed can be directly translated to ship resistance and therefore propulsion power. The method used to determine the resistance versus speed curves for the proposed concepts is a statistical re-analysis of resistance and propulsion data by J. Holtrop (Holtrop, 1984). The Holtrop & Mennen resistance prediction method was first published in 1978, based on regression analysis of random model experiments and full-scale data, available at the Netherlands Ship Model Basin. In 1982 an adaptation to the method was made, resulting in a set of prediction formulae with a wider range of applications. The extension of the method focused on improving the power prediction of slender naval ships with a complex appendage arrangement and immersed transom. The re-analysis done in 1984 by J. Holtrop covered an extension of 64 hull forms, the regression analyses were now based on the results of tests on 334 models. The total resistance of a ship is expressed in Equation 4.1.

$$R_{t,trail} = R_F(1+k_1) + R_{APP} + R_W + R_{TR} + R_A \tag{4.1}$$

where:

R_F: frictional resistance according to the ITTC-1957 friction formula

$1+k_1$: form factor describing the viscous resistance of the hull form in relation to R_f

R_{APP}: resistance o f appendages

R_W: wave-making and wave-breaking resistance

R_B: additional pressure resistance of bulbous bow near the water surface

R_{TR}: additional pressure resistance of immersed transom stern

R_A: model-ship correlation resistance

The resistance curves resulting from Equation 4.1 are considered as ideal trail conditions: sea sate 0, wind speed 0 m/s and no fouling. However, ship resistance strongly depends on the conditions in which the ship operates. Navy ship requirements are generally stated at six months out of dock (6MOOD), Sea Sate Four (SS4) and wind force six on the Beaufort scale (BFT6). In this study, added resistance effects of sea state, wind speed and fouling are compensated for in the same manner as the requirements are generally stated for by navy ships and from now on stated as service conditions.

The effect of sea state (i.e. wave height) on the projected area of the hull can have a negative impact on the resistance. To estimate the total resistance curve of Large Surface Combatants, indication of the added resistance due to sea state envisaged in the area of operation is needed. The added resistance due to sea state are based on on full scale tests of the LCF. In SS4 an added resistance of 50% at 15kts with respect to the total resistance was measured and 5% at 25kts. These measurements are used for the added resistance calculations for all design variations. Linear interpolation and extrapolation is used to determine the the added resistance over the entire speed range. The added resistance effect of SS4 is then calculated according to Equation 4.2.

$$R_{SS4} = \frac{5\% * R_{t,trail} - 50\% * R_{t,trail}}{25-5} * (v_s - 5) + 50\% * R_{t,trail} \tag{4.2}$$

where:

v_s: ship speed

The effect of wind on the superstructure and hull increases the total added resistance. The relative velocity and angle of the wind projected on the surface area is determinative for the wind added resistance component. The formula used for determining the added resistance due to wind is approached by the generic formula for determining wind resistance (Moody, 1996). This formula is shown in Equation 4.3.

$$R_{wind} = 0.5 * \rho_{air} * (v_s + v_{air})^2 * A_{wind} * C_{wind} - 0.5 * \rho_{air} * (v_s)^2 * A_{wind} * C_{wind} \tag{4.3}$$

where:

ρ_{air}: air density

v_{air}: air speed

In carrying out resistance calculations regarding the viability of the proposed propulsion power of a new vessel, it is desirable to estimate the resistances due to fouling at various stages of its operational time out of dock. This knowledge is essential in the stage where the required propulsion power and energy are determined. The frictional resistance is at its lowest point after the vessel is in the water directly out of dock, when the underwater surface is smooth. From this stage on there is a increase in the frictional resistance caused by the fouling of the hull. The rate at which this process of fouling takes place depends on a range of variables. The negative impact of fouling in this study is approximated at an increase of 3% per month out of dock of the frictional resistance as described in equation 4.4 (Moody, 1996).

$$R_{foul} = 3\% * MOOD * R_F \tag{4.4}$$

Thus the total service resistance, which includes the added resistance effects of sea state, wind speed and fouling is calculated according Equation 4.5

$$R_{t,service} = R_{t,trial} + R_{SS4} + R_{wind} + R_{foul} \tag{4.5}$$

Finally, the break power versus ship speed curves are determined using Equation 4.6 and (Klein Woud and Stapersma, 2002).

$$P_b = \frac{R_{t,service} * v_s}{\eta_O * \eta_R * \eta_s * \eta_{GB}} \tag{4.6}$$

where:

η_O: open water efficiency

η_R: relative rotative efficiency

η_s: shaft efficiency

η_{GB}: gearbox efficiency

To improve the accuracy of the resistance prediction, parameters describing the hull form are directly derived from the available 3-D hull form drawn in Rhino, instead of the predicted form parameters resulting from the Holtrop & Mennen prediction method. To verify the prediction results of Holtrop & Mennen, a classified DMO prediction model is used to make a comparison. It was observed that the Holtrop & Mennen predictions are established within an acceptable error range of a few percent in the regions of interest, i.e., 18 and 29 kts. The aim of this research is to present an overview of the impact of the proposed energy systems, while the error of the predicted resistance is constant for every design. Therefore, it is assumed that the Holtrop & Mennen resistance prediction method is sufficient for this purpose.

4.5 Power plant configuration

The choice of the components for the power and propulsion configuration are based on the required power and selected by comparing to existing components available on the market shown in Appendix: B. Based on these existing components, the configuration and therefore dimensions of the engine rooms are composed. The ratio between the engine room's dimensions and machinery of the baseline concept is kept constant over the different concept designs. Additionally, 2 m around the propulsion components is necessary to be able to perform maintenance work. The sequence in which the engine rooms are placed is as follows: the gearbox is placed in the middle, to the front and aft of the gearbox room, the propulsion engine rooms are located. To the front and aft of the propulsion rooms, the generator rooms are situated. The size, weight and volume of the gearbox are kept constant for all concepts and are equal to the gearbox in the baseline design. Furthermore, it is assumed that methanol dual-fuel engines have the same dimensions, weight, volume and availability as the selected diesel engines from Appendix B

4.6 Energy calculation and fuel cost

From the energy calculation in the conceptual design model three different result are derived: the required fuel capacity, the energy consumption and the operational fuel cost. For the energy calculation, the initial design requirements and the results from the conceptual design model are given as input. It is assumed that the efficiency of both the diesel engine and the gas turbine are independent of the fuel choice.

The required fuel capacity is determined by the range stated in the operational requirements of the design, i.e., 5000 nm at cruise speed (18 kts) in service conditions. The required fuel capacity is expressed in weight m_{fuel} and is defined as follows:

$$m_{fuel} = sfc_{propulsion} * P_{B,transit} + P_{Aux,transit} * t_{required} * sfc_{generator} \tag{4.7}$$

where: sfc is the specific fuel consumption, dependent on the engine composition in service, the sfc is chosen from two typically used engines onboard of naval combatants and used in the designs as shown in Appendix E. For the MT30 gas turbine which is used in the concept designs, the sfc used is provided by Rolls Royce (2018); $P_{B,transit}$ is the brake power at cruise speed in service conditions; $P_{Aux,transit}$ is the auxiliary power in transit mode; and $t_{required}$ is the sailing time of 5000 nm at 18 kts.

The energy consumption is calculated in the same manner as the required fuel capacity. The energy usage is calculated at each ship speed per unit of time and multiplied with the corresponding time of a typical operational profile of a Large Surface Combatant, as shown in Appendix C. It is assumed that the required power is met in the most economical way. As a result, in some scenarios the vessel is driven by one engine, and therefore one propeller. In these scenarios there are no losses taken into account of a trailing shaft. To calculate the energy consumption for one year it is assumed that a Large Surface Combatant is 200 days at sea in one operational year. Specifically, in which the vessel is sailing 80% of the time and 20% in foreign harbors where its energy generation is covered by its diesel generators. Subsequently, the fuel cost derived from the existing literature presented in Section 2.2.3 and the energy usage of each design are used as input for the fuel consumption cost and annual fuel cost calculations.

4.7 Sizing

To accommodate for the additional volume and weight caused by varying the energy system and to keep the weight-displacement ratio in balance, the final design is sized appropriately. As a direct effect of adding weight to the design, the displacement increases, as weight equals displacement. If the hull form and the parameters dictating its size are kept constant, the final design draft increases accordingly, which is not desirable. Instead, the design needs to be sized by increasing either its breadth and/or length. One of the options to increase ship volume and displacement is by sizing with constant form factors. As a consequence, all volumes describing the spatial description of the design change. Consequently, the volumes that are not researched change as well and rearrangement of the entire layout is required to keep these volumes constant. Additionally, scaling the design with constant form factors may not be the most suitable manner to accommodate the additional volume and weight for the methanol energy system.

The energy system is often considered not a key driver for the breadth of the design, as a strong driver for the breadth of a Large Surface Combatant is the integrated topside design (ITD). This can relate to either the weight of the ITD or its spatial layout. Weighty systems high up in the ITD have a strong influence on the stability of the design and can therefore dictate the breadth of the vessel. Examples of these weighty systems are the radar systems, the cannon, the vertical launch system (VLS) and the helicopter. Although the center of gravity of the VLS is fairly low, still they have to come out at deck level. The helicopter is located on the helicopter deck, which in principle can be lower, but this would reduce the machinery volume drastically below the helicopter deck. The spatial layout is driven more by voluminous objects, which can have a strong influence on the breadth of the design. A clear example is the number and orientation of the hangars, i.e., if two helicopter hangars are oriented side by side, it requires sufficient width, which is most likely the key driver dictating the maximum breadth of the design. To determine the impact of the design variations, all design variables which are not affected by the energy system, are kept constant. This includes the ITD, which is assumed to be the primary driver for breadth of Large Surface Combatants.

In contrast, the length of a Large Surface Combatant is predominantly driven by the energy system. This is mainly caused by the required tank top surface on which the power and propulsion architecture is situated. The width is mainly determined by the widest part of the propulsion train, often the gearbox room. The required length of the tank top is then determined by the amount of propulsion engines and energy generators.

The objective in this research project is to establish the effect of changing the energy system. Lengthening the design is therefore seen as the most favorable manner to increase the displacement of the design and to increase its carrying capacity to accommodate the weight increase of the different design iterations. By lengthening the design, it is important to ensure that the density of the extended section where the extra machinery systems are located remains constant. This helps to keep a well balanced design and ensures the well elaborated and thought-out initial design is not drastically influenced.

Extending the design to maintain the initial design draft for every design variation is done with constant hull form, breadth and depth. The intention is to keep all other variables of the design constant so only the effect of change the energy systems is established. However, by extending the design with constant hull, the bow of the ship tapers and the stern of the design rises sooner. As an effect, the volume in the bow and stern decreases considerably. For the most part, the spatial layout in the bow and stern is filled with volumes and weights that are not covered by the energy system. To compensate for this effect, a weighted average of the lost weight and volume of the payload is taken and implemented as a functional building block in the intermediate compartment as a result of the extension.

4.8 Floodable length

Ship stability is the potential of a vessel to re-erect after being unbalanced. Too little stability can lead to the capsize of a vessel. Therefore, it is legally required to calculate the stability of a seagoing vessel, so that it is know whether it can go to sea safely. Stability calculations start in the preliminary design phase of a vessel, this applies to both the intact stability and the damage stability of a vessel.

In this research it is assumed that the stability of the initial design is well elaborated and thought-out. By extending the design, the intact stability is minimally affected. Since the compartment placed in the extended section does not increase the center of gravity of the design and additionally, the section is placed close to the longitudinal center of gravity of the design. However, an extension can have a significant influence on the damage stability of a design.

Deterministic damage stability is the method of assessment for naval ships when flooded. The design must meet the damage stability criteria of predetermined damage cases. For a Large Surface Combatant this translates to a damage length of 15% of the length between perpendiculars, where after different scenarios are assessed. One of these scenarios is to ensure that the vessel is designed with enough reserve buoyancy in the event of such damage. This is a critical design scenario for Large Surface Combatants, particularly if a design undergoes extension.

In the event of a damage, to provide adequate buoyancy and to prevent progressive flooding, the design is compartmentalized through watertight transverse bulkheads. This makes compartment length and therefore the placement of watertight transverse bulkheads an important driver for the required damage stability of Large Surface Combatants. An important factor that determines the subdivision and compartment length of a design in terms of stability is the allowable floodable length. Floodable length is the amount of ships length that can be flooded without the marine line being submerged. The margin line is an imaginary line 75 mm below the upper most watertight deck. A design is considered to be safe if the margin line is not submerged after a certain amount of compartments are flooded. Plotting the floodable length vertically along the length of the ship results in the floodable length curve. This facilitates the naval architect in the preliminary design phase to judge the feasibility of the design. Furthermore, by analyzing the floodable length curve it becomes clear how the ship should be compartmentalized.

Note that this is not a damage stability analysis. A floodable lengths analysis is a quick and inexpensive process and examines if the design remains floating when damaged. A damage stability analysis is a more time consuming involved process, which ensures the design remains floating and upright. In later stages of the design process, a damage stability analysis is required.

4.9 Procurement cost model

To calculate the procurement costs, an indicative cost estimation model for a surface combatant was issued by DMO and used in this thesis which can be found in Appendix D and seen in Figure D.1. The cost estimation model is based on the SWBS groups; where SWBS-800 specifies engineering costs and SWBS-900 specifies ship assembly and support service costs. The model excludes Integrated Logistic Support (ILS) and includes project costs, as well as costs for supporting DMI for the implementation of the project and costs for acceptance tests; specifically, the Harbour Acceptance Test and Sea Acceptance Test. The cost breakdown involves a notional surface combatant.

5 Results

In this section the results are presented of the ship synthesis model as presented in 4.2 for each design variation. The final designs are established by varying the energy concept proposed in 1.2. For the established designs, the baseline model issued by DMO is extended and redesigned to implement the different energy systems. First, the visual design, main dimensions and the energy system which includes the propulsion architecture, tank layout and capacity are shown for each concept separately. Secondly, the floodable length curves are presented for the baseline and longest design. Finally, the results for all concepts are summarized in a table.

5.1 1A. Diesel fuel with gas turbine hybrid propulsion

Figure 5.1 shows the simplified model of the design issued by DMO as described in chapter 4. The legend for the design concepts created in FIDES can be found in Appendix F. This model, which has detail added in a standardised way for confidentiality reasons, serves as the baseline for the other models as the proportions of the energy concept and the volume necessary for the payload are set here. The payload of this model is then used as a normalised constant for the other models, whilst the energy concept varies. The vessel is 144 m long and has a displacement of 6052 tonnes.

The propulsion installation is situated amidships in the lower hull of the vessel. The bunker fuel tanks are in the double bottom between the keel and 1.80 m above the keel, underneath the propulsion installation. The service day tanks are located one deck above the tank top, between 4.8 , and 7.8 m above the keel. Figure 5.2 shows the propulsion architecture with the length of each element. This propulsion architecture displays a combined diesel electric or gas turbine hybrid propulsion (CODLOG) system.

The necessary propulsion power in service conditions for this concept at the maximum speed of 29 knots amounts to 38 MW, and for the cruise speed at 18 knots the required propulsion power is 8 MW as shown in Appendix G. To meet the requirements at top speed there is a MT30 gas turbine, and for cruise speed two Renk AED electromotors of 4 MW apiece. To be able to generate the required power for the electric propulsion and to deliver sufficient power to other electric users, like the HVAC and SEWACO with peak consumption of 4 MW and a to add a certain amount of redundancy, there are four MTU4000 20V 3 MW diesel generators. A LCF-like gearbox is situated in the middle of the propulsion architecture.

For the MTU 4000 engines to deliver the required power for the Renk AED electromotors to sail 5000 nautical miles at 18 knots, and to deliver 1 MW electric power at service conditions, the gross tank capacity is 661 m^3 which translates to a net capacity of 516 tonnes.

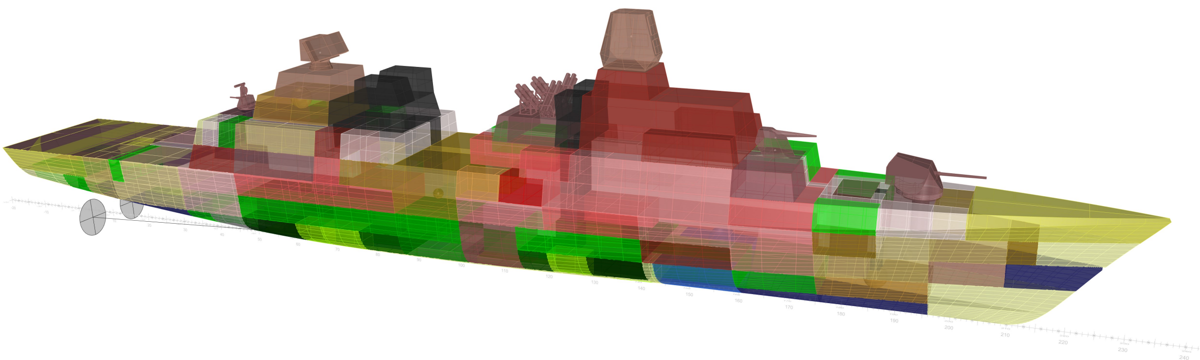

Figure 5.1: Concept 1A. Diesel fuel with CODLOG propulsion, 144m , 6052 tonnes

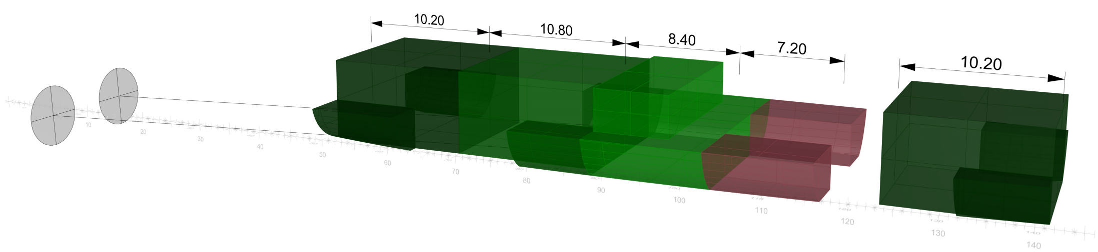

Figure 5.2: CODLOG propulsion architecture with the length of each building block

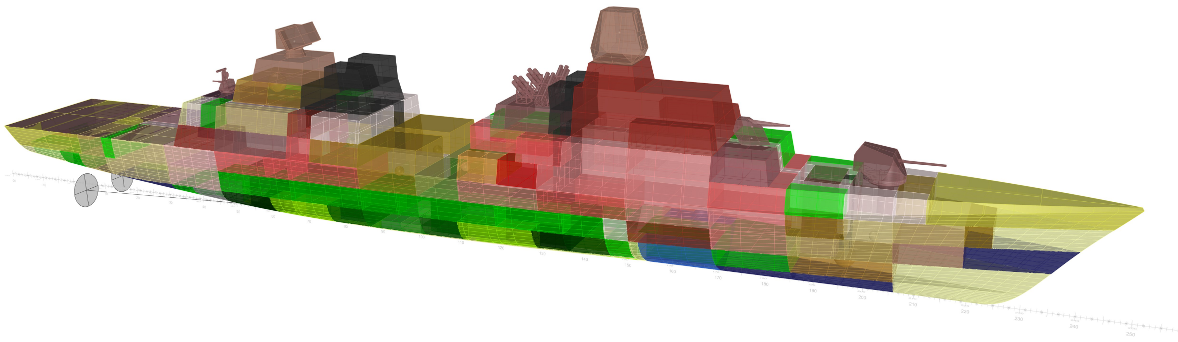

Figure 5.4: Concept 1B. Diesel fuel with CODAD propulsion, 153m , 6420 tonnes

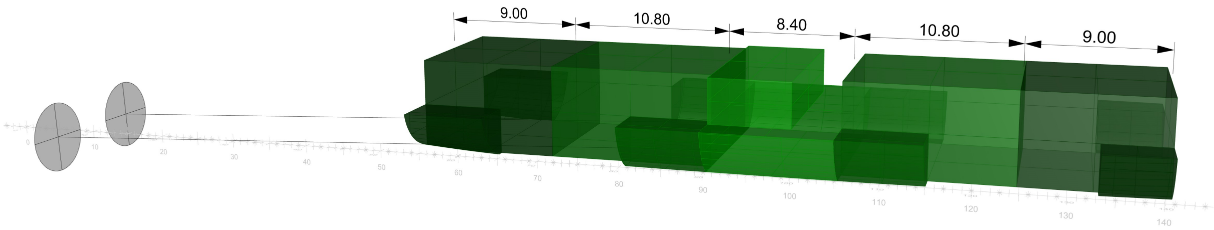

Figure 5.3: CODAD propulsion architecture with the length of each building block

5.2 1B. Diesel fuel with diesel engine propulsion

Figure 5.4. shows the model for the diesel fuel with diesel engine propulsion concept. The vessel is 153 m long and has a displacement of 6420 tonnes. The difference in length and displacement in comparison to concept 1A is caused by additional engines.

The propulsion installation, bunker fuel tanks and service day tanks have the same position as in concept 1A. Figure 5.3 shows the engine room layout with the length of each element. This engine room layout displays a combined diesel and diesel hybrid propulsion (CODAD) architecture. The engine room layout's total length is 1 m longer than that of concept 1A, which is not in agreement with the total lengthening of the design. The total volume of the engine rooms has increased significantly with 731 m^3 (26%) as the gas turbine and electric motors of concept 1A are replaced by four diesel engines. Additionally, the CODAD propulsion concept is 84 tonnes heavier then the CODLOG concept. To accommodate this extra volume and weight, the lengthening of the design totals at 9 metres and an increment of 368 tonnes.

Because of the lengthening of the vessel, the power requirements at top speed decrease as can be seen in Appendix G. Therefore, the necessary propulsion power in service conditions for this concept at the maximum speed of 29 knots amounts to 35.5 MW, which is a decrease of 2.5 MW compared to concept 1A. For the cruise speed at 18 knots the required propulsion power remains 8 MW. To meet the requirements at top speed there are four MTU8000 engines of 10 MW each used simultaneously. For cruise speed, one or two of these engines can be used to meet the required power. For the electric power requirement of 4MW, there are four MTU4000 8V of 1 MW.

For the MTU8000 engines to deliver the required propulsion power to sail 5000 nautical miles at 18 knots, and a MTU4000 diesel generator to deliver 1 MW electric power at service conditions, the gross tank capacity is 620 m^3 which translates to a net capacity of 480 tonne. This is less than concept 1A, because there are no losses to overcome in both the generator and electric motor for the required propulsion power.

5.3 2A. Methanol fuel with gasturbine hybrid propulsion

Figure 5.5 shows the model for the methanol fuel with gas turbine hybrid propulsion concept. The vessel is 165 m long and has a displacement of 6936 tonnes. The difference in length and displacement in comparison to concept 1A is caused by the addition of the methanol energy system.

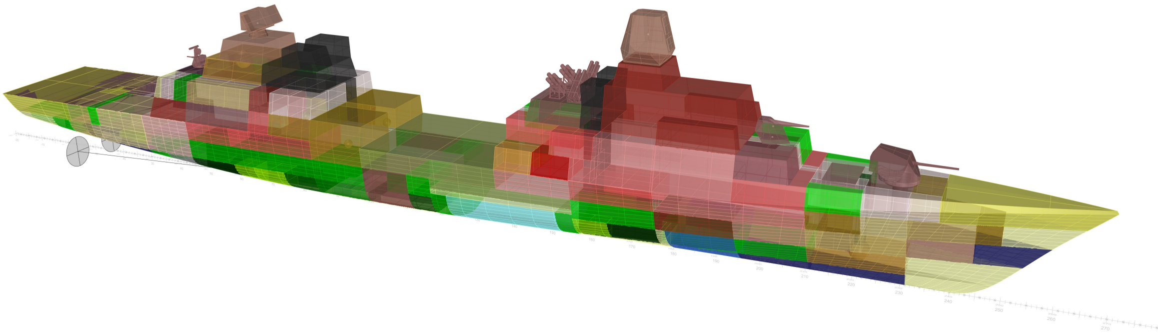

Figure 5.5: Concept 2A. Methanol fuel with CODLOG propulsion, 165m , 6936 tonnes

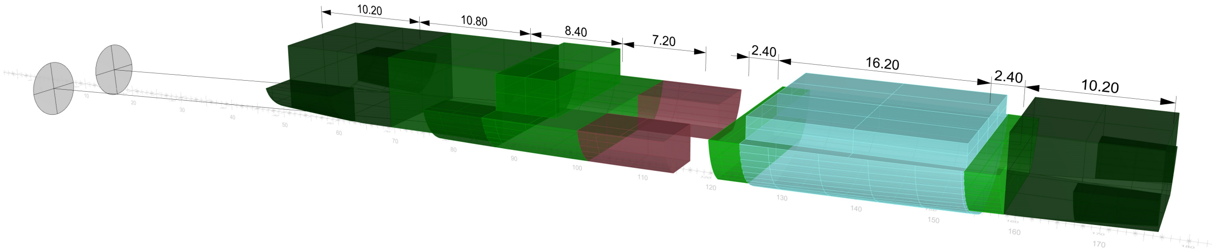

Figure 5.6: Engine room layout of concept 2A including methanol section and separate methanol pump rooms

The methanol fuel tank is placed amidships in the lower hull of the vessel up to the lowest possible water line of the vessel as one tank, because of necessity of cofferdams around a methanol tank. To further reduce the impact of protective cofferdams, the methanol pump rooms are located aft and forward of the methanol fuel tank. In the baseline concept 1A, the fuel storage tanks are placed in the double bottom, but for methanol this would include adding cofferdams below the whole tank top where fuel tanks are located. This would decrease the available volume to 35% and would add more steel construction weight. Because of the decrease of tank volume, only 170 tonnes of methanol can be carried which would leave a range of only 850 miles at cruise speed. The diesel tanks necessary for the methanol dual fuel engines have the same position as the diesel day tanks in concept 1A. Figure 5.6 shows the engine room layout with the length of each element, and the methanol tank and pump rooms. This propulsion architecture is a combined diesel electric or gas turbine hybrid propulsion (CODLOG) system. To accommodate the extra weight and volume of the methanol tank, the lengthening of the design totals at 21 metres and an increment of 884 tonnes compared to concept 1A.

Because of the lengthening of the vessel, the power requirements at top speed decrease as shown in Appendix G. Therefore, the necessary propulsion power in service conditions at the maximum speed of 29 knots amounts to 33,5 MW, which is a decrease of 4,5 MW compared to concept 1A. However, for the cruise speed at 18 knots the required propulsion power is 8.1 MW. This is a slight increase because at this speed the increase of the wetted area is larger than the decrease of the wave-making resistance. Even though the required power for both top speed and cruise speed are different than in concept 1A, this does not result in a change in both the gas turbine for top speed and the electric motor for cruising speed in the configuration. Components are offered in discrete steps and therefore can not always match the exact required power.

For the electric propulsion to deliver the required power to sail 5000 nautical miles at 18 knots, the required energy is $2.22 * 10^4$ GJ. Methanol dual fuel engines require 8% pilot diesel fuel for good operations at 85 %MCR. This translates to a net ratio of 1025 tonnes methanol and 42 tonnes diesel. The gross tank capacity is therefore 1396 m^3 for methanol and 53 m^3 for diesel. This is an increase compared to concept 1A of 551 tonnes in weight and 788 m^3 in volume.

5.4 2B. Methanol fuel with diesel hybrid propulsion

Figure 5.7 shows the model for the methanol fuel with diesel and diesel hybrid propulsion concept. The vessel is 173 m long and has a displacement of 7313 tonnes. The difference in length and displacement in comparison to concept 1A is caused by the addition of the methanol energy system and additional engines, it is a variation of

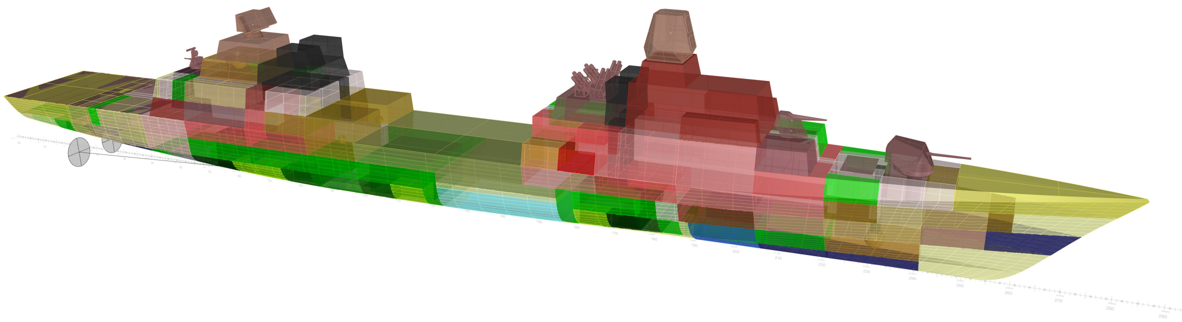

Figure 5.7: Concept 2B. Methanol fuel with CODAD propulsion, 173m , 7313 tonnes

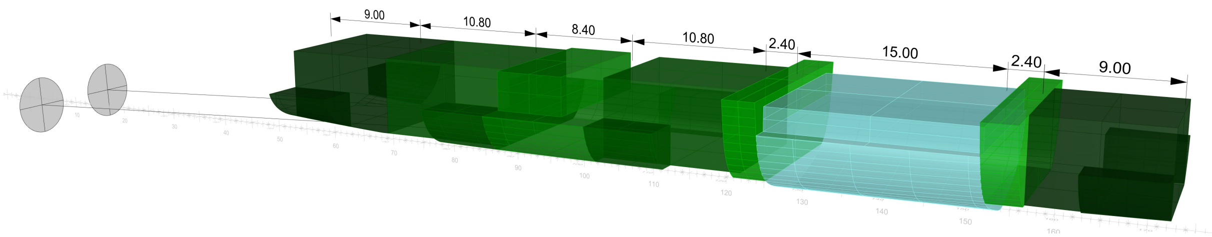

Figure 5.8: Engine room of layout concept 2B including methanol section and separate methanol pump rooms

concept 1B.

The propulsion installation and methanol fuel tank have the same position as in concept 2A. The methanol pump rooms are located aft and forward of the methanol fuel tank. Due to the additional engines, extra auxiliary systems are required which add more space and weight than they do in concept 2A. As a result the pump rooms are enlarged. The difference is 16 tonnes.

Figure 5.8 shows the engine room layout with the length of each element, and the methanol tank and pump rooms. This engine room layout displays a combined diesel and diesel hybrid propulsion (CODAD) architecture. To accommodate the extra weight and volume of the methanol tank, the lengthening of the design compared to 1A totals at 29 metres and an increment of 1215 tonnes and 847 tonnes compared to concept 1B.

Because of the lengthening of the vessel, the power requirements at top speed decrease as shown in Appendix G. Therefore, the necessary propulsion power in service conditions at the maximum speed of 29 knots amounts to 32.5 MW, which is a decrease of 5.5 MW compared to concept 1A. For the cruise speed at 18 knots the required propulsion power is 8.2 MW which is again a slight increase compared to concept 1A.

Even though the required power for both top speed and cruise speed are different, this does not result in a change in the propulsion architecture proposed in 1B. Components are offered in discrete steps and therefore can not always match the exact required power. The power output of the MTU 8000 20V ranges between 8.2 MW and 10 MW whereas one engine size smaller, the MTU8000 16V, maxes out at 8MW which is not sufficient. Another reason for keeping the propulsion plant constant is to maintain a like for like comparison. The absolute decrease of power at top speed seems significant, but in the top speed range 1 knot of speed difference is associated with an increase of 5 MW required propulsion power.

To deliver the required power to sail 5000 nautical miles at 18 knots, the required energy is $2.02 * 10^4$ GJ. This translates to a net ratio of 945 tonnes methanol and 38 tonnes diesel. The gross tank capacity is therefore 1284 m^3 for methanol and 49 m^3 for diesel. This is an increase compared to concept 1A of 466 tonnes weight and 672 m^3 volume.

5.5 *3A. two-fuel strategy with gas turbine hybrid propulsion*

In the two-fuel strategy, the vessel can operate on high requirements with diesel and with reduced requirements on methanol where the tank volume is driven by the energy density of diesel. The fuel can be held in three ways. The first option (3A1), which matches concept 1, where the fuel tanks are located inside the double bottom both fit for methanol and diesel without safety requirements of methanol in place, as mentioned earlier, if cofferdams are used in the double bottom it is not a feasible solution. The second option (3A2) is also both fit for methanol and diesel, but with the safety measures for methanol in place and can therefore match concept 2. The third and last option (3A3) is to carry the fuel in two separate tanks, where the operational requirements determine the volume of the diesel tanks and the methanol fuel tanks are encased by protective cofferdams. To keep the displacement increase to a minimum, the displacement weight ratio is kept in balance with the minimum amount of energy on board to meet the operational requirements, i.e., the methanol tank is empty.

5.5.1 3A1 Combined tank without cofferdams

The vessel is 146 m long and has a displacement of 6133 tonnes, note that for 3A1 the methanol safety measures are neglected. The difference in length and displacement in comparison to concept 1A is small because the only additions are two methanol pump rooms and additional auxiliary systems. Because this impact is minimal, the rest of the design is identical to concept 1A. For peacetime, the amount of methanol that can be carried in the tank configuration as described in concept 1A is 486 tonnes which corresponds to a range of 2187 nm.

5.5.2 3A2 Combined tank with cofferdams

The vessel is 148m long and has a displacement of 6217 tonnes. The difference in length and displacement in comparison to concept 2 is caused by a significant reduction of required tank volume, as shown in Figure 5.9. The rest of the design is identical to concept 2A. For peacetime, the amount of methanol that can be carried in the two-fuel storage tank is 484 tonnes which corresponds to a range of 2187 nm.

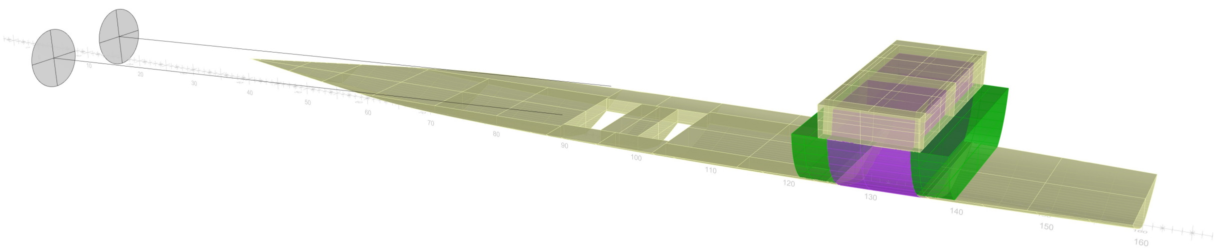

Figure 5.9: Two-fuel tank both fit for methanol and diesel, with the safety measures for methanol in place

5.5.3 3A3 Separate tanks with cofferdams

This design is a combination of concept 1 and 2 where the diesel fuel is stored in the double bottom, and the methanol tank in the middle section up to the lowest possible water line as one tank , as shown in Figure 5.10. Unlike in 3A1 and 3A2, the size of the methanol tank is independent from the diesel tank. This gives freedom to choose a desired amount of methanol tank space. If the same peacetime range is accepted as in 3A2, the design slightly increases in displacement as the building block for fuel tank is slightly heavier than for void space.

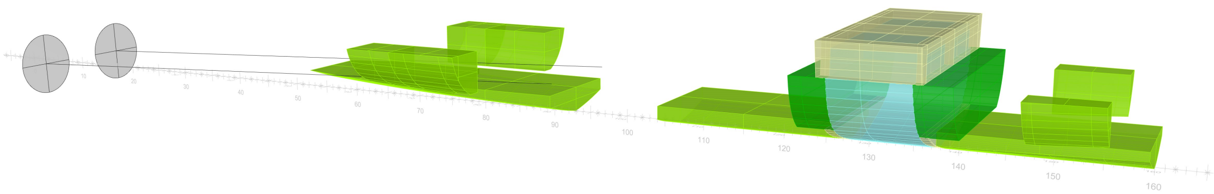

Figure 5.10: Fuel tank layout for the two-fuel concept in which methanol and diesel are stored separately

5.6 3B. two-fuel strategy with diesel hybrid propulsion

The difference between concept 3A and 3B is caused by the implementation of additional engines as a result of the combined diesel and diesel propulsion architecture. The compositions and layout of the fuel tanks from design 3A correspond with 3B. Therefore, the displacement increase of the designs from 1B to 3B are in the same order of magnitude as the displacement increase from 1A to 3A, but in a higher displacement range.

5.6.1 3B1 Combined tank without cofferdams

The vessel is 156 m long and has a displacement of 6553 tonnes, note that for 3B1 the methanol safety measures are neglected. The difference in length and displacement in comparison to concept 1B is small because the additions are two methanol pump rooms and additional auxiliary systems. Because this impact is minimal, the rest of the design is identical to concept 1B. For peacetime, the amount of methanol that can be carried in the tank configuration as described in concept 1B is 442 tonnes which corresponds to a range of 2187 nm.

5.6.2 3B2 Combined tank with cofferdams

The vessel is 159m long and has a displacement of 6678 tonnes. The difference in length and displacement in comparison to concept 2B is caused by a significant reduction of required tank volume. The rest of the design is identical to concept 2B. For peacetime, the amount of methanol that can be carried in the two-fuel storage tank configuration is 445 tonnes which corresponds to a range of 2187 nm.

5.6.3 3B3 Separate tanks with cofferdams

As described in section 5.5.3, this design represents a combination of concept 1 and 2 where the diesel fuel is stored in the double bottom as in concept 1B, and the methanol tank in the middle section up to the lowest possible water line as one tank and enclosed by cofferdams, as in concept 2B. Unlike in 3B1 and 3B2, the size of the methanol tank is independent from the diesel tank, since the operational requirements are attached to the volume of the combined diesel tanks. This gives freedom to choose a desired amount of methanol tank volume. If the same peacetime range is accepted as in 3A2, the design slightly increase in displacement as the building block for fuel storage tanks are slightly heavier then for void space building blocks.

5.7 Floodable length

The design issued by DMO was designed in a way that the deterministic damage length, 15% of the length between perpendiculars resulted in a three compartments vessel, i.e., that the maximum of 3 compartments can be flooded when damaged, as shown in Figure H.1 in Appendix H. It can be seen that all damage scenarios plotted remain below the allowable floodable length curve.

The design that has been extended the most is at greatest risk of failing to meet the floodable length requirement, since the damage length increases linear with lengthening of the vessel. This holds for the methanol fuel concept with diesel and diesel hybrid propulsion (2B). The maximum damage length increased due to extension resulted in a four compartment vessel. Furthermore, the methanol section is implemented as one compartment into the design. In Figure H.2 the floodable length curve and the possible damage scenarios are shown for concept 2B. It can be seen that the allowable floodable length is overwritten 3 times. Two of these cases are attributable to the length of the methanol compartment and one to the increase of the damage length resulting in a four compartment vessel.

For concept 2B it was observed that the lowest allowable floodable length increased to 40m compared to the baseline. By extending the compartments, to ensure that the maximum damage length cannot cover more than two entire compartments, it is possible to reduce the effect of the maximum damage length to a three compartment vessel. Furthermore, the methanol compartment has to be divided in at least two compartments to match the compartment length of the design and to not overwrite the allowable floodable length curve. However, this requires the designer to rearrange the entire spatial layout of the design. If this is not desirable or even possible, the design must be sized in a different way to increase its stability.

5.8 Procurement costs

In the literature review of this thesis, it was concluded that due to the lower specific energy of methanol the endurance of the ship is more than halved or the tank capacity has to be increased by 700 to 900 m^3, which directly adds 10% to 15% to the displacement with similar costs.

In the design study it was concluded that the projected lightship weight of the Large Surface Combatant when switching from diesel to methanol increases from 4478 to 4803 tonnes for a gas turbine hybrid propulsion configuration and from 4815 to 5169 for a diesel and diesel hybrid propulsion configuration. As there is specific interest in the increase in procurement cost of the methanol fuel system, a comparison is made between similar propulsion configurations.

The weight increase when switching to methanol results in an increase in cost. This increase in cost is calculated by the weight-cost ratio provided by the cost estimation model for a surface combatant as issued by DMO shown in Table D.1, which incorporates greater detail than the estimation of the literature study. This model allows for separate weight-cost ratio's for each SWBS groups. A significant portion of the weight increase is assigned to SWBS groups with low weight-cost ratio's, namely the hull structure and auxiliary systems. Consequently, this mitigates the increase in procurement cost in comparison with the literature review. The increases in procurement costs when switching to methanol, based on Table 5.1, are 2,5% and 3% for the gas turbine hybrid propulsion system and the diesel and diesel hybrid propulsion system, respectively.

Calculating the procurement cost increase in this way is solely based on weight and stems from historical data, while the addition of methanol systems, safety equipment, engineering capacity and innovation necessary

Table 5.1: Overview of the separate weight-cost ratio's for each SWBS groups and lightship weight increase of the methanol design concepts per SWBS group

SWBS	Description	Cost [%]	1A Diesel[1]	2A Methanol[2]	1B Diesel[3]	2B Methanol[4]
100	Hull structure	6%	35%	1.10	35%	1.09
200	Propulsion plant	7%	8%	1	9%	1
300	Electrical plant	10%	6%	1.02	6%	1.03
400	Command & surveillance	42%	4%	1.01	4%	1.01
500	Auxiliary systems	9%	10%	1.14	10%	1.17
600	Outfit and furnishings	6%	8%	1.03	8%	1.03
700	Armament	10%	3%	1	3%	1

1. Weight percentage of the displacement per SWBS group of concept 1A diesel gas turbine hybrid propulsion
2. Factor weight increase per SWBS group for concept 2A methanol gas turbine hybrid propulsion
3. Weight percentage of the displacement per SWBS group of concept 1B diesel and diesel hybrid propulsion
4. Factor weight increase per SWBS group for concept 2B methanol diesel and diesel hybrid propulsion

at a shipyard bring considerable cost increases. In a feasibility assessment by GGM consortium partners (2020), the lengthening of the vessel as a result of implementing a methanol energy system only accounts for 5% of the increase in procurement cost. The total increase was estimated at 7.3%.

To get a procurement cost estimate closer to reality, an updated model should be created that includes all additional costs of the methanol energy system. This is especially important when creating an estimate for the two-fuel concept. This concept only has a slight increase in displacement, and with the current model this would result in a slight increase in procurement costs. While with the two-fuel concept, the increase in cost is in the implementation of the methanol energy system, which is not represented in the current model.

Table 6.1: Overview of the quantitative impact of the fuel choice on the design concepts of a Large Surface Combatants of around 6000 tonnes, with respect to: length, displacement, energy consumption and fuel cost

Concept	**Length [m]**	**Δ [tonnes]**	**Energy consumption[1] [GJ]**	**Fuel cost[2] [M€]**
1A. Diesel fuel with gasturbine hybrid propulsion	144	6052	$2.86*10^5$	14.28
1B. Diesel fuel with diesel engine propulsion	153	6420	$2.55*10^5$	12.73
2A. Methanol fuel with gasturbine hybrid propulsion	165	6936	$2.81*10^5$	12.51
2B. Methanol fuel with diesel engine propulsion	173	7267	$2.52*10^5$	11.21
3A. two-fuel strategy with gasturbine hybrid propulsion	146-149[3]	6133-6261[4]	$2.85*10^5$	12.51-14.28[6]
3B. two-fuel strategy with diesel engine propulsion	156-159[3]	6553-6678[4]	$2.54*10^5$	11.21-12.73[6]

1. This represents the energy consumption of the corresponding concept design, fully operational for one year. This energy consumption is based on a typical operational profile of a Large Surface Combatant.
2. The column fuel costs are based on the yearly energy consumption in combination with the cost price of sustainable diesel and sustainable methanol which are 50€/GJ and 44€/GJ, respectively.
3. The low range matches option 3x1, where a combined fuel tank is located inside the double bottom without safety requirements, like concept 1. The high range corresponds with option 3x2, where a combined fuel tank is modeled as one section tank with safety requirements, like in concept 2.
4. The lowest displacement corresponds to the shortest design, where the longest design corresponds to the the largest displacement.
6. The price range is caused by the possibility to sail on both diesel and methanol. The lowest projected fuel costs corresponds to solely operating on sustainable methanol and the highest projected fuel costs amounts to operating on fully sustainable diesel.

6 Discussion

In this section, an overview is presented in Table 6.1 on the quantitative impact of the fuel choice on the design of a Large Surface Combatant. Specifically, on the length, displacement, energy consumption and fuel cost of each concept. This overview is used to discuss a few striking results. Finally, in Section 7 the overview is used to compare the concepts and draw conclusions on the impact of the fuel choice.

The implementation of methanol as a fuel does appear technically feasible for naval combatants based on propulsion systems with diesel engines alone. However, its impact on the displacement and size is significant. The size increase when operating on methanol consists of extra ship length to allow both for diesel and diesel hybrid propulsion, as the marine gas turbine operating on methanol is unlikely to become available in the near future and for extra volume for the methanol energy system. Together this results in a 29 meters longer vessel, which is an increase of 20% compared to the baseline concept, which is a gas turbine hybrid propulsion configuration operating on sustainable diesel fuel. However, a longer vessel is more difficult to maneuver and a larger target to air threats, while one of the important requirements is to limit the susceptibility of threats and thus ship size needs to be minimized. Moreover, placing a methanol tank as one section is currently the most favorable way to minimize additional volume and weight of the protective cofferdams. As a result, redundancy is lost since one singular damage in this section will cause loss of all fuel storage. However, this could be mitigated by implementing transfer bulk heads in this section.

If operating on methanol is desirable, but to reduce the impact of operating fully on methanol, navies could consider operating the vessel on a two-fuel strategy, on methanol during operations with limited autonomy, typically in peace time, and on diesel during operations with high autonomy, during (certain) peacetime operations. The two-fuel strategy significantly mitigates the impact on the increase in displacement.

Large Surface Combatants are part of a system of systems, they operate in NATO task-forces that pool their resources and capabilities together. NATO task-forces currently operate on naval distillate fuels meeting the F-76 product requirements. This could be a strong influence to continue operations on diesel, while the navy has the intention to contribute to the operational energy strategy at the same time. Therefore, the availability of sustainable diesel is compulsory. However, there is uncertainty in future availability of long chain sustainable fuels and if they will become available at all for maritime use. Land used to produce sustainable fuels competes with land needed to solve global food shortages. Furthermore, there is competition between different parties that have a need for sustainable energy. Therefore, navies could consider preparing for investment in production of Bio-diesel or E-diesel, as the development in aviation towards SAF might be a crucial enabler for this strategy.

7 Conclusions and future research

Progressing targets on GHG emission reduction urge the NL MoD to reduce the use of fossil fuels; however, without sacrificing striking power, because future naval combatants need to perform their operations on the highest end of the violence spectrum and need to have sufficient autonomy to perform their operations at sea independently of logistic supply lines. In this thesis, the aim was:

to assess the impact of sustainable methanol and diesel on the design of Large Surface Combatants.

To achieve this, the current and future developments of sustainable methanol and diesel have been reviewed from existing literature. Subsequently, comparable concept designs have been established from which the length, displacement, energy consumption and fuel cost are obtained. The impact is presented for three different design concepts with respect to its fuel composition.

To generate comparable concept designs and to explore feasible designs, an iterative conceptual design model is established which represents a design spiral. To avoid undesired influences on the results, as there is specific interested in the impact of the fuel choice, the volumes and weights of the energy system are changed and all other volumes and weights are kept constant, describing the spatial layout and weight of the design. Additionally, the concepts are designed with the same maximum speed, range and operational profile. To accommodate the weight increase of the different design iterations, the design is extended with constant breadth, depth, draft and hull form; moreover, this has ensured comparability between the concept designs and has maintained the same operational capability of the different concept designs.

7.1 Conclusion on the impact of sustainable diesel as a fuel

When operating on diesel, blending of sustainable diesel with fossil diesel is possible in the existing infrastructure as this is a drop-in fuel. This allows a gradual transfer from fossil diesel to sustainable diesel. The main uncertainty in the feasibility of this option is the future availability of sustainable fuels. Both sustainable methanol and sustainable diesel are expected to become available. The interest for sustainable methanol as marine fuel seems larger than for sustainable diesel; therefore, it might be more easily available. However, developments of SAF production facilities for aviation might prove an enabler for future availability of sustainable diesel. It is expected that, due to stimulating government policies, the prices of the proposed fuels will become equal and eventually lower than fossil fuel prices between 2030 and 2040, while the availability will become higher. The production cost of sustainable diesel is 5% to 30% more expensive with a mean estimated additional cost of 6 €/GJ compared to methanol, due to the inherent difference in the thermodynamic conversion efficiency. Navies should take additional cost of sustainable diesel compared to sustainable methanol into account during the entire lifetime, since the procurement costs of a vessel including a methanol energy system are currently estimated higher than that of a vessel solely operating on diesel. Whether the operational costs of sustainable diesel are higher than including methanol in the design has to be determined with an economic trade-off after with an updated cost model that takes into account additional costs of the methanol energy system.

7.2 Conclusion on the impact of sustainable methanol as a fuel

Operating on methanol has a significant impact on the design of Large Surface Combatants. In previous research on a Large Surface Combatant of 6000 tonnes, an increase in displacement of 60% was concluded when operating on methanol (Streng, 2021). In other research on a slightly different vessel, an increase in displacement of 40% was concluded (Astley et al., 2020). Both studies calculated the impact of the fuel choice in a parametric way and based on scaling with constant form factors. In this work a conceptual model is used to size the design in a more realistic way. It was shown that implementing the methanol energy system as one section caused a weight problem and resulted in a increase in displacement of 15%. This is independent of the two considered propulsion configurations, i.e., there is no advantage in choosing a diesel- or gas turbine hybrid propulsion system for methanol specifically. However, marine gas turbines are unlikely to become available for methanol. Consequently, the impact when switching to methanol with respect to gas turbine hybrid propulsion results in a 20% displacement increase. It can be concluded that the established displacement increase in this work is more promising to achieve feasible and affordable designs. It is recommended to do more research on the storage of methanol. The currently necessary cofferdams are heavy and voluminous. If the safety requirements could be met in a different way, for example by using a sandwich construction that prevents leakage of methanol and limits heat ingress in the case of fire, the design impact will be reduced drastically and the design freedom is greatly increased making it easier to store methanol and to ensure redundancy. Furthermore, it is recommended for future research to explore a larger area of the design space. In doing so, different possibilities can be compared, to give more insight in the uncertainty of the design and the impact of the different design drivers can be investigated, bearing in mind future developments of energy system components.

7.3 Conclusion on the impact of the two-fuel strategy

As the employability of the armed forces is of great importance, the uncertainty in future availability of long chain sustainable fuels may form a limiting factor. Operations should not become too expensive and fuel should be easy to procure. A two-fuel strategy might therefore be most future proof. Operating on methanol with limited autonomy, typically in peace time, and on diesel during operations with high autonomy, during (certain) war time operations. Implementing the two-fuel energy system resulted in an increase in displacement between 1% and 5%, which again is independent of the two considered propulsion configurations. Operating on methanol in the two-fuel strategy has a reduced range of 2187 nm, which is 43% of the baseline range of 5000 nm. For the two-fuel concept, the compatibility of the same tanks for two-fuels needs to be further investigated. Furthermore, limitation on flexibility of the navy to change operations in a short time might prove the factor that blocks this option for naval commanders. If switching between fuels in the same storage tank is not possible, but a two-fuel solution is desirable, the fuels need to be stored separately. Therefore, peacetime requirements need to be formulated by the Royal Netherlands Navy for the required methanol capacity, when there are two or more tanks to store the fuel separately. Besides the two-fuel concept, a dual fuel solution can be explored as well in which the operational requirements can be met by a combination of methanol and diesel with enough redundancy. In this concept, the methanol capacity of the vessel can then be used in peacetime, dependent on the requirements set. This can be especially interesting considering the uncertainty of future availability of the fuels.

Assessing the impact of sustainable methanol and diesel for Large Surface Combatants at this level of detail and considering a two-fuel strategy is novel for the field. The results can be used by the Royal Netherlands Navy to compare the different concepts and serve as an indicative substantiation in the acquisition of a new Large Surface Combatant. Moreover, it can help in forming the strategy to migrate future naval combatants from current fossil fuels to future sustainable fuels.

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A Propulsion architectures

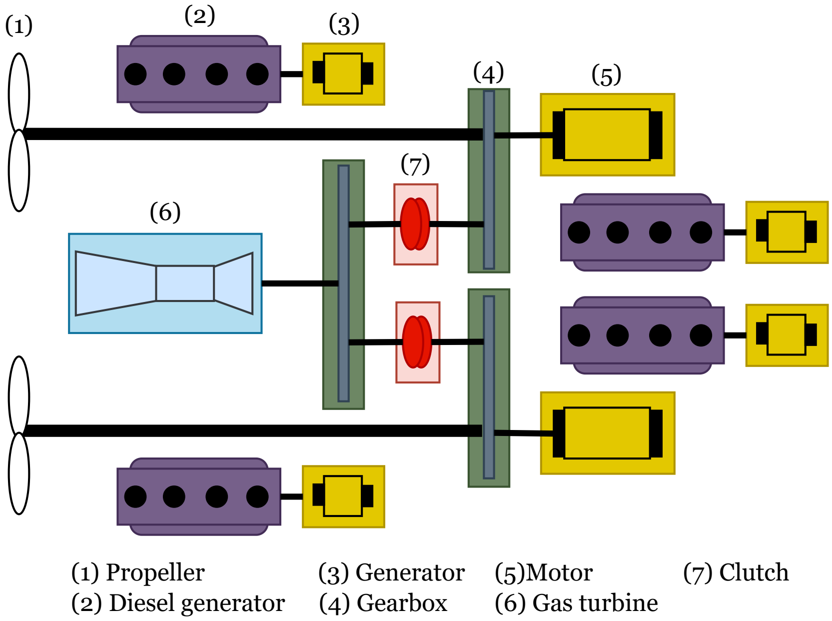


Figure A.1: Schematic representation of combined diesel electric or gas (CODLOG) propulsion architecture

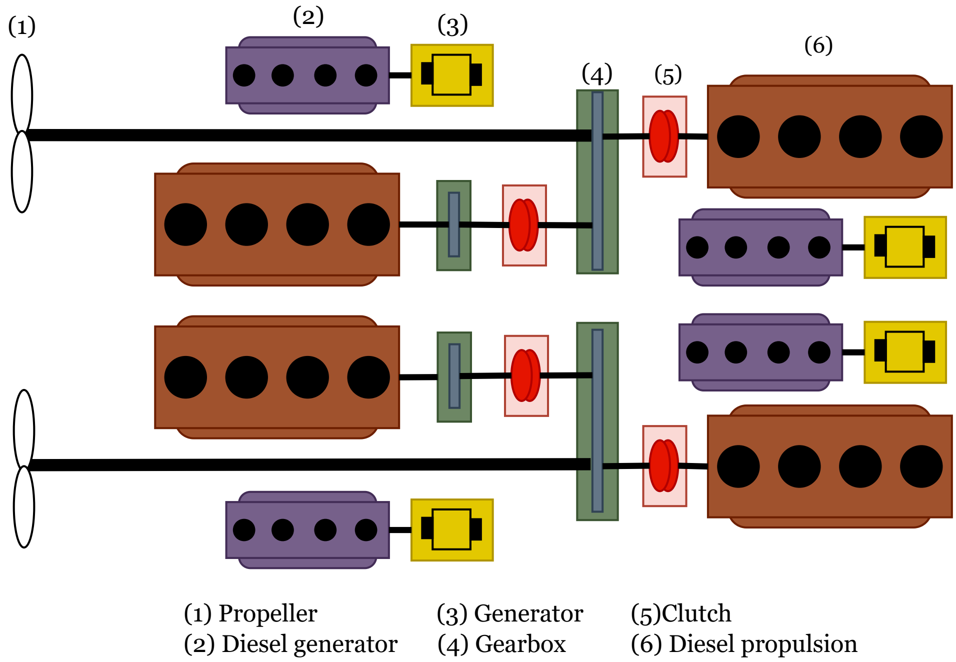


Figure A.2: Schematic representation of combined diesel and diesel (CODAD) propulsion architecture

B MTU and MAN components for naval solutions

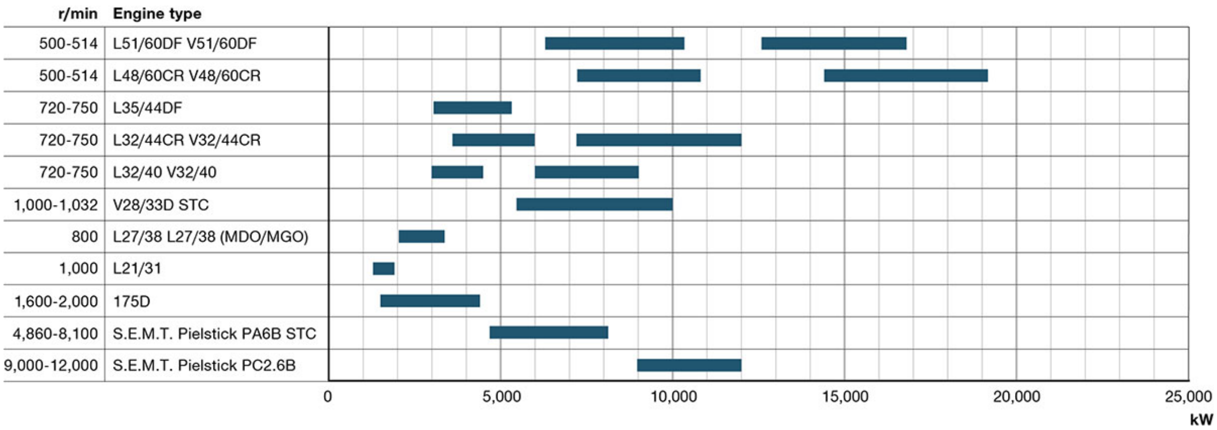


Figure B.1: MAN four-stroke propulsion engine program (MAN Energy Solutions)

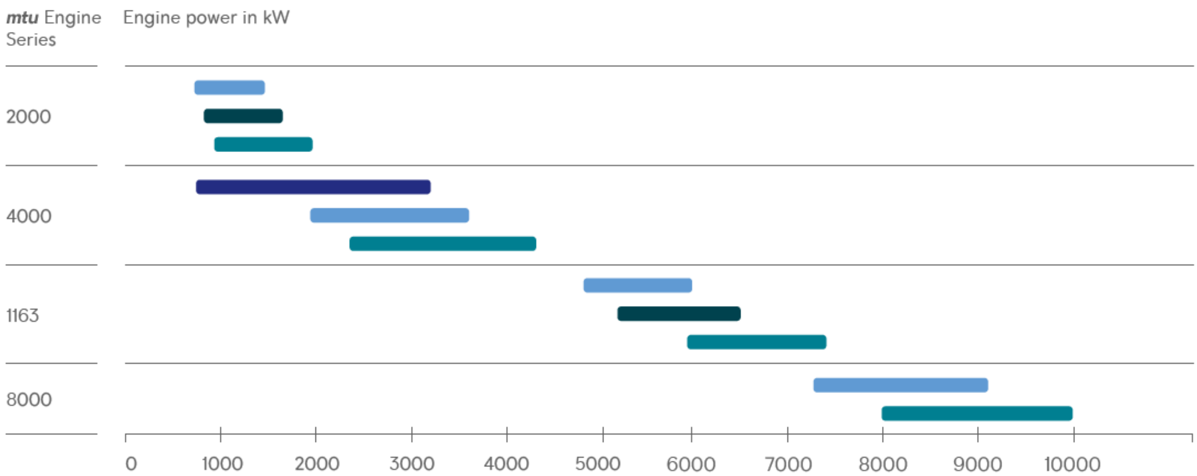
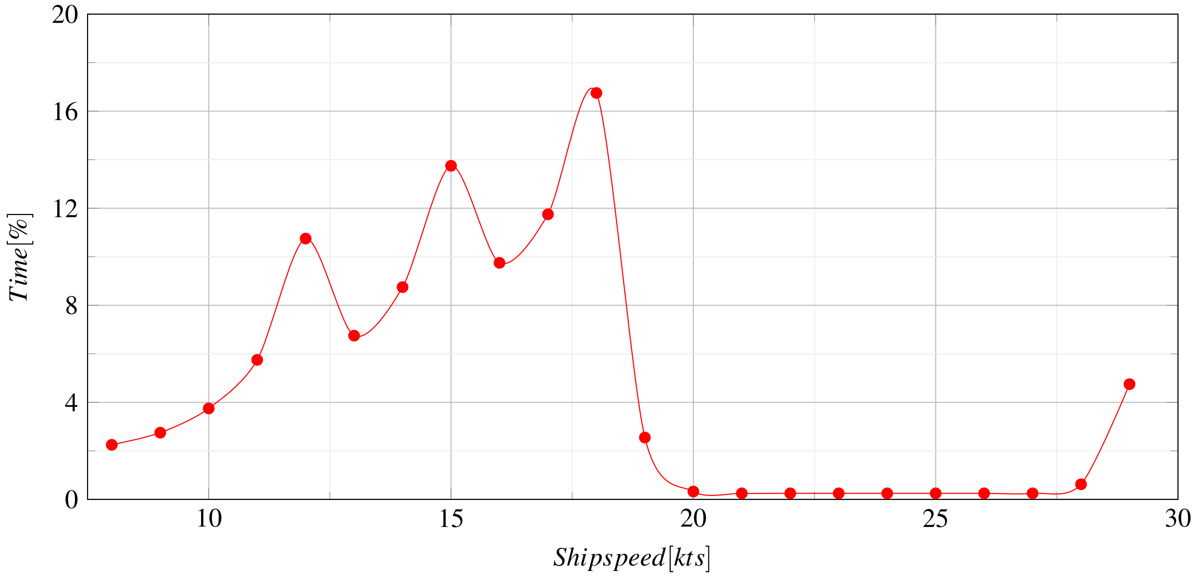


Figure B.2: MTU four-stroke propulsion components for naval solutions (MTU, 2022)

C Typical operational profile

Figure C.1: Typical operational profile of a notional frigate that are used to determine the energy consumption

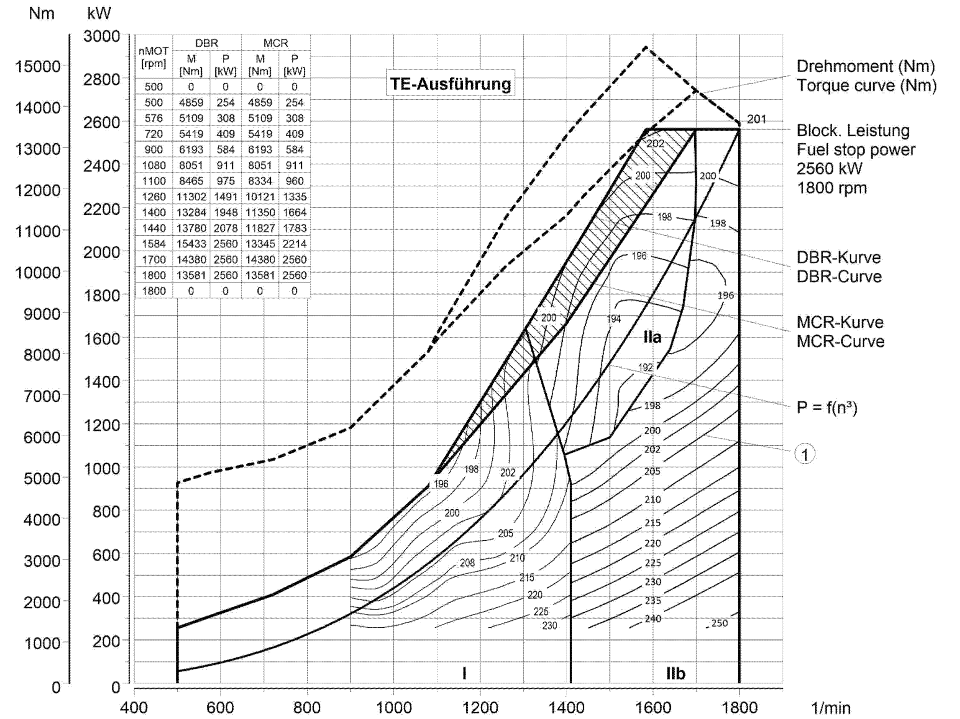


D Cost model

Table D.1: Summary of the cost model for a notional surface combatant (platform + SEWACO)

SWBS	**Description**	**Cost [%]**
100	Hull structure	6%
200	Propulsion plant	7%
300	Electrical plant	10%
400	Command & surveillance	42%
500	Auxiliary systems	9%
600	Outfit and furnishings	6%
700	Armament	10%
800	Integration/engineering	4%
900	Ship assembly and support services	6%
		100%

E Specific fuel consumption DE



nMOT [rpm]	DBR M [Nm]	DBR P [kW]	MCR M [Nm]	MCR P [kW]
500	0	0	0	0
500	4859	254	4859	254
576	5109	308	5109	308
720	5419	409	5419	409
900	6193	584	6193	584
1080	8051	911	8051	911
1100	8465	975	8334	960
1260	11302	1491	10121	1335
1400	13284	1948	11350	1664
1440	13780	2078	11827	1783
1584	15433	2560	13345	2214
1700	14380	2560	14380	2560
1800	13581	2560	13581	2560
1800	0	0	0	0

Deutsch		English
Anwendungsgruppe	**1A**	**Application group**
Kommerzielle Schiffe mit unbegrenztem Fahrbereich		Commercial vessels with unlimited operating range
Bezugsdaten		**Reference conditions**
Ansauglufttemperatur*	25 °C	Intake air temperature*
Rohwassertemperatur*	25 °C	Raw water temperature*
Luftdruck	1000 mbar	Barometric pressure
Ansaugunterdruck bezogen auf TEN Baustein Nr. 3330, in Kapitel 2. Randbedingungen (für die höchste Leistung)		Intake depression related to TEN Nr. 3330, chapter 2 boundary conditions (for maximum power)
Abgasgegendruck bezogen auf TEN Baustein Nr. 3343 oder 4098, in Kapitel 2. Randbedingungen (für die höchste Leistung)		Exhaust gas backpressure related to TEN Nr. 3343 or 4098, chapter 2 boundary (for maximum power)
Kraftstofftemperatur am Motorzulauf	25 °C	Fuel temperature at fuel feed
Spezif. Kraftstoffverbrauch	①	**Specific fuel consumption**
Verbrauchsangaben (g/kWh), Toleranz +5% entspr. DIN/ISO 3046, Kraftstoff nach DIN EN 590 mit einem unteren Heizwert von mind. 42800 kJ/kg.		Fuel consumption (g/kWh), tolerance +5% per DIN/ISO 3046, Diesel fuel to DIN EN 590 with a min. L.H.V. of 42800 kJ/kg (18390 BTU/lb).
Ausführung TE-Kühlkreislauf**		**TE cooling ciruit****
Begriffsbestimmungen		**Definitions**
Leistungen sind Nutzleistungen entspr. DIN/ISO 3046		Ratings are net brake power per DIN/ISO 3046
MCR-Kurve: Dauerbegrenzungskurve		MCR-Curve: Maximum continuous rating
DBR-Kurve: Zeitlich begrenzt		DBR-Curve: Temporary operation
Drehmomentkurve		Torque-Curve
Status Registeraufladung	I - IIb	Status, sequential turbo charging
Temporäre Funktion zur Drehmomentverlängerung (DBR/MCR-Funktion)		**Temporary function for torque-extension is suitable (DBR/MCR-functionality)**
1) Transientenbetrieb ist von der Begrenzung ausgenommen		1) Transient operation is excluded from the limitation
2) Stationärbetrieb auf 30 min von 10 h begrenzt		2) Stationary operation limited to 30 minutes out of 10 hours
3) Hinweis: Stationärer Betrieb > 30 min von 10 h führt zu Reduzierung der TBO		3) Note: stationary operation > 30 min out of 10 h leads to a reduction in the TBO
Motoreinstellung und Bauzustand:		**Engine settings and design configuration:**
Abgasoptimiert (IMO Tier III (Basis EPA Tier 4)) entspr. ISO 8178		Optimized for exhaust emission (IMO Tier III (Basic EPA Tier 4)) per ISO 8178

** mit Seewasserpumpe: +2g/kWh
**** with sea water pump: +2g/kWh**

* Bis 45°C Ansaugtemperatur und 32°C Rohwassertemperatur: **Keine Leistungsreduktion**
* Up to 45°C Intake air temperature and 32°C raw water temperature: **No power reduction**

Metric units	US customary units
1 kW	1.341022 bhp
1 Nm	0.737561 lb-ft
1 g/ kWh	0.001644 lbs/(hp·h).
x degC	(x degC * 9/5) + 32 = y degF
1 mbar	0.01450377 PSI
1 m	3.28083 ft

Aenderungsbeschreibung/Description of Revision: Hülle in Diagramm angepasst und Textblöcke überarbeitet | Kommt vor/Frequency

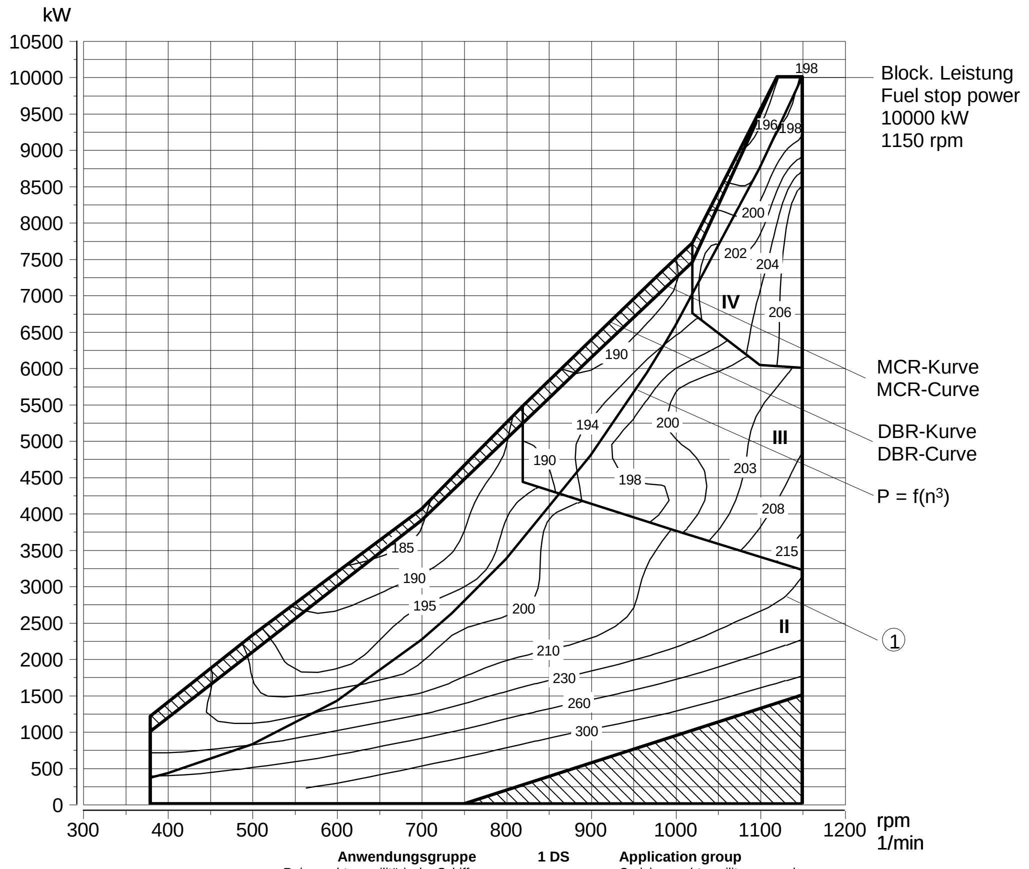
Buchst./Rev.Ltr.	Aenderungs-Nr./Revision Notice No.	Bearbeitungsstatus/Lifecycle
c.3	PR084563	Released

mtu — A Rolls-Royce solution — Rolls-Royce Solutions GmbH

WORD	Datum/ Date	Name
Erstell. Drawn	23.09.2020	zwisler pe
Bearb. Change	03.03.2022	zwisler pe
Inhalt Content	23.09.2020	Mantaj
Gepr. Checked	03.03.2022	rehm chris

Projekt-/Auftrags-Nr. Project/Order No.
Verwendbar f. Typ Applicable to Model
Format/Size: A3
Material-Nr./Material No.: **XZ54800100069**
Motortyp / Engine Type: **16V4000M65L**
Benennung/ Title: **LEISTUNGSDIAGRAMM** **PERFORMANCE DIAGRAM**
Zeichnungs-Nr./Drawing No.: **ZNG00034699**
Beschreibung/Description: IMO Tier III, EPA Tier4
Blatt/ Sheet **1** von/of **10**

Figure E.1: Specific Fuel Consumption used in the calculation for the consumption of the diesel generators (MTU, 2022)



Anwendungsgruppe	1 DS	Application group
Reiseyachten, militärische Schiffe		Cruising yachts, military vessels
Bezugsdaten		**Reference conditions**
Ansauglufttemperatur	25 °C	Intake air temperature
Rohwassertemperatur	25 °C	Raw water temperature
Luftdruck	1000 mbar	Barometic pressure
Ansaugunterdruck	25 mbar	Intake depression
Abgasüberdruck	30 mbar	Exhaust back pressure
Kraftstofftemperatur am Motorzulauf	25 °C	Fuel temperature at fuel feed
Spezif. Kraftstoffverbrauch	①	**Specific fuel consumption**
Verbrauchsangaben (g/kWh), Toleranz +5% entspr. DIN/ISO 3046, Kraftstoff nach DIN EN 590 oder DMA nach ISO 8217 mit einem unteren Heizwert von mind. 42800 kJ/kg.		Fuel consumption (g/kWh), tolerance +5% per DIN/ISO 3046, Diesel fuel to DIN EN 590 or DMA to ISO 8217 with a min. L.H.V. of 42800 kJ/kg (18390 BTU/lb).
Inclusive aller zum Motorbetrieb notwendigen Pumpen.		**All pumps necessary for engine operation included.**
Begriffsbestimmungen		**Definitions**
Leistungen sind Nutzleistungen entspr. DIN/ISO 3046		Ratings are net brake power per DIN/ISO 3046
MCR-Kurve: Dauerbegrenzungskurve		MCR-Curve: Maximum continuous rating
Bereich für Dauerbetrieb (zeitlich begrenzt)	(hatched)	Continuous operation (limited duration)
Status Registeraufladung	II, III, IV	Status, sequential turbocharging
Motoreinstellung und Bauzustand		**Engine settings and design configuration**
Abgasoptimiert		Optimized for exhaust emission
IMO Stufe 2 (Revised NOx Technical Code 2008)		IMO Tier 2 (Revised NOx Technical Code 2008)

* Bis 45 °C Ansauglufttemperatur und 32 °C Seewassertemperatur:
Keine Leistungsreduktion, Kraftstoffverbrauchserhöhung: 2,0 %
* Up to 45°C intake air temperature and 32°C sea water temperature:
No power reduction, increase of fuel consumption: 2,0%

MTU Friedrichshafen GmbH	Datum/Date	Name/Name	Benennung/Title: **Leistungsdiagramm Performance Diagram**
Bearbeiter/Drawn by	02.09.2015	Zwisler	
Geprüft/Checked	02.09.2015	Vogel	
Org.-Einheit/Dept.	TCD	Dr. Eckstein	Zeichnungs-Nr./Drawing No.: **20V 8000 M91L**
Motortyp/Engine type: **XZ56900100010**	Auftrag/Projekt-Nr. / Order/Project No.	Bemerkung/Note: ---	Ursprung/Origin

Buchstabe/Revision	Änderung/Modifikation	Auftragsnummer/Release No.	Datum/Date	Name/Name
--	Freigabe	129604	02.09.2015	Zwisler

T-600-0108

Figure E.2: Specific Fuel Consumption used in the calculation for the consumption of the diesel engine propulsion (MTU, 2022)

F FIDES Model Legend

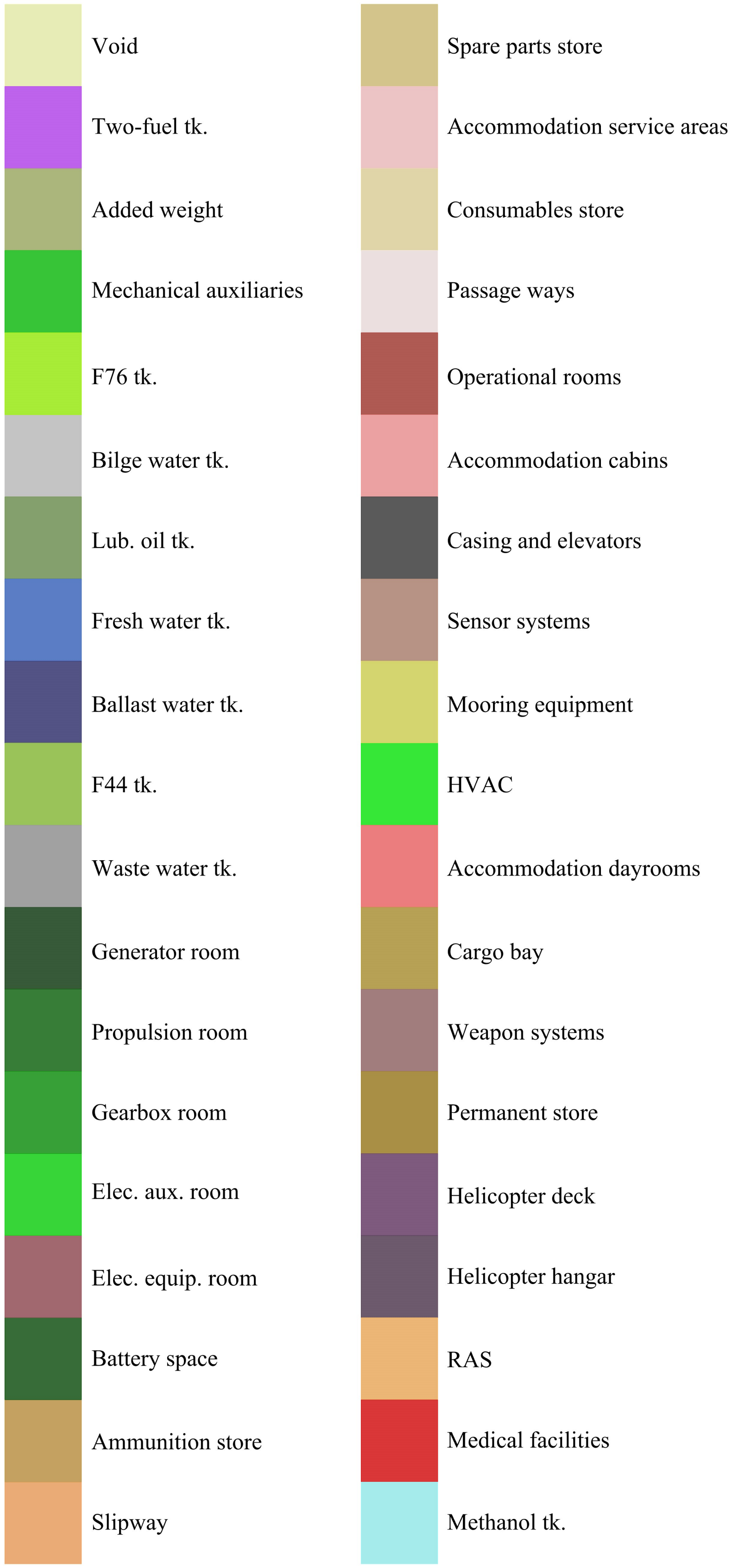


Figure F.1: Legend with each building block colour representing the spatial layout of each design concept created in FIDES

G Break power speed curves

Figure G.1: Speed versus Break power curves for service conditions by sizing the design by lengthening

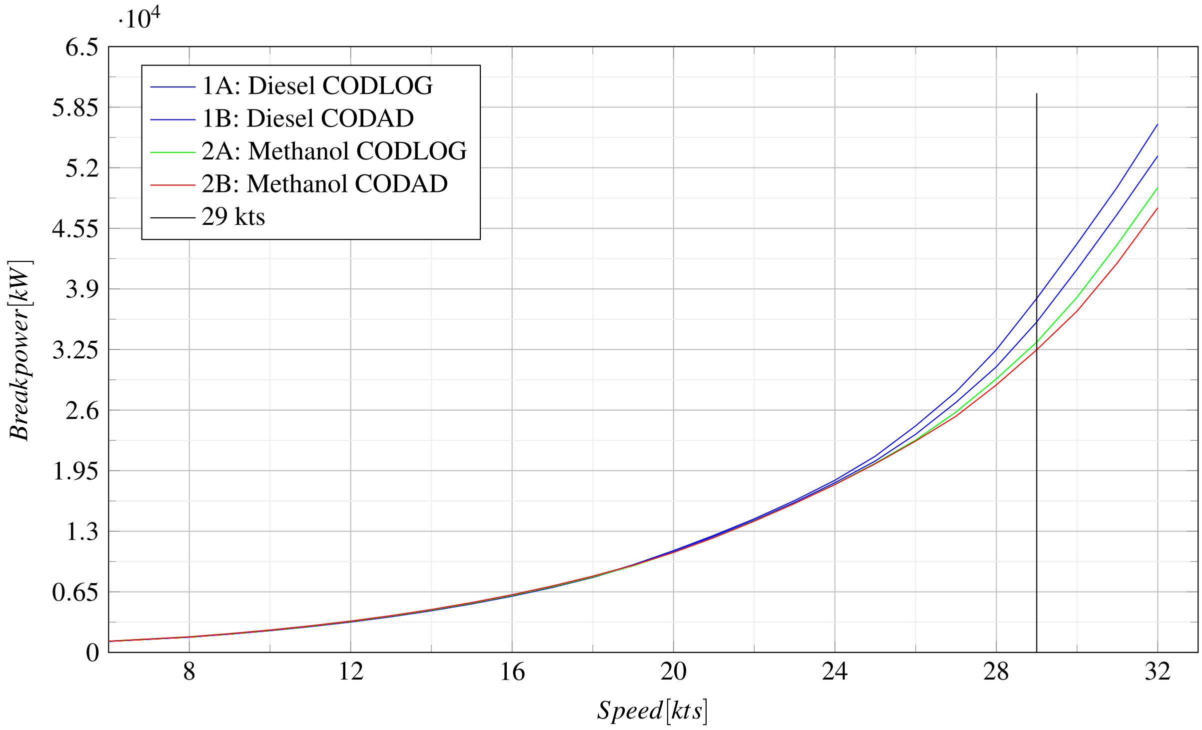
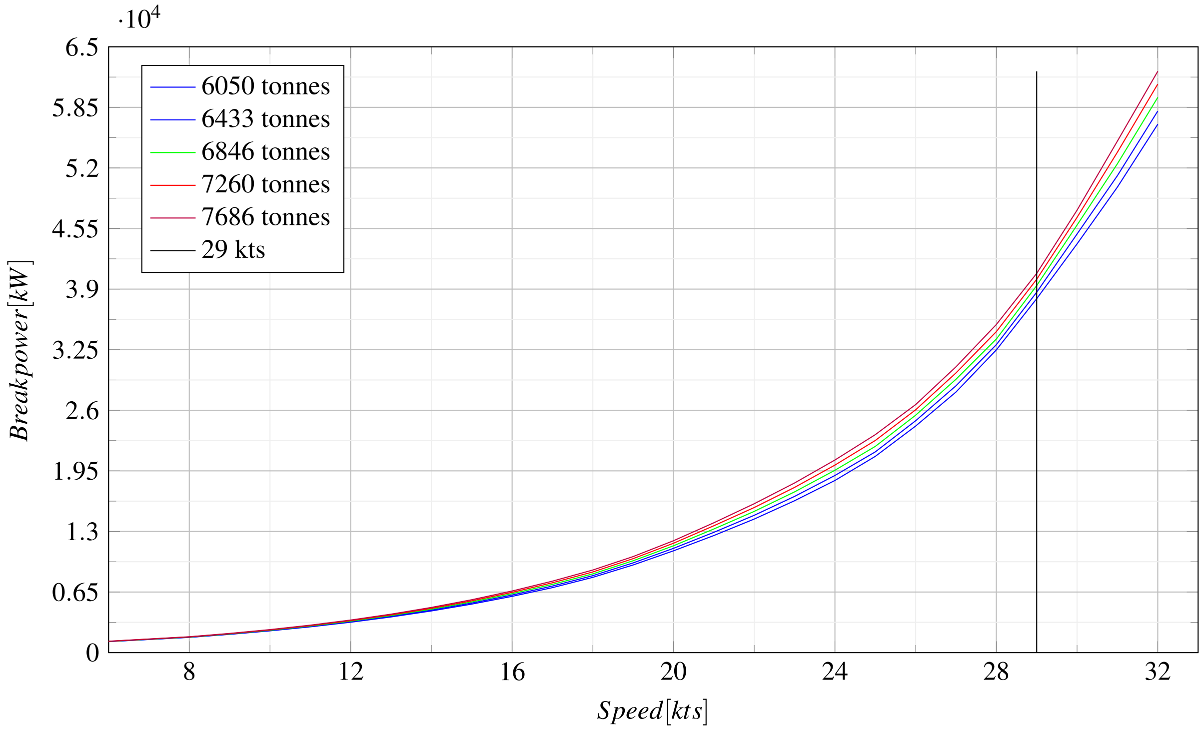


Figure G.2: Speed versus Break power curves for service conditions scaling with constant form factors



H Floodable length curves

Figure H.1: Floodable Length Curve: 144m 1A. Diesel fuel with gas turbine hybrid propulsion

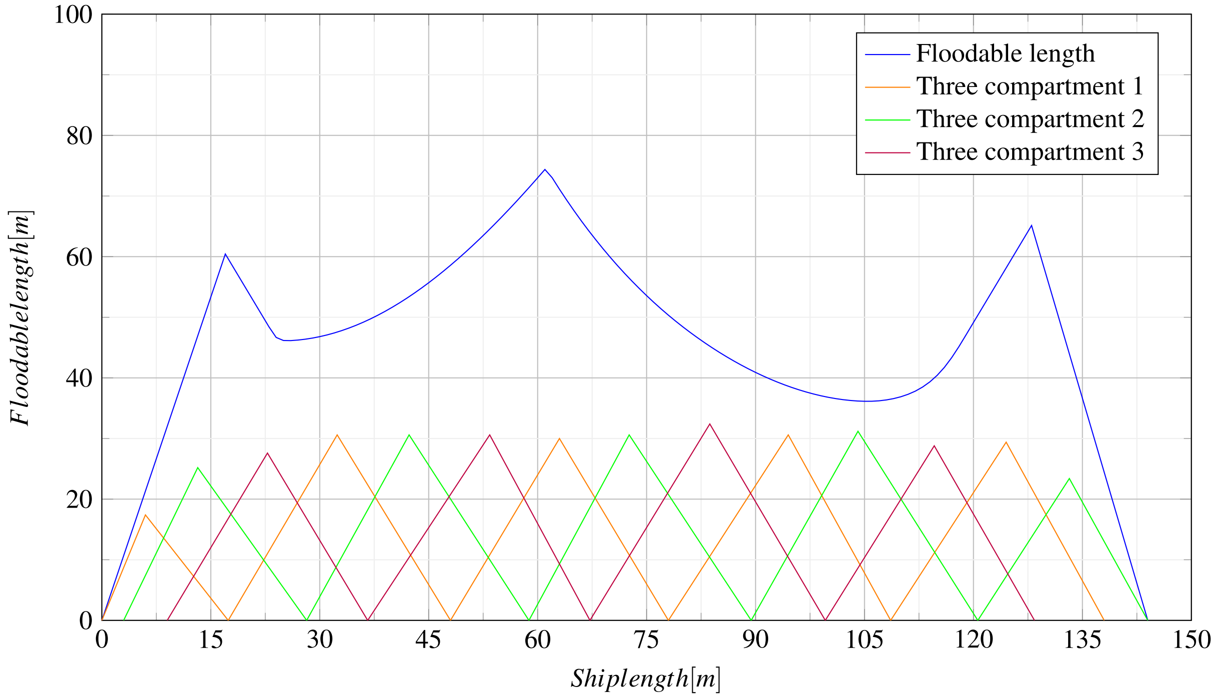
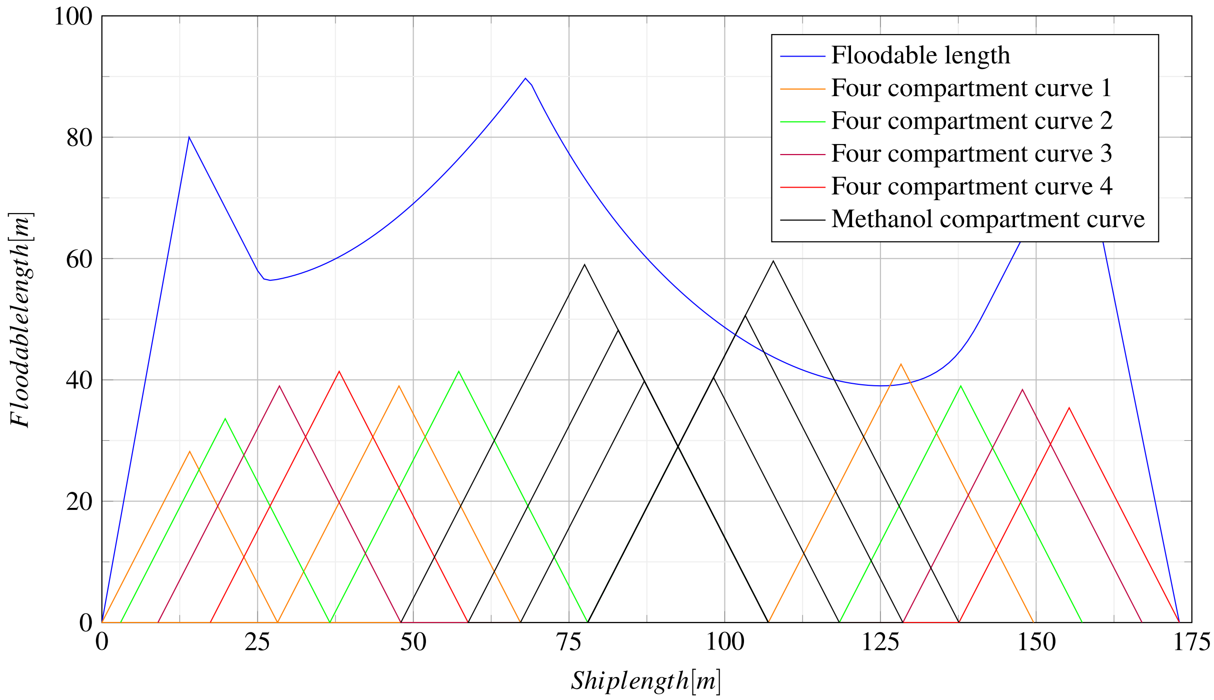


Figure H.2: Floodable Length Curve: 173m 2B. Methanol fuel with diesel and diesel hybrid propulsion



Assessing the impact of sustainable fuels for Large Surface Combatants

by Maarten R. J. Pothaar