MARIN

BETTER SHIPS, BLUE OCEANS

Green Maritime Methanol 2.0 – Work Package 3: Veerhaven pushboats

Report No.	:	33604-1-SHIPS
Date	:	January 2023
Version	:	1.0
		Final Report

Green Maritime Methanol 2.0 – Work Package 3: Veerhaven pushboats

MARIN order No. : 33604
MARIN Project Manager : ir. J.J. A. Schot

Number of pages : 37

Ordered by : GMM 2

Reported by : ir. J. J. A. Schot
Reviewed by : ing. A. de Jager

Version	Date	Version description
1.0	January 2023	Final

CONTENTS PAGE

REVIEW OF TABLES AND FIGURES

1 INTRODUCTION

December 2020 the Green Maritime Methanol (GMM) project has finished. This project was meant to put effort in the use of methanol as a fuel for the shipping industry. Topics elaborated in this project were the application on ship engines, bunkering and handling on board, market potential, production, supply chain routes, emissions, safety and the impact on the ship design and operation. However, a follow up was appreciated. For further development the following topics were identified:

- Ventilation related safety issues.
- Injection and ignition techniques for engines.
- Experience of the application on board ships, pilot projects.
- Sorting out of uncertainties with respect to availability and pricing.

Therefore, follow up project Green Maritime Methanol 2.0 (GMM 2) was initiated. For Green Maritime Methanol 2.0 objectives have been defined for this study:

- Develop solutions for current safety issues when applying methanol,
- Perform additional lab tests with application of different variants for applying methanol in the engine,
- Developing practical ship designs, based on results of GMM 1.0 and developing future pilot projects,
- Further development of options to strengthen the business case of methanol (price development, supply solutions, policy measures).

Main aim of the proposal is to bring the technology from TRL 5/6 to TRL 7/8.

In work package 3 of the GMM 2 project the application of methanol in real-life pilot projects was investigated. In this report the results of one of the pilot projects is discussed, the pushboats of ThyssenKrupp Veerhaven BV (Veerhaven). The shipping company operates a fleet of pushboats transporting coal and ore from the Dintelhaven in Rotterdam towards ThyssenKrupp Steel Europe in Duisburg and aims to reduce their environmental footprint by transitioning to methanol propelled vessels. In addition to this the to be build pushboats have to cope with low water levels for periods of the year. For this reason the draught of the pushboat should be limited to 1.6m during these conditions.

The investigations for the new design are shared between MARIN and C-Job Naval Architects (C-Job). MARIN started with evaluation of the operation of the vessel based on available bunker data to support the required tank capacities and the analysis of monitoring data gathered by Veerhaven during the project for the required installed power. This was used to draw up the specification of the new design together with information given by Veerhaven. Various concepts for the drive train were defined and compared based on fuel efficiency and weight using a preliminary weight assessment.

C-Job followed up with detailing the weight assessment, reducing the uncertainty on the impact of the change in beam of the vessel. Furthermore, the internal layout was defined keeping practical restraints in mind. These investigations are reported separately.

2 GENERAL DESCRIPTION OF CURRENT DESIGN

The current design of the pushboat is detailed here. The particulars are described in the loaded condition for the pushboat and barges separately. The configuration in this loading condition is shown in Figure 2-1 and a photo of the convoy is shown in Figure 2-2. The nominal rotation rate of the main engines varies within the fleet between 900 and 1000 RPM.

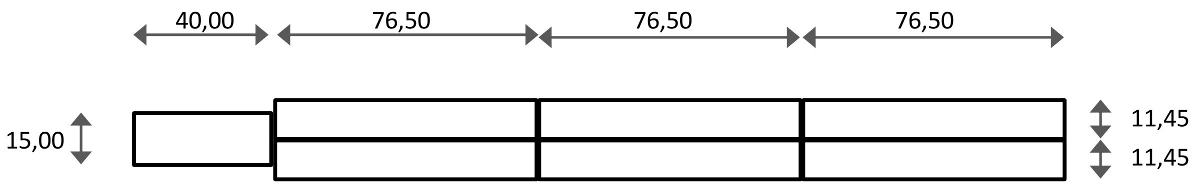


Figure 2-1: Dimensions of the pushboat configuration in the loaded condition.

The main particulars of the ship are:

	Barges (3 x 2)	Pushboat	Unit	
Length between perpendiculars	76.5	40.0	269.5	m
Breadth moulded	11.45	15.0	22.9	m
Design draught moulded	3.6	1.75	3.6	m
Displacement volume moulded	2948	732	18420	m^3

The table below indicates some main propulsion data of the ship:

Engine type	Diesel, direct drive	-
Number and type of propulsors	3 x fixed pitch propellers (FPP) in duct	-
Available brake power at 100% MCR	3 x 1360	kW
Rotation rate at 100% MCR	900 or 1000	RPM
Propeller diameter	2.05	m
Gearbox reduction ratio	3.56 or 3.95	-

The table below lists the appendages present on the ship:

Bow thruster tunnels (with grids)	2
I-brackets	3
Rudders (fishtail)	3

Figure 2-2: The Veerhaven XI with 6 barges at Ewijk.

3 SPECIFICATION FOR THE NEW DESIGN

The “to be methanol” pushboat design should have a decreased minimum draught of 1.60m compared to a minimum draught of 1.75m of the current pushboats in the Veerhaven fleet. It is allowed to increase the beam from the original 15m to 20m in order to achieve sufficient displacement. In addition it is required to perform at least two round trips without refuelling and to be able to sail both fully on diesel as on methanol for the case when renewable methanol is not available. It is acceptable to perform the operations at the minimum draught only on diesel to reduce the displacement when needed. The fuel tank capacity is based on an analysis of fuel consumption data discussed in paragraph 4.1. The diesel capacity is transformed to the amount of methanol with the same energy storage capacity based on the lower heating value (LHV) of the fuels.

The stated required propulsion power is determined in paragraph 4.2 using monitoring data of the shaft power for the current vessel. The vessel cannot have an higher propulsive power than 4500 kW stated in the “Rijnvaart Politie Regelement” (RPR, art. 11.02 lid 3.5e cc. aaa.). In addition the current bow thruster power should be available at all time, also when full main engine power is used. Finally, an average use of the auxiliary systems is given by Veerhaven.

3.1 Dimensions

Length overall (LOA)	40.0	m
Beam overall (BOA)	15.0 up to 20.0	m
Maximum draught	1.6 (minimum consumables)	m

3.2 Propulsion system

Required propulsion power	3600 (<4500 kW)	kW
Required bow thruster power	2 x 400	kW

3.3 Auxiliary systems

Average hotel load	80	kW

3.4 Performance

Range (2 x Rotterdam-Duisburg-Rotterdam)	920 (2 x 2 x 230)	km

3.5 Tank capacities

Fuel (Diesel)	>61.8 (2 x 24.7 x 1.25)	m^3
Fuel (Methanol)	>141.7	m^3

4 OPERATIONAL PROFILE

Veerhaven operates their fleet of pushboats to transport coal and ore along a fixed route on the Rhine between Rotterdam and Duisburg of roughly 230 km. The vessel sails upstream with 6 loaded barges when the water level is above 750 cm at Lobith and 233 cm at Ruhrort. When water levels are lower, a convoy of 4 barges is used. The cargo capacity depends on the water depth. During the return trip the barges are empty.

4.1 Fuel requirement

The required tank capacity is evaluated, using fuel consumption data of the Veerhaven IV Neushoorn for 253 trips during 2017 and 2018. The data is given for the upstream and downstream trip separately and includes the sailing time, water level and amount of transported cargo. The relation between fuel consumption and water level or cargo carried is shown for the upstream part of the trip. The data is shown for both a convoy with 4 barges and 6 barges. It is observed that indeed at a water level (pegel) of less than 233 cm at Ruhrort, only a convoy of 4 barges was used with significantly less cargo carried, resulting in a low fuel consumption.

The fuel consumption data shows a linear trend between the transported cargo and fuel consumption for the upstream part of the voyage, shown in Figure 4-1. The relation between the transported cargo and water level (pegel) at Ruhrort is also shown. It is observed that below the level of 233 cm only 4 barges were used. The maximum loading capacity when using 6 barges was used above a level of 400 cm.

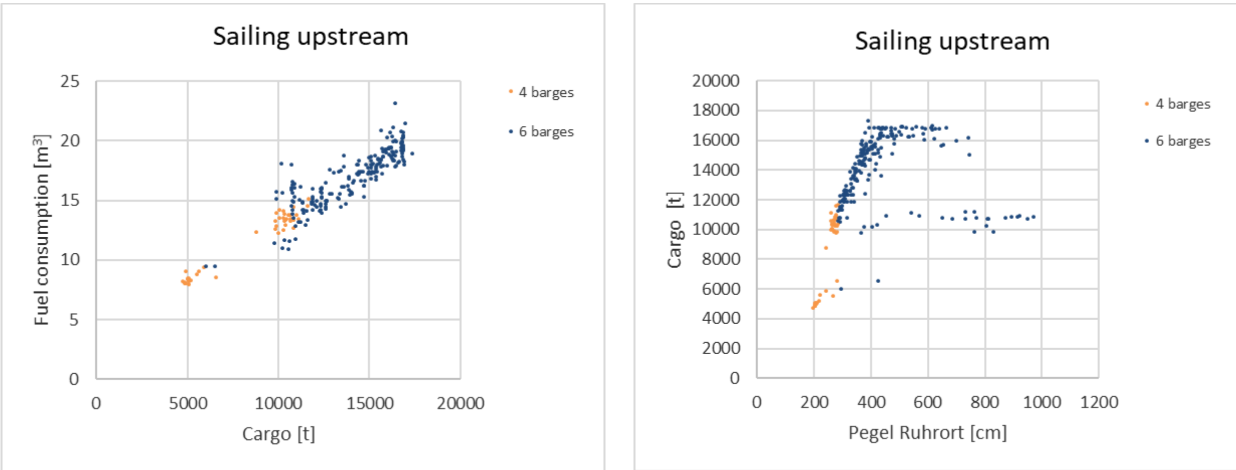


Figure 4-1: Relation between transported cargo and fuel consumption and between the water level (pegel) at Ruhrort and the transported cargo for the upstream part of the voyage.

The more convenient relation between the fuel consumption and water level is shown in Figure 4-2, which clearly shows the influence of the limit on the transported cargo due to the water level. On the right the fraction of the fuel consumption during the upstream part of the voyage is shown relative to the entire voyage. This is roughly 80%, although it decreases for lower water levels towards 60%.

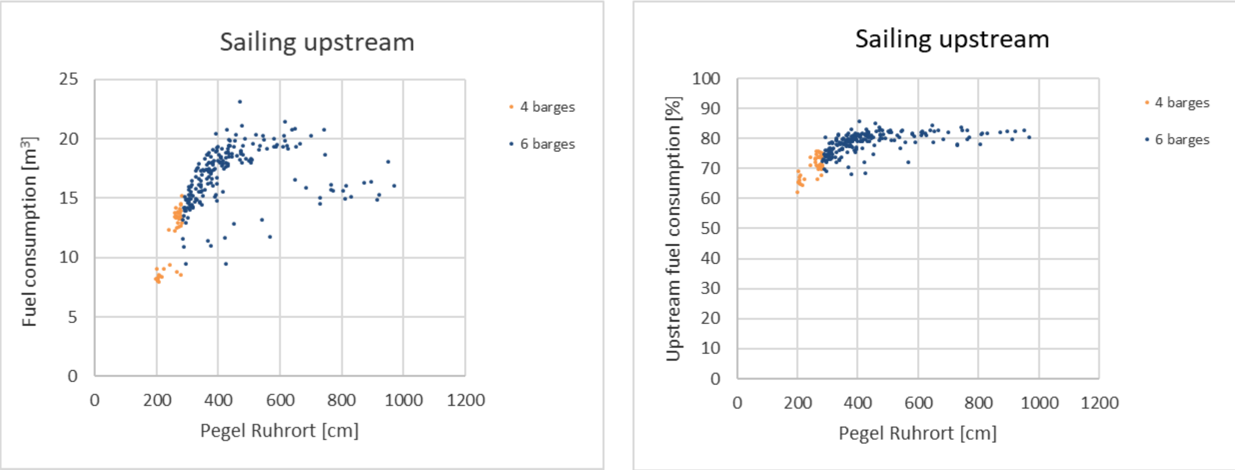


Figure 4-2: Relation between the water level (pegel) at Ruhrort and the fuel consumption for the upstream part of the voyage. The percentage of fuel consumption during the upstream part of the voyage relative to the fuel consumption of the entire voyage is shown on the right.

Using the fuel consumption data, the average voyage time, speed over ground and fuel consumption is obtained. These results are shown in Table 4-1. The fuel consumption is reported both for the shallow water and deep water condition, because the minimum required amount of fuel for the shallow water condition can be critical for the new pushboat design. The vessel has to operate with a draught of 1.6m. During this condition less fuel is consumed, but also less can be carried.

Table 4-1: Results of the analysis of fuel consumption data.

	Upstream	Downstream
Average speed over ground	7.9 km/h	17.3 km/h
Average voyage time	28.8 h	13.1 h

	Round trip shallow water 4 barges (Ruhrort < 233 cm)	Round trip 6 barges
Average diesel fuel consumption	11.8 m^3	21.4 m^3
95% percentile of fuel consumption	**13.4 m^3**	**24.7 m^3**

4.2 Power requirement

Monitoring data of the Veerhaven XI IJsbeer was collected between 21-1-2022 and 13-2-2022. During this period the shaft power (torque and rotation rate), fuel rate, GPS location and speed over ground was measured at a sampling rate of 1 Hz. The campaign was planned during a period with a relatively high water level, as it is expected that the highest propulsion power is required in this condition due to a strong current in the river. In Figure 4-3 the water level is shown, which is ranging between 350 to 665 cm at Rurhort and between 876 and 1156 cm at Lobith.

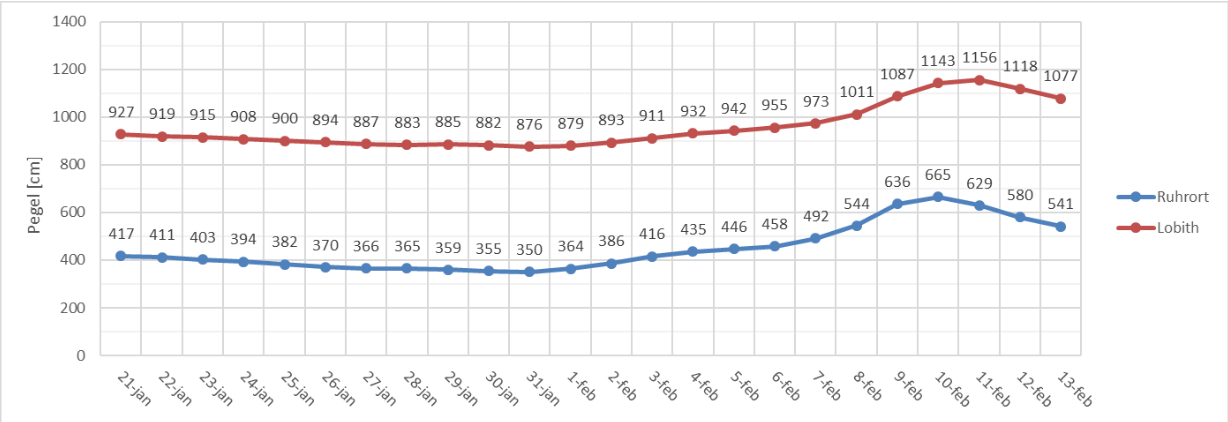


Figure 4-3: Water level (pegel) at Ruhrort and Lobith during the course of the monitoring campaign.

The data was cleaned, filtered and the shaft power measurement was transformed to engine rotation rate and brake power using the gearbox reduction ration and conversion efficiency. The resulting data over the entire measurement period is shown in Figure 4-4.

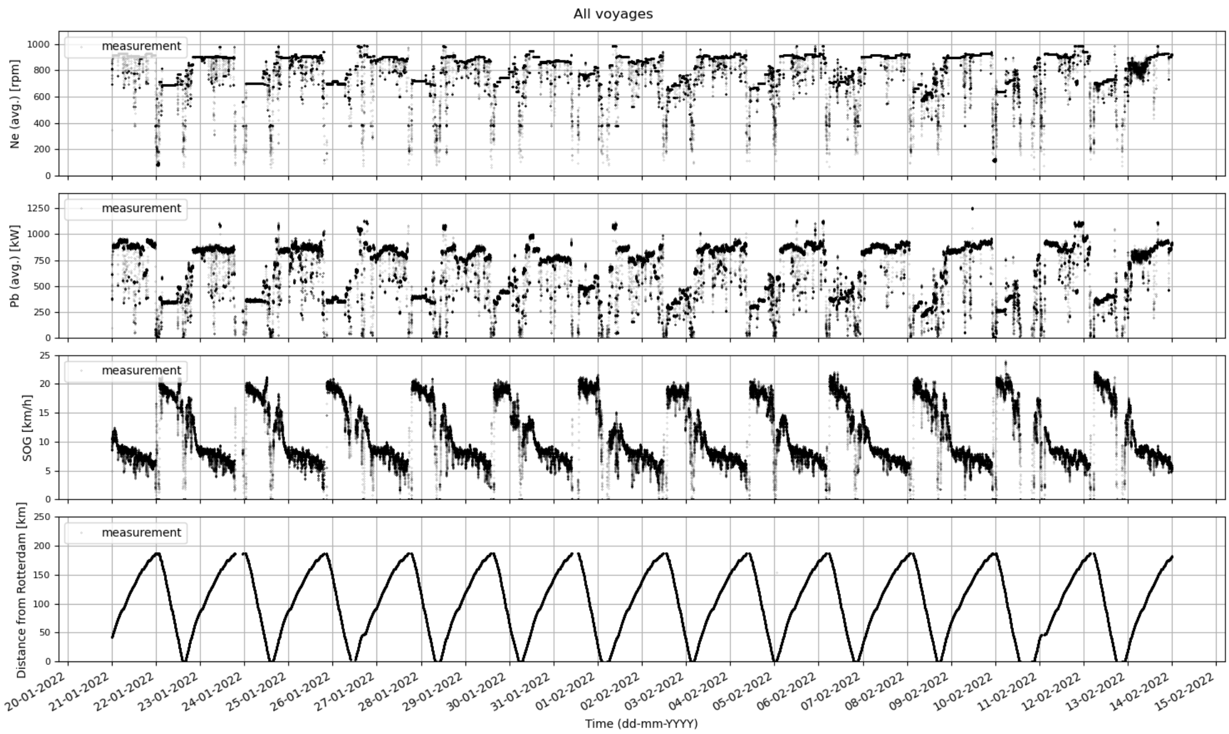


Figure 4-4: Cleaned and filtered data over the entire measurement campaign. Pb (avg.) is the average brake power per engine derived from the shaft power measurements and Ne (avg.) the engine rotation rate. The ship is fitted with the three shaft lines.

The last voyages (22), during the highest water level in the monitoring period, is shown in Figure 4-5. The distribution of shaft power is shown in Figure 4-6. Apart from the monitoring data, also a form is filled out by the crew, giving additional data on the use of the bow thrusters and special events. The start and stop time of the bow thrusters is shown with red dots. In addition it is reported that on 11-2-2022 between 20:00 and 23:00 the engines were operated at full load, related to engine calibration. It is reported by the crew that some situations exist when the maximum propulsion power is absorbed in combination with operating the bow thrusters. Because of that, this reason not further investigated in the measurement data.

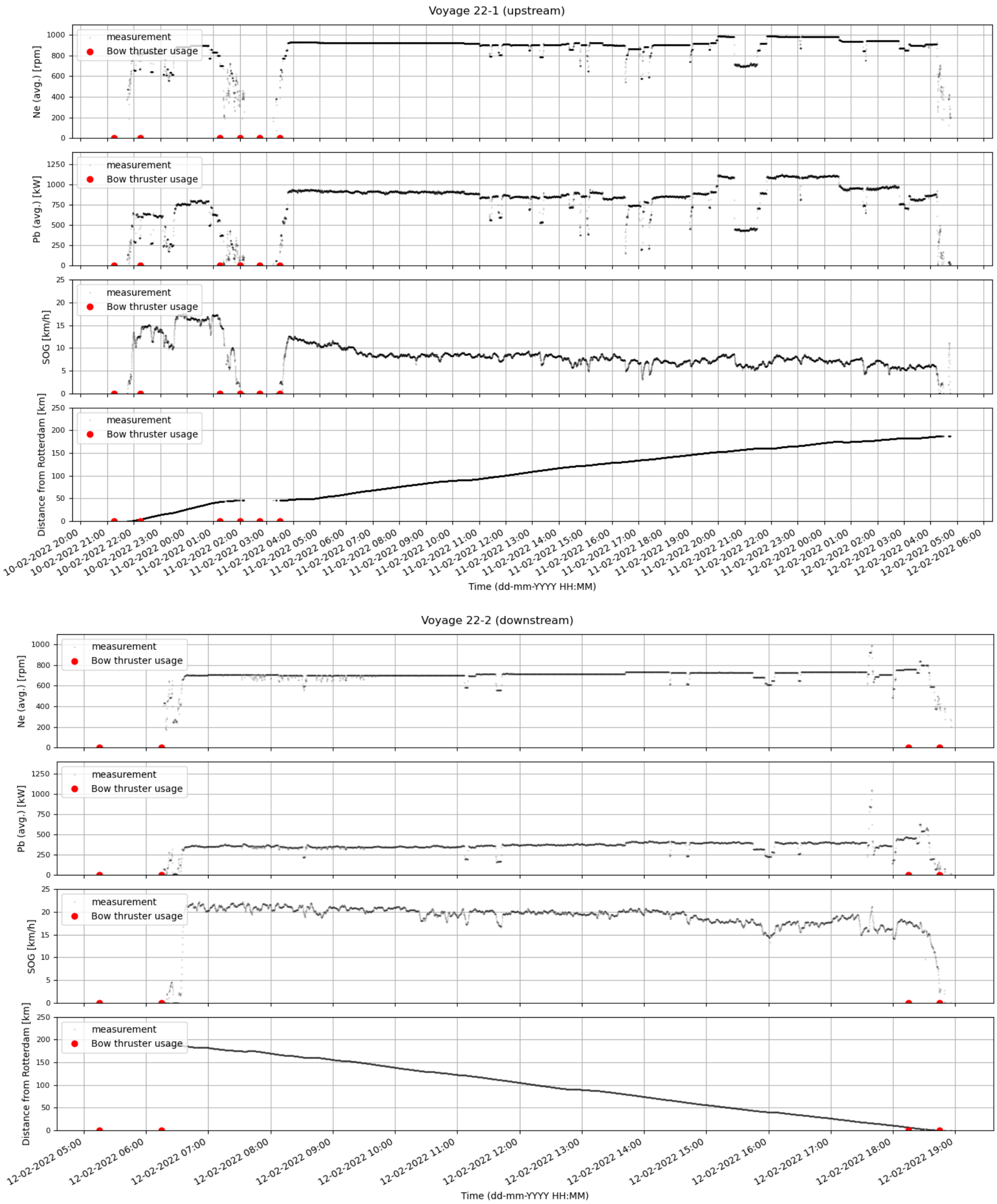


Figure 4-5: Time traces of voyage 22, sailed during the highest measured water level.

Voyage 22-1 (upstream) *Voyage 22-2 (downstream)*

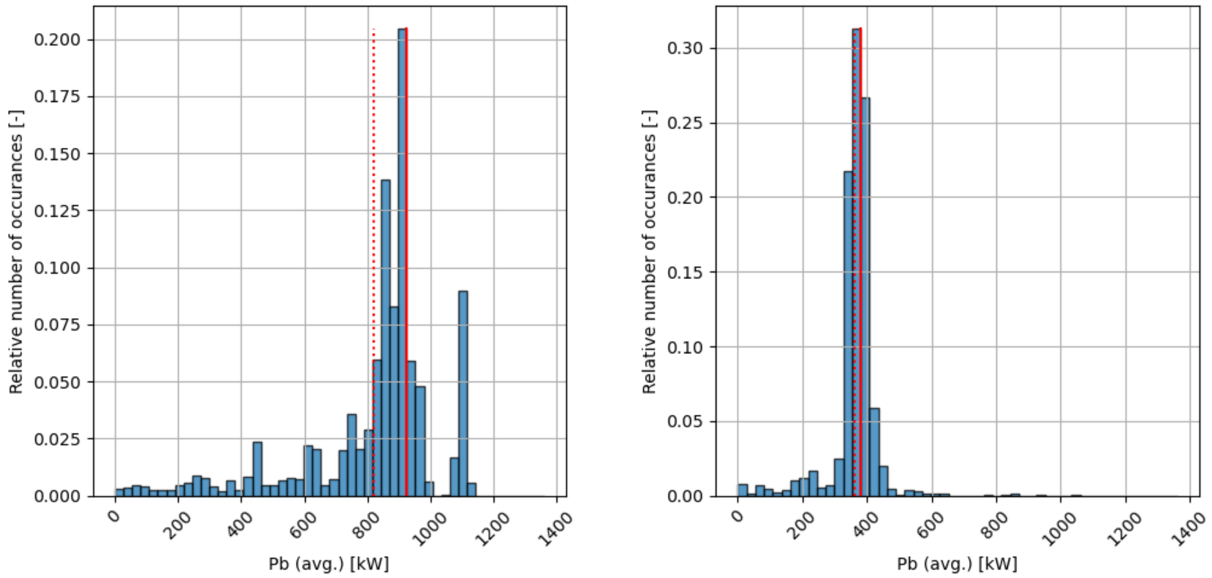


Figure 4-6: Distribution of average shaft power for voyage 22, sailed during the highest measured water level.

In the derived results of engine rotation rate and power over all voyages, shown in Figure 4-7, it is observed that the nominal brake power of 1360 kW per engine was never reached, although the nominal rotation rate of 1000 RPM was. The maximum rotation rate was in general only reached for short periods of time with a few exceptions. The relatively low power use seems related to the design point of the propellers, making them unable to absorb full power under normal sailing conditions. This is illustrated in Figure 4-8 and Figure 4-9 for both the loaded upstream and the empty downstream condition.

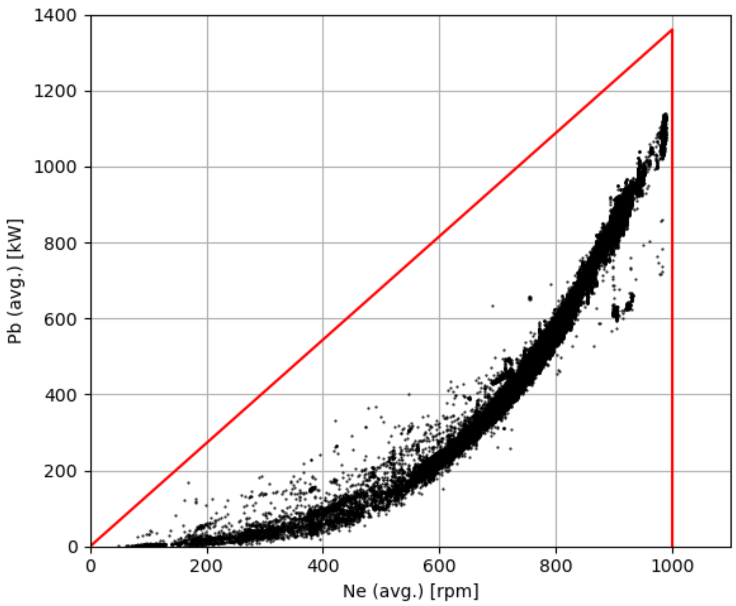


Figure 4-7: Engine rotation rate and power relation over all voyages.

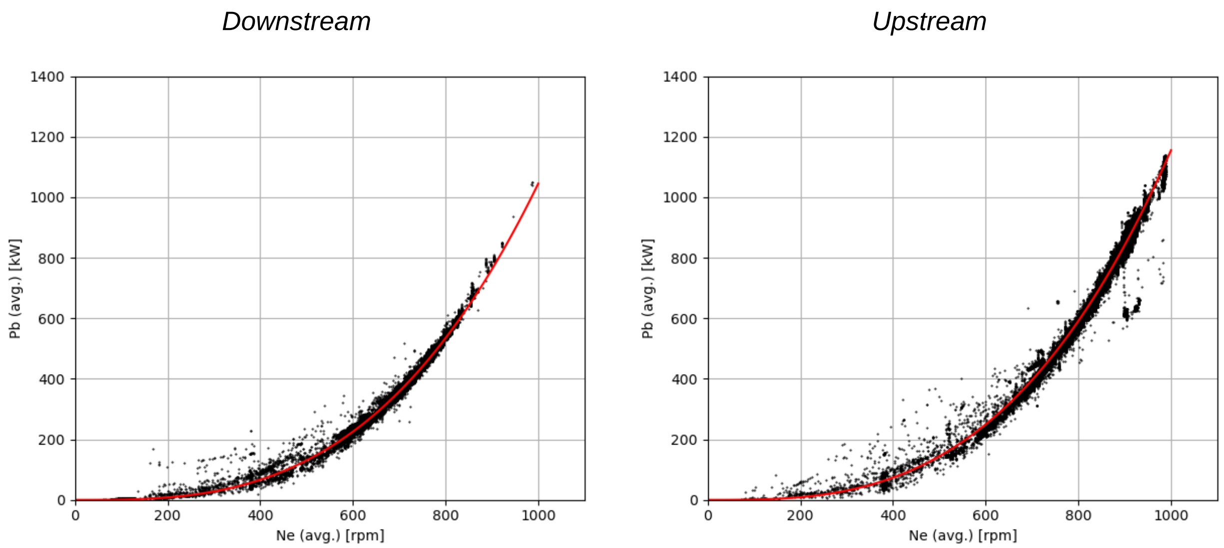


Figure 4-8: Fit of the engine rotation rate and power relation over the downstream and upstream trips.

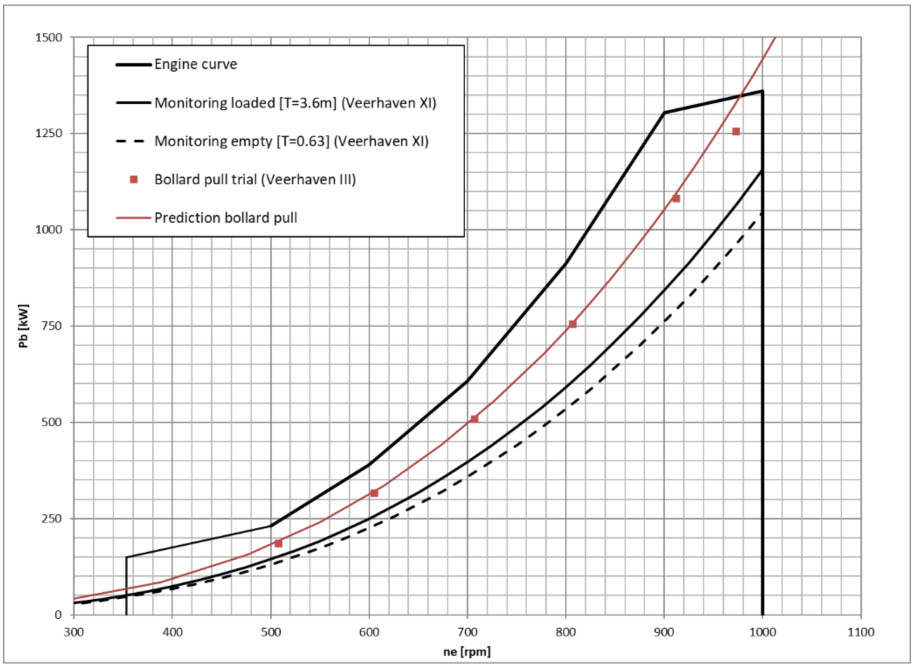


Figure 4-9: Comparison between the engine rotation rate and power relation of the predictions fitted to the bollard pull and deep water trial together with the fits through the monitoring data. The upstream measurements correspond to the loaded condition and downstream to the empty condition.

The distribution of main engine power is analysed for all voyages. The average and most occurring, or modal, value is determined and compared in Figure 4-10. The average of the voyages is shown in Table 4-2 in comparison of previous measurement data as a reference.

Based on the propeller design point it is concluded that 3600 kW propulsion power with a different propeller design point could be sufficient as this is currently above the maximum propulsion power that can be absorbed by the propellers during transit. The value is based on the maximum operational developed power at a MCR of 85% (2900/0.85=3400 kW) with some additional margin.

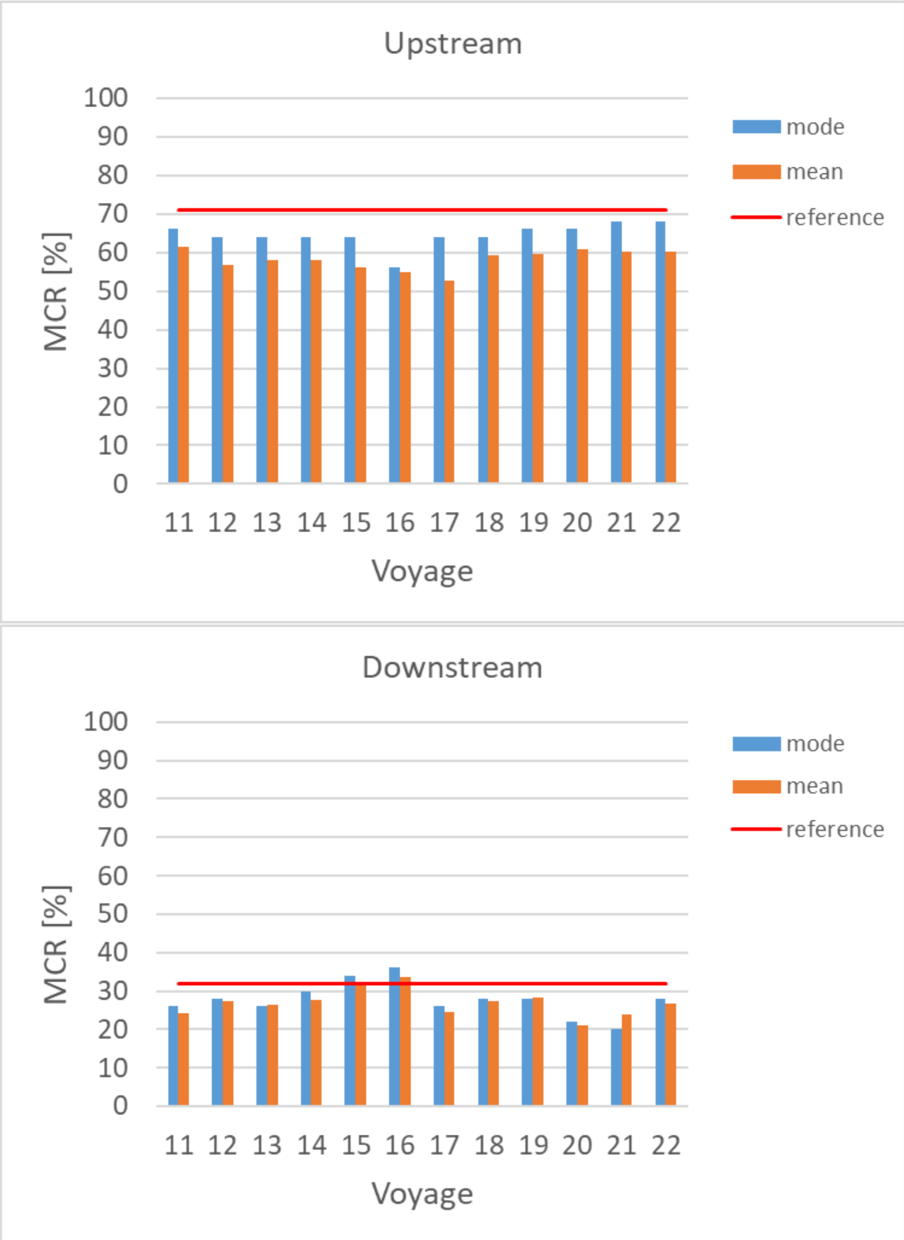


Figure 4-10: Fraction of maximum continuous rating (MCR) of the engines used over the measured voyages compared to the data presented in [1].

Table 4-2: Results of the analysis of monitoring data.

		Upstream (6 barges)	Upstream (4 barges)	Downstream
Current	P_b	2610 kW (64% MCR)		1140 kW (28% MCR)
Reference [1]	P_b	2900 kW (71% MCR)	2500 kW (61% MCR)	1300 kW (32% MCR)
	Time	24 hours (64% of voyage)		13 hours (36% of voyage)

5 POWER SYSTEM SOLUTIONS

In this chapter various drive train systems are described which are a result of discussions held in the working group. The solutions are evaluated based on fuel efficiency and weight. In parallel the design was detailed further by C-Job, refining the weight estimations and defining the layout keeping practical restrictions in mind. This is reported separately.

5.1 Proposed solutions

5.1.1 Current solution

The current design has three medium speed diesel engines, each driving a propeller with direct transmission through a gearbox. Depending on the vessel in the Veerhaven fleet, two of the auxiliary engines can also be directly coupled to the bow thrusters. Instead, only the case with electric transmission to the bow thrusters is used as reference configuration. The generators are connected to an AC grid and used for the hotel load and bow thrusters. All configurations have a harbour generator which is not specified independently.

	Number	Type	Ne [rpm]	Pb (unit) [kW]	Pb (total) [kW]
Main engines	3	MAK 8M20 [CI-ICE]	1000	1360	4080
Auxiliary engine	4	Scania DS-12-62 M [CI-ICE]	1500	315	1260

	Number		Pnom (unit) [ekW]	Pnom (total) [ekW]
Bow thrusters	2		400	800
Hotel load	1		80	80

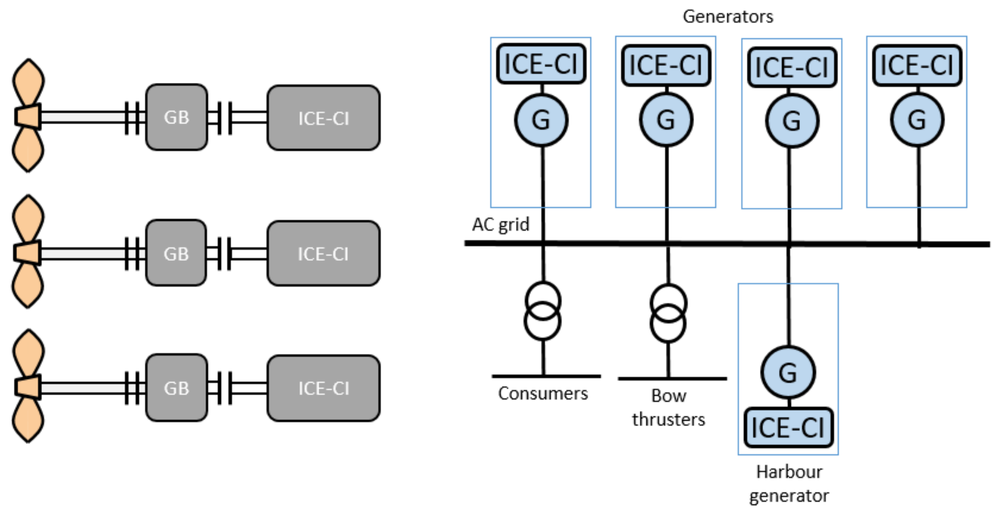


Figure 5-1: Current power system.

5.1.2 Design option 1a: Medium speed engines with direct transmission (4 propellers)

This design option has Dual Fuel (DF) main engines running on methanol and diesel. Due to the increased beam of the vessel expected to cope with the reduced draught for shallow water conditions, it is possible to increase the number of drive trains to 4.

	Number	Type	Ne [rpm]	Pb (unit) [kW]	Pb (total) [kW]
Main engines	4	ABC 6DZD-720-166[1] [DF-CI-ICE]	720	956	3824
Auxiliary engines	4	Scania DS-12-62 M [CI-ICE]	1500	315	1260

	Number	Type	Pnom (unit) [ekW]	Pnom (total) [ekW]
Bow thrusters	2		400	800
Hotel load	1		80	80

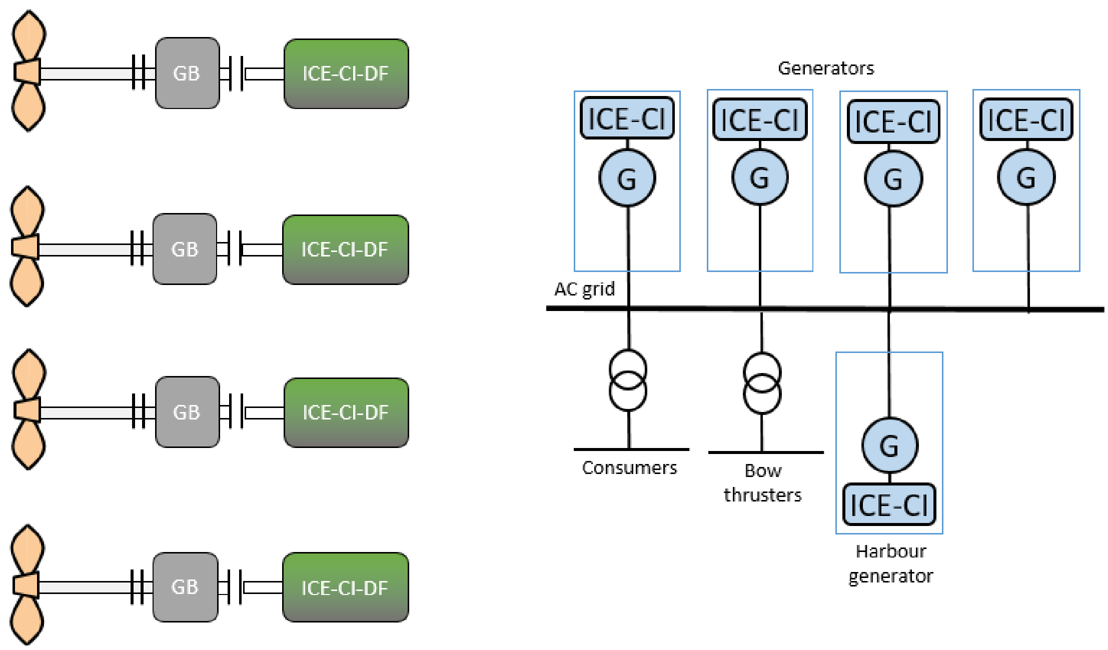


Figure 5-2: Solution 1a: Medium-speed engines with direct transmission and four propellers.

[1] Engine rating not available in supplier specifications, based on reduction of MEP from 18.1bar to 16.6bar.

5.1.3 Design option 1b: Medium speed engines with direct transmission (3 propellers)

This design option also has the Dual Fuel (DF) main engines, but retains the original three drive trains.

	Number	Type	Ne [rpm]	Pb (unit) [kW]	Pb (total) [kW]
Main engines	3	ABC 6DZD-900-166 [DF-CI-ICE]	900	1194	3582
Auxiliary engines	4	Scania DS-12-62 M [CI-ICE]	1500	315	1260

	Number	Type	Pnom (unit) [ekW]	Pnom (total) [ekW]
Bow thrusters	2		400	800
Hotel load	1		80	80

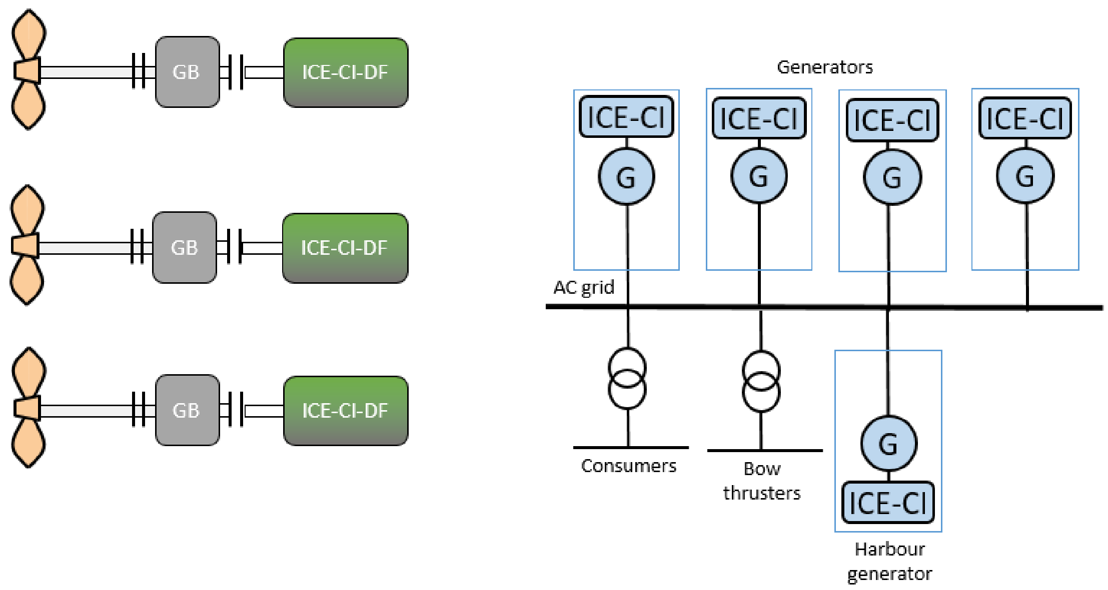


Figure 5-3: Solution 1b: Medium-speed engines with direct transmission and three propellers.

5.1.4 Design option 2: Medium speed engines with hybrid transmission (4 propellers)

This option has the four drive trains with Dual Fuel (DF) main engines. In addition Power Take In and Power Take Off (PTI/PTO) is applied using an electric motor connected to the gearbox. This results in a hybrid configuration where load can be shared over the propellers. One of the use cases is to run four propellers downstream powered by two main engines. Also the power of the bow thrusters can be produced by the main engines instead off the auxiliary engines. However, in practice this is difficult due to the 4500 kW limit on the propulsion power posed in the RPR. For this reason two different types of main engines are specified.

	Number	Type	Ne [rpm]	Pb (unit) [kW]	Pb (total) [kW]
Main engines	2	ABC 6DZD-720-166 [DF-CI-ICE]	720	956	4300
	2	ABC 6DZD-900-166 [DF-CI-ICE]	900	1194	
Auxiliary engines	2	Scania DS-12-62 M [CI-ICE]	1500	315	630

	Number	Type	Pnom (unit) [ekW]	Pnom (total) [ekW]
Gearbox PTO/PTI	4	Reintjes WAF-RHS 763	400	1600
Bow thrusters	2		400	800
Hotel load	1		80	80

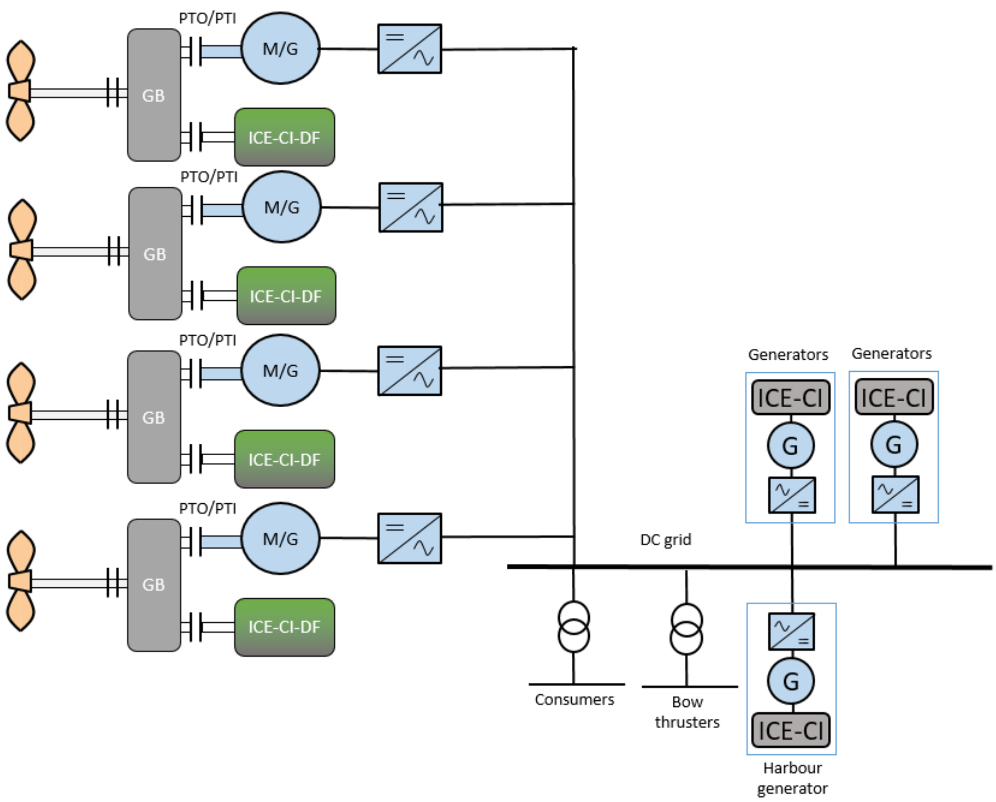


Figure 5-4: Design option 2: Medium-speed engines with hybrid transmission and four propellers.

5.1.5 Design option 3: Medium speed engines with electric transmission

This option uses electric transmission to drive the propellers, using Dual Fuel (DF) main engines. This leads to a reduction in the number of required auxiliary engines.

	Number	Type	Ne [rpm]	Pb (unit) [kW]	Pb (total) [kW]
Main engines	3	ABC 6DZD-1000-166 [DF-CI-ICE]	1000	1326	3978
Auxiliary engines	1	Scania DS-12-62 M [CI-ICE]	1500	315	315

	Number	Type	Nnom [rpm]	Pnom (unit) [ekW]	Pnom (total) [ekW]
Electric motor	4	Oswald TF46.200	300	900	3600
Bow thrusters	2			400	800
Hotel load	1			80	80

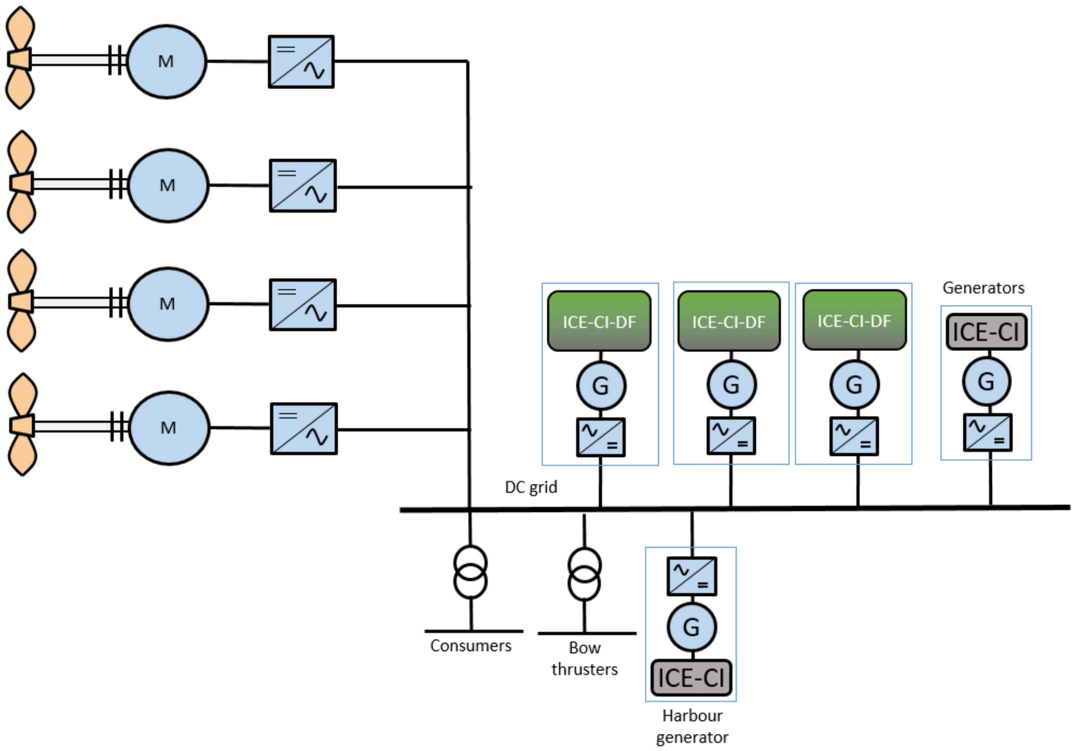


Figure 5-5: Design option 3: Medium-speed engines with electric transmission and four propellers.

5.1.6 Design option 4: High-speed engines with electric transmission

This option uses electric transmission, but with high speed single fuel engines. These engines are lighter, but can also have lower fuel efficiency. As currently only single fuel engines of this type are available, it is required to double the installed power for diesel and methanol to meet the requirement to sail both on methanol and diesel depending on the fuel availability.

	Number	Type	Ne [rpm]	Pb (unit) [kW]	Pb (total) [kW]
Main engines	4	Wärtsilä 14 16V [Diesel CI-ICE]	1600	1055	4220
Main engines	4	ScandiNAOS DI16 [Methanol CI-ICE]	2100	415	3735

	Number	Type	Nnom [rpm]	Pnom (unit) [ekW]	Pnom (total) [ekW]
Electric motor	4	Oswald TF46.200	300	900	3600
Bow thrusters	2			400	800
Hotel load	1			80	80

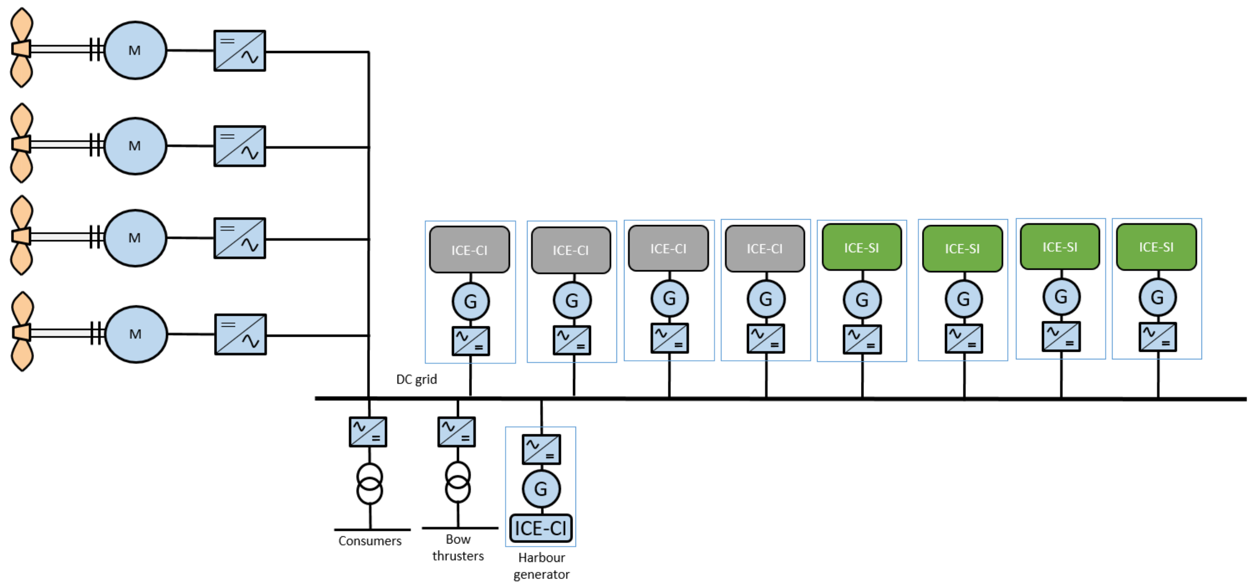


Figure 5-6: Design option 4: High-speed engines with electric transmission and four propellers.

5.2 Fuel efficiency analysis

The solutions for the new pushboat design are compared based on the estimated methanol fuel consumption. The operational profile is simplified to an upstream and downstream voyage in conditions that allow for 6 fully loaded barges. The hotel load is neglected in the analyses for simplicity, although small gains could be made by producing the required power by other means as the auxiliary generator sets.

Based on the most occurring brake power obtained from the operational analysis, described in paragraph 4.2, an estimate is made for the representative speed through water. This is done using the speed-power curve from the trials in a water depth of 6m performed for the Veerhaven X [2] .The difference in resistance between the loaded and empty condition is obtained by calibrating with the rotation rate-power curves obtained from the monitoring data for both conditions. This results in the assumed operational profile shown in Table 5-1.

Table 5-1: Simplified operational conditions for analysis of the fuel efficiency.

	Loaded (upstream)	Empty (downstream)	
Most occurring brake power	2610	1140	[kW]
Most occurring shaft power	2532	1106	[kW]
Representative speed through water	15.6	16.4	[km/h]

The required shaft power for the various propeller configurations is estimated, assuming the same resistance as the current design. This is done as it is expected that the resistance is dominated by the barges and therefore similar for both pushboat designs. Using propeller series, the effects of the propeller diameter and number of propellers is estimated for the various solutions and compared with the performance of the current design. The propeller diameter is reduced to meet the lower draught of 1.6m compared with 1.75m of the current design. The effect of the choices in propeller configuration on the shaft power is given in Table 5-2. The effect on performance is also shown when downstream only two propellers are used instead of four. Here, no losses are included for the two propellers that are not driven and likely rotating freely.

Table 5-2: Effect of propeller configuration on the required shaft power.

	Propeller diameter [m]	Required Ps - Loaded (upstream) [kW]	Required Ps - Empty (downstream) [kW]
Original solution	2.05	2610	1140
New design 4 propellers	1.89	2498 (-4%)	1120 (-2%)
2 propellers active			1240 (+9%)[2]
New design 3 propellers	1.89	2676 (+3%)	1158 (+2%)
2 propellers active			1240 (+9%)[2]

Depending on the drive train solution, the transmission losses and specific fuel consumption (sfc) of the engines differs. The solutions are both compared, using the nominal values and more detailed by using the off-design values of the transmission losses and sfc. Using mathematical models, the description of these off-design losses is obtained and using the equilibrium solver E&S the equilibrium condition with minimum fuel consumption is obtained. The nominal efficiencies, used as an input for both approaches, are given in Table 5-3. The methanol specific fuel consumption of the medium speed dual fuel engines

2 No drag of free rotating propellers included.

is calculated based on the by the supplier specified fuel consumption of the current MAK engines of 190 g/kWh. The efficiency of the high speed engines is derived from the supplier data of the ScandiNAOS DI16 engine. The generator and electromotor efficiency is based on supplier data of similar components. General assumptions are made for the gearbox and frequency convertor efficiency.

The assumed nominal efficiencies and specific fuel consumption for the analysis are given in Table 5-3. For the current design the fuel consumption for diesel is given, for the other designs that of methanol. The conversion efficiency is kept equal for all medium speed engines. The possible additional losses required after treatment for stage-V certification, are neglected.

Table 5-3: Assumed nominal efficiencies in the analysis.

	Main engine		Generator	Frequency convertor	Gearbox	Electric motor	Frequency convertor
	sfc	η_c	η	η	η	η	η
	[g/kWh]	[-]	[-]	[-]	[-]	[-]	[-]
Current solution (diesel)	190	0.444			0.97		
Solution 1a: Medium speed DF-ICE Direct transmission 4 propellers	408	0.444			0.97		
Solution 1b: Medium speed DF-ICE Direct transmission 3 propellers	408	0.444			0.97		
Solution 2: Medium speed DF-ICE Hybrid transmission 4 propellers	408	0.444			0.97		
Solution 3: Medium speed DF-ICE Electric transmission 4 propellers	408	0.444	0.95	0.98		0.98	0.98
Solution 4: High speed CI-ICE Electric transmission 4 propellers	470	0.385	0.95	0.98		0.98	0.98

Based on these assumptions, the fuel efficiency of the solution is compared. First a simplified analysis was performed using only nominal values. Here, changes in off-design conditions are neglected. The results are shown for the upstream condition in Table 5-4. In this condition the hybrid configuration performs similar to the direct drive configuration, because the PTO/PTI is not used and the hotel load is neglected. The difference with the current design is a result of the change in propulsive efficiency due to the decrease in propeller diameter and increase in number of propellers. For electric transmission, larger transmission losses are present leading to an increased fuel consumption. When using high speed engines, the specific fuel consumption and derived main engine efficiency also increases.

Table 5-4: Total fuel efficiencies using nominal efficiencies (upstream).

	Main engine η_c [-]	Transmission η_{tr} [-]	Propulsion η_d [-]	Combined η_t [-]	[%]
Current solution	0.444	0.970	0.424	0.183	0
Solution 1a: Medium speed DF-ICE Direct transmission 4 propellers	0.444	0.970	0.440	0.189	-4
Solution 1b: Medium speed DF-ICE Direct transmission 3 propellers	0.444	0.970	0.411	0.177	+3
Solution 2: Medium speed DF-ICE Hybrid transmission 4 propellers	0.444	0.970	0.440	0.189	-4
Solution 3: Medium speed DF-ICE Electric transmission 4 propellers	0.444	0.894	0.440	0.175	+5
Solution 4: High speed CI-ICE Electric transmission 4 propellers	0.385	0.894	0.440	0.151	+21

In addition the analysis is performed using models for the off-design efficiencies of the main engines and components. For the solution with direct transmission (1a) and electric transmission (3) diagrams of the results of these models are shown in Figure 5-7 up to Figure 5-11. This illustrates the background of the resulting efficiency and fuel consumption reported later.

It can be observed that the specific fuel consumption increases during the downstream voyage, due to the lower main engine load. This is shown both for the current diesel engines (Figure 5-7) and the methanol engines of the new design (Figure 5-8). The models for the electric transmission are shown in Figure 5-10 and Figure 5-11. It can be seen that the optimum efficiency of the generator and main engine do not match, which might be the case in practice, but could also be due to the assumptions made. This can have a slightly negative impact on the result. Finally, the electric motor off design efficiency is shown.

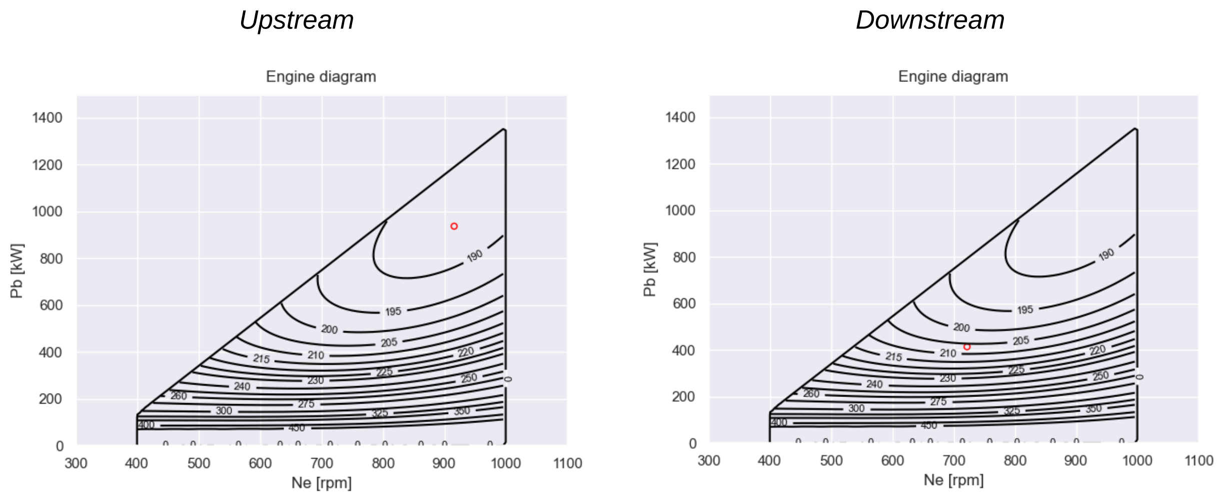


Figure 5-7: Assumed engine diagram and MGO specific fuel consumption distribution in g/kWh for the original MAK engine with operational point for upstream and downstream sailing.

Upstream *Downstream*

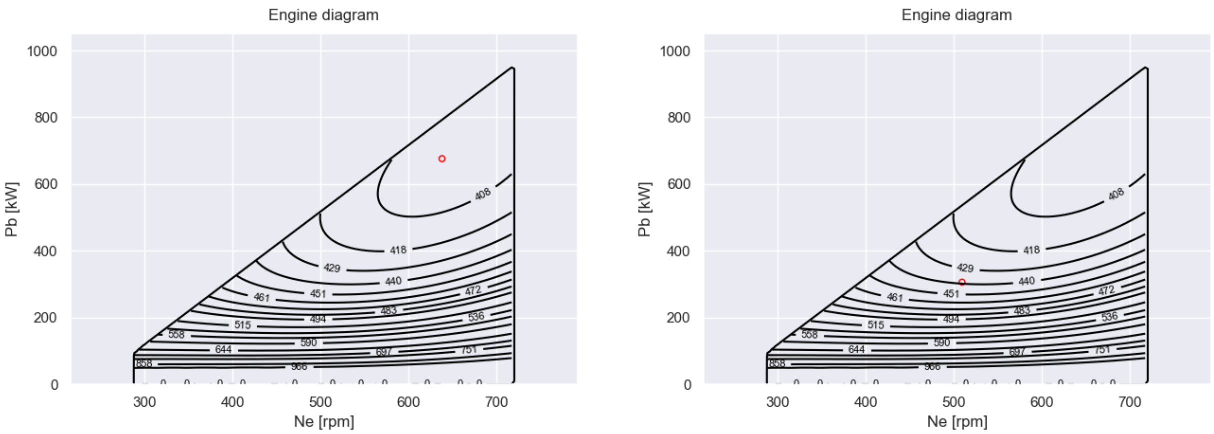


Figure 5-8: Assumed engine diagram and methanol specific fuel consumption distribution in g/kWh for the ABC 6DZD-720-166 engine of solution 1a with operational point for upstream and downstream sailing.

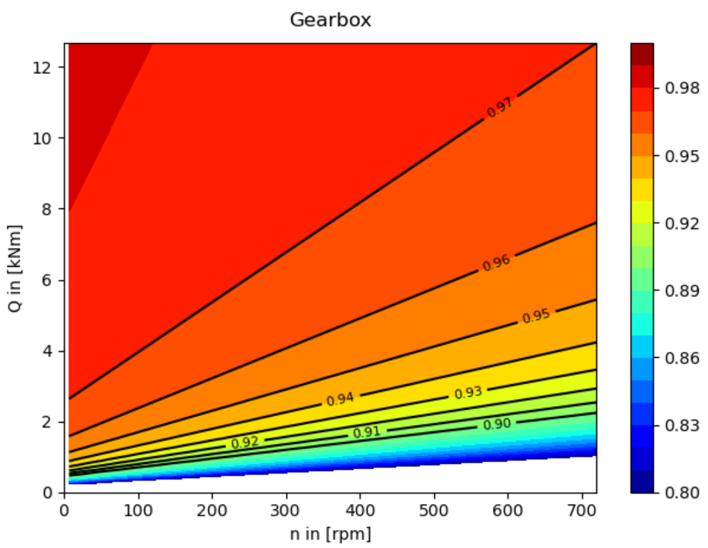
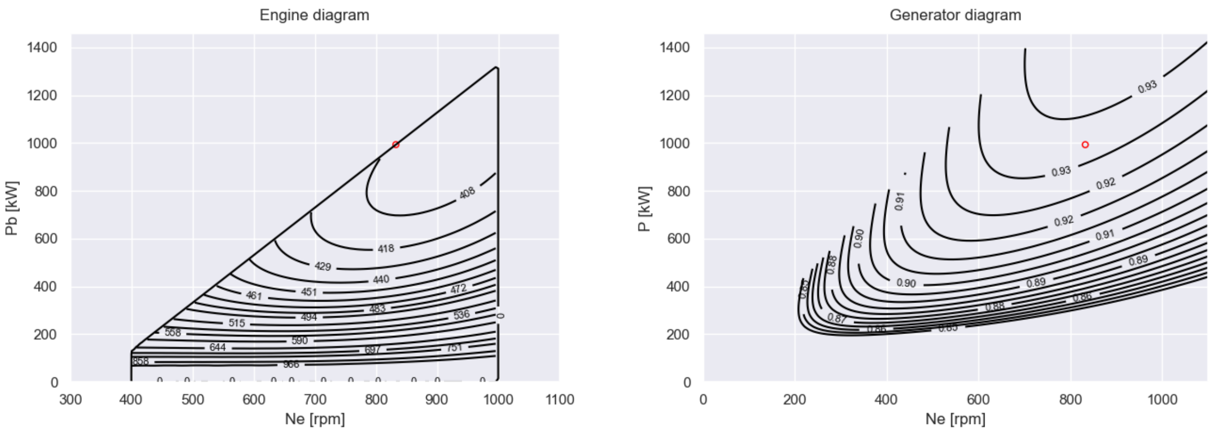


Figure 5-9: Assumed distribution of the efficiency for the gearbox of solution 1 depending on the input torque and rotation rate.

Upstream



Downstream

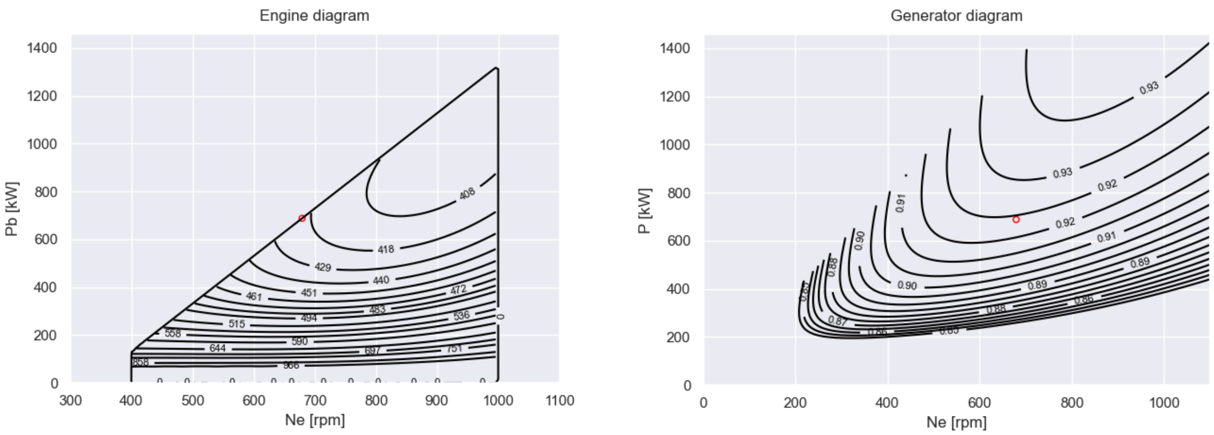
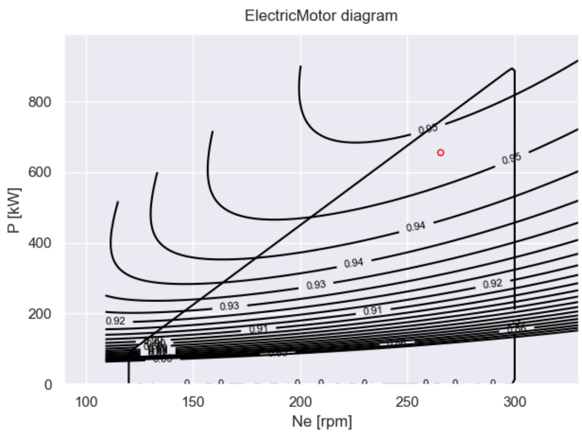


Figure 5-10: Assumed engine diagram and methanol specific fuel consumption distribution in g/kWh for the ABC 6DZD-1000-166 engine and generator efficiency including frequency convertor losses of solution 3 with operational point for upstream and downstream sailing.

Upstream



Downstream

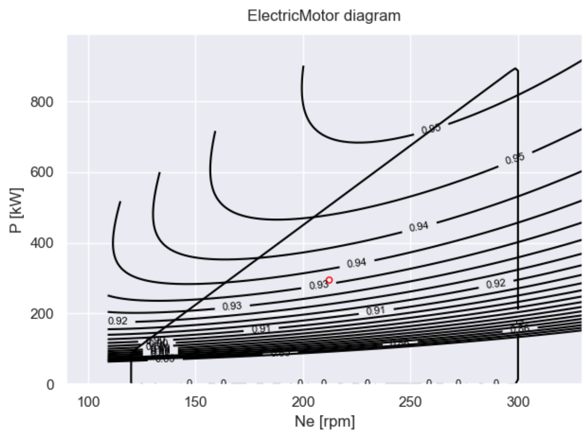


Figure 5-11: Assumed electric motor diagram and efficiency distribution for the Oswald TF46.200 motor including frequency convertor losses of solution 3 with operational point for upstream and downstream sailing.

The resulting efficiencies in off-design conditions are shown in Table 5-5. The specific fuel consumption change is captured in the conversion efficiency of the main engines. It is observed that the overall result is similar as when using the nominal efficiencies, although the absolute efficiencies mainly in downstream condition differ. For the solution with hybrid transmission, solution 2, the effect of driving two propellers is not evaluated as the used solver cannot deal with deactivating engines. This is analysed using the MARIN Emission Calculator (MEC) tool discussed later.

As the PTO/PTI is not used, no differences are observed from the direct drive solution. For the solutions with electrical transmission the losses due to electrical transmission cannot be regained using the changes in off-design efficiencies. Similar as for the hybrid propulsion it was not possible to optimise the number of engines running. This was fixed to an assumed number as shown in the table. The refined results using the MEC tool are shown later.

Generally speaking, it is observed that the specific fuel consumption increases and the related conversion efficiency decreases in the downstream part of the voyage. The same holds for the transmission efficiency. The propulsive efficiency however increases due to the lower propeller load.

Table 5-5: Total fuel efficiencies using models including off-design efficiencies (E&S).

	Main engine η_c [-]	Transmission η_{tr} [-]	Propulsion η_d [-]	Combined η_t [-]	[%]
Current solution Upstream	0.450	0.966	0.425	0.185	0
Downstream	0.409	0.957	0.496	0.194	0
Solution 1a: Medium speed DF-ICE Direct transmission 4 propellers Upstream	0.450	0.968	0.440	0.192	-4
Downstream	0.412	0.960	0.501	0.199	-2
Solution 1b: Medium speed DF-ICE Direct transmission 3 propellers Upstream	0.449	0.969	0.411	0.179	+3
Downstream	0.420	0.961	0.485	0.196	-1
Solution 2: Medium speed DF-ICE Hybrid transmission 4 propellers Upstream	0.450	0.968	0.440	0.192	-4
Downstream	0.412	0.960	0.501	0.199	-2
Solution 3: Medium speed DF-ICE Electric transmission 4 propellers Upstream	0.445	0.879	0.440	0.172	+7
Downstream 2/3 engines running	0.430	0.856	0.499	0.184	+6
Solution 4: High speed CI-ICE Electric transmission 4 propellers Upstream	0.387	0.880	0.440	0.150	+23
Downstream 4/9 engines running	0.387	0.865	0.499	0.167	+16

Finally, the results are further refined by optimising the number of running engines and including the auxiliary power by using the MARIN Emission Calculator (MEC) tool. Some slight differences in the modelling of the off-design efficiencies exists between the tool and the previously shown approach. Still one average condition for the upstream and downstream part of the voyage is used. The results in terms of fuel consumption are presented in Table 5-6.

It is observed that both configurations with four propellers have an expected higher fuel efficiency due to the higher propulsive efficiency from the reduced load per propeller. The hybrid transmission does not increase the overall efficiency. In this refined analysis the effect of the different engine sizes in the hybrid configuration (solution 2) and their effect on the specific fuel consumption is taken into account, making the result slightly worse than the direct drive solution (solution 1a). It could still be an consideration to reduce run time and maintenance on the engines. The solutions with electric transmission are not able to regain their nominal transmission losses by increasing the off design efficiency.

Table 5-6: Fuel consumption using off-design efficiencies (MEC).

	Time [h]	Shaft power [kW]	Methanol Fuel consumption [kg]	Difference [%]
Current solution Upstream	24	2610	34700	0
Downstream	13	1140		
Solution 1a: Medium speed DF-ICE Direct transmission 4 propellers Upstream	24	2500	33500	
Downstream	13	1120		-3.5
Solution 1b: Medium speed DF-ICE Direct transmission 3 propellers Upstream	24	2610	35400	
Downstream	13	1140		+2.1
Solution 2: Medium speed DF-ICE Hybrid transmission 4 propellers Upstream	24	2500	33800	
Downstream	13	1120		-2.7
Solution 3: Medium speed DF-ICE Electric transmission 4 propellers Upstream	24	2500	36900	
downstream	13	1120		+6.5
Solution 4: High speed CI-ICE Electric transmission 4 propellers upstream	24	2500	40000	
downstream	13	1120		+15.3

6 WEIGHT AND HYDROSTATICS

The amount of weight available for the power system and fuel storage is based on the current Veerhaven X design. For this vessel the hull shape with appendages was available to determine the hydrostatics and a specification of the consumables at a draught of 1.75m. In addition, the specifications of the current machinery is gathered to arrive at the weight budget within the current main dimensions. From here the effect of decreasing the draught and increasing the beam is included, both on the hydrostatics and structural weight.

6.1 Machinery and consumables of Veerhaven X

The combined weight of the part of the machinery and consumables of the Veerhaven X that will be replaced in a new design is given in Table 6-1. It is assumed that diesel tanks are part of the hull construction and therefore do not add to the weight.

Table 6-1: Weight of machinery and consumables to be replaced for the Veerhaven X at a draught of 1.75m.

Machinery	Number [-]	Unit mass [t]	Total mass [t]
Main propulsion (MAK 8M20 C)	3	13.8	41.4
Gearbox (Reintjes WAF 1943)	3	4.5	13.4
Shafts	3	2.5	7.5
Generator set (Scania DS-12-62M + Stamford generator)	4	2.5	10.2
Generator set (John Deere 4045TF258 + Stamford generator)	1	1.9	1.9
Electric systems	1	1.6	1.6
Total:			76
Consumables	Volume [m^3]	Density [kg/ m^3]	Total mass [t]
Diesel fuel	34.9	860	30.0
		Total:	30

6.2 Hydrostatics and weight estimation for Veerhaven X

The hydrostatics are obtained from a lines plan with appendages of the Veerhaven X design. The hydrostatics are given in Table 6-2 for the condition with minimum supplies and in empty condition. For the empty condition a displacement of 650 m^3 is described in the “meetbrief” which differs slightly from the displacement based on the hydrostatics of the lines plan.

Table 6-2: Hydrostatics of the Veerhaven X with appendages.

Lines plan	Beam [m]	Displacement [m^3]	LCB [m]	C_B [-]
Veerhaven X (T=1.75m – minimum supplies)	15	739	21.74	0.707
Veerhaven X (T=1.57m – empty)	15	646 (650)	21.99	0.698

The effect of the change in main dimensions on the construction weight was determined from a rough weight estimation, set up by Scheepswerf gebroeders Kooiman for the research reported in [3]. This was done for a pushboat concept design with a beam of 18.5m. The data is combined with the data presented in Table 6-1 and the "Meetbrief", resulting in an empty displacement to arrive at the estimated residual lightship weight given in Table 6-3. It is assumed that the weight of the deckhouse scales linearly with the beam. The residual lightship weight, remaining from the difference between the displacement and estimated weight components, was assumed to be mainly construction weight. This is scaled using the quadratic number as given in equation (6-1). This simple relation uses a factor (k) representing the weight of decks, scaling with length times beam and the longitudinal sides scaling with the length times moulded depth. This analysis was to be refined at a later stage by C-Job, separating the construction weight from other constant factors.

$$w_{hull} = k\,\big(L\,(B + D)\big) = k\,(L\,B\ + \mathrm{L}\,D) \qquad (6\text{-}1)$$

Table 6-3: Estimated residual lightship weight for the Veerhaven X in empty condition.

	Number [-]	Unit mass [t]	Total mass [t]
Hull			
Deck house	1	110	110
Bow thrusters	2	8	16
Other lightship	1	443	443
		Subtotal:	569
Other			
Machinery			76
Minimum supplies			5
		Total:	650

6.3 Weight estimation for new design and power solutions

Scaling the weight estimate to the new design with a beam of 20m instead of 15m resulted in the masses as presented in Table 6-4. It is observed that a significant weight increase of 162 t is expected based on this rough weight estimation for a wider pushboat with reduced draught. This means that the displacement of the widened hull should increase with at least 162t at the reduced design draught, to fit the current diesel configuration. For the methanol configurations, additional increase in displacement is required.

Table 6-4: Estimated hull weight for the new design with a beam of 20m.

Hull	Number [-]	Unit mass [t]	Total mass [t]
Hull			
Deck house	1	147	147
Bow thrusters	2	8	16
Other lightship	1	568	568
		Subtotal:	731
		Increase from hull weight of Veerhaven X:	162

For the drive train solutions described in chapter 5, a weight estimation is made for the shallow water condition for the required two round trips. In this condition less fuel has to be carried compared to the deep water condition as shown earlier in Table 4-1, however the draught of the pushboat is limited to 1.60m. An overview of the estimated required fuel capacity and weight is given in Table 6-5.

Table 6-5: Required fuel capacity and weight for after-treatment (urea), diesel mode and methanol mode.

After treatment (all modes)	Volume [m³]	Density [kg/m³]	Total mass [t]
Urea	1.7	1090	1.8
Urea capacity	3.4		0.2
		Subtotal:	2
Diesel mode	Volume [m³]	Density [kg/m³]	Total mass [t]
Diesel fuel	33.5	860	28.6
Diesel tank capacity (and tank weight)	76.9		0.0
Methanol fuel	0.0	790	0.0
Methanol tank capacity (and tank weight)	141.7		39.9
		Subtotal:	69
Methanol mode	Volume [m³]	Density [kg/m³]	Total mass [t]
Diesel pilot fuel (10% of volume)	7.7	860	6.6
Methanol fuel	76.9	790	60.9
Methanol tank capacity (and tank weight)	141.7		39.9
		Subtotal:	107

Table 6-6: Resulting solution weight with diesel fuel for shallow water conditions and the needed displacement.

	Weight *Methanol mode* [t]	Weight *Diesel mode* [t]	Needed displacement *Diesel mode* [t]
Current solution		100	880
Solution 1a: Medium speed DF-ICE Direct transmission 4 propellers	200	160	930
Solution 1b: Medium speed DF-ICE Direct transmission 3 propellers	180	140	910
Solution 2: Medium speed DF-ICE Hybrid transmission 4 propellers	200	160	940
Solution 3: Medium speed DF-ICE Electric transmission 4 propellers	220	190	960
Solution 4: High speed CI-ICE Electric transmission 4 propellers	220	190	960

6.4 Hydrostatics for the new design

In order to verify if the needed displacement is realistic, lines plans are drawn for the new pushboat design with a beam of 20m. The appended hull shape is shown in Figure 6-1. This is done both for a configuration with three and four propellers to find the maximum achieved displacement in these conditions. It is noted that the fullness of the vessel was to be increased significantly to achieve the required displacement. The hydrodynamic performance of such a full hull in very shallow water should be confirmed with further studies and is a potential risk of the design. It is observed in Table 6-7 that still the displacement is critical and comes only close to the solution with hybrid transmission. For the solution with electric transmission it seems required to increase the draught as only limited gains are made by further increasing the beam due to the expected increase in construction weight.

Table 6-7: Hydrostatics achieved for a concept lines plan of the new design compared to the original.

Lines plan	B [m]	Displacement [t]	LCB [m]	C_B [-]
Current design (T=1.75m)	15	739	21.74	0.707
Current design (T=1.60m)	15	662	21.94	0.692
New design 4 propellers (T=1.60m)	20	934	22.50	0.730

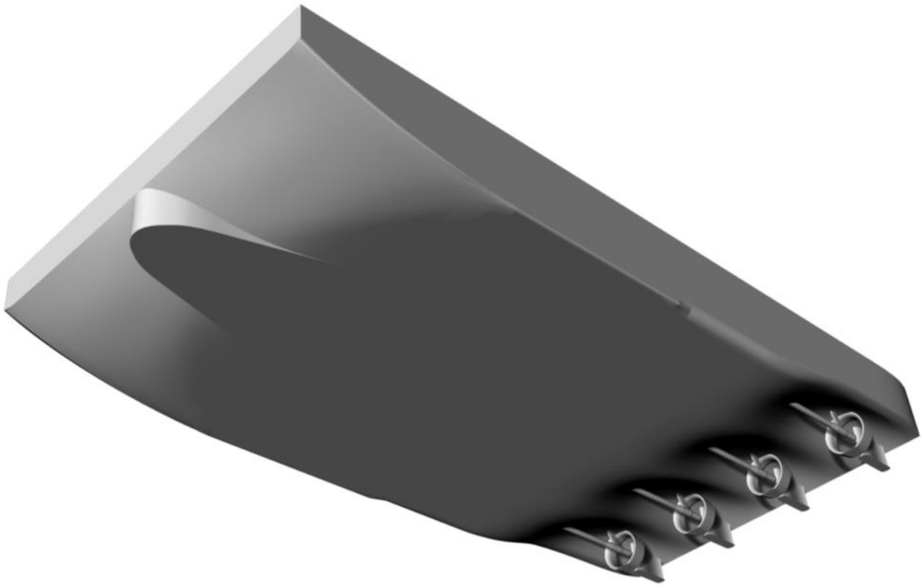


Figure 6-1: Render of the new lines plan with four propellers.

7 CONCLUSIONS AND RECOMMENDATIONS

Parts of the design study are conducted and reported to develop a methanol-diesel driven pushboat design that is able to sail during periods of decreased water level on the river for the operations performed by Veerhaven.

First, the operation of the current vessel was assessed looking at bunkering data over a period of two years and monitoring data of the shaft power over a period with high water levels performed in this project. During this period the vessel can be fully loaded and the current is highest, resulting in the largest shaft power demand. This leads to the following constraints for the new design:

- Average fuel consumption in deep water (fully loaded 6 barges) and shallow water (limited load and 4 barges) conditions.

	Round trip shallow water 4 barges (Ruhrort < 233 cm)	Round trip 6 barges
Average diesel fuel consumption	11.8 m^3	21.4 m^3
95% percentile of fuel consumption	**13.4 m^3**	**24.7 m^3**

- The installed main engine power can be reduced to 3600 kW from the current 4080 kW

Using this data and information from Veerhaven, the specifications for the new design were summarized. Based on this multiple drive trains, solutions were defined and evaluated based on fuel efficiency and weight. This resulted in the following conclusions:

- Increasing the number of drive trains from 3 to 4 increases the fuel efficiency with roughly 7 percent due to the increased propulsive efficiency of the less loaded propellers. When using 3 propellers the fuel efficiency is reduced compared to the current design with 3 percent due to the decreased propeller diameter due to the smaller design draught.

- The medium speed dual fuel solution has the best fuel efficiency. The hybrid propulsion has at best similar fuel efficiency and is only favourable for other aspects such as maintenance by reducing the runtime by sailing on two engines instead of four. The electric transmission gives a large decrease in fuel efficiency based on the nominal values, which cannot be regained sailing in off-design conditions.

- A first weight estimation using simple methods was made and it is concluded that the direct drive methanol solutions can fit within a widened pushboat. The solutions with electric transmission are expected to be more critical. It is however recommended to refine the weight estimation, separating constant weight components that do not scale with the beam. This was planned in the part of C-Job in this task.

- It is recommended to evaluate and optimise the hydrodynamic aspects of the widened and fuller hull using higher fidelity methods, such as CFD, especially in the shallow water conditions with low under keel clearance.

- It is recommended to refine the assumed specific fuel consumption of the main engines in further studies. It is mentioned that practical observed values of the conversion efficiency are about 0.02 and 0.04 less in the upstream and downstream part of the voyage respectively. This could be due to the assumed nominal values by the supplier, the used engine map model in this analysis or the different design point of the propeller in the current design. For the current vessels the propeller absorbs roughly 85% power at 100% rotation rate in transit mode as a result of the chosen design point.

Wageningen, January 2023
MARITIME RESEARCH INSTITUTE NETHERLANDS

Ir. G. Gaillarde
Head of Ships Department

REFERENCES

[1] M. Drijver, “Future pusher project: Alternative power configuration for a future pusher of ThyssenKrupp Veerhaven BV,” TU Delft, Delft, 2013.

[2] MARIN, “Move IT: D1.2 Measurements,” MAIN, Wageningen, 2013.

[3] MARIN, “Emissie reductie duwboten, een verkenning. Onderzoek naar mogelijke energiedragers en impact op scheepsindeling,” MARIN, Wageningen, 2021.

M A R I N
P.O. Box 28

6700 AA Wageningen
The Netherlands

T +31 317 49 39 11
E info@marin.nl

I www.marin.nl