AALTO UNIVERSITY
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Development and Utilization of Multi-Domain Energy Flow Simulator for Bulk Carrier Energy Efficiency Improvement

Master's Thesis submitted in partial fulfilment of the requirements for the degree of Master of Science in Technology

Espoo 26.6.2014

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AALTO UNIVERSITY SCHOOL OF ENGINEERING PL 11000, 00076 AALTO http://www.aalto.fi	ABSTRACT OF THE MASTER'S THESIS

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Title of the thesis: Development and Utilization of Multi-Domain Energy Flow Simulator for Bulk Carrier Energy Efficiency Improvement

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Due to more stringent legislation regarding ship emissions and higher fuel prices, ships owners and naval architects have lately been focusing more on energy efficiency. Traditionally, ship design process has been concentrating on optimizing the ship in one design point, where the ship is the most efficient in. However, ships are not always operating near design points, and thus, the optimization to a single design point does not lead to holistic optimization of ship energy efficiency. Therefore, ship designers require a tool that takes into account varying operation conditions and ship parameters.

This thesis introduces a simulation tool for handysize bulk carrier for utilization in concept design phase. The tool is based on multi-domain energy flow method. This tool covers all the main machinery components such as main engine, diesel generators, exhaust gas and oil fired-boilers and cooling circuits. The dynamic results acquired from the tool include fuel and energy consumption for main- and auxiliary engines, steam energy produced from the exhaust gas and oil-fired boilers, sea water pump mass flow and evaporator energy consumption.

Simulation tool was applied to two different case studies. First, a steam system was modified by lowering steam pressure produced by the exhaust gas boiler. Secondly, cooling circuit components were optimized for obtaining lower total fuel consumption. In the first case, the energy recovered from the exhaust gas was higher and thus oil fired boiler was less utilized, as was expected. This also leads to lower fuel consumption and maintenance costs. In the second case, the results were also as expected. The variable speed drive sea water pump decreases the total fuel consumption and maintenance costs of auxiliary engines due to less electrical energy utilized.

The validation of results was excluded from the thesis, and thus, the results are just guide values rather than absolute truth. Therefore, the simulation tool is suitable for quick analysis to be utilized in concept phase and is usable by any designer, without an extensive background of ship machinery.

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Tiukentuvat säädökset laivojen päästöjen osalta ja polttoainehintojen noususta on ohjannut varustamot ja laivasuunnittelijat keskittymään lisää energiatehokkuuteen. Perinteisesti, laivan suunnitteluprosessi on fokusoitunut optimoimaan laivan yhteen suunnittelupisteeseen, jossa laiva on hyötysuhteeltaan parhaimmillaan. Laivat eivät aina kuitenkaan operoi lähellä suunnittelupistettä, ja täten laivan optimointi suunnittelupisteen ympärille ei ole kokonaisvaltaisesti tehokkainta. Näin on tarve kehittää laivan suunnittelijoille työkalu, joka ottaa huomioon vaihtelevat operointi olosuhteet ja laivan parametrit.

Tässä työssä esitellään handy-kokoluokan irtotavara-aluksen simulointityökalu, jota käytetään konseptivaiheessa. Työkalu käyttää monifysikaalista energiavirtaus menetelmää. Työkalu käsittää kaikki pääkomponentit kuten pääkoneen, diesel-generaattorit, lämmöntalteenoton- ja öljypoltinkattilat sekä jäähdytyspiirin. Työkalulla saadaan dynaamisia tuloksia kuten polttoaine- ja energiankulutuksia pää- sekä apumoottoreille, höyryenergian tuotto lämmöntalteenotto- ja öljypoltinkattilasta, merivesipumpun massavirta sekä makeanvedenkehittimen energian kulutus.

Simulointityökalua sovellettiin kahdessa eri tapaustutkimuksessa. Ensimmäisessä tapauksessa höyrysysteemi modifioitiin alentamalla lämmöntalteenottokattilan tuottamaa höyrynpainetta. Toisessa tapauksessa jäähdytyspiirin komponentit optimoitiin pienemmälle polttoaineenkulutukselle. Ensimmäisen tapauksen tulos oli odotettavissa eli lämmöntalteenottokattilan tuottama höyryenergia kasvoi ja vastaavasti öljypoltinkattilaa käytettiin vähemmän. Tämä johti pienempään polttoaineen kulutukseen ja pienempiin huoltokustannuksiin. Myös toisessa tapauksessa tulos oli odotettavissa. Taajuusmuuttajaan kytketty merivesipumppu alentaa kokonaispolttoainekustannuksia ja apumoottoreiden huoltokustannuksia pienemmän sähkönkulutuksen takia.

Tulosten varmentaminen rajattiin työn ulkopuolelle, joten ne ovat vain suuntaa-antavia. Tästä syystä simulointityökalu on sopiva nopeaan analyysiin, jota käytettäisiin konseptivaiheessa ja olisi kenen tahansa suunnittelijan käytettävissä, riippumatta kyseisen suunnittelijan taustasta laivan koneistoissa.

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Helsinki 26.6.2014

Su Len Quach

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Appendices

Symbols

$\dot{Q}$	$\left[\frac{J}{s}\right]$	heat transfer rate
$\dot{q}$	$\left[\frac{J}{s}\right]$	heat transfer rate
$\dot{m}$	$\left[\frac{kg}{s}\right]$	mass flow
C_p	$\left[\frac{J}{kg*K}\right]$	specific heat capacity
T	$[K]$	temperature
P	$[W]$	power
Q	$\left[\frac{kg}{s}\right]$	mass flow
p	$[Pa]$	pressure

Lower indexes

$\mathrm{HOT_{In}}$	Inlet of hot side of the cooler
$\mathrm{HOT_{Out}}$	Outlet of the hot side of the cooler
$\mathrm{COOL_{In}}$	Inlet of the cold side of the cooler
$\mathrm{COOL_{Out}}$	Outlet of the cold side of the cooler

Abbreviations

DMO	Diesel Marine Oil
EGB	Exhaust Gas Boiler
EPA	Environmental Protection Agency
EMS	Energy Management System
FOC	Fuel Oil Consumption
HVAC	Heating, Ventilation, Air Conditioning
HFO	Heavy Fuel Oil
HT	High Temperature
KPI	Key Performance Indicator
LHV	Lower Heating Value
LT	Low Temperature
MCR	Maximum Continuous Rating
NCR	Nominal Continuous Rating
OFB	Oil Fired Boiler
ORC	Organic Rankine Cycle
PID	Proportional-Integral-Derivative
SFOC	Specific Fuel Oil Consumption
SW	Sea Water
VFD	Variable Frequency Drive
VSD	Variable Speed Drive
WHR	Waste Heat Recovery
WHRS	Waste Heat Recovery System

1. Introduction

1.1. Background

Ship emissions have been widely discussed in recent years, which is due to stricter regulations issued by the IMO (International Maritime Organization). These regulations include Nitride (NO_x), Sulphur (SO_x), and new Carbon (CO_2) emission-related measures EEDI (Energy Efficiency Design Index) and EEOI (Energy Efficiency Operational Indicator) (IMO, 2013a, 2013b). The EEDI is a mandatory computational value applied to all new ships or ships which have undergone a major conversion of 400 gross tonnage and above. Despite its name, gross tonnage is a computational unitless index related to ship volume. (International Convention on Tonnage Measurement of Ships, 1969) The EEDI requires “a minimum energy efficiency level per capacity mile for different ship type and size segments” and thus promotes the usage of energy-efficient equipment and engines. The EEOI is a voluntary monitoring tool, which enables operators to measure the fuel efficiency for each voyage, thus making the estimation of the effects of possible improvements easier. (IMO MEPC.1/Circ.684 2009) IMO has also introduced SEEMP (Ship Energy Efficiency Management Plan), which is an operational measure and strives for better energy efficiency by improving ship management in terms of cost efficiency.

Additionally, fuel prices have steadily increased in the past decade and this trend will probably continue due to an increasing demand. Therefore, the shipping business will face two challenges: environmental and economic. Both of these challenges can be overcome by one solution, decreasing fuel consumption. However, decreasing fuel consumption is not possible with just one particular solution, so one has to think about the ship machinery as a holistic system with different subsystems. For example, optimizing only the main engines does not necessarily mean lower total fuel consumption of the vessel. This is due to lower exhaust gas temperature, which lowers the steam production of exhaust gas boilers and, thus, extra steam production is needed from the oil fired boilers.

Even as an efficient internal combustion engine, less than 50 % of the fuel energy can be utilized to propulsion power as can be seen in Figure 1. The rest of the energy is divided mainly into the cooling water system and the exhaust gas system. Various waste heat recovery methods have already been developed and used, including exhaust gas boilers and using HT (High Temperature) cooling water to produce fresh water using evaporators. More efficient engines produce less exhaust gas energy, thus making the steam production demand from the boilers higher, as mentioned earlier. However, operational efficiency of different processes is not fully understood due to their complexity. These complexities need more research before a comprehensive system can be modelled and designed.

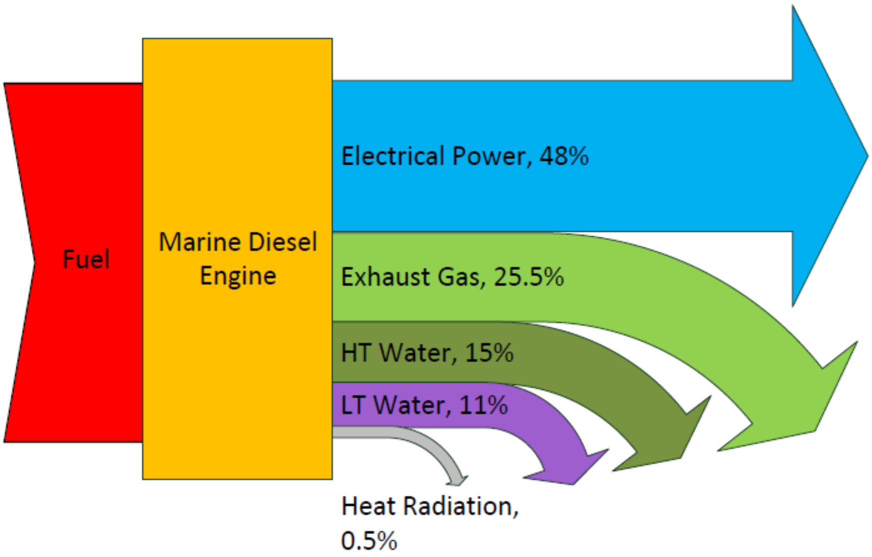


Figure 1. Fuel energy distribution (Zou et al., 2013)

Another perspective to this thesis is the current design process. The choices made in the early design stage are very influential, but the designer has very little information to base these choices. The freedom to change the primary variables of the design decreases as a design progresses through phases (Figure 2). On the other hand, the designer's information increases as a design progresses through phases. Some estimation about the weight and spaces are required to allocate the main components such as main movers, electric production and operational rooms. This is very often done according to designer's experience or earlier designs. (Annevald *et al.*, 2014), (Gaspar *et al.*, 2014)

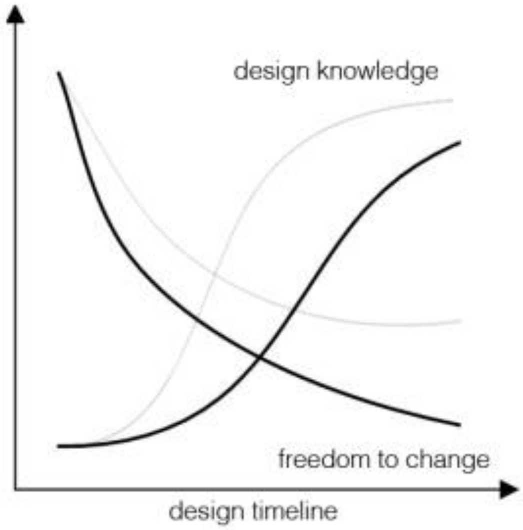


Figure 2. Design process (Gaspar et al., 2014)

1.2. Purpose of the study

Designing more efficient machinery including waste heat recovery systems in real conditions bring more challenges due to the varying operational conditions of the ship and occasional complicated operation profiles. Varying operation conditions include different sea states and changing surrounding temperature. These factors have an impact on the operation profiles that in turn affect the necessary energy demand. Fluctuating energy demand causes components such as pumps and engines to run on partial loads. Optimization for partial load and by-passing some energy flows without heat recovery may end up with higher total efficiency than trying to always recover energy from rare full-load conditions. This should be taken into account in the design process.

Component manufacturers can provide data about the part load behaviour of their components. However, the use of this data is quite limited with the current tools for practical ship design due to invariably changing operational conditions. These tools include, for example, the energy balance tool, where all the machinery specification and operation profile are input and fuel oil consumption is acquired as output. More detailed results, such as fuel oil consumption in timescale requires new tools, and simulation is identified as a potential option to improve ship design process.

This study aims to develop a simulation tool that includes different machinery components, *i.e.*, main engines; auxiliary engines with generators, different cooling water systems, exhaust gas and oil fired-boilers. These components are then combined into a holistic machinery system, which can be used to calculate different energy flows such as fuel oil consumption, auxiliary engine power take out and exhaust gas waste heat recovery. Unlike energy balance tool that calculates the results as a cumulative total, the simulation tool calculates the results dynamically in real time. This enables to closely analyse the results in each time step. The simulation tool utilizes the data straight from the component manufacturers such as exhaust gas mass flow, HT-water temperature, engine specific fuel oil consumption curve and operation data that includes speed-power curve, steam and electric demand. The simulation tool can also model complicated operation profiles and many different simultaneous effects of processes including main engine, thus improving the energy efficiency of the system.

In addition, the applicability and potential advantages of the simulation tool is illustrated via two case studies: the modification of steam system, and the optimization of cooling circuit components. These cases present just a fraction of the potential possibilities of this simulation tool.

Since the design choices in the early phase of design have higher influence, it seems suitable to utilize this simulation tool in the early stages of design. A further objective is to develop a simulation tool, which is easy to use in terms of designer’s perspective and takes into account its usability in practice.

1.3. Restrictions and targets

This thesis is limited to developing and testing the simulation tool with the intention of maintaining the maximal simplicity of the component, thus giving more limitations to the thesis. This is done by modelling the components with as little initial parameters as possible.

The simulation tool developed in this thesis can be used for any ship type provided that the components needed are constructed for the ships in question. This thesis is focused on a case study of bulk carrier machinery simulation, since *Deltamarin* has a *B.Delta*-bulk carrier product family. Its machinery is quite simple, and brings more restrictions to the thesis.

2. Present practice of simulations in marine technology

2.1. History of simulations

Computer simulations have been done as early as mid-1940's since the construction of the first computers used for specific purposes and the introduction of Monte Carlo method. Simulations for different technical fields have been utilized already for decades. Computer simulation of building energy use was developed as a tool for analysing buildings from 1970's (Thumann *et al.*, 2013).

2.2. Machinery related simulations in marine technology

Simulations in the field of marine technology ranges all the way from simulation of marine air-condition (Yan et al., 2011) to simulation of marine natural recirculation drum-boiler (Hong *et al.*, 2011). More machinery related simulations in the field of marine technology include, for example, design platform for marine electric propulsion system by Chen *et al.* (2012). They present a designed platform, which aims to characteristic analysis of plants and systems, and intelligent control strategy development of automation and operation.

2.3. Energy flow simulations

2.3.1. Energy flow simulation in vehicles

Tuncay *et al.* (2007) introduces energy flow simulation in hybrid electric vehicles in 2007. This study also adopts energy conservation and energy balance method, which was mentioned earlier in introduction. With this method, the performance of a hybrid electrical vehicle was possible to model by defining energy producing, energy conserving and energy consuming elements, and also investigations of energy flows between these elements were made. This model was modelled using Matlab/Simulink environment using the domain library of Simulink.

2.3.2. Energy flow simulation in ships

Lately, there have been some energy flow simulations in marine engineering. Nagel (2014) presents the integration of energy saving technologies in the early design stage using advanced simulation models to be developed for the energy grid of the ship. This energy grid consists of energy producers, energy converters and energy consumers. An example of an energy grid is presented in Figure 3.Unlike in vehicles, which have batteries (Tuncay, 2007), Nagel does not present an energy conserving elements for ships. The simulation results of the model described by Nagel include mainly environmental assessments of KPIs (Key Performance Indicators) such as Global Warming Potential, Acidification Potential, and Eutrophication Potential.

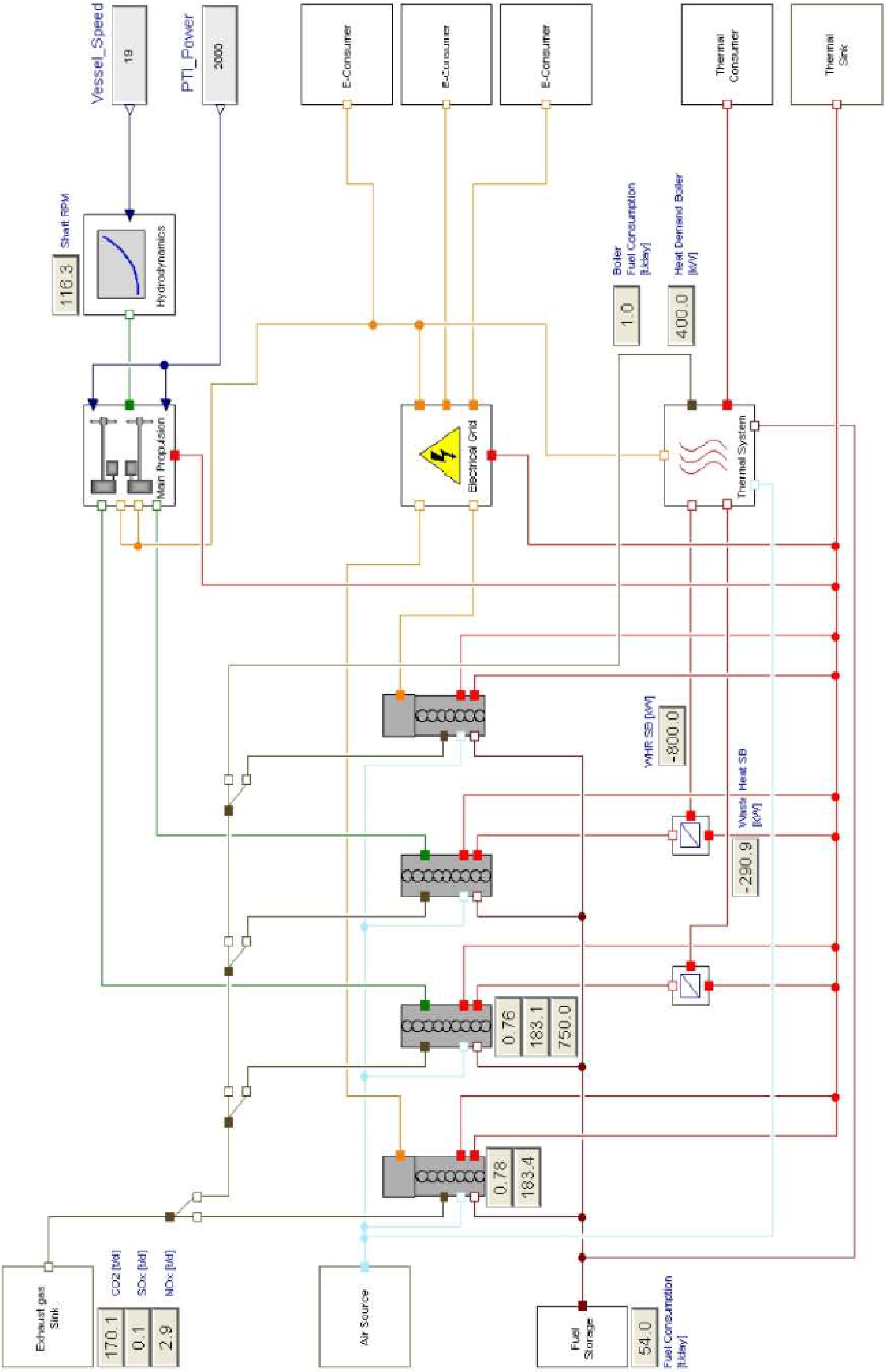


Figure 3. Example of an energy grid for I/O definition (Nagel, 2014)

Marty *et al.* (2012) presents a ship modelling platform that simulates the different energy flows and energy systems on board in the time domain. This simulator takes into account interactions between the various energy producers and consumers such as diesel generators, waste heat recovery boilers, oil-fired boilers, electrical motors, HVAC (Heating, Ventilation, Air Conditioning) systems, distillers and various electricity, steam and heat consumers thus making it a holistic system. An example of a cruise vessel model is presented in Figure 4. The interactions amongst the energy vectors in this example are correctly described such as chemical energy from the fuel, mechanical energy for the propeller shaft power, electricity and heat for steam, cooling water and exhaust gases.

The model utilizes the operational data in time-domain as input such as ship speed, instantaneous fresh water consumption, fuel consumed in boilers and diesel engines, navigation mode, sea water temperature and ambient temperature. The results in turn include fuel mass flow and total fuel consumption, CO_2-, NO_x-, SO_x-mass flow and emission amount, and water level in fresh water tanks.

The simulation model can also be utilized as a verification tool. This is done by using measured values for the operational profile parameters, and comparing the calculated results with the corresponding sea data. The sea data collected in order to perform a verification exercise includes ship speed, wind speed draft, boiler and diesel engine fuel consumption, electrical power consumption of various devices, thermal power consumption, temperatures from ambient air, sea water, cooling loop, etc.

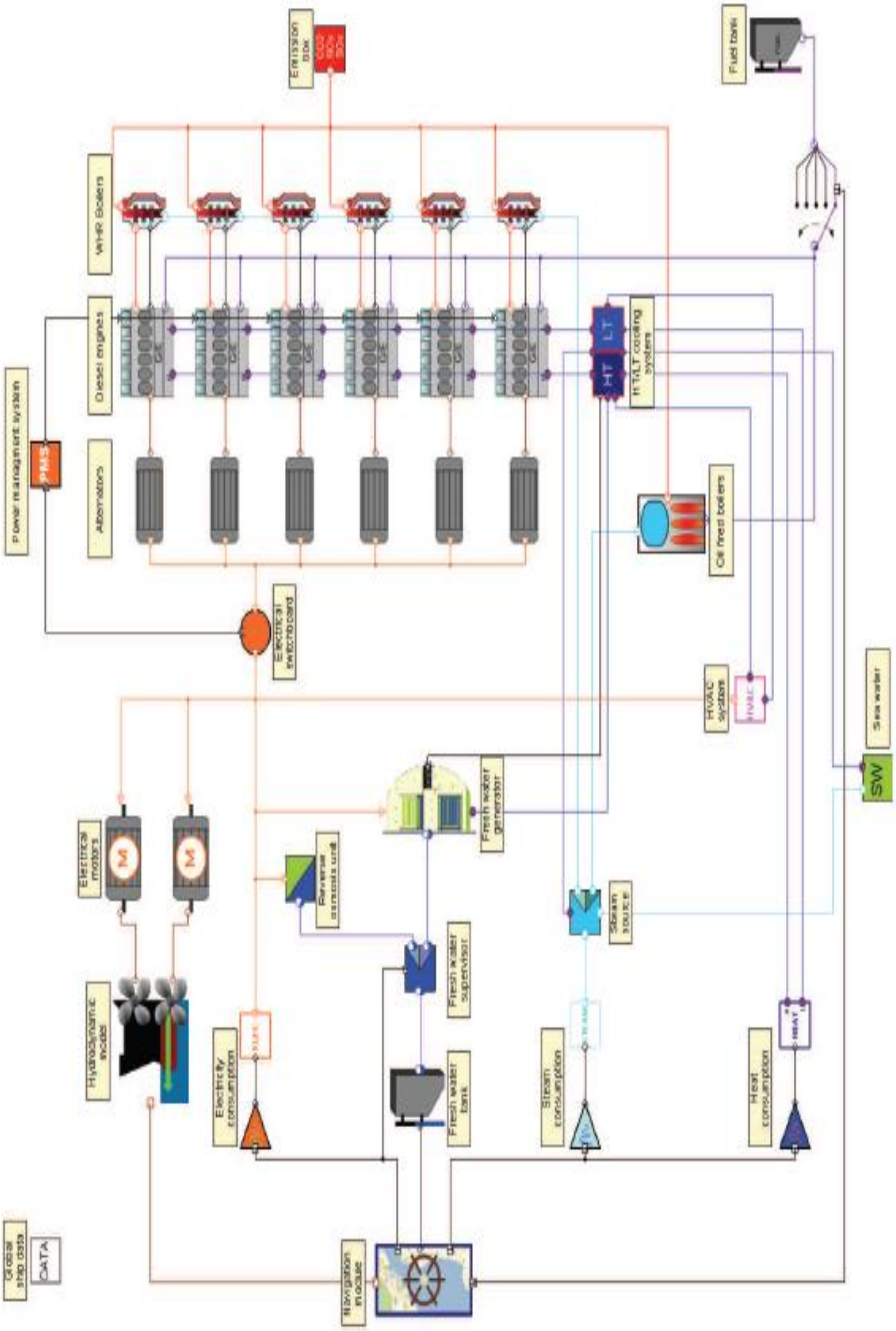


Figure 4. Modelled cruise vessel (Marty et al., 2012)

Zou *et al.* (2013) presents a simulator (Figure 5) that models ship machinery energy flows to fully understand the dynamic energy distribution of the marine energy systems. Since energy in marine systems is physically in different domains, multi-domain simulation is utilized. The energy processes are described as multi-domain energy flow as a function of time. The energy is modelled in five physical domains that include mechanical, thermal, electrical, thermal fluid and steam domains.

The simulator is also modelled on a system-level. All the main energy processes are modelled as subsystems at a general and system level, and are built as simple, but feasible as possible to facilitate the simulation interactions among different main subsystems.

The input for this simulator and its validation is acquired from the selected case ship. The inputs include parameters from the automation system of the ship that include diesel generator power, exhaust gas temperature and mass flow, fuel flow of engines, etc. The results of the simulator are, for example, energy produced from the exhaust gas boilers, fuel oil consumption of engines and boilers, heat dissipation to cooling water, temperatures for different points of cooling circuit, etc.

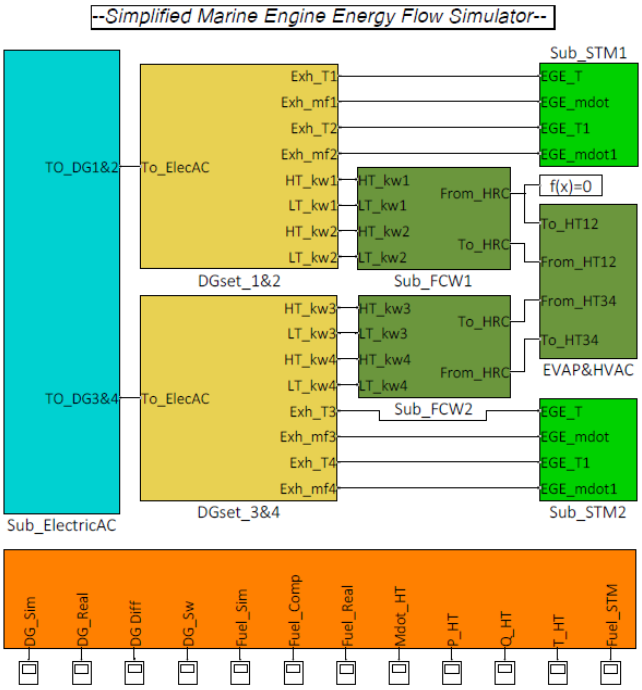


Figure 5. An example of simplified marine engine energy flow simulator (Zou et al., 2013)

3. Energy efficiency and energy saving technologies in marine industry

3.1. Energy efficiency in marine industry

Ship energy efficiency has recently drawn significant attention from research institutes and marine industry. ABB (2012a) claims that energy efficiency is today the top agenda of the marine community. This is due to high level of fuel costs that reflect to rising operating costs. Another factor is related to the increased public awareness of pollution and environmental emissions that lead to political decisions of global or local rules and regulations.

Some energy-related studies focus on energy conservation, others address energy efficiency. While energy conservation aims at decreasing total energy consumption by reducing the demanded output, energy efficiency aims to utilize less energy with the same amount of demanded output. (Croucher, 2011) Energy conservation and energy efficiency should be considered simultaneously as improvement in energy efficiency may lead to increased ship speed instead of reduced fuel consumption. In other words, only energy conservation has the effect of lowering total fuel consumption on the contrary to energy efficiency, which may have the effect of increasing total fuel consumption. This is called “rebound effect” in various sectors. (Jafarzadeh, 2014)

However, the industry have been mixing these two terms and using the term energy efficiency in fuel saving technologies. An example of this is a WHR-unit (Waste-Heat Recovery) by MAN Diesel & Turbo, which utilizes waste heat for electricity production. This “facilitates improved energy efficiency” and reduces the amount of fossil fuels consumed during operation by 5-10%. (MAN Diesel & Turbo, 2014) To avoid any confusion, these terms are used interchangeably in this thesis.

One important concept in ship design is the design point, a combination of the main variables, around which the vessel is designed and optimized. These variables include, for example, draft, speed, consumption and many more, depending on the ship type and operational profile. In general, the vessel is the most efficient in its design point. However, this single design point optimization is a trade-off with the range optimization, which is presented in Figure 6. Especially with the bulk carrier, the speed varies considerable with different drafts according to different cargo situations (ballast, design, and full) and thus the design point is rarely the operation point. Therefore, the energy efficiency must be viewed from a much broader perspective according to the vessels operation profile. (ABB, 2013)

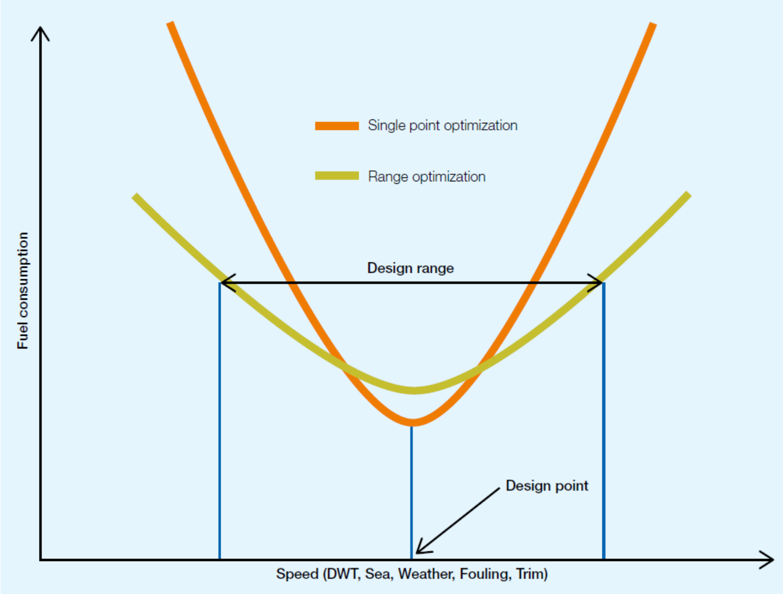


Figure 6. Trade-off between single point and range optimization (ABB, 2013)

3.2. Different methods for saving energy

This chapter introduces some methods for acquiring better energy efficiency. Some of these solutions can be retrofitted and some can only be installed on a new-building.

3.2.1. Variable frequency drive for cooling systems

Although the ship is required to operate in its maximum design condition, this rarely happens in every-day situations. The engines operate rarely on 100% load and seawater temperature very seldom reaches the design value. However, the ship has been design to maintain fully working system with the maximum conditions, which is redundant part of the time.

According to Räsänen and Schreiber (2012) using Variable Frequency Drives (VFD) can cut the energy consumption for pump and fan applications by as much as 60%. Electric motors could be fitted with VFD for pumps on cooling systems to operate them more efficiently on partial loads during slower sailing speeds or lower sea water temperatures. The electric power consumption of a pump is related to the pump volumetric flow according to affinity law. Branan (2005) explains the affinity laws:

1. Capacity varies directly with impeller diameter and speed.
2. Pressure varies directly with the square of impeller diameter and speed.
3. Power varies directly with the cube of impeller diameter and speed.

For example, a reduction in the pump speed of 10% will save 27% of the consumed power. Since sea water pump is the largest pump in cooling circuit, it would be natural to equip this pump with VFD.

3.2.2. Improved fuel efficiency with waste heat recovery system

A waste heat recovery system (WHRS) is any system that recovers waste heat energy for utilization that would otherwise be lost to atmosphere or sea water. As mentioned earlier, the mechanical efficiency of the main engine can be close to 50%. The rest of the energy contained in the fuel is not converted to shaft power, but is lost, mainly as heat in exhaust gases and cooling water and friction. (ABB, 2013) The Sankey-diagram in Figure 1 in chapter 1.1 explains further how the energy in the fuel is divided among consumers.

WHRS applications may include exhaust gas boiler (EGB), exhaust gas power turbine or WHR with Organic Rankine Cycle (ORC) system from the cooling water. The exhaust gas boiler is just a quite common in all vessels that operate in the higher range of engine loading. More detailed information about EGB is presented in chapter 4.6.3.

Energy can also be mechanically recovered from the exhaust gas flow of the main engine, where part of the exhaust gas flow is diverted into a power turbine, which is connected to a generator. This generator then produces electricity for the ship machinery system. (ABB, 2013)

An efficient way to take benefit from the main engine cooling water waste heat is through ORCs. (Peris *et al.* 2013) The ORC (Organic Rankine Cycle) is based on the same thermodynamic cycle as the classical traditional Rankine cycle, with the exception of the working fluid. Organic oils with a lower boiling temperature than water are usually the working fluid used in the ORC. This enables operation at low temperatures (70–300°C). (Speight 2011 p. 464)

The Rankine cycle is the basis of all vapour power cycles. The working fluid in Rankine cycle is converted from liquid to vapour in one process and condensed from vapour to liquid in another. Figure 7 shows the basic components of the Rankine cycle. These include a boiler or an evaporator to produce steam, turbine to produce the work, condenser to cool the fluid and pump to circulate the fluid. According to Thumann and Mehta (2013) this is a standard boiler / steam turbine arrangement found in many power plants throughout the world.

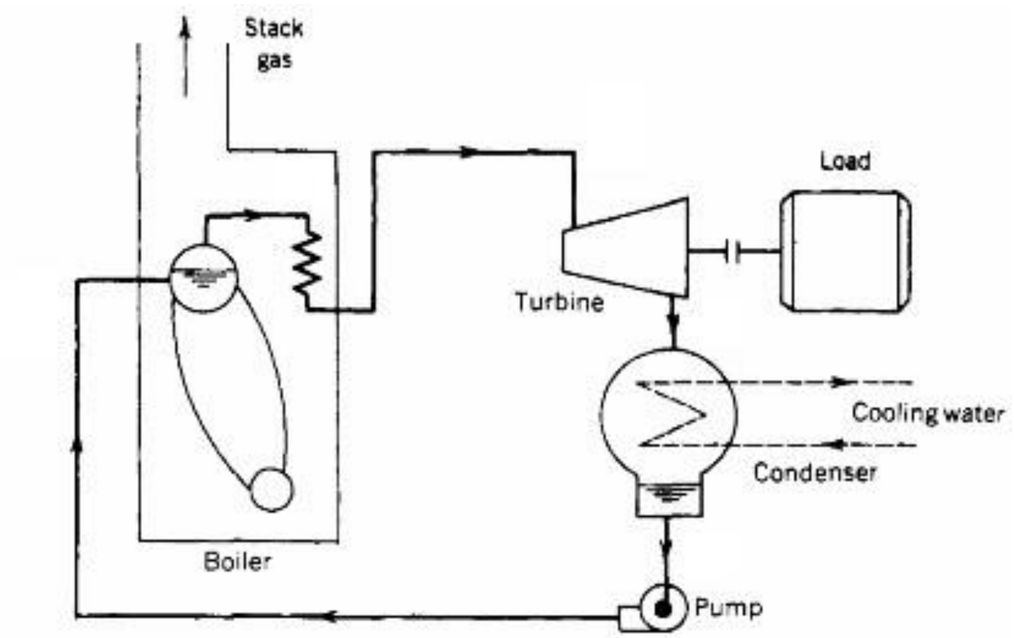


Figure 7. Basic Rankine power cycle (Tapley, 1990)

3.2.3. Energy management systems

Energy management systems (EMS) do not directly improve the energy efficiency, but the aim of this system is to monitor, control and optimize the performance of the vessel. EMS may include trim optimization, hull performance tracking, and voyage planning and weather optimization.

Trim optimization is based on an algorithm that takes into account vessel's displacement, speed and operating conditions. The model uses data collected from several sources on board, such as an integrated automation system, an integrated navigation system and attitude sensors that measure ship movements. This can account to 1 to 5 % of a vessel's fuel consumption depending on vessel type. (Eniram, 2012) (ABB, 2012b)

Voyage planning provides the officers with the most optimal route and trim, speed profile, and engine configuration for any given voyage. It utilizes an accurate 3D ship simulation model in calculations in combination with up to-date weather and sea current forecasts for efficient voyage planning. An example of an on-board management system, where energy parameters are shown is presented in Figure 8.

Since EMS takes into account operating conditions such as wind, sea state, speed, currents etc., it gives a benchmark for the propulsion system's performance and the hull condition. One interesting by-product that can be built on these measurements is a hull maintenance planning aid. (ABB, 2012b)

Figure 8. An example of on-board screen of EMS (ABB, 2012b)

4. Development of the simulator

4.1. Background

Traditional approaches focus on improving efficiency and cost-effectiveness via the optimisation of individual machinery components. In order to achieve measurable improvement in ship machinery, integrated machinery systems should considered as the basis of new alternatives. (Kakalis *et al.* 2014) The efficiency of a specific component is not so important, but the effects of it and how it fits in holistic machinery system. (Papanikolauou 2009) For example, a 5% decrease of main engine efficiency leads to less thermal energy loss which is often recovered on board via exhaust gas boilers. Less thermal energy may lead in certain cases to starting an oil-fired boiler, and hence the total fuel consumption might be increased. Since the holistic ship design is more important than a design of a specific component, only the main components of ship energy systems are modelled in this simulator.

Heiskanen (2007) presents a ship as a physically open system, where all energy brought on-board are in different forms. This energy is utilized in different operations and the final product of this is freed to vessel’s environment in different forms. Typical energy brought on-board are material and radiation. Material is usually provisions, fuel and other operation-related accessories. Radiation is usually energy current from the environment: air and water. One example of this is heating radiation from the sun. This; however, affects mainly on the vessels cruising in the equator or places near it. Different forms of energy produced by the ship energy flows are usually kinetic energy, wasted heat energy and exhaust gasses. Also heat losses from air conditioned spaces to open air and useless waste are energy flows flowing out of the ship. Energy brought in and out of the ship creates an energy balance, where energy brought on-board equals to energy consumed and energy stored on-board.

Apart from the energy flows that are connected to each other, also different parameter and machinery components are connected to each other. Figure 9 depicts detailed connections between different parameters, components and consumers. The first row represents different parameters, the second machinery components and the third consumers. Some parameters also affect other parameters, such as fuel type affects the engine SFOC (Specific Fuel Oil Consumption). For example, using HFO (Heavy Fuel Oil) instead of DMO (Diesel Marine Oil) increases fuel consumption due to lower energy content.

One notable connection is the connection between ambient temperature and steam production. Ambient temperature affects the engine parameters and heat demand. As for engine parameters they in turn affect on steam production via exhaust gas boilers.

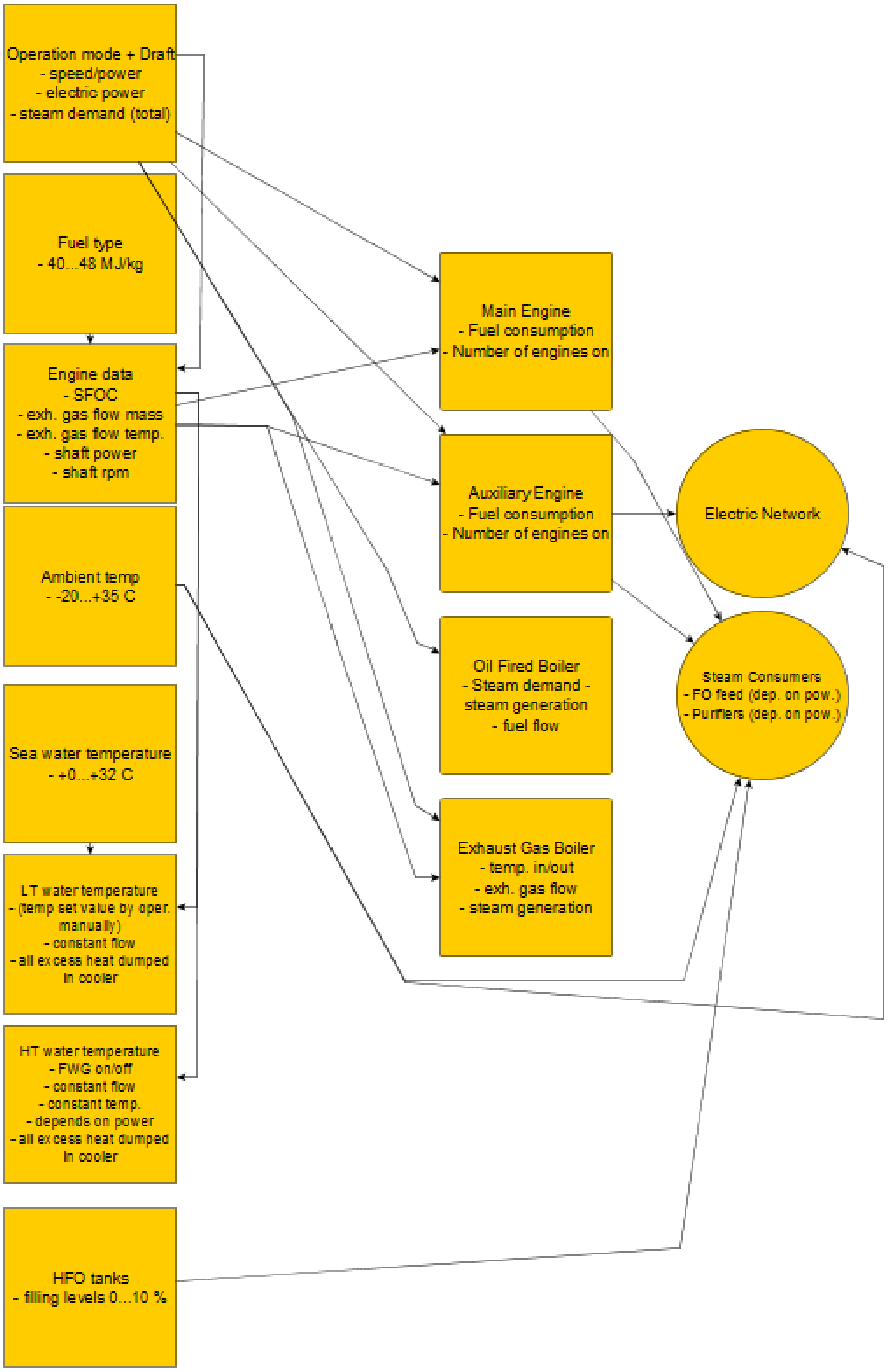


Figure 9. Connections between parameters and components

4.2. Description of the used approach

The developed simulator tool is based on a simulator model by Zou *et al.* (2013) presented in section 2.3.2. This simulator was chosen due to its holistic approach on energy flows and their connections between parameters and components. However, this simulator needs a large number of input data from the automation system of the case vessel in order to run the model. The simulator tool required for ship design purposes is aimed to be used in the concept phase. Therefore, the input data in designed model should be available already in the concept phase.

The simulator presented by Zou *et al.* (2013) is thus modified to suit our purposes. Instead of having real time data from an already built case vessel, our model is modified to utilize the parameters from existing machinery components. The block diagram of the completed simulator model is presented in Figure 10. Details about the components are presented in detail in this chapter.

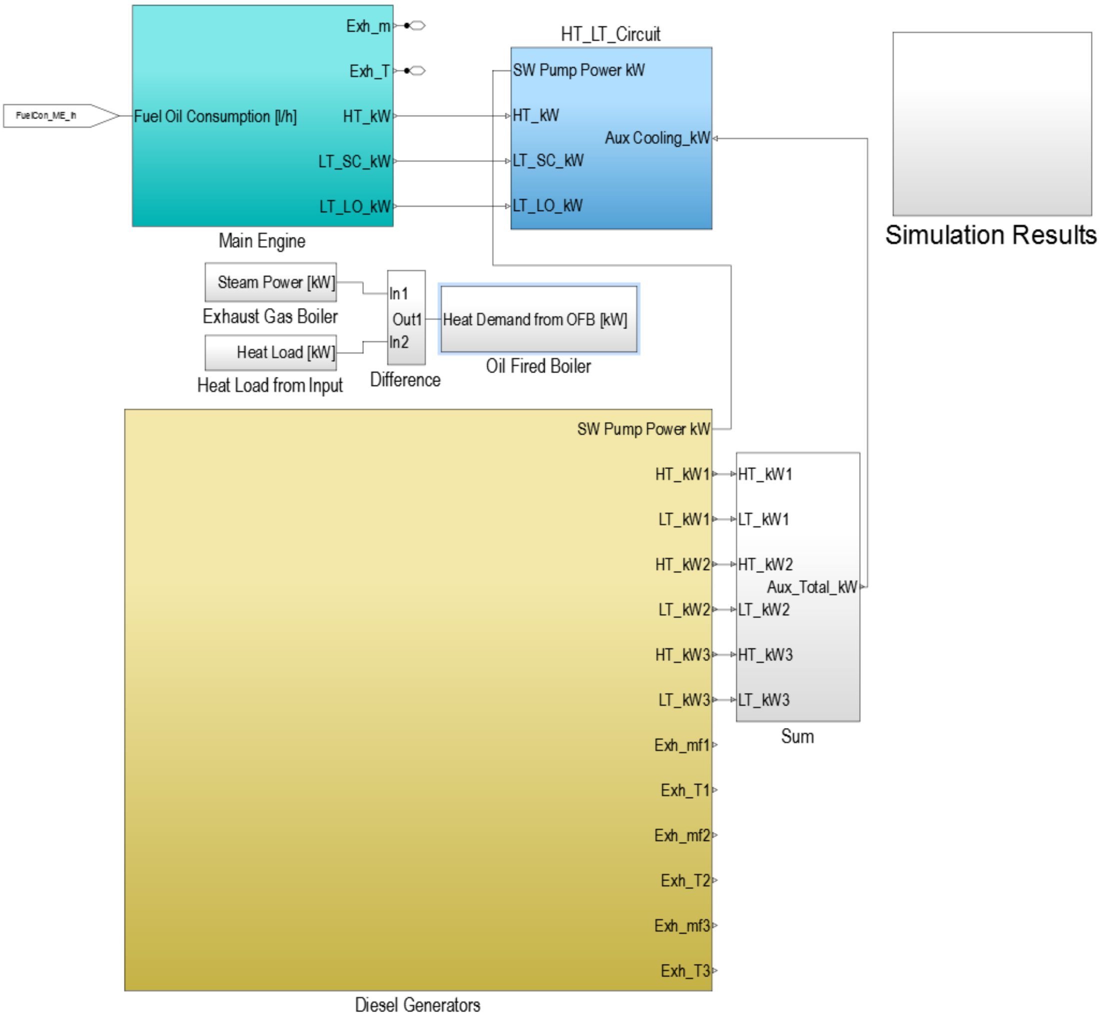


Figure 10. Simulator model seen as a block diagram

4.3. Matlab / Simulink / Simscape

The simulator is coded in *Matlab*-programming language using physical models of Simscape. The ship machinery consist of different energy flows in different domains and Simscape provides an environment for modelling and simulating physical systems such as mechanical, electrical, hydraulic and thermal domains. (Mathworks Ltd, 2014) It also provides building blocks that can be connected to each other to build a realistic model.

Simscape needs *Simulink*, because it is an extension of *Simulink* that is a block diagram environment for multidomain simulation. However, *Simulink* does not provide physical domains, and thus Simscape is needed.

4.4. Case vessel and speed profile

The case vessel is a handysize bulk carrier with a traditional propulsion system. Electric power is produced with three diesel generators and heat energy is produced with exhaust gas boiler attached to the main engine and oil fired boiler. There is also an evaporator attached to the HT-loop. Some main particulars are presented in Table 1.

Table 1. Main particulars of the case vessel

Length Overall	179,99 m
Breadth	30,0 m
Depth	15,0 m
Design Draft	9,5 m
Design Speed	14 kn
HT Pump Capacity	260 m^3/h
LT Pump Capacity	425 m^3/h
SW Pump Capacity	530 m^3/h
SW Pump Nominal Power	57 kW
Main Engine Type	MAN B&W 5S50ME-B9.3
Main Engine Max Speed	99 rpm
Main Engine Rated Power	6050 kW
Diesel Generators Rated Power	3 x 740 kW
Evaporator Power	500 kW
Exhaust Gas Boiler Heat Energy at 75 % load at ISO cond.	189,1 kW

In order for simulation model to work properly, an operation profile is also needed. A fictitious operation profile was created according to general knowledge about operation profiles in this size class. This is presented in Figure 11.

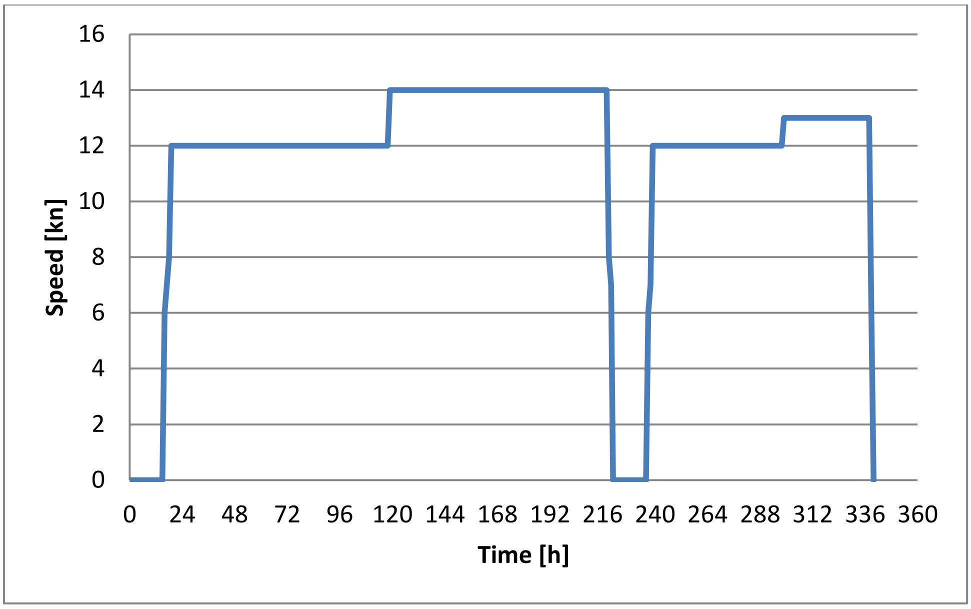


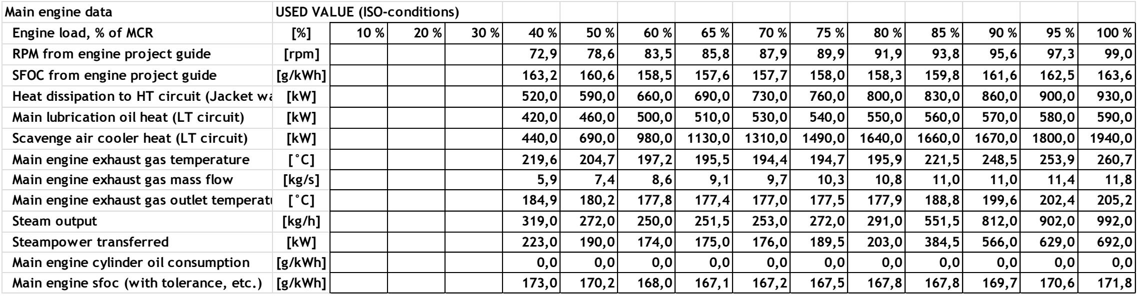
Figure 11. Operation profile of case vessel

4.5. Input file

The input file is an excel-file based on machinery specifications, operational conditions, speed-power curves, heat and electric load. This data is then exported to the simulation model. The whole input file can be seen in Appendix 1. The variables with blue box affect the simulation and the ones with red box are needed if applicable. The input file is divided into two sheets, the first consisting main and auxiliary engine specifications, ambient conditions, speed-power curves, boiler and other machinery related data such as cooling circuit pump capacities, LT (Low Temperature) - and HT-loop temperature setpoints after heat exchanger and possible evaporator specifications.

Machinery specifications include main engine data such as SFOC, heat dissipations to HT and LT circuit, exhaust gas temperature and mass flow. Engine parameters are acquired from engine project guide (MAN, 2010) and performance data (MAN Turbo & Diesel, 2013) for this specific engine. Steam output and transferred power are also included here, which are acquired from boiler design calculations (Alfa Laval, 2013a) and are presented in Table 2. All this input is a function of the engine load and depends on ambient condition. Therefore, all the specifications are input in three separate parts, each corresponding to their respective ambient conditions. The ambient condition is chosen later (*e.g.* ISO, tropical or winter) and the data table will update itself automatically, which is then exported to the simulation model. The ambient condition variable also affects the heat load from heat balance *i.e.* heat load is higher in winter condition than in summer condition.

Table 2. Main engine specification



Main engine data	USED VALUE (ISO-conditions)													
Engine load, % of MCR	[%]	10 %	20 %	30 %	40 %	50 %	60 %	65 %	70 %	75 %	80 %	85 %	90 %	95 %	100 %
RPM from engine project guide	[rpm]				72,9	78,6	83,5	85,8	87,9	89,9	91,9	93,8	95,6	97,3	99,0
SFOC from engine project guide	[g/kWh]				163,2	160,6	158,5	157,6	157,7	158,0	158,3	159,8	161,6	162,5	163,6
Heat dissipation to HT circuit (Jacket wa	[kW]				520,0	590,0	660,0	690,0	730,0	760,0	800,0	830,0	860,0	900,0	930,0
Main lubrication oil heat (LT circuit)	[kW]				420,0	460,0	500,0	510,0	530,0	540,0	550,0	560,0	570,0	580,0	590,0
Scavenge air cooler heat (LT circuit)	[kW]				440,0	690,0	980,0	1130,0	1310,0	1490,0	1640,0	1660,0	1670,0	1800,0	1940,0
Main engine exhaust gas temperature	[˚C]				219,6	204,7	197,2	195,5	194,4	194,7	195,9	221,5	248,5	253,9	260,7
Main engine exhaust gas mass flow	[kg/s]				5,9	7,4	8,6	9,1	9,7	10,3	10,8	11,0	11,0	11,4	11,8
Main engine exhaust gas outlet temperatu	[˚C]				184,9	180,2	177,8	177,4	177,0	177,5	177,9	188,8	199,6	202,4	205,2
Steam output	[kg/h]				319,0	272,0	250,0	251,5	253,0	272,0	291,0	551,5	812,0	902,0	992,0
Steampower transferred	[kW]				223,0	190,0	174,0	175,0	176,0	189,5	203,0	384,5	566,0	629,0	692,0
Main engine cylinder oil consumption	[g/kWh]				0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Main engine sfoc (with tolerance, etc.)	[g/kWh]				173,0	170,2	168,0	167,1	167,2	167,5	167,8	167,8	169,7	170,6	171,8

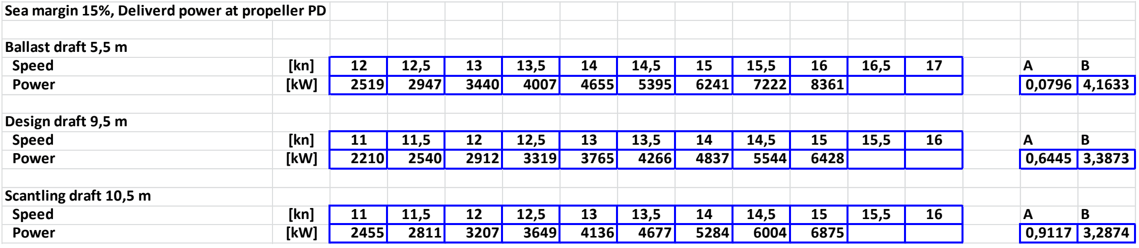
Other machinery specifications include possible evaporator power, oil-fired boiler power and auxiliary engine data. All the information is acquired from project guides or manufacturers data sheets. The input file can be constantly updated as the new information is acquired during the design process.

Speed-power curves are obtained typically from the model tests. In this case, they are acquired from an Excel-based resistance calculation tool, which utilizes Holtrop-Mennen method. They are input with different loading conditions *i.e.* different drafts of the ship (Table 3). These loading conditions are usually ballast, design and scantling drafts. The input is done by defining vessel speeds and their respective power need with adding a 15 % sea margin. From these values, the input file will automatically draw a speed-power curve and their trendline equation. These numbers are written in places intended for them (Seen as A and B on Table 3) and are used later when calculating the power in an operation profile setup in the following equation:

$$P = A * v^{B}, \text{ where} \qquad (1)$$

P = power
v = speed

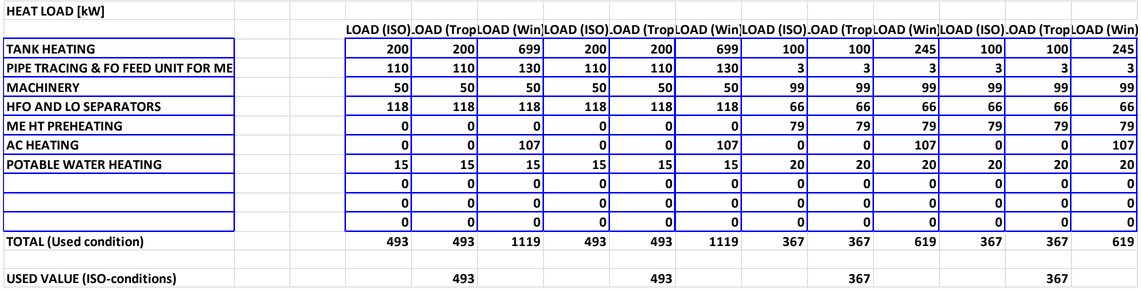
Table 3. Speed-Power curve setup



Sea margin 15%, Deliverd power at propeller PD															
Ballast draft 5,5 m															
Speed	**[kn]**	**12**	**12,5**	**13**	**13,5**	**14**	**14,5**	**15**	**15,5**	**16**	**16,5**	**17**		**A**	**B**
Power	**[kW]**	**2519**	**2947**	**3440**	**4007**	**4655**	**5395**	**6241**	**7222**	**8361**				**0,0796**	**4,1633**
Design draft 9,5 m															
Speed	**[kn]**	**11**	**11,5**	**12**	**12,5**	**13**	**13,5**	**14**	**14,5**	**15**	**15,5**	**16**		**A**	**B**
Power	**[kW]**	**2210**	**2540**	**2912**	**3319**	**3765**	**4266**	**4837**	**5544**	**6428**				**0,6445**	**3,3873**
Scantling draft 10,5 m															
Speed	**[kn]**	**11**	**11,5**	**12**	**12,5**	**13**	**13,5**	**14**	**14,5**	**15**	**15,5**	**16**		**A**	**B**
Power	**[kW]**	**2455**	**2811**	**3207**	**3649**	**4136**	**4677**	**5284**	**6004**	**6875**				**0,9117**	**3,2874**

The second sheet of input file consists of electric and heat load and operation profile setup. Heat load presented in Table 4 is obtained from the heat balance. Heat load is given as a sum of main consumers for certain operating and ambient conditions. These ambient conditions include ISO, tropical and winter conditions. The used value is determined in the first sheet, where user defines the ambient condition. This way the used value will be updated automatically to the value that is needed. These values are used later in an operation profile setup.

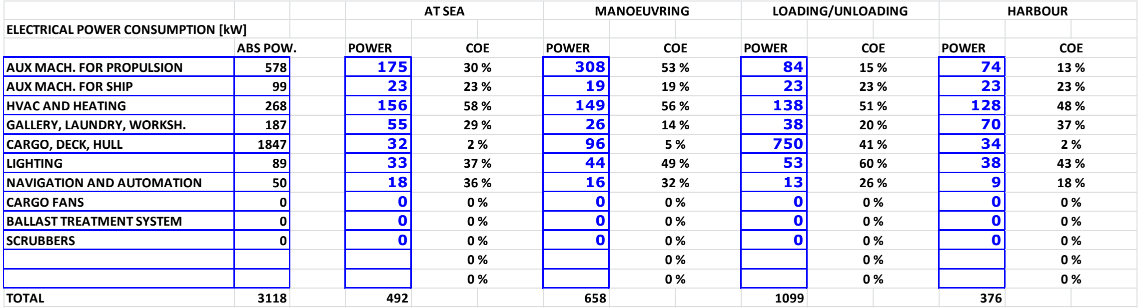
Table 4. Heat Load



HEAT LOAD [kW]												
	LOAD (ISO)	.OAD (Trop	LOAD (Win	LOAD (ISO)	.OAD (Trop	LOAD (Win	LOAD (ISO)	.OAD (Trop	LOAD (Win	LOAD (ISO)	.OAD (Trop	LOAD (Win)
TANK HEATING	200	200	699	200	200	699	100	100	245	100	100	245
PIPE TRACING & FO FEED UNIT FOR ME	110	110	130	110	110	130	3	3	3	3	3	3
MACHINERY	50	50	50	50	50	50	99	99	99	99	99	99
HFO AND LO SEPARATORS	118	118	118	118	118	118	66	66	66	66	66	66
ME HT PREHEATING	0	0	0	0	0	0	79	79	79	79	79	79
AC HEATING	0	0	107	0	0	107	0	0	107	0	0	107
POTABLE WATER HEATING	15	15	15	15	15	15	20	20	20	20	20	20
	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0
TOTAL (Used condition)	493	493	1119	493	493	1119	367	367	619	367	367	619
USED VALUE (ISO-conditions)		493			493			367			367	

Electric load presented in Table 5 is obtained from the electric balance. Electric load is given as a sum of the main consumers for different operating conditions that includes harbour, loading condition, manoeuvring and at sea. These loads are used later in an operation profile setup.

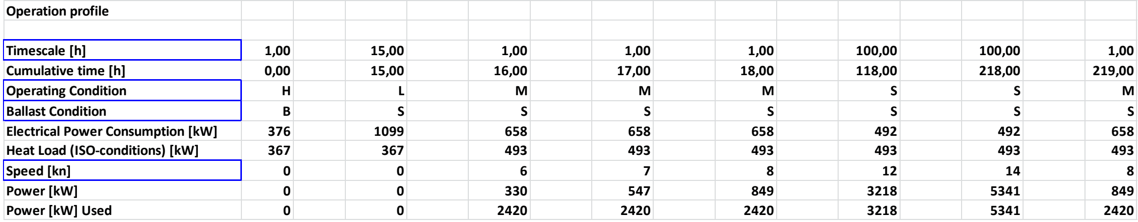
Table 5. Electric load



		AT SEA		MANOEUVRING		LOADING/UNLOADING		HARBOUR	
ELECTRICAL POWER CONSUMPTION [kW]									
	ABS POW.	POWER	COE	POWER	COE	POWER	COE	POWER	COE
AUX MACH. FOR PROPULSION	578	175	30 %	308	53 %	84	15 %	74	13 %
AUX MACH. FOR SHIP	99	23	23 %	19	19 %	23	23 %	23	23 %
HVAC AND HEATING	268	156	58 %	149	56 %	138	51 %	128	48 %
GALLERY, LAUNDRY, WORKSH.	187	55	29 %	26	14 %	38	20 %	70	37 %
CARGO, DECK, HULL	1847	32	2 %	96	5 %	750	41 %	34	2 %
LIGHTING	89	33	37 %	44	49 %	53	60 %	38	43 %
NAVIGATION AND AUTOMATION	50	18	36 %	16	32 %	13	26 %	9	18 %
CARGO FANS	0	0	0 %	0	0 %	0	0 %	0	0 %
BALLAST TREATMENT SYSTEM	0	0	0 %	0	0 %	0	0 %	0	0 %
SCRUBBERS	0	0	0 %	0	0 %	0	0 %	0	0 %
			0 %		0 %		0 %		0 %
			0 %		0 %		0 %		0 %
TOTAL	3118	492		658		1099		376	

Operation profile setup presented in Table 6 connects all the previously mentioned inputs together to a holistic operation profile as a function of time. The inputs needed are timescale, operating condition, ballast condition and speed at that certain time. The first row is timescale, which represents the duration of the operation profile on those exact settings. The third row is operating condition, which affects both the heat load and electric load. The inputs include *H*, *L*, *M* and *S*, which are Harbour, Loading, Manoeuvring and At Sea conditions. Fourth row is ballast condition, which affects the power needed according to speed, which is input in the seventh row. The ballast conditions are *B*, *D*, and *S*, which are Ballast, Design and Scantling. The used power on the last row represents the minimum power produced by the main engine. Because the propeller is coupled straight to the main engine without a clutch, the delivered power to the propeller in lower speeds is under the operation area of the main engine. Therefore, a minimum of 40 % MCR (Maximum Continuous Rating) is assumed to be the lower limit.

Table 6. Part of operation profile setup



Operation profile								
Timescale [h]	1,00	15,00	1,00	1,00	1,00	100,00	100,00	1,00
Cumulative time [h]	0,00	15,00	16,00	17,00	18,00	118,00	218,00	219,00
Operating Condition	H	L	M	M	M	S	S	M
Ballast Condition	B	S	S	S	S	S	S	S
Electrical Power Consumption [kW]	376	1099	658	658	658	492	492	658
Heat Load (ISO-conditions) [kW]	367	367	493	493	493	493	493	493
Speed [kn]	0	0	6	7	8	12	14	8
Power [kW]	0	0	330	547	849	3218	5341	849
Power [kW] Used	0	0	2420	2420	2420	3218	5341	2420

4.6. Simulator components

Simulator components are constructed for a case ship. These are however applicable with other ship types after some modification, since they are general components. This model covers the main propulsion model with heat and electric power. Since this model is to be used in an early phase of design, all the necessary input data are not available. This induces some big modification to a model made by Zou et al (2013). These modifications are mainly look-up tables inserted in the model due to high amount of concept phase information instead of data gained from on-board automation system.

4.6.1. Main engine

Main engines are the prime movers of the ship. They can be differentiated by their type. These include, for example, diesel engines, otto engines (petrol engine), gas turbines, steam turbines and nuclear power. This thesis focuses more on the slow-speed diesel engines, since they are the most commonly used engine type as a power plant of the ship. One reason for this is their high thermal efficiency compared to other options. Rawson (2001) presents that the thermal efficiency of diesel engine is 43 % compared to 35 % of gas turbine and 20 % steam turbine.

The slow-speed engines are two stroke engines that are used for main propulsion units, since they can be coupled straight to the propeller and shafting without any gearbox. It provides high powers, can burn low-grade fuels and has high thermal efficiency. The cylinders and crankcase are also isolated in a two-stroke engine, which reduces contamination and thus different specialized lubricating oils can be used in each area. There also lacks the inlet and exhaust valves, which reduces maintenance and simplifies engine construction. (Taylor 1996)

Main engine component presented in Figure 12 consists of Lookup Tables (closer look in Figure 13), which reads the main engine specification from the input file via Matlab read-file. The data read are HT-heat dissipation, LT-heat dissipation, exhaust gas mass flow and temperature and specific fuel oil consumption. These are all presented as a function of engine loading. The operation profile setup mentioned in the previous chapter defines the main engine loading at certain time from the speed of the vessel. This loading specifies the correct value of engine parameters mentioned above. The results generated from this main engine component are mechanical power produced, energy produced in kWh, cumulative energy consumption in kWh, instant fuel consumption and cumulative total fuel consumption. These are generated as a function of time.

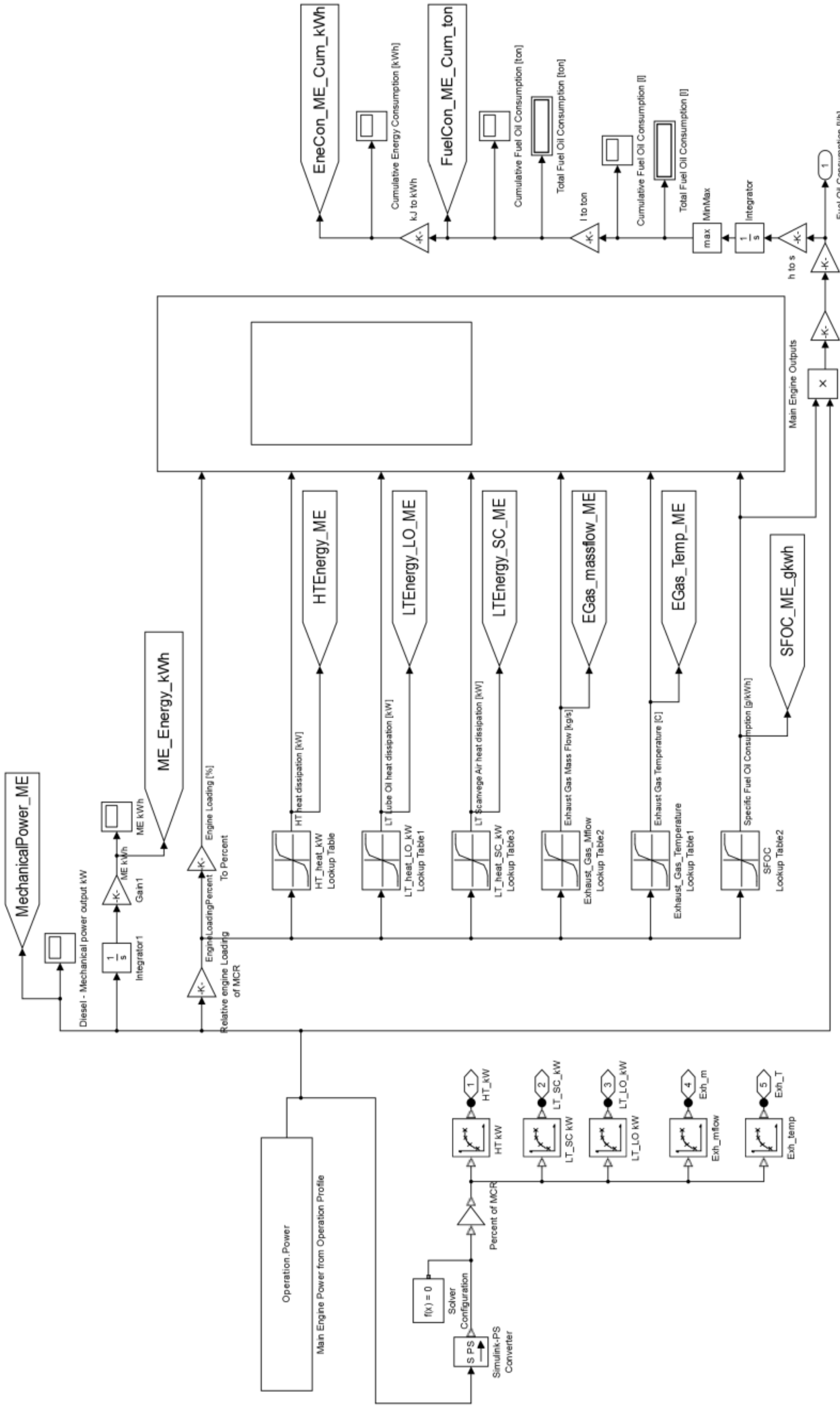


Figure 12. Main engine component

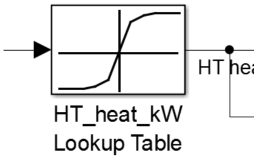


Figure 13. Lookup table of HT-heat in kW

4.6.2. Diesel generators

Diesel generators consist of a coupled auxiliary engine and a generator. Electric generator converts mechanical energy from the auxiliary engine to electrical energy. The auxiliary engine shaft is coupled with a rotor, which rotates inside a stator. The rotors magnetic field induces an AC voltage in the stator windings. Very often there are at least three diesel-generators for ocean-going ships due to conservative practice (Lamb 2003).

Diesel generators are designed so that one unit can maintain the electricity needed for consumers under sea-going situation. In that case second of the units can be ready to start even though the third unit is under maintenance. If the electrical power need fluctuations are high, a fourth unit is a more natural choice. (Häkkinen 1993)

A simulator block consisting three diesel generators is presented in Figure 14. Diesel generator consists of an auxiliary engine and a generator component. The auxiliary engines are identical to main engine components and generators produce electricity from the mechanical energy produced by the engines.

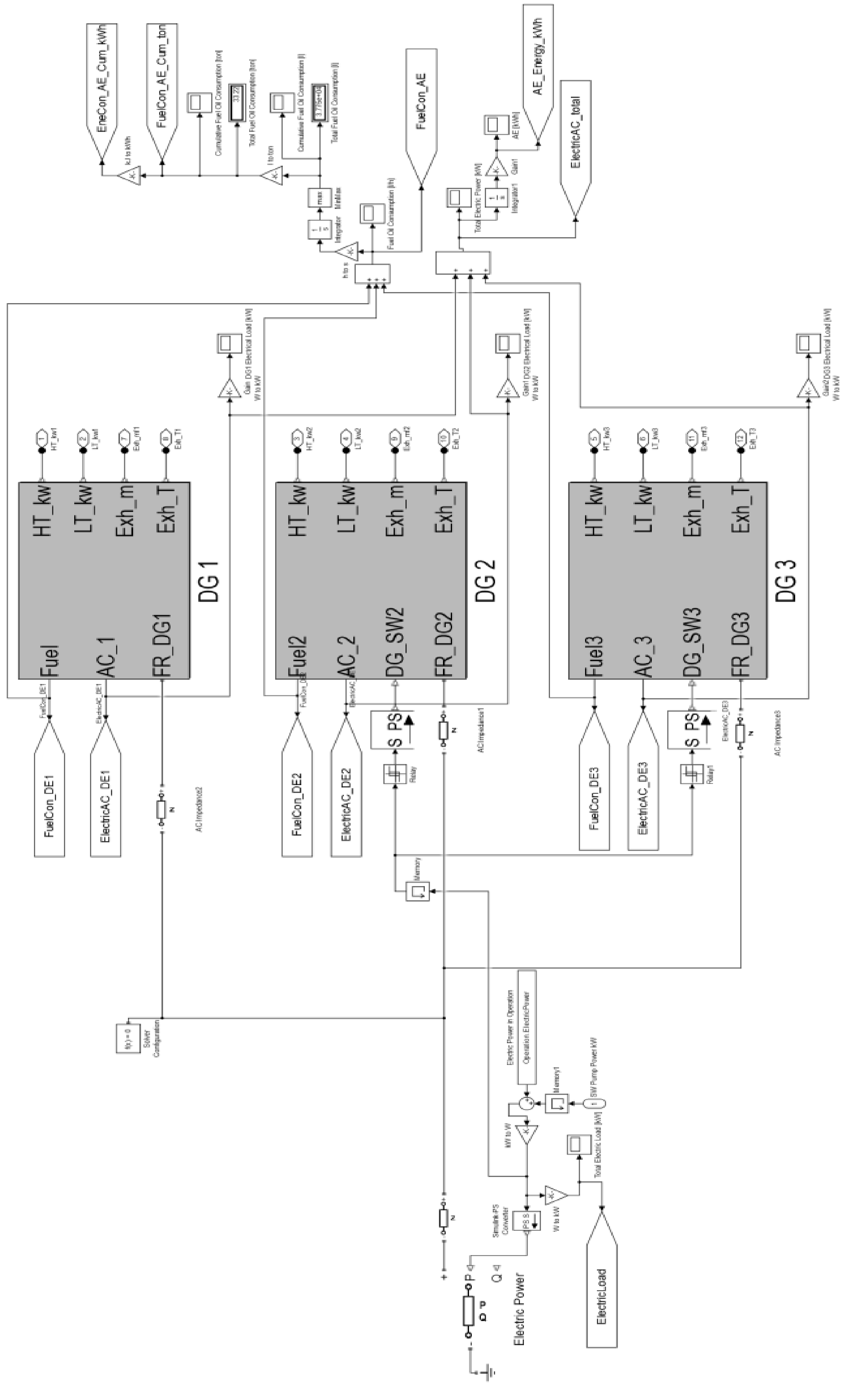


Figure 14. Diesel generators

The electric load is pulled into the model from the input file and represents the amount that is needed to operate the vessel. Since the model has three diesel generators, their switch logic is made with a relay component presented in Figure 15. The relay works as a switch on the second diesel generator (or third), if needed. There is also a possibility to adjust the specified thresholds *i.e.* switch on and switch off points For example, in this vessel the switch on point is 85% loading in the second (or third) engine and switch off point is 80% loading. This way when the second engine is switched on, the electric load divides to two engines equally.

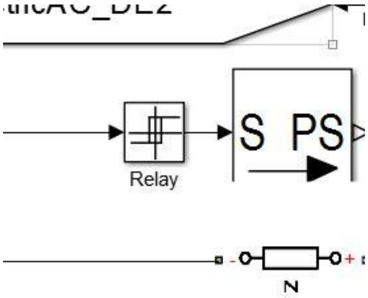


Figure 15. Relay in diesel generators

Since the diesel engines of the diesel generators are identical as the main engine, the results are also the same. In addition to these, the component also produces results characteristic to diesel generators such as produced electrical power for each auxiliary engine, total electrical power in kW and energy in kWh, fuel and energy consumption.

4.6.3. Steam production

Pressurized steam is generally used for heating purposes on board of the ship. Other options include hot water and heating oil. Pressurized steam has several advantages, which include high energy content, no danger of fire and smaller piping dimensions compared to other systems. Steam is produced from circling water with a boiler by evaporation process. A typical ship heat plant with one exhaust gas boiler and one oil-fired boiler is presented in Figure 16.

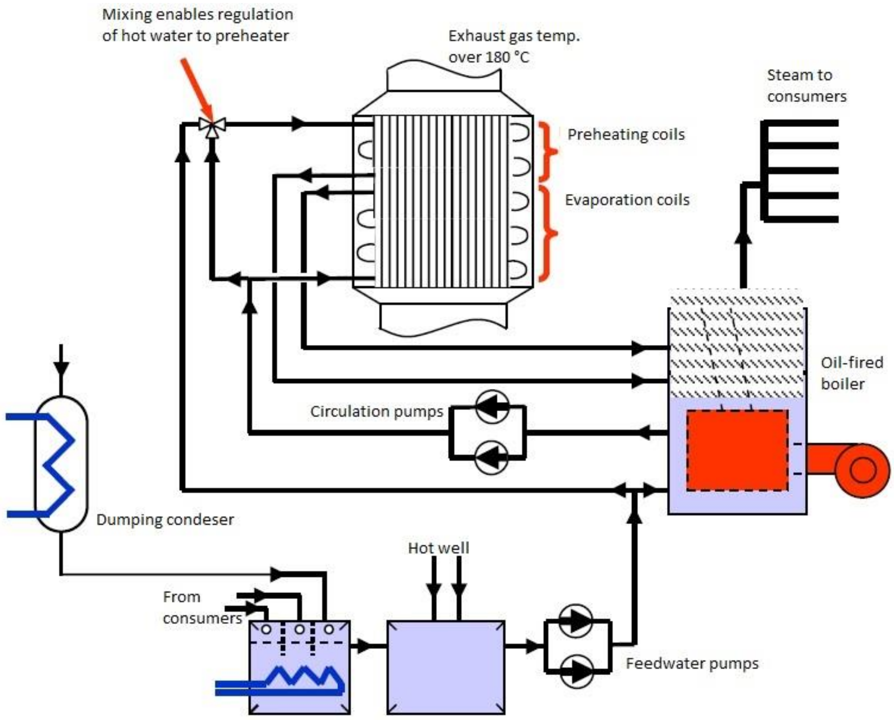


Figure 16. Heating system of a diesel-driven ship (Häkkinen, 1993)

Steam production simulator component consists of EGB and OFB (Oil Fired Boiler) components and heat demand from the heat balance. This is presented in Figure 17. The logic behind this component is straightforward. Each time step has its own value of heat load, which is acquired from the heat balance and varies according to operation and ambient conditions as mentioned in chapter 4.5. EGB produces steam power, which either covers the heat demand entirely and if not, the OFB starts to produce the deficit amount of steam.

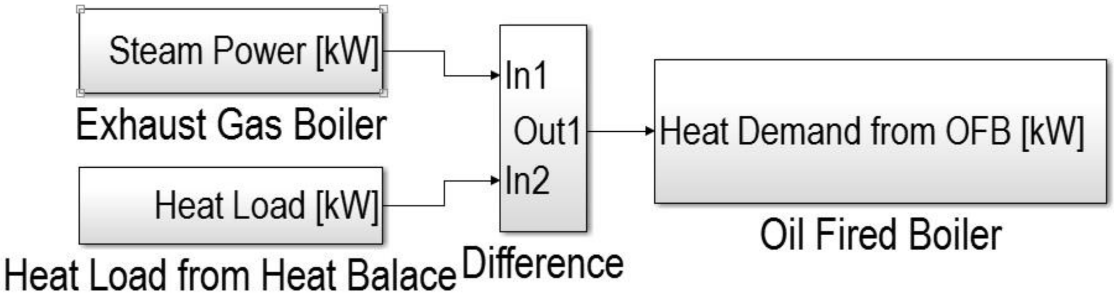


Figure 17. Steam production component

Exhaust gas boiler

Exhaust gas boilers are usually of composite form, enabling steam generation using oil firing or the exhaust gases from the diesel engine. With this arrangement the boiler acts as the heat exchanger and raises steam in its own drum. (Taylor 1996)

Parameters affecting the produced steam power include engine exhaust gas mass flow and temperature, boiler efficiency, ambient temperature and steam system pressure. Boiler manufacturers are only possible to affect the boiler efficiency.

Exhaust gas boiler component presented in Figure 18 works as a steam heat producer. The operation profile mentioned in chapter 4.5 specifies the engine loading from the speed of the vessel, which in turn specifies the steam power produced from the EGB according to boiler design calculations (Alfa Laval, 2013a). The results produced from this block include generated steam power and energy.

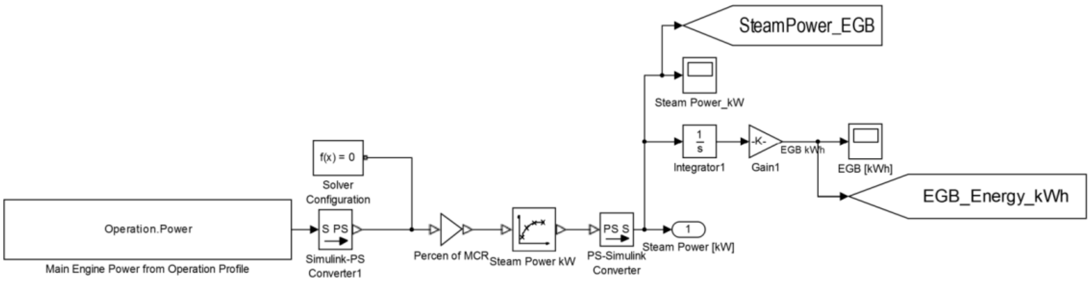


Figure 18. Exhaust gas boiler component

Oil fired boiler

Oil fired boilers are used to evaporate feedwater in order to produce steam in case exhaust gas boilers are not sufficient enough. This actually happens often, since in order for exhaust gas boilers to use their full capacity, the mass flow and temperature of the exhaust gas has to be high enough. This only happens in higher loads than NCR (Nominal Continuous Rating) in a slow-speed diesel engine (Taylor 1996).

The oil fired boiler-component is presented in Figure 19. It is connected to EGB-component and ensures that enough heat power is generated for the vessel. OFB starts only when the heat amount produced in the EGB is insufficient for the ship purposes. This has been done using a relay-component, switching OFB between on and off.

The logic behind OFB-component is rather simple. According to boiler suppliers oil fired boilers have a fuel-to-steam efficiency of around 83% (Bhatia, 2006). Another important part of OFB-component is LHV (Lower Heating Value) of fuel type used in the OFB. Lampinen (2006) explains that LHV is the amount of heat released during the combustion of a specified amount of it. With this information, a simple model can be made.

As mentioned before, the OFB-component starts to produce steam when EGB production is not sufficient enough. This heat demand is given the unit of kW (presented in the Figure 19 as the upmost port). This heat demand is divided by the OFB efficiency, which is 83% in this case. This signal is then divided by LHV of the burned fuel, which gives out fuel consumption given in the unit of kg/s. This can be multiplied by the simulation time with the integrator block gaining total fuel oil consumption in the unit of kg.

Other results include also OFB energy consumption in the unit of kWh, OFB energy demand in the unit of kWh and fuel consumption in the unit of l/h.

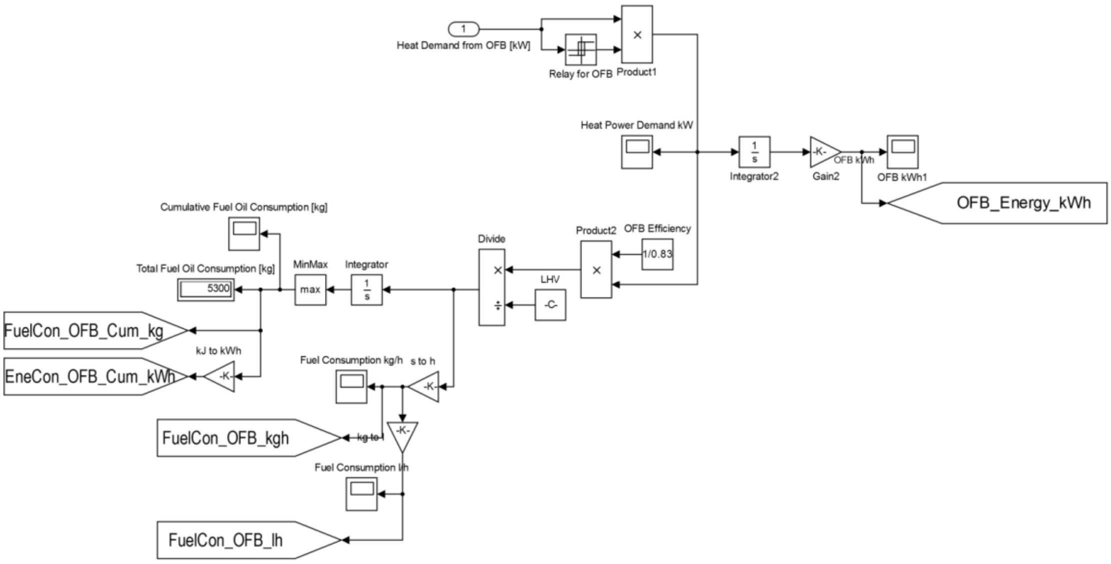


Figure 19. Oil fired boiler component

4.6.4. SW-, HT- and LT-circuit

SW-, HT- and LT-circuit is modelled according to case vessel’s HT- and LT-circuit. The system is presented in Figure 20. The system is constructed around four different variables. These are mass flow $\dot{m}$, heat transfer rate $\dot{q}$, temperature T and pressure p. The system consists of different components such as a reference block, which is needed for each loop, mass flow source, which acts as pump with the given mass flow and pressure rise, local resistance block, which acts as pressure resistance for the loop, heat extractors, which act as a heat injector for heating purposes, heat exchanger, which transfers the heat from warmer loop to colder, a VSD (Variable Speed Drive) SW (Sea Water) Pump, which operates depending on the inlet temperature of LT, and different sensors, such as temperature, pressure and mass flow sensors.

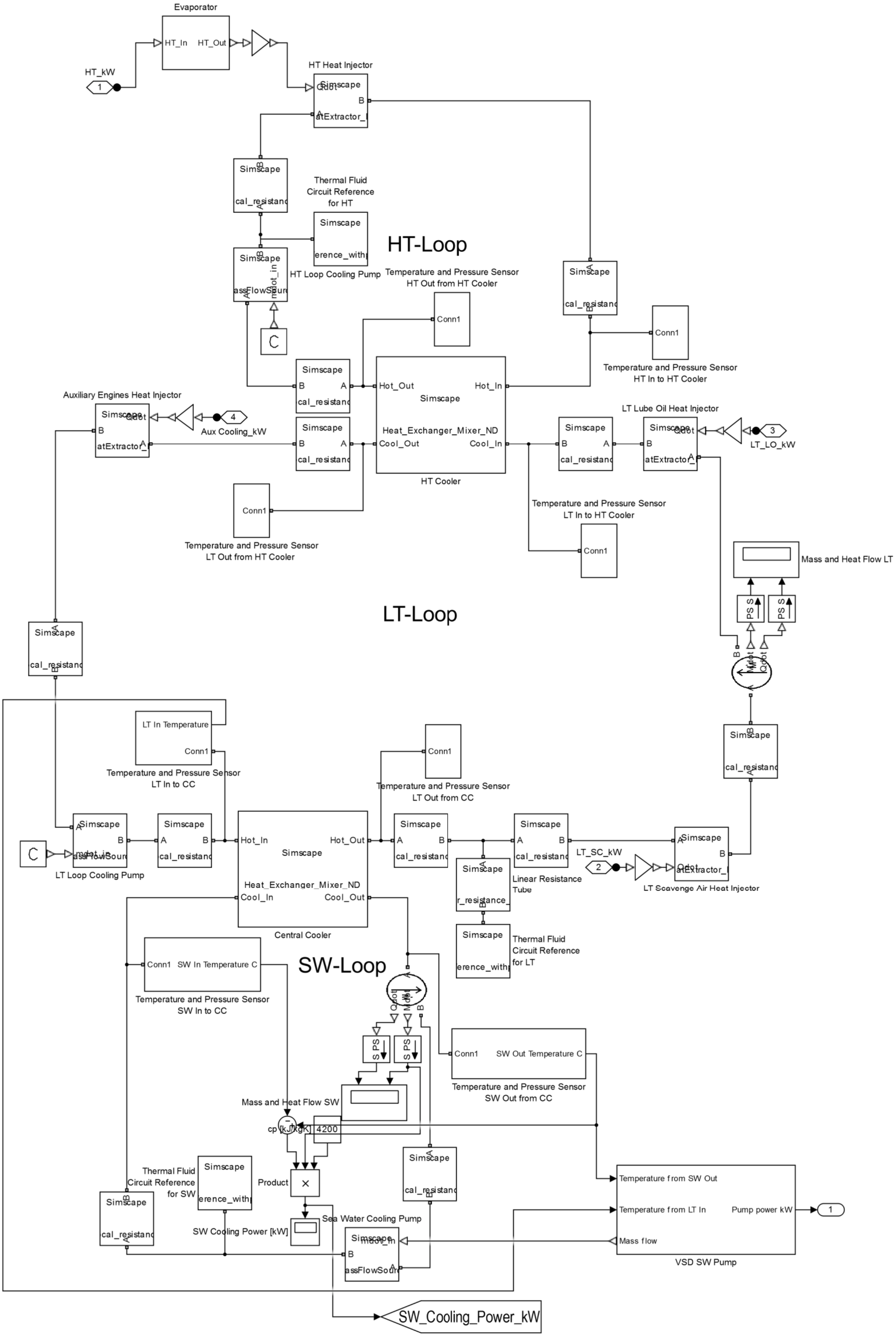


Figure 20. Engine cooling system

The reference block attaches a reference point to a circuit pressure and temperature. Without this block, the model would not run due to unknown computational starting point. Each loop needs an own reference point, since each loop has their own set of temperature and pressure.

The mass flow source adds specified amount of mass flow (kg/m^3) to the loop and raises the pressure and thus works as an ideal compressor and in our case as a pump. The compressor does not add any additional heat. Figure 21 shows LT Cooling Pump as an example. The block "C" is a constant block, which in case is the specified value of mass flow increase. The pump specifications are taken from the concept phase cooling circuit diagram, where only their capacity and pressure raise is needed.

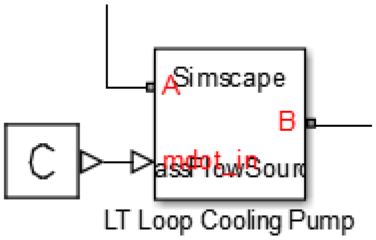


Figure 21. LT Loop cooling pump

Local resistance block gives the loop a pressure resistance and models the flow rate of a thermal fluid through a variable-area orifice. It is assumed that output heat flow is equal to input heat flow, thus this block not affect the heat transferred. This block gives a realistic inertia to the fluid mass flow and without this; the model would not run due to simulation process happening with no delay. Resistance blocks are placed around the loop between other blocks as insulation such as reference blocks and heat extractors. Figure 22 shows how the LT reference is insulated between the resistance blocks.

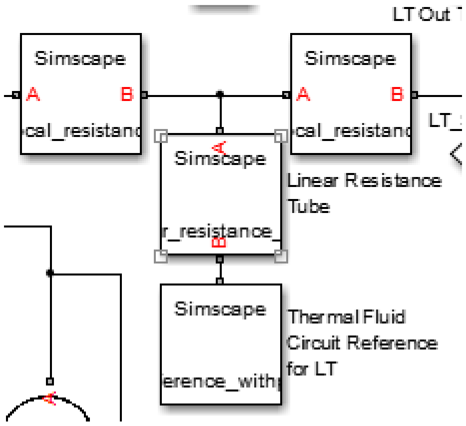


Figure 22. Resistance block acting as insulation

Heat extractor deducts or adds if the number is negative a specified amount of heat flow in kilowatts from or to the loop respectively. In our case, the heat extractor is used as an injector, which adds the heat flow to the loop. Figure 23 shows how heat extractor works. Heat flows (Lube Oil Heat dissipation in the figure) are taken from the main engine and auxiliary engine HT and LT heat dissipation. This heat flow is input in the heat extractor block, which transfers the heat flow into the loop. There is also an option to specify a pressure loss from the block.

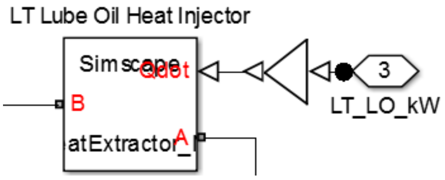


Figure 23. Heat extractor coupled with lube oil heat dissipation.

Heat exchanger block presented in Figure 24 is a simple theoretical heat exchanger, which transfers heat energy from the hot side to the cold side. Heat transfer efficiency is not taken into account and heat from the hot side transfers fully to the cold side. This heat exchanger has also a thermostat, which sets the temperature of hot outlet side to a certain value. Inlet of the cool and hot side are also known, *e.g.* in the central cooler case, cool inlet side is always the sea water temperature, which is constant and set in the input file and hot inlet side is always the total amount of heat produced by the engines. Therefore, only hot outlet side is unknown. This was possible to calculate with equations below (Lampinen, 2006):

$$\dot{Q} = \dot{m}_{HOT_{In}-HOT_{Out}} * C_p * T_{HOT_{In}-HOT_{Out}} \tag{2}$$

$$\dot{q}_{HOT_{Out}} = \dot{q}_{HOT_{In}} - \dot{Q} \tag{3}$$

$$\dot{q}_{COOL_{Out}} = \dot{q}_{COOL_{In}} + \dot{Q} \tag{4}$$

$$\dot{Q} = \dot{m}_{COOL_{In}-COOL_{Out}} * C_p * T_{COOL_{Out}-COOL_{In}} \tag{5}$$

$\dot{Q}$ is the heat to be transferred from the hot side to the cold side per unit time. Therefore the heat from hot outlet side is the difference between heat from the hot inlet side and $\dot{Q}$, and heat from the cool inlet side is the difference between heat from the cool inlet side and $\dot{Q}$.

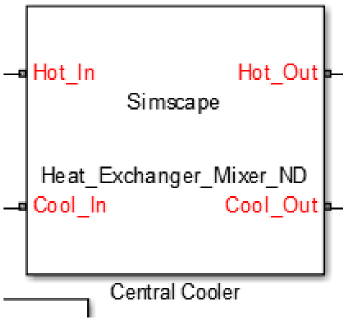


Figure 24. Central cooler

VSD (Variable Speed Drive) SW (Sea Water) Pump is a SW pump, which acts depending on the cooling demand of sea water loop. Without VSD, the SW pump would always operate in its nominal speed and power. A simulation block is presented in Figure 25. The logic behind energy saving using VSD are the pump affinity laws, which was mentioned in chapter 3.2.1. Therefore, regulating the mass flow *i.e.* capacity varies directly with the cube root of power, which is implemented to the block. In mathematical terms the power consumed by the pump is expressed as:

$$P_2 = P_1 \left(\frac{Q_2}{Q_1}\right)^3 \text{ , where} \qquad (6)$$

P_2 = Power consumed by the pump
P_1 = Nominal power of the pump
Q_2 = Mass flow through the pump
Q_1 = Nominal mass flow through the pump

There is always a maximum discharge temperature for SW cooling loop, for example, US EPA's (United States Environmental Protection Agency) states that "The maximum discharge temperature is 140 degrees Fahrenheit", which equals to 60 degrees Celsius (EPA, 1999). Due to this fact, the SW outlet temperature can be very often unnecessarily too low, which can be adjusted by regulating mass flow. The working principle behind VSD SW Pump component is to change the mass flow of the pump according to difference between inlet temperature of LT-loop and outlet temperature of SW-loop. This control happens with PID (Proportional-Integral-Derivative) controller.

PID controller is widely used in feedback control of industrial processes. It consists of three elements: P, I and D, which are "present" error, accumulation of the "past" error and prediction of the "future" error respectively. (Åström et al, 1995)

As the PID controller regulates the mass flow, the power deduction is directly with the root cube of mass flow. There is however a minimum mass flow due to the pump. This amount varies depending on the pump model and manufacturer. In our case, the minimum mass flow is set to 50%.

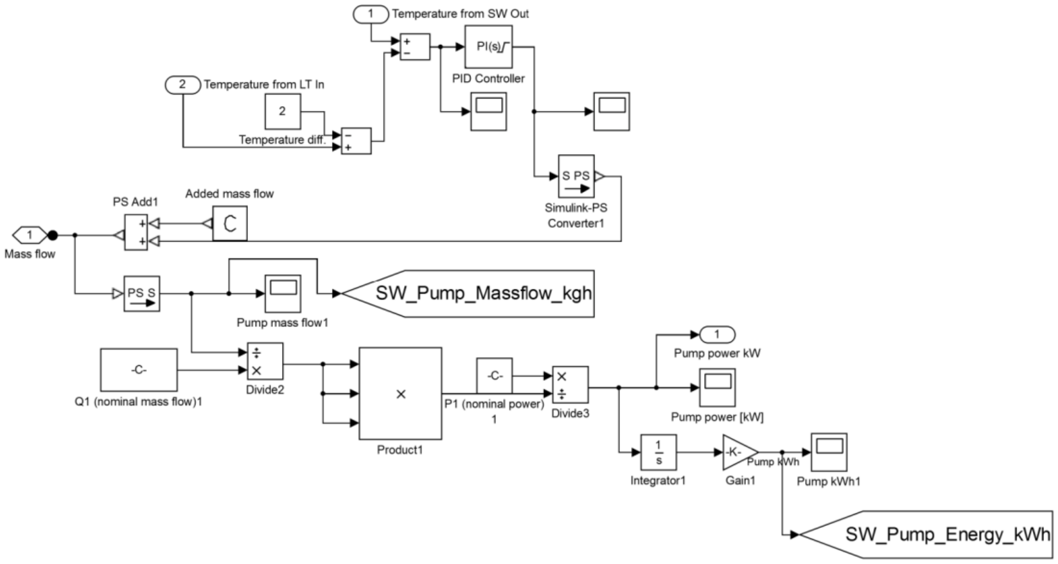


Figure 25. Variable speed drive sea water pump

Evaporator (upmost block in Figure 20) is modelled as a heat extractor which extracts heat from the HT-circuit with the amount of evaporator power. More detailed explanation about its function and operation is in subchapter 4.6.5.

The sensors used in the thermal fluid domain are a combined temperature and pressure sensor and a combined mass and heat flow sensor. The temperature and pressure sensor block seen in Figure 26 represents an ideal pressure and temperature sensor, that is, a device that converts pressure differential and temperature differential measured between two ports into physical measurement signals P and T. The mass and heat flow sensor block presented in Figure 27 represents an ideal mass flow and heat flow sensor, that is, a device that converts mass flow rate and heat flow rate between the two nodes into physical measurement signals $\dot{m}$ and $\dot{Q}$.

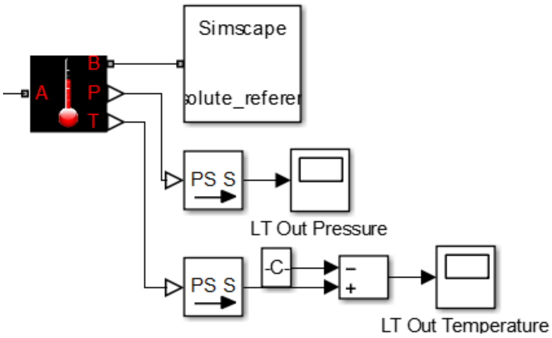


Figure 26. Temperature and Pressure sensor

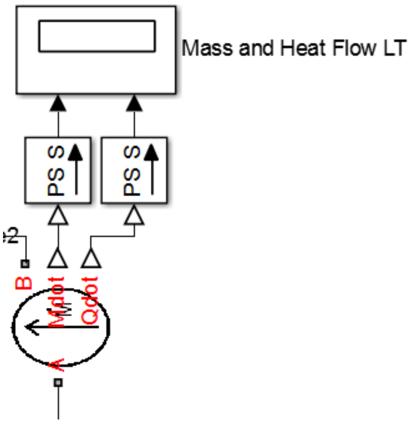


Figure 27. Mass and Heat flow sensor

4.6.5. Evaporator

There is an evaporator seen in Figure 28 is connected to HT-circuit. This was seen in the cooling system on Figure 20 as the uppermost block. The evaporator block was constructed with a simple relay, which opens when HT heat dissipation from the main engine is over nominal power of the evaporator. This way the HT heat dissipation energy is used to produce fresh water and thus not transferred to HT-loop. This reduces the amount of HT heat dissipation to be transferred to HT-loop by exactly the amount of nominal power of the evaporator.

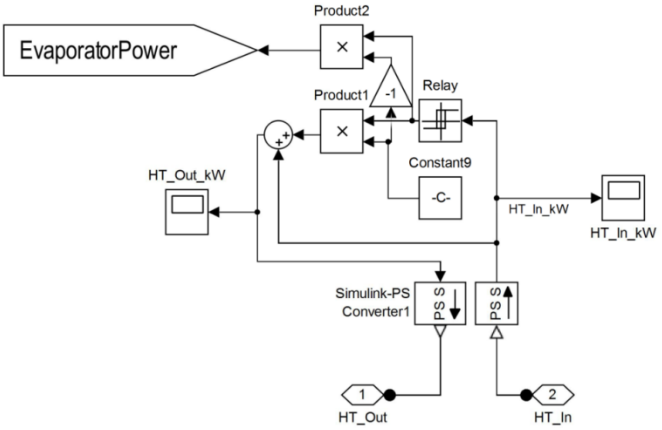


Figure 28. Evaporator system

4.7. Output file

The output file is printed automatically in excel-format as simulation ends. It includes all the results from the simulator. The results are presented as function of time. These are rather simple to add according to users preferences. For example, temperature and pressure sensors can be added to any part of the engine cooling system. Few of the important results can be seen in Table 7.

Table 7. Output file results

Main Engine Fuel Consumption [l/h] & [kg/h]	Total Heat Load [kW]
Cumulative Main Engine Fuel Consumption [ton]	Oil Fired Boiler Fuel Consumption [kg/h]
Main Engine Mechanical Power [kW]	Cumulative Oil Fired Boiler Consumption [ton]
Main Engine Energy Produced [kWh]	Oil Fired Boiler Energy Produced [kWh]
Main Engine Energy Consumption [kWh]	Oil Fired Boiler Energy Consumption [kWh]
Main Engine SFOC [g/kWh]	Exhaust Gas Boiler Steam Power Produced [kW]
Main Engine HT Heat Dissipation [kW]	Exhaust Gas Boiler Energy Produced [kWh]
Main Engine LT Lube Oil Heat Dissipation [kW]	Evaporator Power [kW]
Main Engine LT Scavenge Air Heat Dissipation [kW]	Evaporator Energy Consumption [kW]
Main Engine Exhuast Gas Mass Flow [kg/s]	Sea Water Cooling Power [kW]
Main Engine Exhuast Gas Temperature [C]	Sea Water Pump Energy Consumption [kWh]
Auxiliary Engine Fuel Consumption [l/h] & [kg/h]	Sea Water Pump Mass Flow [kg/h]
Cumulative Auxiliary Engine Fuel Consumption [ton]	Total Fuel Consumption [ton]
Total Generator Load [kW]	
Auxiliary Engine Energy Produced [kWh]	
Auxiliary Engine Energy Consumption [kWh]	

Since output file is printed automatically and cannot be modified, another results file is created for easier usage. This results file is a copy of output file added with graphs and can be modified according to user's preferences. Since simulation results might sometimes include simulation residues *i.e.* results being very small, but are in fact zero, the numbers in results file are rounded so this is not shown for easier to read.

4.8. Development challenges

The development of this simulator tool was difficult and time consuming. The largest obstacles occurred while modelling the cooling circuit. As mentioned earlier, the cooling circuit consists of four different variables. This requires precise management i.e. all of the equations consisting of these variables are to be solved synchronously. This combined with the desired simplicity of the model concluded to many error messages from the program about under-definition of the model. These challenges were either adding more details to the model or just by starting again with a different approach.

Since the reference block sets the temperature and pressure to a preselected certain value from reference point onwards on the loop, the placement of the reference block in each loop of cooling circuit demands a thorough thought. The results from the loop are solved by comparing the temperature and pressure against the reference point from the loop, and if placed in the wrong place, the temperature and pressure changes to this certain value in the wrong point with no delay, which in turn affects the results. Therefore, a precise knowledge about the loop construction is needed in order to model the cooling circuit perfectly.

One continuous problem was the rigidity of the model. Due to the simplicity of the model, it became highly rigid. This is undesirable in simulations, since simulation results are never exact values, but just the imitation of calculated values, and thus, the model is required to be more flexible. A simulation solver was changed from fixed-step solver to variable-step solver for more flexibility.

5. Improving ship energy efficiency with the simulator

The improvement of ship energy efficiency was done with two different cases:

- Modification of steam system
- Optimization of cooling circuit components

Their detailed explanations and objective are explained below. With these two cases the features and capacities of certain components such as boilers and pumps can be dimensioned more accurately according to specific operation profile of the vessel. Modifications also help to achieve a better understanding of the effects of different parameters.

5.1. Modification of steam system

First improvement was to modify the main engine WHT (Waste Heat Recovery) boiler for better steam production. In a case of very efficient main engine, there is not much heat to be recovered due to exhaust gas temperatures being low. Since steam is always needed and if this is not produced enough with EGB, this leads to the point, where additional heat must be produced with OFB. For this study two alternatives were studied:

- 6 bar steam producing boiler
- 7 bar steam producing boiler

The temperature of 6 bar steam system is lower than in 7 bar steam system. This makes it possible to lower the exhaust gas temperature after EGB; therefore, higher theoretical steam production rate is possible.

Steam production data was acquired from boiler manufacturer and inserted to the input file, which is transferred to the simulation model. Every steam production data is distinctive to its parent engine, due to different exhaust gas outlet temperatures. Therefore, a modification with new engine needs to have a new steam production data available. The parameters used are seen in Table 8 and Table 9.

Table 8. Engine and boiler parameters in 7 bar steam system (reference case)

Main engine data	USED VALUE (ISO-conditions)													
Engine load, % of MCR	[%]	10 %	20 %	30 %	40 %	50 %	60 %	65 %	70 %	75 %	80 %	85 %	90 %	95 %	100 %
RPM from engine project guide	[rpm]				72,9	78,6	83,5	85,8	87,9	89,9	91,9	93,8	95,6	97,3	99,0
SFOC from engine project guide	[g/kWh]				163,8	161,2	159,1	158,2	158,3	158,6	158,9	160,4	162,2	163,1	164,2
Heat dissipation to HT circuit (Jacket	[kW]				520,0	590,0	660,0	700,0	730,0	770,0	800,0	840,0	870,0	910,0	940,0
Main lubrication oil heat (LT circuit)	[kW]				420,0	460,0	500,0	520,0	530,0	540,0	560,0	570,0	580,0	590,0	590,0
Scavenge air cooler heat (LT circuit)	[kW]				420,0	670,0	960,0	1100,0	1270,0	1450,0	1600,0	1610,0	1620,0	1760,0	1890,0
Main engine exhaust gas temperature	[°C]				219,6	204,7	197,2	195,5	194,4	194,7	195,9	221,5	248,5	253,9	260,7
Main engine exhaust gas mass flow	[kg/s]				6,1	7,4	8,6	9,1	9,7	10,3	10,8	11,0	11,0	11,4	11,8
Main engine exhaust gas outlet tempe	[°C]				188,4	183,6	181,0	180,6	180,2	180,4	180,6	191,7	202,8	205,6	208,4
Steam output	[kg/h]				287,0	234,0	207,0	206,5	206,0	223,0	240,0	499,0	758,0	846,0	934,0
Steampower transferred	[kW]				201,0	164,0	145,0	144,5	144,0	156,0	168,0	349,0	530,0	591,5	653,0
Main engine cylinder oil consumption	[g/kWh]				0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Main engine sfoc (with tolerance, etc.	[g/kWh]				173,6	170,9	168,6	167,7	167,8	168,1	168,4	168,4	170,3	171,3	172,4

Table 9. Engine and boiler parameters in 6 bar steam system

Main engine data	USED VALUE (ISO-conditions)													
Engine load, % of MCR	[%]	10 %	20 %	30 %	40 %	50 %	60 %	65 %	70 %	75 %	80 %	85 %	90 %	95 %	100 %
RPM from engine project guide	[rpm]				72,9	78,6	83,5	85,8	87,9	89,9	91,9	93,8	95,6	97,3	99,0
SFOC from engine project guide	[g/kWh]				163,8	161,2	159,1	158,2	158,3	158,6	158,9	160,4	162,2	163,1	164,2
Heat dissipation to HT circuit (Jacket v	[kW]				520,0	590,0	660,0	700,0	730,0	770,0	800,0	840,0	870,0	910,0	940,0
Main lubrication oil heat (LT circuit)	[kW]				420,0	460,0	500,0	520,0	530,0	540,0	560,0	570,0	580,0	590,0	590,0
Scavenge air cooler heat (LT circuit)	[kW]				420,0	670,0	960,0	1100,0	1270,0	1450,0	1600,0	1610,0	1620,0	1760,0	1890,0
Main engine exhaust gas temperature	[°C]				219,6	204,7	197,2	195,5	194,4	194,7	195,9	221,5	248,5	253,9	260,7
Main engine exhaust gas mass flow	[kg/s]				5,9	7,4	8,6	9,1	9,7	10,3	10,8	11,0	11,0	11,4	11,8
Main engine exhaust gas outlet tempe	[°C]				184,9	180,2	177,8	177,4	177,0	177,5	177,9	188,8	199,6	202,4	205,2
Steam output	[kg/h]				319,0	272,0	250,0	251,5	253,0	272,0	291,0	551,5	812,0	902,0	992,0
Steampower transferred	[kW]				223,0	190,0	174,0	175,0	176,0	189,5	203,0	384,5	566,0	629,0	692,0
Main engine cylinder oil consumption	[g/kWh]				0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Main engine sfoc (with tolerance, etc.	[g/kWh]				173,6	170,9	168,6	167,7	167,8	168,1	168,4	168,4	170,3	171,3	172,4

5.2. Optimization of cooling circuit components

The second improvement was to study the effects of adding a variable speed drive controlled seawater pump and lowering LT setpoint. The main sea water cooling pump is one of the largest energy consumers of the ship machinery auxiliaries and all the cooling circuit components are dimensioned to maximal cooling load in maximum specified conditions. Therefore, cooling circuit along its components is a potential saving target.

The study was made with three different cases seen in Table 10. Case 1 acts as a base case without SW pump control and LT setpoint of +32 °C. Case 2 is similar as case 1 except for added SW pump-control. Generally SW pumps are used two in parallel. These SW pumps control is limited to 50% mass flow as a practical limit, and thus the total limit is 25% of the total flow. Case 3 has a lower LT setpoint of +25 °C and due to this, main engine parameters have to be updated also. LT setpoint is possible to lower due to three-way valve attached to LT-circuit before central cooler. Three-way valve works as a bypass, which regulates one part of the cooling water to the central cooler and the rest to the pipe passing central cooler.

Table 10. Different cases tested for VSD SW Pump Study

Setting	**Case1**	**Case2**	**Case3**
Name	**Base Case**	**PumpControl**	**ME-Update**
Steam System	7 bar	7 bar	7 bar
SW Pump	No Control	Controlled	Controlled
LT Setpoint	+32 C	+32 C	+25 C
ME-Update due to LT	No	No	Yes

6. Results

6.1. Development of the simulator

With the fictitious operation profile presented in section 4.4 a list of results are obtained. This list was seen in Table 7. Some of the essential graphs produced from the results file are presented below with their respective explanations. Only general results are presented since some of the results listed in Table 7 are only for closer and specific analysis of possible different improvement modifications and, therefore these results are not presented here.

Figure 29 shows the main engine fuel oil consumption in a unit of kg/h. This graph is a general graph that can be acquired from each engine, also from auxiliary engines. The transit phases are rapid due to rapid changes in the input file.

The total electric power produced from the diesel generators is presented in Figure 30. Power produced from each engine and mechanical power from the main engine is also possible to acquire.

Fuel oil consumption in a unit of l/h for diesel generator 1 is seen in Figure 31. This is also possible to apply for other diesel generators.

Steam power produced from the EGB is presented in Figure 32. Steam power produced from the OFB is also possible to acquire.

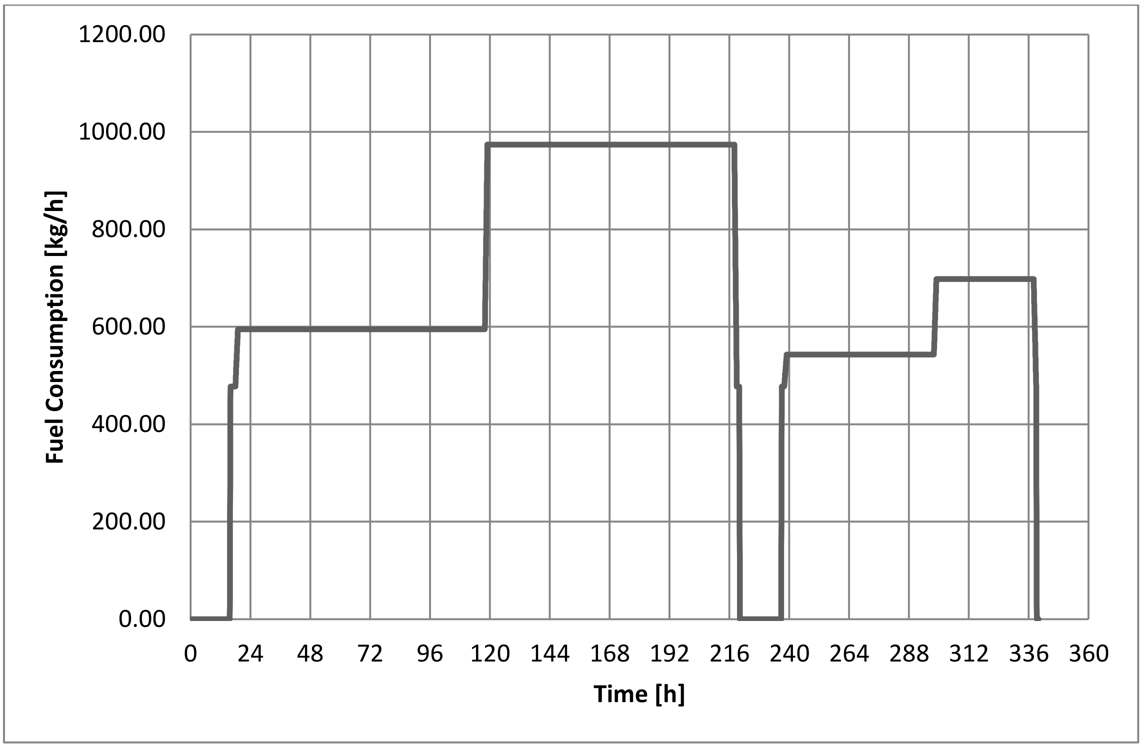


Figure 29. Main engine fuel oil consumption during the operation

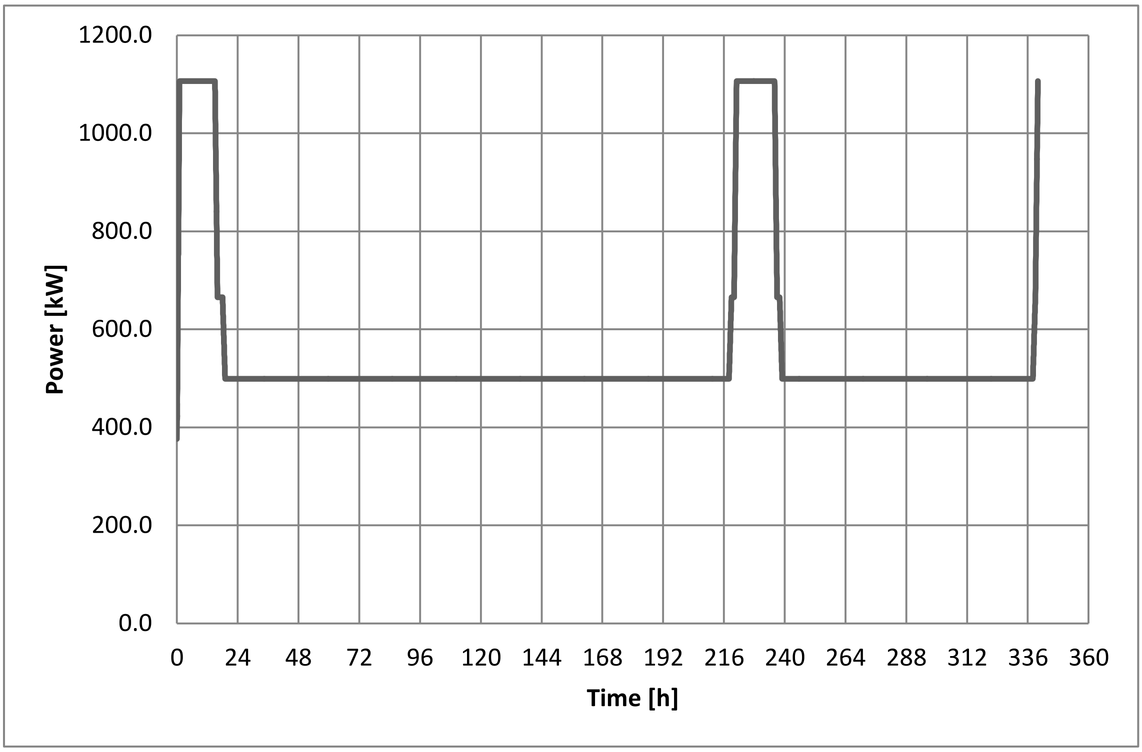


Figure 30. Total electric power

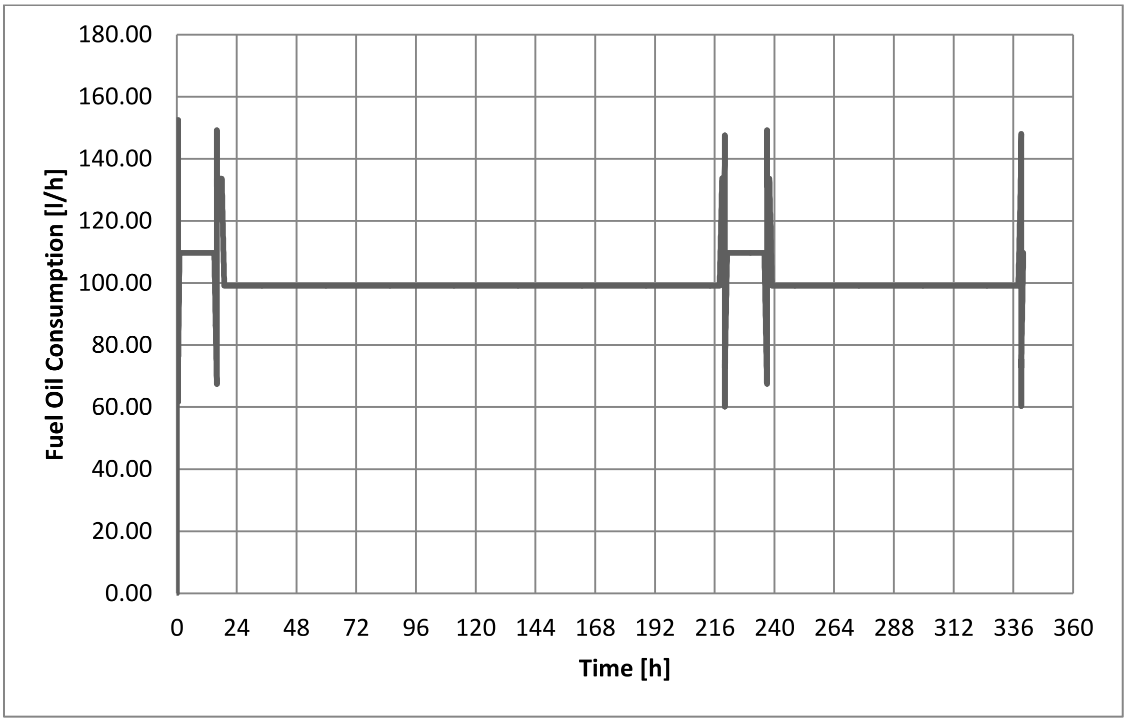


Figure 31. Fuel oil consumption of diesel generator 1

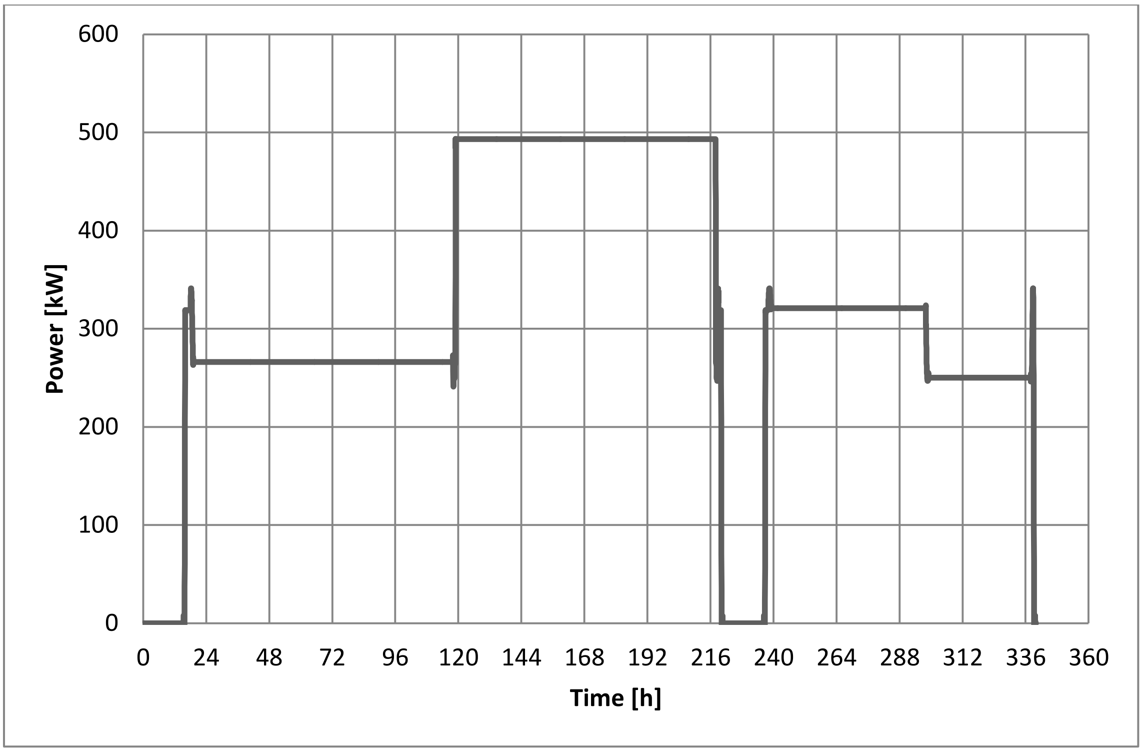


Figure 32. Steam power from exhaust gas boiler

6.2. Modification target

The results of modification targets are seen below. Only essential results are presented, which are affected due to modification and have some impact on the system.

6.2.1. Modification of steam system

Dimensioning of the main engine waste heat recovery boiler has a large impact on the energy produced from EGB as can be seen in Figure 33. About 10 % more energy is produced from EGB with the 6 bar steam system than from 7 bar system. This is due to lower steam temperature in 6 bar steam system, which enables lowering the exhaust gas temperature after the boiler, thus increasing the steam production rate.

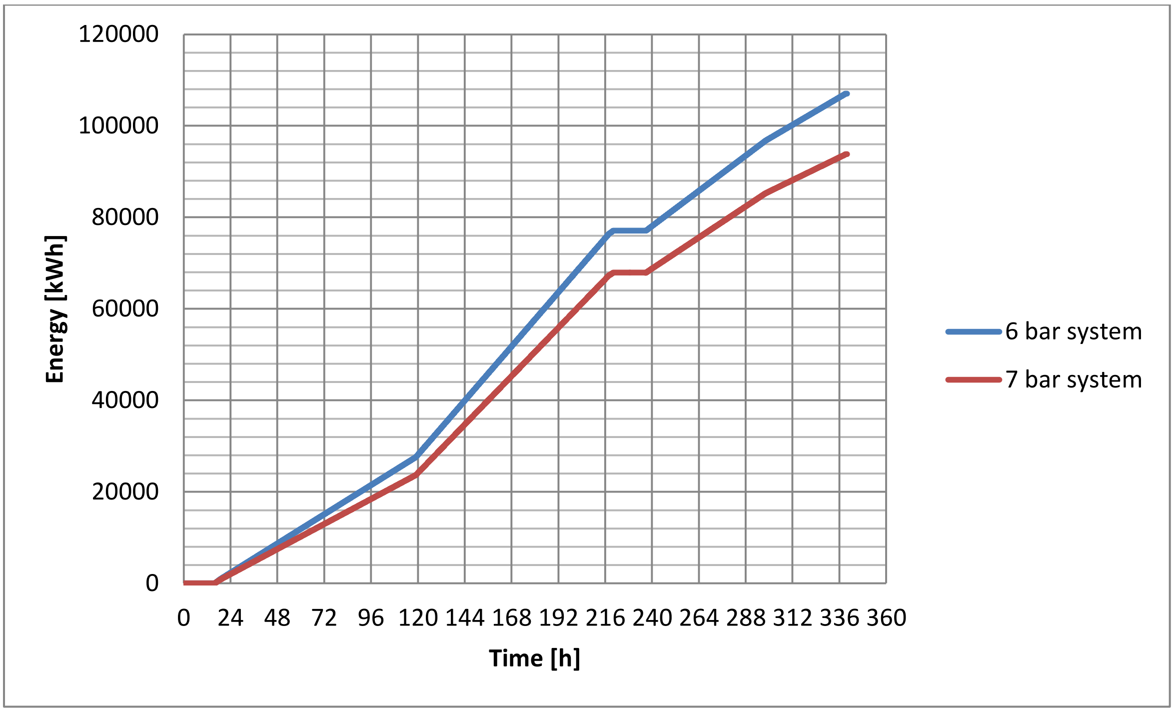


Figure 33. Produced Energy from EGB

Figure 34 shows the energy produced from the OFB. The difference in energy produced between 6 bar steam system and 7 bar system equals to the difference in energy produced from the EGB. This is because the heat demand is the same in both cases, and thus less energy is needed from OFB to compensate the heat otherwise produced from EGB.

One notable detail seen in Figure 34 is OFB usage from 120h to 220h. In 6 bar steam system OFB is not needed, since enough heat energy is produced from the EGB. This not only saves fuel, but also decreases the OFB maintenance costs.

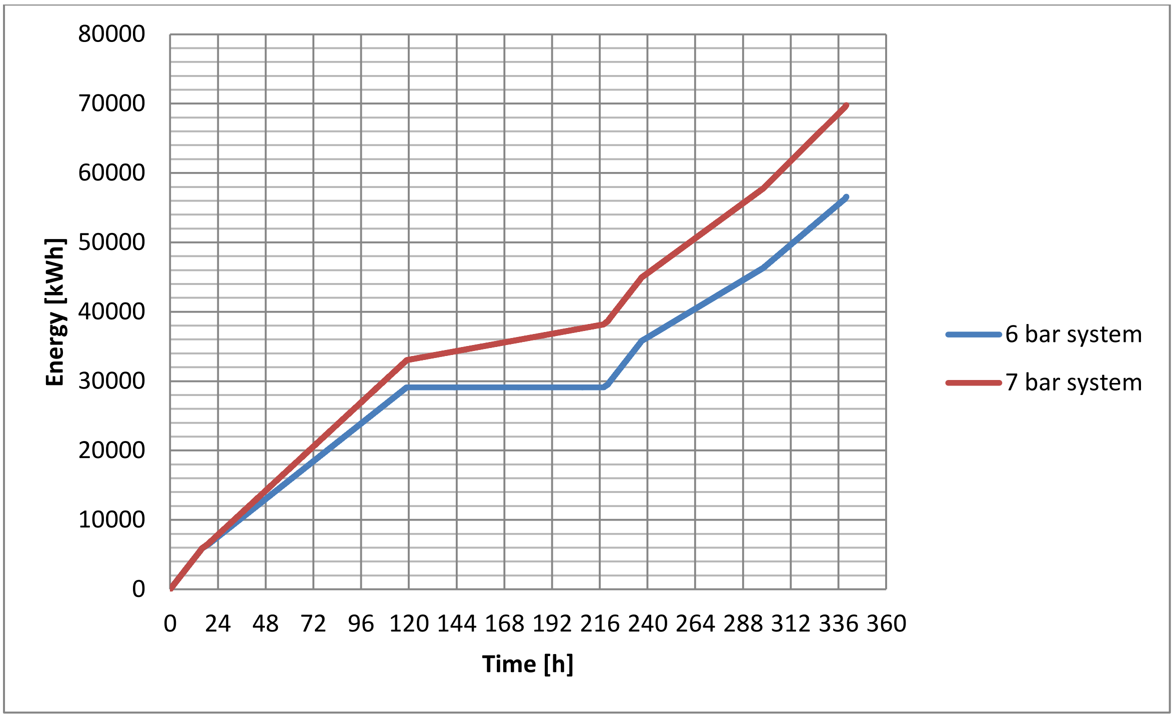


Figure 34. Produced energy from OFB

Theoretical fuel savings with this fictitious two week operation profile is about 1300 kg as can be seen in Figure 35. This equates to about 22% decrease compared to the 7 bar system. Since this calculation was done with only two week period, fuel savings for a one year operation would have theoretically been 33,8 ton.

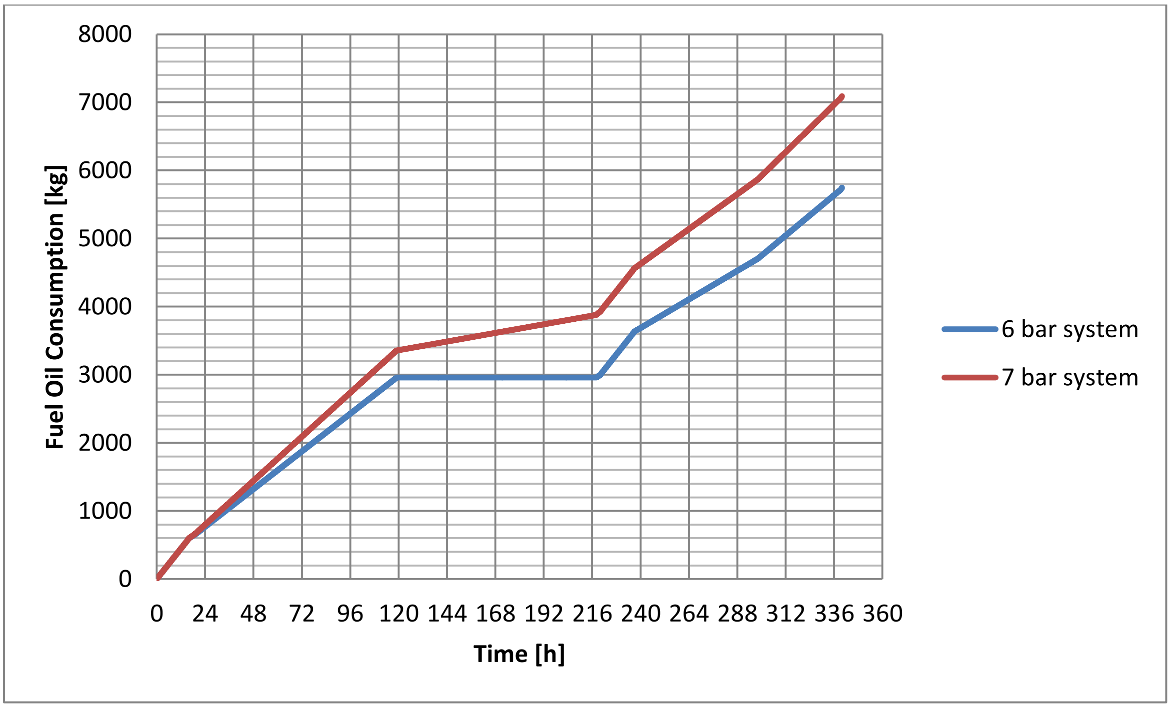


Figure 35. OFB fuel oil consumption

Figure 36 and Figure 37 presents the total fuel energy utilization. Using a 6 bar steam system instead of 7 bar system decreases the energy that the OFB utilizes from 2,5 % to

2,0 %. This 0,5 percentage point decrease equates to increase in utilized energy of EGB. There is also a 0,3 percentage point increase in propulsion power. However, the modification in steam system does not effect on the propulsion system in any level. This is only due to its portion becoming relatively larger, since total fuel energy used is less in 7 bar system than in 6 bar system. The total efficiency is improved from 71,5 % to 71,8 %.

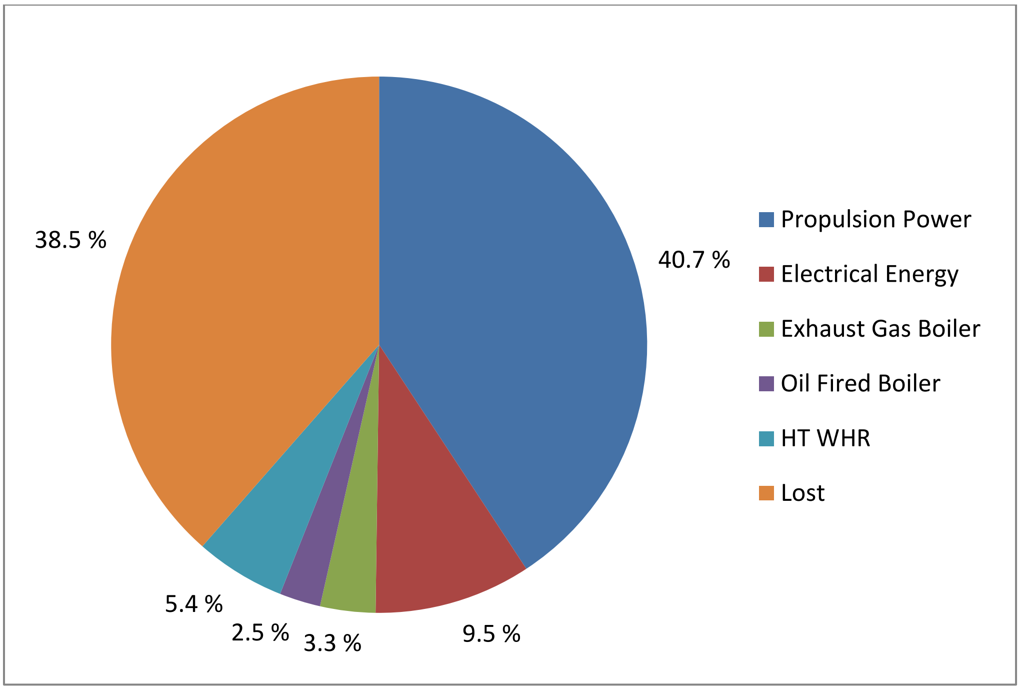


Figure 36. Fuel energy utilization in 7 bar system

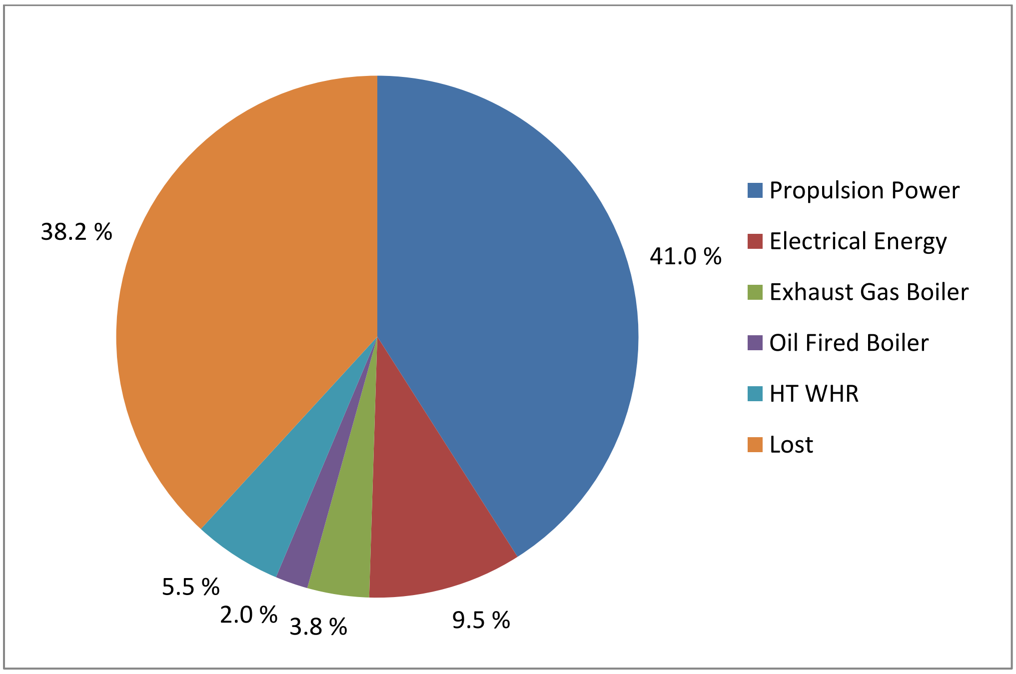


Figure 37. Fuel energy utilization in 6 bar system

6.2.2. Variable speed drive controlled seawater pump

Three different simulations with the cases mentioned in section 5.2 were run and their respective mass flows are shown in Figure 38. With the base case mass flow is clearly constant value of 147 kg/h. With the VSD controlled cases the mass flow varies according to heat energy brought to central cooler. This was because the pump control aims for creating a maximal temperature difference over the central cooler. Dropping the sea water pump mass flow reduces the consumed energy, which in turn decreases the total fuel consumption of auxiliary engines as can be seen in Figure 39. Figure 40 shows the number of auxiliary engines which are online during the voyage. There are two engines online more often in base case than in other cases, thus utilizing VSD controlled pump also decreases maintenance costs of auxiliary engines.

One can notice that the mass flow is larger in case 3 (ME-Update) than in case 2 (Pump Control). This is due to lower LT setpoint of +25 °C. Lower LT setpoint affects on the LT outlet water temperature from the central cooler, which according to heat flow rate equations presented in 4.6.4 increases the mass flow of SW loop through central cooler. However, there is a physical limit to lowering LT setpoint, which is the sea water temperature. Practically there is also a pinch point, which acts as minimum temperature where heat from the hot stream transfers a cold stream. Therefore LT setpoint of +25 °C is not possible in tropical conditions.

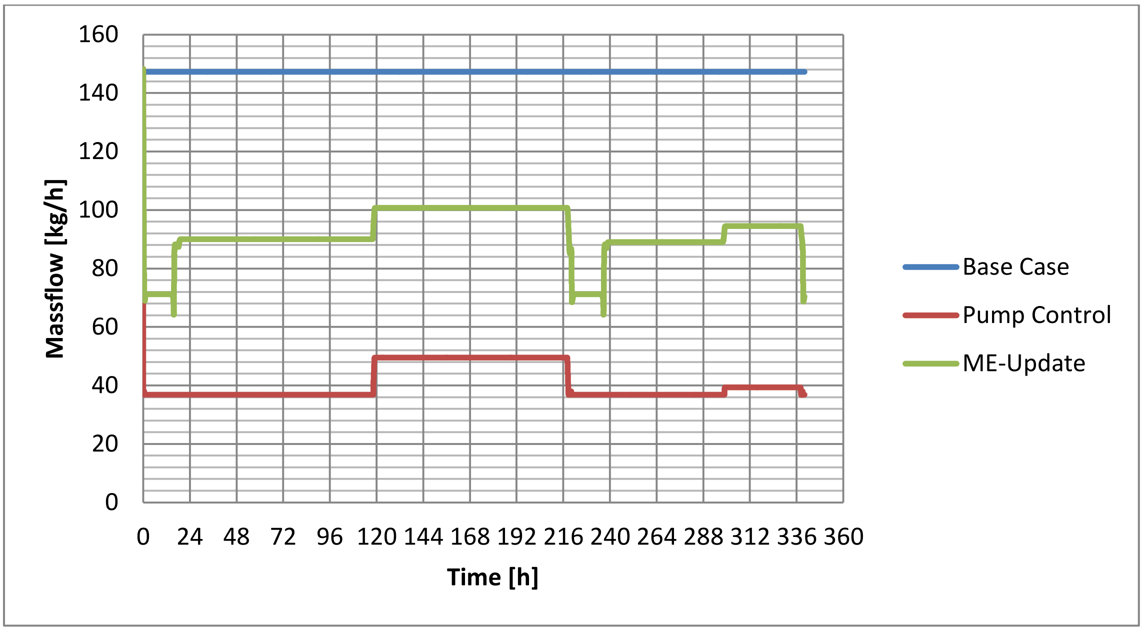


Figure 38. Sea water pump mass flow

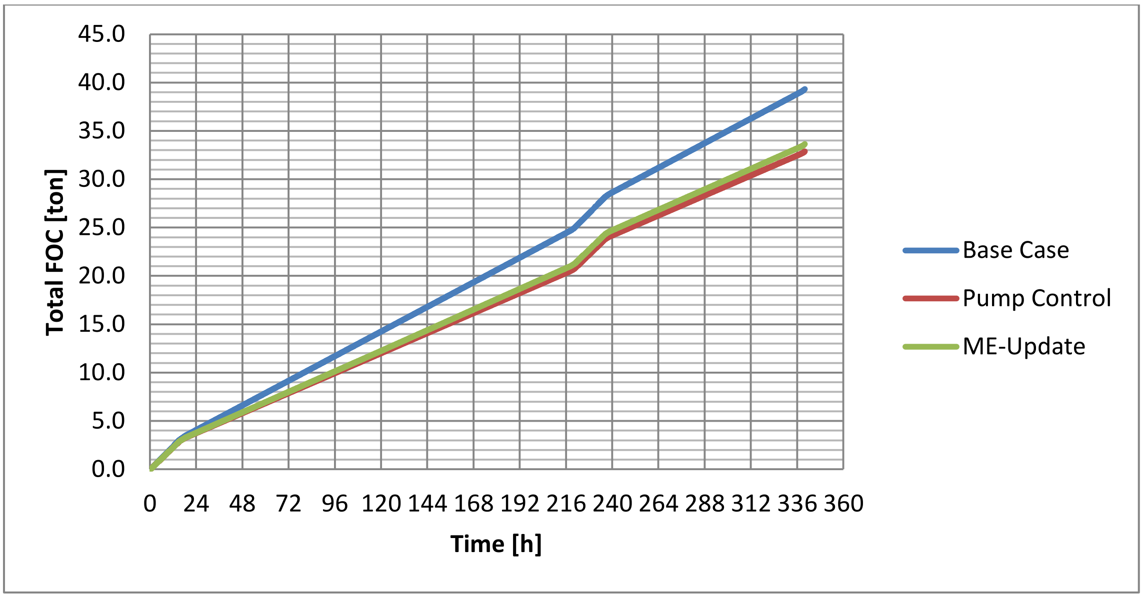


Figure 39. Cumulative auxiliary engines fuel oil consumption

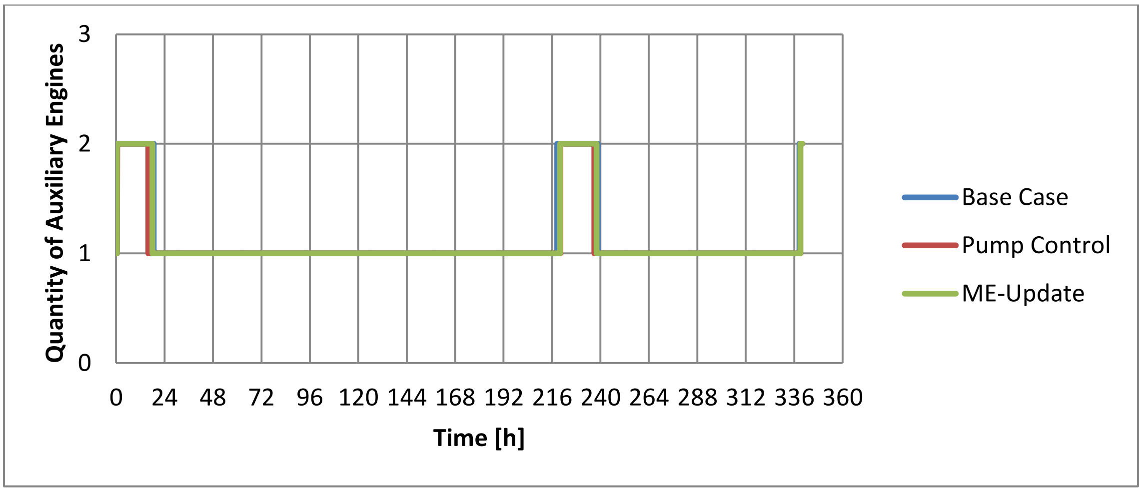


Figure 40. Auxiliary engines modes

As mentioned before, the mass flow is higher in case 3. This alternative uses more energy as can be seen in Figure 41 and thus increases fuel oil consumption of auxiliary engines, which was seen in Figure 39. However, lower LT water temperature affects the engine parameters such as SFOC as can be seen in Figure 42. This compensates the total fuel consumption and thus according to Figure 43 the total fuel oil consumption is nearly the same amount.

Interestingly, lower LT water temperature did not have a remarkable effect on the fuel oil consumption. However, lowering LT water temperature has some additional benefits, such as possible increased efficiency of the water-cooled electrical equipment that are on the same circuit. However, this was not included in this calculation.

The benefits of VSD controlled pump are estimated to be around 6,5 tons of fuel savings during the two week operation. This equals to 170 tons of fuel savings for a one year operation. With current HFO price of $650, money savings are over $100 000.

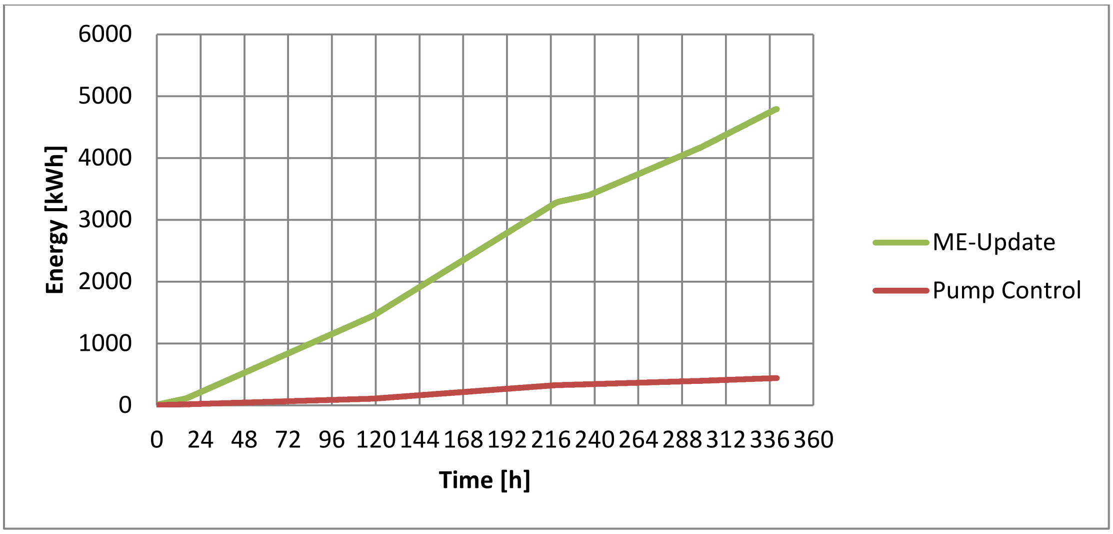


Figure 41. Energy used for running sea water pump in cases 2 and 3

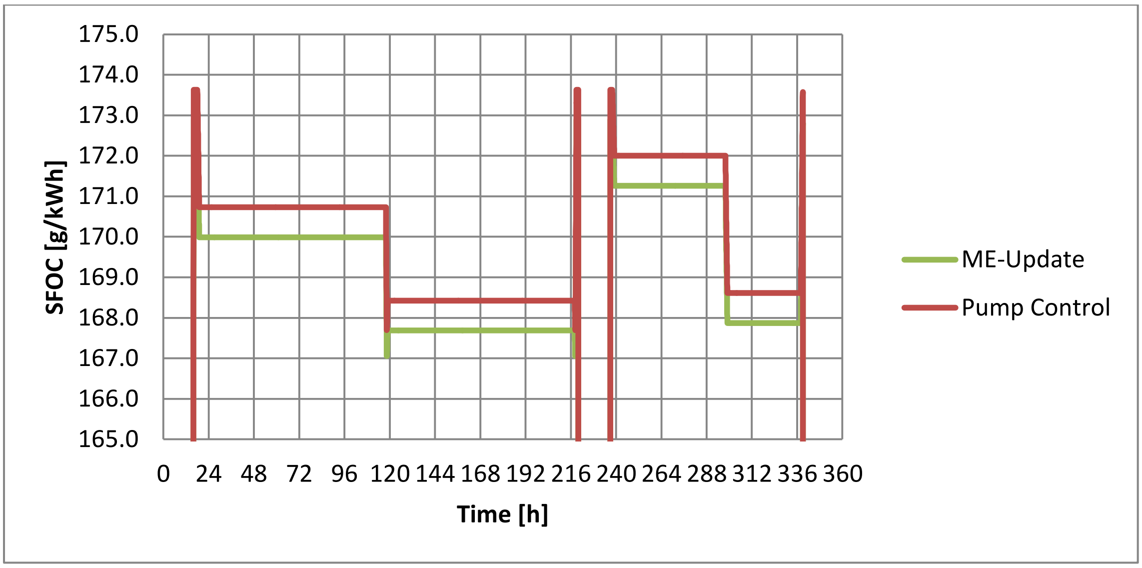
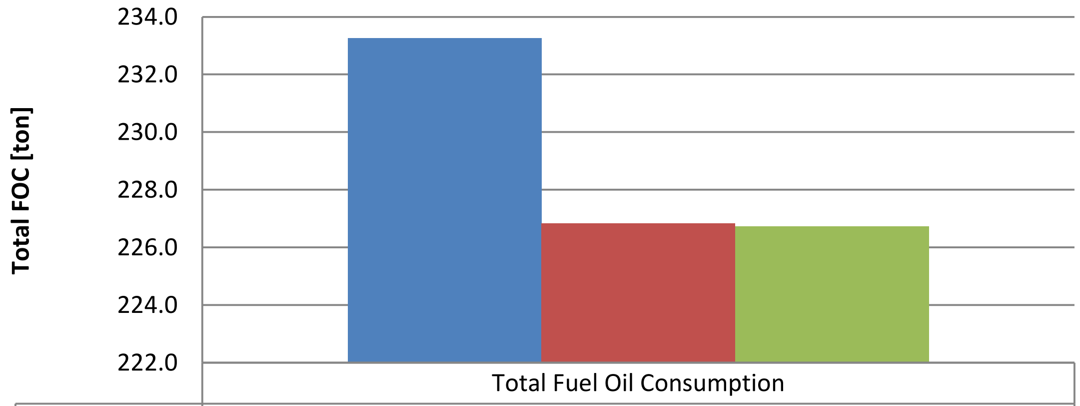


Figure 42. Main engine SFOC for cases 2 and 3



	Total Fuel Oil Consumption
🟦 Base Case	233.3
🟥 Pump Control	226.8
🟩 ME-Update	226.7

Figure 43. Total fuel oil consumption of different cases

7. Conclusion

In this thesis an approach for developing a simulator tool for concept phase is proposed. The simulator model consists of all main machinery components and focuses more on a simple approach of the case vessel. The simulator tool is mainly designed to be used by all project engineers of general discipline. The excel-based input-file, which includes all the essential data to run the simulator tool, is developed so that the input is given according to available data in the concept phase. The tool may be very useful for dimensioning of the key components. A quick analysis of different components can be done just by changing the parameters in the input-file. The importance of utilizing such tools in the early phase of design increases the freedom to change the design and decreases the cost to do so as was identified earlier.

The simulator tool enables ship designers to take energy efficient ship design to a new level. Compared to energy balance tool, the simulation tool can save working hours, but still have a better and more accurate analysis of the energy utilization. The key benefit is that the utilization of the tool is divided in two sections. All the necessary data can be input in the simple and light Excel-type calculations and development of more complex entities can be done in the simulation section, which brings more user-friendliness to the simulation tool.

The simulator model consists of main engine, diesel generators, exhaust gas boiler, oil-fired boiler, cooling water circuit and an evaporator. They were built as simple as possible, since the purpose of this simulation tool was to acquire fast and rough results such as fuel consumption and exhaust gas energy production as a function of time.

The time factor is also essential in a sense that unlike the static energy balance tools used in the concept phase today that present their results only as a cumulative total, the simulation tool presents results dynamically for each time step. This enables the designer to see more closely the effects of possible tuning of the components on certain time step. For example, changing the LT setpoint changes immediately the consumed energy of the sea water cooling pump. The exact amount of this change is now possible to receive due to the time factor.

Since every vessel has a different operation profile according to the vessel type and their transport mission, designing and optimising the vessel for a single design point is not very efficient. This simulator tool can easily calculate the total effect on different operating conditions or machinery components. This way a designer can try different possible operation profiles and perhaps switching between different main engines or just changing the tuning of the main engine. Changing the values of the input-file and running the simulation tool is all that the model user is required to do.

In addition to the development of the simulator tool, two quick studies were made to investigate the possible improvement of ship energy efficiency of a handysize bulk carrier. These studies were modification of steam system from a 6 bar system to a 7 bar system and adding variable speed drive to sea water pump. The first study provided us some useful information about the decreasing effect of 6 bar steam system on total fuel consumption. The second study proved that using variable speed drives lowers fuel consumption in conditions where maximal cooling is not necessary. This also lowers the consumed electricity, which may lead to utilizing one less auxiliary engine during some time of operation. The result of this is lower maintenance costs.

There were some difficulties during the development of the simulator tool. The simplicity of the model brought many error messages due to under-definition of the model. This under-definition causes the model to crash during simulation, because it cannot continue with too little information about the starting values or the definition of the model itself might be too simple. These were solved by defining the model more accurately, or to start again with a different approach.

Future work should be conducted, for example, to develop more blocks to simulation model such as waste heat recovery components, for example power turbine utilizing Organic Rankine Cycle system. This way simulator tool could have a whole library of different components and new machineries for different vessel types could be built. Also, maybe taking the simulator model a bit further for acquiring more accurate results might benefit the design process. Another important work could be validating the results of the simulation tool.

List of figures and tables

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Appendix 1 Input file (Page 1/4)

MAIN ENGINES

Main engine - Type 1	pcs	1
MAN B&W 5S50ME-B9.3 Tier II, FPP	kW (each)	6050
Engine rpm	rpm	99
Fuel lower calorific value from Project Guide	kJ/kg	42700
Fuel Density	ton/kg	0.88
Basic fuel consumption tolerance	%	5
Build-on pumps	yes/no	no

Exhaust gas boiler

Alfa Laval Aalborg OC-TCi

Main engine data

USED VALUE (ISO-conditions)

Engine load, % of MCR	[%]	10 %	20 %	30 %	40 %	50 %	60 %	65 %	70 %	75 %	80 %	85 %	90 %	95 %	100 %
RPM from engine project guide	[rpm]				72.9	78.6	83.5	85.8	87.9	89.9	91.9	93.8	95.6	97.3	99.0
SFOC from engine project guide	[g/kWh]				163.2	160.6	158.5	157.6	157.7	158.0	158.3	159.8	161.6	162.5	163.6
Heat dissipation to HT circuit (Jacket water)	[kW]				520.0	590.0	660.0	690.0	730.0	760.0	800.0	830.0	860.0	900.0	930.0
Main lubrication oil heat (LT circuit)	[kW]				420.0	460.0	500.0	510.0	530.0	540.0	550.0	560.0	570.0	580.0	590.0
Scavenge air cooler heat (LT circuit)	[kW]				440.0	690.0	980.0	1130.0	1310.0	1490.0	1640.0	1660.0	1670.0	1800.0	1940.0
Main engine exhaust gas temperature	[°C]				219.6	204.7	197.2	195.5	194.4	194.7	195.9	221.5	248.5	253.9	260.7
Main engine exhaust gas mass flow	[kg/s]				5.9	7.4	8.6	9.1	9.7	10.3	10.8	11.0	11.0	11.4	11.8
Main engine exhaust gas outlet temperature	[°C]				184.9	180.2	177.8	177.4	177.0	177.5	177.9	188.8	199.6	202.4	205.2
Steam output	[kg/h]				319.0	272.0	250.0	251.5	253.0	272.0	291.0	551.5	812.0	902.0	992.0
Steampower transferred	[kW]				223.0	190.0	174.0	175.0	176.0	189.5	203.0	384.5	566.0	629.0	692.0
Main engine cylinder oil consumption	[g/kWh]				0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Main engine sfoc (with tolerance, etc.)	[g/kWh]				173.0	170.2	168.0	167.1	167.2	167.5	167.8	167.8	169.7	170.6	171.8

ISO / Design conditions

Engine load, % of MCR	[%]	10 %	20 %	30 %	40 %	50 %	60 %	65 %	70 %	75 %	80 %	85 %	90 %	95 %	100 %
RPM from engine project guide	[rpm]				72.9	78.6	83.5	85.8	87.9	89.9	91.9	93.8	95.6	97.3	99.0
SFOC from engine project guide	[g/kWh]				163.2	160.6	158.5	157.6	157.7	158.0	158.3	159.8	161.6	162.5	163.6
Heat dissipation to HT circuit (Jacket water)	[kW]				520	590	660	690	730	760	800	830	860	900	930
Main lubrication oil heat (LT circuit)	[kW]				420	460	500	510	530	540	550	560	570	580	590
Scavenge air cooler heat (LT circuit)	[kW]				440	690	980	1130	1310	1490	1640	1660	1670	1800	1940
Main engine exhaust gas temperature	[°C]				219.6	204.7	197.2	195.5	194.4	194.7	195.9	221.5	248.5	253.9	260.7
Main engine exhaust gas mass flow	[kg/s]				5.9	7.4	8.6	9.1	9.7	10.3	10.8	11.0	11.0	11.4	11.8
Main engine exhaust gas outlet temperature	[°C]				184.9	180.2	177.8	177.4	177.0	177.5	177.9	188.8	199.6	202.4	205.2
Steam output	[kg/h]				319.0	272.0	250.0	251.5	253.0	272.0	291.0	551.5	812.0	902.0	992.0
Steampower transferred	[kW]				223.0	190.0	174.0	175.0	176.0	189.5	203.0	384.5	566.0	629.0	692.0
Main engine cylinder oil consumption	[g/kWh]														
Main engine sfoc (with tolerance, etc.)	[g/kWh]				173.0	170.2	168.0	167.1	167.2	167.5	167.8	167.8	169.7	170.6	171.8

Tropical conditions

Engine load, % of MCR	[%]	10 %	20 %	30 %	40 %	50 %	60 %	65 %	70 %	75 %	80 %	85 %	90 %	95 %	100 %
RPM from engine project guide	[rpm]	0.0	0.0	0.0	72.9	78.6	83.5	85.8	87.9	89.9	91.9	93.8	95.6	97.3	99.0
SFOC from engine project guide	[g/kWh]				166.3	163.6	161.4	160.6	160.7	161.0	161.3	162.8	164.6	165.5	166.7
Heat dissipation to HT circuit	[kW]				530	600	670	700	740	780	810	850	880	920	950
Main lubrication oil heat (LT circuit)	[kW]				420	470	500	520	540	550	560	570	580	590	600
Heat dissipation to LT circuit	[kW]				460	720	1010	1160	1350	1530	1530	1680	1710	1850	1980
Main engine exhaust gas temperature	[°C]				252.0	236.4	228.8	227.2	226.1	226,,4	227.6	253.2	280.2	285.6	292.4
Main engine exhaust gas mass flow	[kg/s]				5.8	7.5	8.1	8.6	9.1	9.7	10.1	10.3	10.3	10.7	11.1
Main engine exhaust gas outlet temperature	[°C]				196.1	191.8	189.8	189.6	189.4	190.0	190.6	201.3	211.9	214.7	217.5
Steam output	[kg/h]				485.0	466.0	472.0	488.0	504.0	534.0	564.0	817.0	1070.0	1166.5	1263.0
Steampower transferred	[kW]				338.0	325.0	329.0	340.5	352.0	372.5	393.0	569.5	746.0	813.5	881.0
Main engine cylinder oil consumption	[g/kWh]														
Main engine sfoc (with tolerance, etc.)	[g/kWh]				176.3	173.4	171.1	170.2	170.3	170.7	171.0	170.9	172.8	173.8	175.0

Winter conditions

Engine load, % of MCR	[%]	10 %	20 %	30 %	40 %	50 %	60 %	65 %	70 %	75 %	80 %	85 %	90 %	95 %	100 %
RPM from engine project guide	[rpm]	0.0	0.0	0.0	72.9	78.6	83.5	85.8	87.9	89.9	91.9	93.8	95.6	97.3	99.0
SFOC from engine project guide	[g/kWh]				160.5	157.9	155.8	155.0	155.1	155.4	155.6	157.1	158.9	159.7	160.9
Heat dissipation to HT circuit	[kW]				510	580	650	680	710	750	780	820	850	880	920
Main lubrication oil heat (LT circuit)	[kW]				410	450	490	500	520	530	540	560	560	570	580
Heat dissipation to LT circuit	[kW]				430	690	970	1110	1290	1470	1620	1630	1640	1780	1910
Main engine exhaust gas temperature	[°C]				194.6	180.3	172.8	171.1	170.0	170.3	171.5	197.1	224.1	229.5	236.3
Main engine exhaust gas mass flow	[kg/s]				6.3	7.6	8.9	9.4	10.0	10.6	11.1	11.3	11.4	11.8	12.2
Main engine exhaust gas outlet temperature	[°C]				175.9	170.9	168.1	167.6	167.0	167.4	167.7	178.8	189.8	192.6	195.3
Steam output	[kg/h]				177.0	107.0	62.0	53.0	44.0	53.5	63.0	324.5	586.0	670.0	754.0
Steampower transferred	[kW]				123.0	75.0	43.0	37.0	31.0	37.5	44.0	226.5	409.0	467.5	526.0
Main engine cylinder oil consumption	[g/kWh]														
Main engine sfoc (with tolerance, etc.)	[g/kWh]				170.1	167.4	165.1	164.3	164.4	164.7	164.9	165.0	166.8	167.7	168.9

Appendix 1 Input file (Page 2/4)

AUXILIARY ENGINES

Auxiliary engines - Type 1	pcs	3
MAN 6L23/30H, Tier II	kW (each)	740
Engine rpm	rpm	720
Fuel lower calorific value from Project Guide	kJ/kg	42700.0
Fuel Density	ton/kg	0.88
Basic fuel consumption tolerance	%	5
Build-on pumps	yes/no	yes

Exhaust gas boiler (if applicable)

Alfa Laval Aalborg OC-TCi

Auxiliary engine data

Standard!! / Design conditions!!

Engine load, % of MCR	[%]	10 %	20 %	30 %	40 %	50 %	60 %	65 %	70 %	75 %	80 %	85 %	90 %	95 %	100 %
RPM from engine project guide	[rpm]	0.0	0.0	0.0	430.0	690.0	970.0	1110.0	1290.0	1470.0	1620.0	1630.0	1640.0	1780.0	1910.0
SFOC from engine project guide	[g/kWh]				204.3	201.0	198.3	197.3	197.4	195.3	195.6	195.9	198.1	199.1	196.5
Heat dissipation to HT circuit	[kW]				111	126	141	148	154	163	170	178	185	191	200
Heat dissipation to LT circuit	[kW]				166	182	199	203	211	215	219	227	227	231	235
Aux. engine exhaust gas temperature	[°C]				50	124	174	199	231	263	290	292	294	319	342.0
Aux. engine exhaust gas mass flow	[kg/s]				1.2	1.1	1.0	1.0	1.0	1.0	1.0	1.2	1.3	1.4	1.4
Aux. engine exhaust gas outlet temperature	[°C]														
Aux. engine cylinder oil consumption	[g/kWh]														
Aux. engine sfoc (with tolerance, etc.)	[g/kWh]	204.8	194.8	184.4	179.9	177.1	175.4	174.8	174.6	174.6	174.8	175.5	176.8	179.0	181.4

AMBIENT CONDITIONS

Ambient temperature	°C	25
Sea water temperature	°C	20
Ambient conditions		ISO

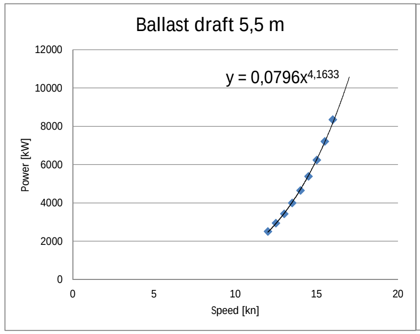
MACHINERY

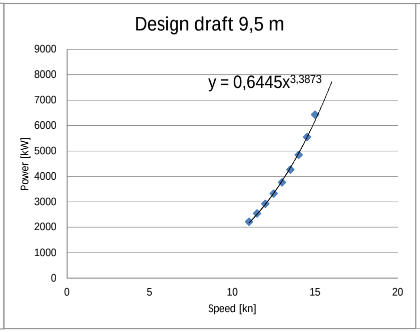
Propeller type	FPP/CPP	FPP
Oil fired boiler	pcs	1
	kW	500
Fuel Density used	ton/kg	0.88
Fuel lower calorific value from Project Guide	kJ/kg	42700
ME Exhaust Gas Boiler	kW (each)	700
AE Exhaust Gas Boiler	kW (each)	
Shaft generator	kWe	
Self unloading equipment (max load)	kW	
Self unloading equipment (average load)	kW	
Ballast water pumps (X pcs)	m3/h	
Ballast water treatment (max load)	kW	
Ballast water treatment (average load)	kW	
Ballast water pumps, including stripping pump (max load)	kW	
Ballast water pumps (average load)	kW	
HT-Loop Pump	m3/h	260
LT-Loop Pump	m3/h	425
Sea Water Pumps (2 pcs)	m3/h	530
Sea Water Pump Power	kW	57
Sea Water Pressure Rise	Pa	250000
LT-Loop Temperature setpoint of thermostat	°C	30
HT-Loop Temperature setpoint of thermostat	°C	80
Desired Sea Water Outlet Temperature	°C	42
Evaporator (1 pc) power	kW	500

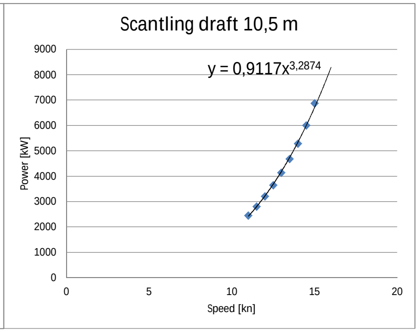
Appendix 1 Input file (Page 3/4)

SHIP DIMENSIONS

Class		
Flag		
Launched		
Delivered		
Operating area		
Autonomy	days	
Autonomy (range)	nm	20000
Distance	nm	20000.0
Maximum speed	kn	
Design service speed	kn	14.0
Crew		25
Length, OA	m	180.0
Length, BP	m	176.7
Beam	m	30.0
Depth	m	15.0
Scantling Draught	m	10.5
Design Draught	m	9.5
Displacement tonnage	t	
Deadweight	t	
Lightweight	t	
Gross tonnage	t	
Net tonnage	t	
Design deadweight	t	35 000
Scantling deadweight	t	40 000
Summer deadweight	t	
Cargo capacity	m3	50 000
Ballast capacity	m3	24 000
Fresh Water tanks	m3	150
DO tanks	m3	150.0
HFO tanks at 95% filled	m3	1425.0







SPEED POWER CURVE

Ballast draft	m	5.5
Design draft	m	9.5
Scantling draft	m	10.5

Sea margin 15%, Deliverd power at propeller PD

Ballast draft 5,5 m

Speed	[kn]	12	12.5	13	13.5	14	14.5	15	15.5	16	16.5	17
Power	[kW]	2519	2947	3440	4007	4655	5395	6241	7222	8361		

A	B
0.0796	4.1633

Design draft 9,5 m

Speed	[kn]	11	11.5	12	12.5	13	13.5	14	14.5	15	15.5	16
Power	[kW]	2210	2540	2912	3319	3765	4266	4837	5544	6428		

A	B
0.6445	3.3873

Scantling draft 10,5 m

Speed	[kn]	11	11.5	12	12.5	13	13.5	14	14.5	15	15.5	16
Power	[kW]	2455	2811	3207	3649	4136	4677	5284	6004	6875		

A	B
0.9117	3.2874

Appendix 1 Input file (Page 4/4)

ELECTRICAL POWER CONSUMPTION [kW]

			AT SEA		MANOEUVRING		LOADING/UNLOADING		HARBOUR	
		ABS POW.	POWER	COE	POWER	COE	POWER	COE	POWER	COE
1	AUX MACH. FOR PROPULSION	578	175	30 %	308	53 %	84	15 %	74	13 %
2	AUX MACH. FOR SHIP	99	23	23 %	19	19 %	23	23 %	23	23 %
3	HVAC AND HEATING	268	156	58 %	149	56 %	138	51 %	128	48 %
4	GALLERY, LAUNDRY, WORKSH.	187	55	29 %	26	14 %	38	20 %	70	37 %
5	CARGO, DECK, HULL	1847	32	2 %	96	5 %	750	41 %	34	2 %
6	LIGHTING	89	33	37 %	44	49 %	53	60 %	38	43 %
7	NAVIGATION AND AUTOMATION	50	18	36 %	16	32 %	13	26 %	9	18 %
8	CARGO FANS	0	0	0 %	0	0 %	0	0 %	0	0 %
9	BALLAST TREATMENT SYSTEM	0	0	0 %	0	0 %	0	0 %	0	0 %
10	SCRUBBERS	0	0	0 %	0	0 %	0	0 %	0	0 %
11				0 %		0 %		0 %		0 %
12				0 %		0 %		0 %		0 %
	TOTAL	3118	492		658		1099		376	

HEAT LOAD [kW]

		LOAD (ISO)	LOAD (Trop)	LOAD (Win)	LOAD (ISO)	LOAD (Trop)	LOAD (Win)	LOAD (ISO)	LOAD (Trop)	LOAD (Win)	LOAD (ISO)	LOAD (Trop)	LOAD (Win)
1	TANK HEATING	200	200	699	200	200	699	100	100	245	100	100	245
2	PIPE TRACING & FO FEED UNIT FOR ME	110	110	130	110	110	130	3	3	3	3	3	3
3	MACHINERY	50	50	50	50	50	50	99	99	99	99	99	99
4	HFO AND LO SEPARATORS	118	118	118	118	118	118	66	66	66	66	66	66
5	ME HT PREHEATING	0	0	0	0	0	0	79	79	79	79	79	79
6	AC HEATING	0	0	107	0	0	107	0	0	107	0	0	107
7	POTABLE WATER HEATING	15	15	15	15	15	15	20	20	20	20	20	20
8		0	0	0	0	0	0	0	0	0	0	0	0
9		0	0	0	0	0	0	0	0	0	0	0	0
10		0	0	0	0	0	0	0	0	0	0	0	0
	TOTAL (Used condition)	493	493	1119	493	493	1119	367	367	619	367	367	619
	USED VALUE (ISO-conditions)		493			493			367			367	

Operation profile

Timescale [h]	1.00	15.00	1.00	1.00	1.00	100.00	100.00	1.00
Cumulative time [h]	0.00	15.00	16.00	17.00	18.00	118.00	218.00	219.00
Operating Condition	H	L	M	M	M	S	S	M
Ballast Condition	B	S	S	S	S	S	S	S
Electrical Power Consumption [kW]	376	1099	658	658	658	492	492	658
Heat Load (ISO-conditions) [kW]	367	367	493	493	493	493	493	493
Speed [kn]	0	0	6	7	8	12	14	8
Power [kW]	0	0	330	547	849	3218	5341	849
Power [kW] Used	0	0	2420	2420	2420	3218	5341	2420