Applicability of a modular power plant with alternative fuels

A case study to determine the impact on ships operation capabilities and power plant performance, when using a modular power plant for a 2999 gross tonnage general cargo concept ship, called the Future Trader.

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Abstract

This paper examines a case study to determine the effects on system performance of the power plant and ship operational capabilities, this case is a ship designed by the company DEKC. It is a small general cargo vessel of 2999 GrT (Gross Tonnage) called the Future Trader. The ship design is finished and the ship will be equipped with a modular power plant and fuel storage on the aft of the ship. In total four different power plants will be compared.

The first is the base line system, this consists of a single internal combustion engine fuelled by Marine Diesel Oil (MDO). The three other systems will be modular systems. They all use the concept of distributed generation. There is looked into a system with three internal combustion engines fuelled by MDO. Besides this there are two fuel cell systems. Each consists of two separated fuel cells and one uses hydrogen and the second ammonia as fuel. For those systems mathematical models are created to compare three modular power plants to each other and to a base line. With those models the effects on the Future Trader's range, fuel costs (operational capabilities) and emissions are researched. A modular power plant is installed on the aft of the ship, constructed of four power packs each in a Twenty foot Equivalent Unit (TEU). The four systems will be simulated on four voyages and the results will be normalised with respect to the first setup.

It can be concluded that a modular system with the concept of Distributed Generation (DG) will reduce the ships overall performance in comparison to the single engine diesel electric system (base line). When reviewing the fuel cell systems with respect to the base line system it is found that the ammonia fuel cell system has zero emissions and it still offers a sufficient range. The increases in fuel costs are lower than that of the hydrogen fuel cell system. Hydrogen will also reduce harmful emissions to zero but the reduction in range is more severe. The increase in fuel costs is also significantly higher than for the base line. Overall ammonia seems the most promising of the non hydrocarbon fuels. The DG system is also useful as long as emission regulations remain unchanged. The MDO DG system can be loaded for large distance voyages and hydrogen can be loaded for short voyages if desired.

1 Introduction

The last couple of years climate change becomes more and more visible, the effects are more extreme and more common now than they were a few decades ago. Due to the effects of climate change there is a global discussion about the use of fossil fuels. Besides this discussion a lot of companies and governments are performing research into the effects of climate change and how we (humans) can solve the problems that come with climate change [1]. One of the fields of research is focused on finding a replacement fuel for fossil fuels, these replacement fuels are so called "alternative fuels". However it is hard to predict the fuel that will be used in the future.

The uncertainty of which fuel will be used in the future brings a challenge for engineers. This challenge is, that they do not know which power plant should be selected for a vessel since different power plants, or power plant components (e.g. internal combustion engines and fuel cells), require different fuels. So it is challenging to select engines that are available now and will still be suitable for the fuel of the future. This is a complex challenge for the shipping industry, due to the fact that the economic lifespan of ships is a couple of decades. Therefore choices made today need to still be suitable choices in 10 to 20 years from now. For new build ships that are developed now this is a difficult situation, engineers need to be ready for the fuel and power plant of the future today. Since it is uncertain what this fuel will be, other solutions to counter this problem are explored.

One of the possible solutions to deal with the inherent uncertainty of the energy transition is a modular power plant that can be removed and added to a ship. Such a ship is designed by the company DEKC (see figure 1). Using a modular power plant results in a ship that can be upgraded or adapted to other fuels and engines by only changing the power plant. This will make the ships developed at the moment suitable for future fuels and engines. However, this strategy brings a couple of challenges that will be addressed later in this study. On top of those challenges a power plant of a marine vessel has to perform well on many criteria such as: fuel consumption, emissions, radiated noise, propulsion availability, manoeuvrability, comfort due to minimal noise, vibrations and smell and cost. [2].

The ship that is designed by DEKC is called the Future Trader and will be presented next. The design is used for this case study and no changes to the ship design will be made, i.e. this study fully focuses on the design of the power plant of the Future Trader and not on other ship design aspects. The Future Trader is a general cargo vessel. The vessel has an overall length of 83.30 meters and has a Gross Tonnage (GrT) of 2999. The ship has a design speed of 10 kn and the resistance characteristics of the ship are known. The installed power of the ship is not decided and will be a result of the present study.

The Future Trader is designed so that the power will be supplied to the propeller using an full electric propulsion, this can be found inside the ship close to the propeller. The electric power needed to drive this motor and other on-board systems needs to be generated by a modular power plant, which will be designed in this thesis. For this modular power plant a space is reserved by DEKC on the stern of the ship. The footprint has the following dimensions: 6058 mm x 10310 mm (length x width). This is equal to the footprint of four Twenty foot Equivalent Unit (TEU) next to each other. The space reserved for this can be seen in figure 1. On top of this four TEU an extra row of TEUs can be added in which the fuel is stored. This study analyses the effects on system performance of the power plant and ship operational capabilities when using the modular power plant concept of the Future Trader. This ship will be used as a case study to answer the following question:

What are the effects on system performance of the power plant and ship operational capabilities when using different power plant concepts and different fuels in the Future Trader concept ship?

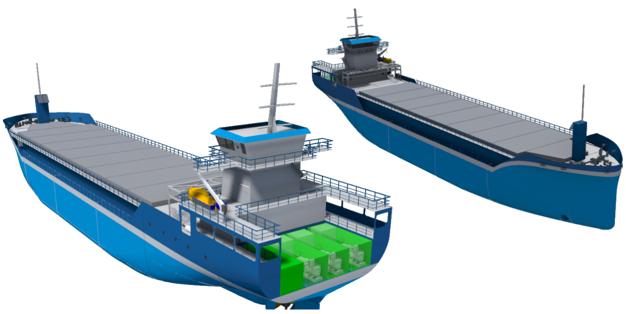

Figure 1: The Future Trader with four power packs at the aft

2 Ship and distributed generation

The Future Trader designed by DEKC is a concept ship that should provide the ship's owner with a ship of which the power generation can easily be altered. This is done by making the power plant modular, in this way the uncertainty of what fuel would be used in the future is reduced since the ships powerplant can be changed easily. Due to the design of the Future Trader and to create an easy transportable solution, multiple smaller power packs will be installed. Doing so relates to two concepts that look and sound similar but there is a fundamental difference between them. Those concepts are power plant (modular engine room) versus power pack, the definitions are:

- Power plant: this refers to the complete power generation system which can consist of multiple power packs. This is without the propulsion engine and systems. In the energy flow diagram of the ship this can be found on the left side, see figure 2.

- Power pack: This is a single smaller (sub)system of the power plant with one energy converter which is installed in a single TEU. Multiple of those power pack will form the power plant (modular engine room).

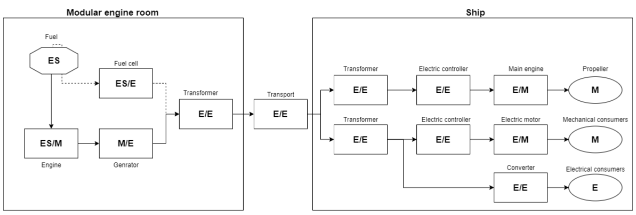

Figure 2: The modular power plant on the left (2 different systems, fuel cell or generator set) and power consumers on the right.

When using a modular plant the total power plant can be customised, not only during building but also years later new technology can be fitted on the vessel. This can optimise the ship now, and in the future the ship is able to keep up with regulations. Due to the modularity, in the future retro fitting could be done quickly and a ship can be modernised in this way. When looking at the engine technology this can lead to increased range and a reduction in emissions. Research should be done to determine the possible scale of the benefits. However this depends on the fuel, engines and systems used in the modular plant. The design of DEKC results in the application of the concept of Distributed Generation (DG), this makes it possible to keep the power plant in separated power packs. This offers easy handling and quick (un)loading on to the ship, this is desired by DEKC.

2.1 Distributed Generation (DG) in shipping

For a modular plant, using DG provides the possibility to keep the modules compact and easily transportable. Within the shipping industry a DG system is not new. In recent years there are ships with a DG setup to deliver power to all of the ships' systems. In those ships a couple of generator sets are installed to provide the ships with power for auxiliary users and for the propulsion. This type of system is mostly found in ships in the offshore branch, those ships are often equipped with Dynamic Positioning (DP) capabilities. In other ship types those systems are seldom used. Why are those setups chosen for DP ships?

A frequently mentioned reason is the increase in efficiency but also the flexibility in energy supply and the capability of adding energy storage aboard are reasons for a DG system [3]. Another reason for a DG system for DP ships is the response time of this setup, to make DP effective thrusters need to give a lot of power in a specific direction almost instantly. If a large diesel engine was used for a DP task, the engine could not keep up with the quick change in power demand due to slow response. Therefore smaller and more engines can be used to keep up with the fast change in power demand [4].

Ships with DP often use thrusters that are located at the far end of the ship, this location makes a mechanical drive unpractical. So, those ships have engines that generate electric energy that is used for the propulsion [4]. The placement of the generating engines is then disconnected from the location of the propulsion engine. This is also the case for the ship the Future Trader, since the modular power system has no mechanical connection to the propulsion system.

Another reason for the use of a DG system in DP ships is the increase in redundancy. When a single engine fails the other generators are capable of picking up the loss in power and therefore the ships can continue the operation at least for the time needed to stop working in a safe manner [3, 5] .

2.2 Sailing profile and routes

Normally a sailing profile would be used to design the ship and its systems. The Future Trader of DEKC however does not have a complete sailing profile. The absence of a complete sailing profile was made by DEKC, this is done to explore many modular power plant concepts for the Future Trader. However some general information is known, the ship is a general cargo vessel that will be active in the short sea shipping. The main area of operation is in European waters where no ice class is needed. The assumption is made that most of the voyages are similar and that the voyage profile will be similar to other short sea vessels. However for the range and distances no requirements are set, so in the research the voyages shown in table 1 are created to use in the simulation. The routes are different in length and some routes will pass through canals.

Table 1: Simulated voyages for all the models

Departure	Arrival	Open sea [km]	At canal [km]	km total	Max v in canal [kn]
Rotterdam	Antwerp	170.1	0	196.0	-
Rotterdam	Gdansk	1121.8	98.7	1237.1	8
Rotterdam	Hamburg	540.8	0	561.2	-
Rotterdam	Marseilles	3827.3	60	3900.3	13

3 Alternative fuels

In present days Marine Diesel Oil (MDO) is almost always used as a fuel in short sea shipping. Therefore a system with MDO will be designed as a base line and a DG system will be created using this fuel. Since there are many options for alternative fuels and a lot of research on this topic is available [6, 7, 8, 9, 10] etc. Not all the options can be researched, therefore a selection is made. LNG and hydrogen are often found in literature. Ammonia is not always taken into account in older studies, however it gets more attention in more recent studies and therefore will be considered. The fuel selection will be based on the mass and volume of the fuel and the possible range of the ship using this fuel type. The mass volume and range will be normalised with respect to the fuel properties of MDO. The results are called the volume, mass and range factor. The result of this normalisation are found in table 2.

Table 2: Volume, mass and range factors normalised to MDO

Fuel	Volume factor	Mass factor	Range factor
MDO	1.00	1.00	1.00
LNG	1.84	0.88	0.5
Ammonia (liquid)	2.90	2.26	0.5
Hydrogen (liquid)	4.64	0.36	0.3
Methanol	2.44	2.15	
Ethanol	1.82	1.59	
CNG	796		

In the table it is seen that CNG needs too much volume to be interesting for use in the Future Trader. Methanol and ammonia are both relatively heavy and since methanol is a hydrogen carbon fuel, it will be eliminated. Ethanol will be excluded due to the fact that LNG performs better in weight and in volume.

When we look into the range, seen is that the range of hydrogen is relatively low. However, this range could be sufficient for the use in short see shipping. Since hydrogen is a carbon free fuel, like ammonia, no harmful emissions will be produced. This is one the performance parameters of interest in this study. The range of ammonia is close to that of LNG only ammonia is carbon free and will therefore do better when looking at the emissions, this makes it more interesting than LNG. Therefore, LNG will be excluded. For a detailed explanation and the non normalised values please read the thesis *'Applicability of a modular powerplant with alternative fuels'* [11].

However there are challenges that need to be overcome when using ammonia as a single fuel in a ship. Those challenges are mostly related to the combustion of ammonia. In the present when ammonia is used as a fuel a starter fuel is used to make ammonia suitable. Another option is a spark ignition engine so ammonia does not require a starter fuel. A last option is using fuel cells in combination with ammonia. Therefore ammonia is a suitable option for the Future Trader.

For hydrogen there are two main options, it can be used in a fuel cell (FC) or it can be burned in an internal combustion (IC) engine. Where the FC seems to be the most promising because of the higher efficiencies [12]. This fuel has a great potential to keep up with all the future regulations, as long as it is produced in a green manner. The challenge is the storage and safety of hydrogen, this is however out of scope. Additionally the range of hydrogen is low in comparison to other fuels, see table 2. Since the Future Trader will use a modular power plant for the short voyages hydrogen can be used, if needed another system can be installed for the longer voyages.

Even though there are a lot of others fuels, the fuels that are used in this project are ammonia, hydrogen and MDO. The first two will be selected as possible alternative fuels for the future. MDO will be used in this research as a base line and to find the effect of using a DG setup.

4 Engine type and modular system

Now that the fuels are known the next step is to look into suitable energy converters for those fuels.

4.1 Engine type

The considered engine types are Internal Combustion (IC) engines, turbines and fuel cells. For most IC engines (diesel) the optimal load demand is around 75% of the Maximum Continuous Rating (MCR) as seen in figure 3 [13]. A total system efficiency around 40% can be reached for (diesel) IC engines (see equation 5 for the definition of efficiency). An IC engine will be used for the base line system because this is the most common system fuel combination these days. Also a DG setup will be modelled using MDO as a fuel to see the effect of using DG on the ships performance.

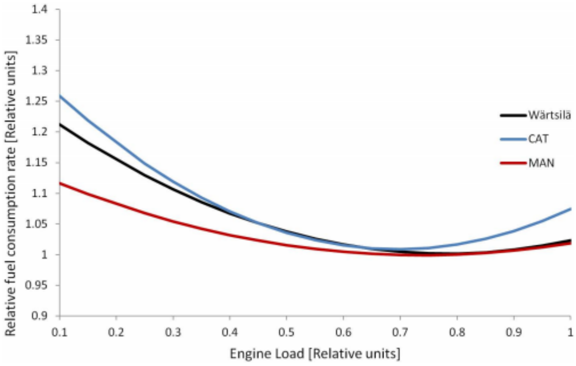

Figure 3: SFC curves. Caterpillar four stroke engines, MAN large 2 stroke engine and Wartsila 467 family [13]

For fuel cell systems (so with the Balance Of Plant BOP) the efficiencies are low until 10% MCR, then up to 90% MCR the efficiency is almost the same, after that the efficiencies will decrease. The total system efficiencies for fuels cells are between 45 to 65% [12, 14]. Because of this increase in system efficiencies a FC system will be modelled and used in the modular plant on the Future Trader for the ammonia and hydrogen fuelled systems.

For the turbines a completely different pattern can be found. For turbines the efficiencies are highest at maximum load and will drop if a turbine runs at partial load. Additionally the total efficiencies of turbine systems are low (around 30%) in comparison to fuel cells or diesel IC engines [15]. The overall efficiencies of a turbine are lower than those of the two other systems. Turbines are mainly used for their high power density and quick reaction time [16]. Because this quick response time and the high power density are not of importance for a general cargo ship like the Future Trader a turbine is less interesting.

4.2 Engine power

The power calculation is done following the procedure presented in "Design of Propulsion and Electric Power Generation Systems" chapter 3 [17]. In table 3 the information from DEKC about the Future Trader is shown, this information is based on the open water diagram of the ship.

Table 3: Resistance and general data from DEKC about the Future Trader

Name	Data	Unit
Speed	10	kn
	5,14	m/s
Resistance	80	kN
Wake	0,20	
Trust	94	kN
η_o	0,607	
Draft	6,00	m
Installed power	-	kW
Propeller type	KA 4-70 nozzle 19A	
Propeller P/D	1,30	
Propeller diameter	3,00	m
Water density	1,026	t/m3

The break power of the propulsion engine can be found in table 4, this power is at 80% MCR since a sea and engine margin of 20% is set by DEKC. Taking the losses into account (see table 5) a power of 734 kW at 80% MCR is found, the total installed break power is 918 kW at 100% MCR. Besides this propulsion power, the ship is also in need of auxiliary power. This is calculated using an electric load balance and a similar ship from the DEKC database. The electric load balance was made for three operations: manoeuvring in port, sailing at design speed and waiting for port/laying at the quay. The limiting factor is the operation sailing at design speed. This resulted in additional power of 290 kW break horse power of the engines for auxiliary systems when sailing.

Table 4: Break power calculation electric motor.

va	4,112	m/s
P_e	411	KW
P_T	387	KW
η_{Hull}	1,064	
Trust reduction	0,149	
P_o	637	KW
$\eta_{rotative}$	0,99	
P_p	643	KW
η_{shaft}	0,99	
P_s	650	KW
η_{gb}	1	
P_b	650	KW

Table 5: Propulsion power engine room.

Name	Data
$P_{b-electric}$	**650**
$\eta_{electricmotor}$	0,98
$\eta_{transport}$	0,97
$\eta_{conversion}$	0,98
$P_{engineroomout}$	**697**
$\eta_{conversion}$	0,98
$\eta_{generators}$	0,97
$P_{b-main-engine}$	**734**

Adding the propulsion and auxiliary power together gives a total power of 1208 kW that needs to be installed. However for fuel cells this power is slightly less because a conversion from mechanical to electrical power is not needed, so a generator is not needed. Resulting in a power for the FC system of 1171 kw.

4.3 Number of engines

Now that the power and the engine types are known there will be looked into the number of modular systems that need to be installed on the ship. Due to the fixed and finished ship design and the need for easy loading and unloading of the modular plant, the concept of DG for the modular system will be used. Using more engines is also a way to minimise the risk of a complete system failure (fatal failure) [1] and to make the ship more reliable. However, increasing the number of engines to infinity is useless and there will be a point where adding an extra engine will not result in a significant increase in system performance. It is challenging to find the most optimal number of engines (modular power packs). Using more than one engine by dividing the total power over multiple engines should give a gain for the reliability of the ship [18]. Brocken states that a FC will improve reliability. The number of modular systems and therefore engines installed on the Future Trader is four at maximum since there is room for a maximum of four TEU. Since using more than one engine results in a better redundancy the amount of engines (modular power boxes) will be at least two and four at maximum.

With the total power known of all the different systems, the number of engines is determined and will depend on the optimal MCR point. For multiple optimal engine running points a table is made and there is looked at the best corresponding option. In table 7 and 6, there are four different setups with one to four engines. Each colour represents the number of engines that are active. The large bold numbers represent the optimal MCR point (index) for all the engines active. So green means that one engine is running and orange means that two engines are running, the bold green number is the optimal point for one engine and the bold orange number represents the optimal working point of two engines, etc. Each cell represents the index number to provide the needed power with respect to the power of a single engine (see equation 1). The index numbers are divided equally over the number of engines that are running.

$$Index = \frac{P_{total-needed}}{Pb_{one-engine}} \tag{1}$$

For fuel cells it is found that the optimal points are all on the relatively low MCR values of 20% and are almost constant up to 90% (see table 6). So installing an extra engine will not result in better system performance or running point for other engines. Therefore for fuel cells two engines are used. For the IC engine with an optimal point around 0.75 the operation during the manoeuvring in port was the deceive operation about the number of engines that should be installed. This operation is seen in table 7 the manoeuvring is done in the grey rows of the table, from this table seen is that installing a third engine gives an optimal working point during manoeuvring in port at 20 or 30% MCR. Therefore one engine could be switched off and a better efficiency could be found. During design speed all engines are on and at the optimal point.

Table 6: Optimal engine load over MCR for a fuel cell system, with auxiliary power when sailing

			Nr of systems installed (running)			
Auxiliary power [kW]	290		1	2	3	4
optimal load point (MCR)	0.4	**Pb [kW]**	1208	604	403	302
Power demand [% mcr]	**Speed [kn]**	**power [kW]**	**index mcr**	**index mcr**	**index mcr**	**index mcr**
32%	5.0	382	0.32	**0.63**	**0.95**	**1.26**
37%	6.0	449	**0.37**	**0.74**	**1.11**	**1.49**
45%	7.0	542	0.45	0.90	1.35	1.79
50%	7.5	600	0.50	0.99	1.49	1.99
55%	8.0	666	0.55	1.10	1.65	2.20
61%	8.5	741	0.61	1.23	1.84	2.45
68%	9.0	825	0.68	1.37	2.05	2.73
76%	9.5	919	0.76	1.52	2.28	3.04
85%	10.0	1024	0.85	1.70	2.54	3.39
100%	10.8	1208	1.00	2.00	3.00	4.00

Table 7: Optimal engine load over MCR for a diesel engine system, with auxiliary power when manoeuvring (grey rows)

			Nr of systems installed (running)			
Auxiliary power [kW]	433		1	2	3	4
optimal load point (MCR)	0.75	**Pb [kW]**	1208	604	403	302
Power demand [% mcr]	**Speed [kn]**	**power [kW]**	**index mcr**	**index mcr**	**index mcr**	**index mcr**
43%	5.0	525	0.43	**0.87**	1.30	**1.74**
46%	5.5	555	0.46	0.92	1.38	1.84
49%	6.0	592	0.49	0.98	**1.47**	1.96
53%	6.5	635	0.53	1.05	1.58	2.10
57%	7.0	685	0.57	1.13	1.70	**2.27**
61%	7.5	743	0.61	1.23	1.84	2.46
67%	8.0	809	0.67	1.34	2.01	2.68
80%	9.0	968	**0.80**	**1.60**	**2.40**	**3.21**
97%	10.0	1167	0.97	1.93	2.90	3.86
100%	10.2	1208	1.00	2.00	3.00	4.00

5 Mathematical models of modular systems

Within this paper the models will be explained on a general level, for a more detailed model description please read the thesis report. The model consists of four major sub systems as seen in figure 4. The power demand (blue block) and the efficiencies (green block) are identical for all the modular power box models. The red emission blocks depend on the selected fuel and engines, the yellow modular system represents the actual energy converter (engine/fuel cell) model.

[1] The definition of fatal failure is made together with DEKC, if the speed of the ship is less than 7 kn (harbour speed) the ship has to stop its voyage and is assumed to be a fatal failure.

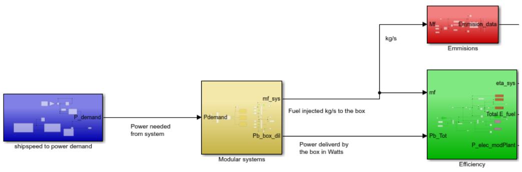

Figure 4: General structure of the model

5.1 Speed to power demand

In the first block, the data that is provided by the user trough excel will be compiled to a power demand for all the power boxes. The data from the Excel is a time speed table and tells the program which speed is required at a certain time. The incoming speed translates into the propeller power according to formula 2. This is applicable for low Froude numbers between 0.10 and 0.20, the Future Trader has a Froude number of 0.18 and therefore this formula can be used. The difference here is that instead of Pe and c1, c2 is used and gives a propeller power P_p, meaning that the propulsive efficiency is taken into account [14]. The calculated power is the required P_p and this is divided by the efficiencies as seen in formula 3 and table 8. This results in the power demand that needs to be delivered by the power box(es).

$$P_p = c_2 * v_s^3 \tag{2}$$

$$P_{boxout} = \frac{P_p}{\eta_{shaft} * \eta_{GB} * \eta_{EM} * \eta_{conv} * \eta_{trans}} \tag{3}$$

With:

η_{shaft}	0.98
$\eta_{gearbox}$	1 (no gearbox installed)
$\eta_{Electric-Engine}$	0.98
$\eta_{conversion}$	0.98
$\eta_{transportation}$	0.97

Table 8: Used efficiencies [14]

5.2 Modular system

Within the yellow block of figure 4 the required power for the ship can be generated by different modular systems. Those are: for MDO as a fuel an one engine IC engine or a DG setup with three IC engines, for hydrogen and ammonia a DG system with two FC systems.

For the single IC engines the Mossel model [19] is used and for the FC model a model from the DPO department is used, both are created at the TU Delft. The data used in the models is altered for the engine system of the Future Trader, since the models from the TU Delft are for a single engine and multiple power boxes are used on the Future Trader. Meaning that a power division needs to be done for the system. This is done using an if else block from SIMULINK. The total system power for the ship is divided by the total installed power to get a number (u1) between 0 and 3 for the MDO DG setup and two for the fuel cells. This number represents the MCR values of the energy converter (engine). A division is made based on the optimal running point of the selected energy converter. In table 9 the division for the DG MDO setup is shown, with an optimal running point of one engine at 0.8 MCR. For the FC system a similar division is done only over two systems and with a running point of 0.45.

Table 9: Functions corresponding to u(1) values per engine, within the power division block

	U(1) value	Function P_{dem}
eng 1	≤ 1	$u(1) * ENG.P_{nom} * \eta_{shaft}$
	≤ 1.8	$u(1) * ENG.P_{nom} * \eta_{shaft}/2$
	else	$u(1) * ENG.P_{nom} * \eta_{shaft}/3$
eng 2	≤ 1	$u(1) * 0$
	≤ 1.8	$u(1) * ENG.P_{nom} * \eta_{shaft}/2$
	else	$u(1) * ENG.P_{nom} * \eta_{shaft}/3$
eng 3	≤ 1	$u(1) * 0$
	≤ 1.8	$u(1) * 0$
	else	$u(1) * ENG.P_{nom} * \eta_{shaft}/3$

The powers from this division are sent to the individual modular systems in which a single FC or IC system is installed. This will be simulated and the fuel flow and power output of the system will be the outputs of the yellow block.

5.3 Efficiencies

In figure 4 within the green box all the efficiencies will be determined. The incoming data consists of the fuel flow in kg/s and the total power of the modular systems. The first value calculated in the efficiency block is the Specific Fuel Consumption (SFC) [g/kWh], this will be calculated the following equation 4 [20].

$$SFC = \frac{36000 * \dot{m_f}}{P_{electric-delivered}} \tag{4}$$

Besides the SFC, the total efficiency will also be calculated. This is done by multiplying the fuel flow with the LHV (Lower Heating Value), this results in the energy flow of the fuel in [J/s]. Then equation 5 is used resulting in the efficiency of each time step. The overall efficiency is calculated with equation 6.

$$\eta = \frac{P_b}{\dot{Q}_f} \tag{5}$$

$$\eta_{tot-Average} = \frac{\sum(box - eff - data)}{n_{simulations}} \tag{6}$$

Besides the efficiencies and the SFC the fuel flow itself will also be recorded in the form of stepped data in kg/s and the total in kg of used fuel during the simulated voyage. This data will then be used to calculate the effect on the range of the Future Trader.

5.4 Emissions

There are two types of emissions, engine related and fuel related emissions, the model is based on the procedure described in the book "Lecture Notes WB4408B Diesel Engines Volume 3 Combustion" chapter 13 [21]. The engine related emissions are based on the emissions simulated by the Mossel model [19]. To determine the emissions in the model it is assumed that the fuel composition is known in mass fractions. For MDO it is assumed that the composition is as follows X_C= 0.87 X_h= 0.12 X_S= 0.1 [21].

As an input the fuel flow from the engine is used and the stoichiometric air fuel ratio (σ) of the incoming air. σ air is calculated by following the next procedure: when complete combustion of the fuel is assumed, the amount of mol in the reactions is found in equation 7. The n is the amount of mol in a curtain fuel mass, see equation 10.

$$n_c^f \cdot C + n_c^f \cdot O_2 = n_c^f \cdot CO_2 \tag{7a}$$

$$n_H^f \cdot H + \frac{1}{4} n_H^f \cdot O_2 = \frac{1}{2} n_c^f \cdot HO_2 \tag{7b}$$

$$n_S^f \cdot S + n_S^f \cdot O_2 = n_S^f \cdot SO_2 \tag{7c}$$

$$n_{O2} = n_c^f + \frac{1}{4} n_H^f + n_S^f = \{\frac{X_C^f}{M_C} + \frac{1}{4} \cdot \frac{X_H^f}{M_H} + \frac{X_S^f}{M_S}\} \cdot m_f \tag{7d}$$

With the required amount of oxygen the stoichiometric air fuel ratio σ can be calculated using equation 8, with y_{o_2} the mol fraction of oxygen in air and M_A is the molecular mass of the air.

$$\sigma = \frac{M_a}{y_{O_2}} \cdot \{\frac{X_C^f}{M_C} + \frac{1}{4} \cdot \frac{X_H^f}{M_H} + \frac{X_S^f}{M_S}\} \tag{8}$$

This results in a σ_{da} of 14.30 and for humid air this is 14.14. Depending on the settings this number is multiplied with the fuel flow from the engine. For the λ of the engine a value of 2.5 is used [21]. Multiply this with the minimal air needed gives us the airflow that goes into the engine. The air fuel ratio is calculated according to formula 9.

$$AFR = \frac{\dot{m}_{air-in}}{\dot{m}_{fuel}} \tag{9}$$

The fuel and air flows are the inputs for the emission calculation. This is used in the orange block of figure 5. The fuel related emissions are CO2, SOx, H2O and N2, each will be calculated using the same procedure, this procedure is based on the fuel flow and assumes complete combustion. By using chemical formulas the emissions are calculated, the procedure is explained for CO2.

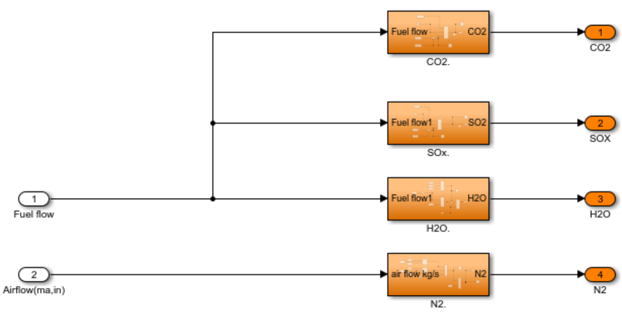

Figure 5: Emission sub system (fuel related part)

For CO2 there is started with the reaction equation when complete combustion is assumed (eq. 7a). It can be seen that the amount of mol carbon dioxide in the exhaust equals the amount of mol carbon within the fuel. This means that if the amount of mol in the fuel is known we can calculate the amount of CO2 in the exhaust. The amount of mol in the fuel can be calculated using equation 10 [21].

$$n_C^f = \frac{X_C^f}{M_C} \tag{10}$$

With the amount of mol carbon in a kg fuel known and knowing that this equals the produced CO2, the amount of CO2 can be calculated according to equation 11. This equation is modelled within Simulink and used to calculate the fuel related emissions of CO2. For the other fuel related emissions an equal procedures is followed, each in their own block as represented in figure 5.

$$\dot{m}_{CO_2} = M_{CO_2} * n_C^f * \dot{m}_f \tag{11}$$

For the engine related emissions this procedure can not be followed, since those emissions can be related to the engine process. The emissions can be different for every engine and are not constant for every power output of the engine. Therefore this data needs to be measured data gathered in real life testing. Since no real data is known for the engines within this research a set of measured engine characteristic from the TU Delft is loaded into the model [19]. Now that all the parts of the model are explained the voyages as found in table 1 are simulated one at a time, the results are gathered and they are presented next.

6 Results

6.1 Efficiencies of modular power plant systems

For the range there will be looked into the SFC and efficiencies of every system, this is calculated using formula 4 and 5. The formulas in this chapter are from the book Design of Propulsion and Electric Power Generation Systems [20], unless mentioned otherwise. The overall efficiency will be calculated using formula 6. Besides this the amount of fuel needed for the voyage is shown as the amount of storage units needed to store this fuel. Both can be found in table 10. As seen in table 10 for hydrogen and ammonia four cells are filled red. This is because those voyages can not be completed with the fuel stored in the four containers aboard. This voyage can be completed with both the MDO setups.

Table 10: Fuel needed

	fuel	MDO				Hydrogen		Ammonia	
	Nr engines	one		three		two		two	
Departure port	Arival port feul needed	[kg]	TEU	[kg]	TEU	[kg]	TEU	[kg]	TEU
RTD	ANT	2163	0.09	2351	0.10	575.3	0.33	3755	0.26
RTD	GDA	1.345E+04	0.57	1.469E+04	0.63	3572	2.04	2.325E+04	1.59
RTD	HAM	6181	0.26	6742	0.29	1646	0.94	1.072E+04	0.73
RTD	MAR	4.216E+04	1.79	4.605E+04	1.96	1.123E+04	6.42	7.31E+04	5.00

The efficiencies and SFC values of all the different systems are found in table 11. Those values are the average values across the whole trip.

Table 11: Average system efficiencies and SFC values

	fuel	MDO				Hydrogen		Ammonia	
	Nr engines	one		three		two		two	
Departure port	Arival port	η_{sys}	SFC	η_{sys}	SFC	η_{sys}	SFC	η_{sys}	SFC
RTD	ANT	41.3	205.8	37.6	222.6	43.2	58.65	52.4	369.8
RTD	GDA	41.2	204.4	37.5	223.0	43.6	58.22	53.1	365.5
RTD	HAM	41.2	204.8	37.6	223.0	43.2	58.63	52.6	369.0
RTD	MAR	41.3	204.3	37.5	223.1	43.2	58.64	52.6	368.7

6.2 Emissions modular power plant systems

For the emissions there are three values that will be used for the comparison, those are the PER in kg and mile and SPE [20], [21]. PER is the pollutant emission ratio and is the amount of polluting emissions that are emitted per kg fuel (see formula 12). A PER with respect to distance in nautical mile will also be calculated (equation 13). SPE stands for specific pollutant emission and is in g/kWh (see formula 14). The average emissions are as shown in table 12.

$$PER_{mass} = \frac{\dot{m_{pe}}}{\dot{m_f}} \tag{12}$$

$$PER_{mile} = \frac{m_f}{nm_{trip}} \tag{13}$$

$$SPE = \frac{\dot{m_{pe}}}{P_B} = PER * sfc \tag{14}$$

Table 12: Average emission values PER modular power system PER

fuel	MDO						Hydrogen			Ammonia		
Nr engines	one			three			two			two		
Emissions	PER	kg /nm	spe	PER	kg /nm	spe	PER	kg /nm	spe	PER	kg /nm	spe
CO_2	3.19	64.60	652.30	3.19	70.44	711.40	0.00	0.00	0.00	0.00	0.00	0.00
SO_X	0.02	0.41	4.09	0.02	0.44	4.46	0.00	0.00	0.00	0.00	0.00	0.00
H_2O	1.46	29.6	299	1.46	32.3	326	9.96	53.6	1833	1.72	60.4	634
N_2	26.67	539.9	5454	26.67	588.9	5947	50.31	271.0	2947	7.401	259.8	2727
NO_X	0.064	1.29	13.0	0.052	1.1	12	0.000	0.000	0.000	0.000	0.000	0.000
CO_e	0.002	0.047	0.47	0.002	0.049	0.49	0.000	0.000	0.000	0.000	0.000	0.000
PM	0.001	0.017	0.18	0.001	0.020	0.20	0.000	0.000	0.000	0.000	0.000	0.000
HC	0.002	0.050	0.51	0.002	0.049	0.49	0.000	0.000	0.000	0.000	0.000	0.000

7 Overall conclusion

Now that the effects of a DG MDO system, hydrogen and ammonia fuel cell systems are known. The research question can be answered, this was:
What are the effects on system performance of the power plant and ship operational capabilities when using different power plant concepts and different fuels in the Future Trader concept ship? It can be concluded that a DG setup will reduce the ships overall performance in comparison to the single engine diesel electric system (base line). The fuel cost and consumption will be 109% of that of the base line. Fuel related emission will rise, however the

engine related emissions, NOx, COe and HC will be lower if we look into the per_{mass}. When looking at the per_{mile} especially the NOx is reduced even with the higher fuel consumption. The gain in COe reduction will be lost due to higher fuel consummation. The HC will be higher but will still give a slight reduction. So the DG systems performance with respect to emissions will be better when looking at the emissions per kg fuel burned, however due to the higher fuel consumption this improvement is lost for almost all emissions except for NOx. When reviewing the fuel cell systems with respect to the base line system found is that the ammonia fuel cell system has zero emissions, still offers a sufficient range and increases the fuel costs (370% of MDO costs). However this increase is lower than for hydrogen, for hydrogen the cost are 1076% compared to the MDO costs. Hydrogen will reduce harmful emissions to zero but the reduction in range is more severe than for ammonia. Overall ammonia seems most promising of the non hydrocarbon fuels. The DG system is also useful as long as emission regulation remain unchanged. The MDO DG system can be loaded for large distance voyages and hydrogen can be loaded for short voyages if desired.

To summarise, using a modular power plant for the Future Trader will always bring an increase in costs but with the ammonia fuel cell system the ship has zero emissions. The volume needed for fuel is 2.8 times that of a traditional diesel electric setup. Ammonia still gives a suitable range, so most voyages can be completed. However for longer voyages (e.g. Rotterdam Marseilles) a MDO DG system should be installed on the aft of the Future Trader, since neither of the FC systems could complete those voyages.

8 Discussion

The conclusion of this study is similar to conclusions that can be found about non-modular DG power plants on ships. This suggest that using a modular power plant as used in this study will perform similar to the same non-modular systems. If this is true, this means that choosing a modular platform will give the flexibility to switch between systems and fuels with a minimal loss in performance compared to ships with the same platform installed in the heart of the ship. However, this claim needs to be researched in more depth. When this is true this means that each ship equipped with a DG system could adopt the concept of modularity for its power plant and that gives the same flexibility as that of the Future Trader. In this way it can keep up with regulations and the uncertainty of which fuel will be used in the future.

As seen from the results, the setup with one MDO engine outperforms the three engine setup. However, it is found that at lower MCR this advantage is lost. A combination of a small and large engine could be a more optimal solution. This is the father-son layout. This layout is left out of scope for this thesis because it was needed to reduce the amount of possible engine layouts. However considering the results it could be possible that combining engines with different power ratings can result in a more optimal system. The effects of such a father son layout could be interesting and can be researched using the generic models that were applied in this study. It is therefore recommended to examine the father-son power plant in future research.

A hybrid electric power plant solution could also be an option, in this thesis only one system and fuel type was used at a time. However, there are ships with different power supply units aboard, due to the flexibility of the Future Trader it is possible to install hybrid power plants in an easy way. In this study the focus was on the effect on the ships performance of different types of power boxes, this resulted in the knowledge on the effects of individual systems running on a specific fuel. The next step could be to research the effects when combing systems. If hybrid solutions are used the Future Trader could for example make a voyage from Marseilles to a fjord in Norway. This can then be done on MDO since this has a sufficient range and the last part of the voyage within the fjord can be done on hydrogen since in some fjords emissions should be 0 in 2026 [22].

The effects of dynamic loads and handling those are not taken into account. In literature [23] it was found that those dynamic load changes can have an effect on the systems stability and ship safety. Power electronics and capacitors which can handle dynamic loads are looked into in the literature study but are left out of scope due to the limited impact on the selected engine performance and the overall ships operational performance. However if you look at a smaller time frame (e.g. minutes) the effects of power electronics can influence and help to solve the challenges of dynamic loading, those in combination with the modular power plant design can be an interesting topic for a future research.

Looking at the models there are areas which could be refined. The current model has one MCR point at which extra engines are switched on/off. This results in an even distribution of power along all engines. An optimisation for switching an engine on and off at a certain MCR request can be added. In this way engines can be run at different MCRs which could result in a more optimal system and therefore have an effect on the performance of the overall system.

Within the model the power asked from a specific power box can change rapidly. This due to the instant switching in number of engines running in the power distribution block, this is seen from spikes in the total power graphs around the time an engine is switched on or off. The effects on the results however are rather small because the total simulation time is large in comparison to those small time periods. However, if the engines were turned on earlier and extra time is given to let the engines adjust to a certain set point it is expected is that this results in smaller spikes. For the end result the difference would be small. However, when the models will be used for simulations to get results for smaller time ranges this needs to be adjust in the model.

Lastly it needs to be mentioned that the found engine related emission values need to be handled with care. Since the models used for the MDO system are mathematical models that are designed to match measured data. This measured data is not known for a number of the used power plant components. So the found values are found using other engine data. The Mossel model will also not model the cylinder process like cylinder temperature, pressure, scavenging or ignition timing. All of those are determined within the engine design and can have effects on the engine related emissions. The found values in this thesis therefore have a large error margin (e.g. an educated guess is that, for NOx (6.4e-3 kg/kg) in the single MDO engine the error in the percentages could be in the order of the high 10s and for the HC (2.5e-3 kg/kg) in the high 20s). For a better result a more detailed model and more information about the engine design is needed, or the selected engines need to be measured in real life and the values found need to be used in the Mossel model.

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