*Lauri Tammero*

# SHIP ENERGY EFFICIENCY IMPROVEMENTS WITH SIMULATION-BASED DESIGN

**ABSTRACT**

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**Ship Energy Efficiency Improvements with Simulation-Based Design**

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The objective of this thesis is to create the basis for simulation-based ship energy efficiency studies conducted at Elomatic Consulting & Engineering Oy (hereafter Elomatic). These types of studies have previously been mostly conducted with spreadsheet calculations and simulation-based analysis is expected to improve the quality of the results while making it less time-consuming.

The thesis begins with a literature review of shipping-induced emissions, current state of simulation-based evaluation of ship energy systems and introduction to systems theory. Literature review is followed by a review of the case study. The focus is on system level analysis which Elomatic sees as the key area for ship energy efficiency as component level improvement is a responsibility of the equipment manufacturer. According to the findings and analysis performed in this study, simulations can be considered to be in a key role in holistic evaluation of ship energy systems.

# TIIVISTELMÄ

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Energiatekniikka

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**Laivan energiatehokkuuden parantaminen simulointipohjaisella suunnittelulla**

Diplomityö, 2021

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Hakusanat:     Simulointi, laiva, energiatehokkuus, kasvihuonekaasupäästöt

Tämän työn tarkoitus on luoda perusta simulointipohjaiseen energiatehokkuusanalyysiin Elomatic Consulting & Engineering Oy:lle (tästä eteenpäin Elomatic). Vastaavat tutkielmat on aikaisemmin toteutettu taulukkolaskentaan perustuen, joten simulointipohjaisen analyysin odotetaan parantavan tulosten laatua ja samalla vähentäen työhön käytettyä aikaa.

Työ alkaa kirjallisuuskatsauksella merenkulun päästöjen arviointiin, simulointipohjaisen laivojen energiasysteemien tarkastelun nykytilaan ja johdatuksella systeemiteoriaan. Kirjallisuuskatsausta seuraa tämän tutkimuksen esittely. Työ keskittyy systeemitason analyysiin, jonka Elomatic näkee olevan avainasemassa laivan energiatehokkuuden suunnittelussa, sillä komponenttitason kehitys on laitetoimittajien vastuulla. Tämän työn tuloksiin pohjautuen simulointi on avainasemassa laivan energiatehokkuuden arvioinnissa.

**ACKNOWLEDGEMENT**

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LIST OF SYMBOLS AND ABBREVIATIONS

# LIST OF SYMBOLS AND ABBREVIATIONS

## Romans

| | | |
|---|---|---|
| $p$ | pressure | bar, Pa |
| $q_m$ | mass flow | kg/s |
| $\dot{m}$ | mass flow | kg/s |
| $q_v$ | volumetric flow | m³/s |
| $\dot{Q}$ | heat flow | kW |
| P | Power | kW |
| $T$ | Temperature | ºC, K |
| $E$ | Charge | kWh |

## Greek

| | | |
|---|---|---|
| $\rho$ | density | kg/m³ |
| $\eta$ | *efficiency* | *%* |

## Abbreviations

| | |
|---|---|
| AC | Alternating Current |
| AHTS | Anchor-Handling, Tug and Supply Vessel |
| APS | Aveva Process Simulation |
| CAPEX | Capital Expenditures |
| CFD | Computational Fluid Dynamics |
| DC | Direct Current |
| DF | Dual-Fuel |
| DME | Dimethyl Ether |
| EEXI | Energy Efficiency Existing Ship Index |
| ESS | Energy Storage System |
| FEM | Finite Element Method |
| GHG | Greenhouse Gas |
| HFO | Heavy Fuel Oil |
| HT | High Temperature |
| HVAC | Heating, Ventilation and Air Conditioning |

| | |
|---|---|
| HVO | Hydrotreated Vegetable Oil |
| ICE | Internal Combustion Engine |
| IMO | International Maritime Organization |
| ITTC | International Towing Tank Convention |
| LBG | Liquified Bio Gas |
| LHV | Lower Heating Value |
| LMG | Liquified Methane Gas |
| LNG | Liquified Natural Gas |
| LT | Low Temperature |
| MGO | Marine Gas Oil |
| NDA | Non-Disclosure Agreement |
| NG | Natural Gas |
| NOx | Nitrogen Oxide particles |
| NTU | Number of Transfer Units |
| OEM | Original Equipment Manufacturer |
| ORC | Organic Rankine Cycle |
| OPEX | Operational Expenditures |
| P&ID | Piping & Instrumentation Diagram |
| PEMFC | Proton-Exchange Membrane Fuel Cell |
| PI | Proportional-Integral |
| PM | Propulsion Motor |
| PSV | Platform Supply Vessel |
| RANS | Reynolds-Averaged Navier-Stokes |
| SFOC | Specific Fuel Oil Consumption |
| SOFC | Solid Oxide Fuel Cell |
| SCR | Selective Catalytic Reduction |
| VFD | Variable Frequency Drive |
| WHR | Waste Heat Recovery |

# 1 INTRODUCTION

## 1.1 Background and motivation

The shipping industry is, to a great extent, affected by continuous development of more stringent greenhouse gas (GHG) emission reduction requirements that aim to mitigate the industry's impact on climate change as defined in Paris Agreement (IMO, 2020a). The latest IMO GHG study highlights that the shipping-induced GHG emissions have increased from 977 million tonnes to 1076 million tonnes between 2012 and 2018 where GHG emissions are understood as the sum of carbon dioxide ($CO_2$), methane, ($CH_4$) and nitrous oxide ($N_2O$) (IMO, 2020b). The impact of these emissions to the total global anthropogenic emissions were 2,76 % in 2012 and 2,89 % in 2018 (IMO, 2020b).

There has been an increasing interest towards carbon neutral transportation by means of utilizing alternative fuels, such as ammonia or hydrogen in the shipping industry. These alternative fuels bring a plethora of unprecedented challenges onboard. Hydrogen requires extremely complicated storage systems and ammonia might cause the whole ship to be contaminated in case there is a breach in the storage or transfer system. (MotorShip, 2020a).

IMO is developing new regulation for limiting carbon dioxide emissions of existing ships with Energy Efficiency Design Index for Existing Ships (EEXI), a regulation that has previously been relevant for newbuilds only (IMO, 2020a). The more demanding shipping environment requires more from the ship builders and design offices. Design of ship machinery systems can no longer be done by only relying on good practise, thus there is a need for simulation-based design.

It is seen at Elomatic that one of the shipowners' main incentives on meeting the GHG emission targets is the improved energy efficiency of their fleet as making improvements to the existing system parameters is much more cost-effective than investing in e.g. novel fuel technology or additional technology. Based on vast experience in the shipping industry, Elomatic sees that substantial fuel savings can be obtained by more careful and efficient way of operating the ship power plant.

## 1.2   Research problem and objective

The purpose of this thesis is to find the most suitable way for simulation of ship energy systems. Crucial factors for the simulation model are that the model is easy to build and that the results are easy to process and present to the customers. Two different simulation tools are reviewed, and emphasis is put on the one that gives the most promising results for system-level evaluation of ship's energy efficiency.

## 1.3   Methods

Energy systems of a case study ship are simulated with two different softwares and the suitability of these softwares for further use is evaluated. The scope of simulation is adjusted according to the softwares capabilities, so the simulation model complexities are not equal, and the main focus of this thesis is to present the results acquired with the best candidate.

## 1.4   Scope of research

The ship energy system flows are evaluated based on simple energy and mass balance equations. Evaluation of detailed dynamic behaviour of fluid flows and various electro-magnetic phenomena in electric network are excluded as these increase modelling complexities to the extent where quick modelling of energy system would become impossible.

Also, propulsion power requirement is taken as an input value as calculating this is typically task of ship theory department.

## 1.5   Contribution

This study contributes to improving the understanding of ship energy systems and related design work in Elomatic. The principles used and concluded in this study are well-known within the academic community, thus the thesis results do not result in advances in ship energy efficiency research. The overall benefit comes from contributing to the popularization of energy simulations in marine industry and from providing a low threshold approach for shipowners and shipyards to gain better understanding of the behaviour of energy systems on their ships.

## 2 FUTURE OF SHIP ENERGY SYSTEMS

### 2.1 Climate impact of shipping

When considering the overall fuel consumption in shipping, the biggest group of consumers are container ships, bulk carriers and oil tankers (Figure 1), where biggest consumers onboard are main engines for propulsion (IMO, 2014).
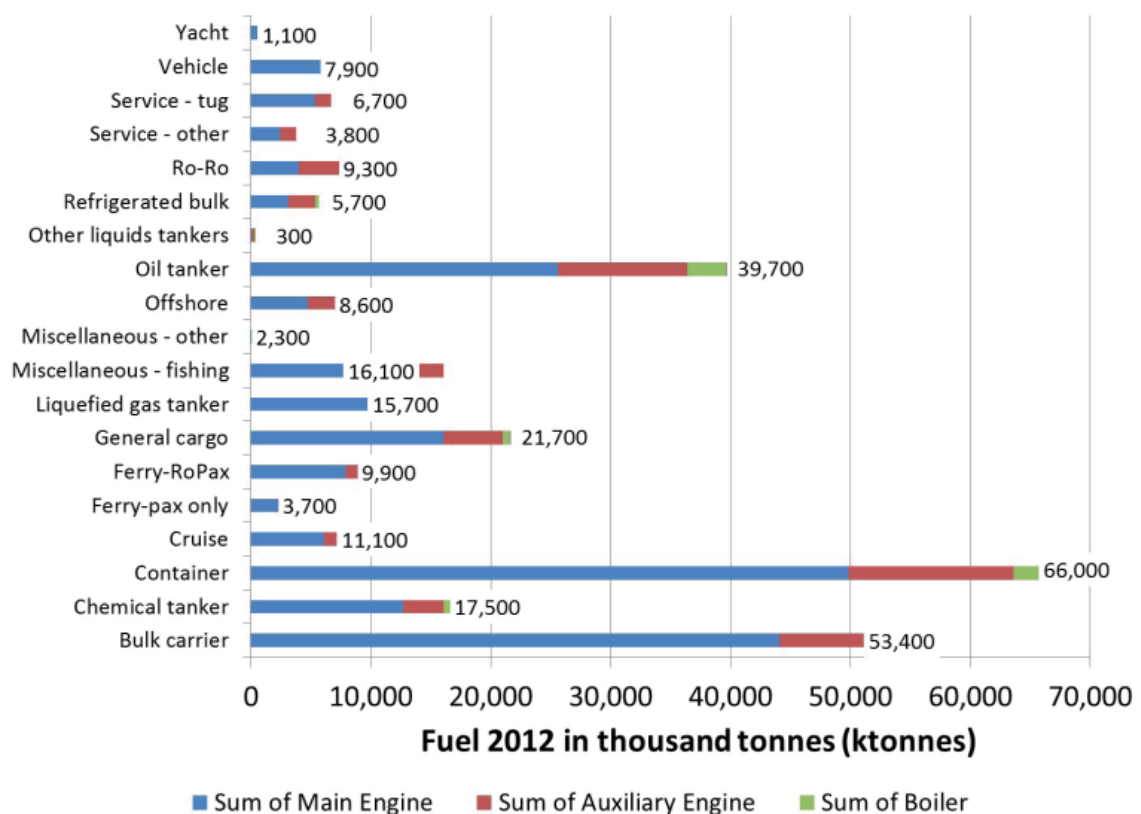


**Figure 1:** Annual fuel consumption of shipping in 2012 by ship type and major component (IMO 2014, p. 38).

Nowadays the most common fuel type in shipping is heavy fuel oil (HFO) by a large margin. Even after being introduced to shipping two decades ago the share of liquid natural gas (LNG) is just a fracture of the whole energy consumption. This is evaluated and estimated by the classification society Lloyd's Register which predicts that even in 2030 the share of HFO will still be 47 % - 66 %. (LR, 2021).

IMO presents hydrogen and ammonia as two promising zero carbon fuels for the shipping industry as part of their plan to cut GHG emissions of the whole international shipping (IMO, 2021). However, there are multiple problems concerning the GHG emissions and energy efficiency of hydrogen that might prevent it from ever gaining popularity over other energy sources. Kreith and West discuss these problems in their article *Fallacies of a Hydrogen Economy: A Critical Analysis of Hydrogen Production and Utilization.* The article presents that hydrogen is an inefficient fuel in transportation and every kilo-watt-hour of energy used for producing hydrogen could be used better if simply making electricity. In addition, wider utilization of hydrogen requires completely new infrastructure and with current state of the technology it is unlikely to happen. (Kreith and West, 2004).

Research studies also conclude that hydrogen's Global Warming Potential (GWP) emissions at well-to-tank phase are marked as "remarkably higher than those from MGO and natural gas" (Hwang, et al., 2020).

Further challenges of using hydrogen as a fuel in shipping are its low energy density, fast ignition rate and low boiling point, which requires a powerful chiller system to maintain the fuel at liquid state at -253 °C. (MotorShip, 2020a).

The storage of hydrogen onboard a ship poses safety issues due to its proneness for leakage and combustion which can lead to an explosion onboard. Safe operation of hydrogen ship requires additional measures to mitigate these risks. The areas where improvement is required are at least ship design, management and escape schemes. (Mao et al., 2021).

Thermodynamic assessment of fuel cell powered ship concludes that hydrogen powered ship can be a compact when bunkering interval can be 10 hours. The proposed energy efficiency of the complete energy system is 41,53 %, which includes evaluation of main propulsion, power generation, absorption chiller and steam systems. (Evrin and Dincer, 2021). The layout of the concept ship is shown in Figure 2.
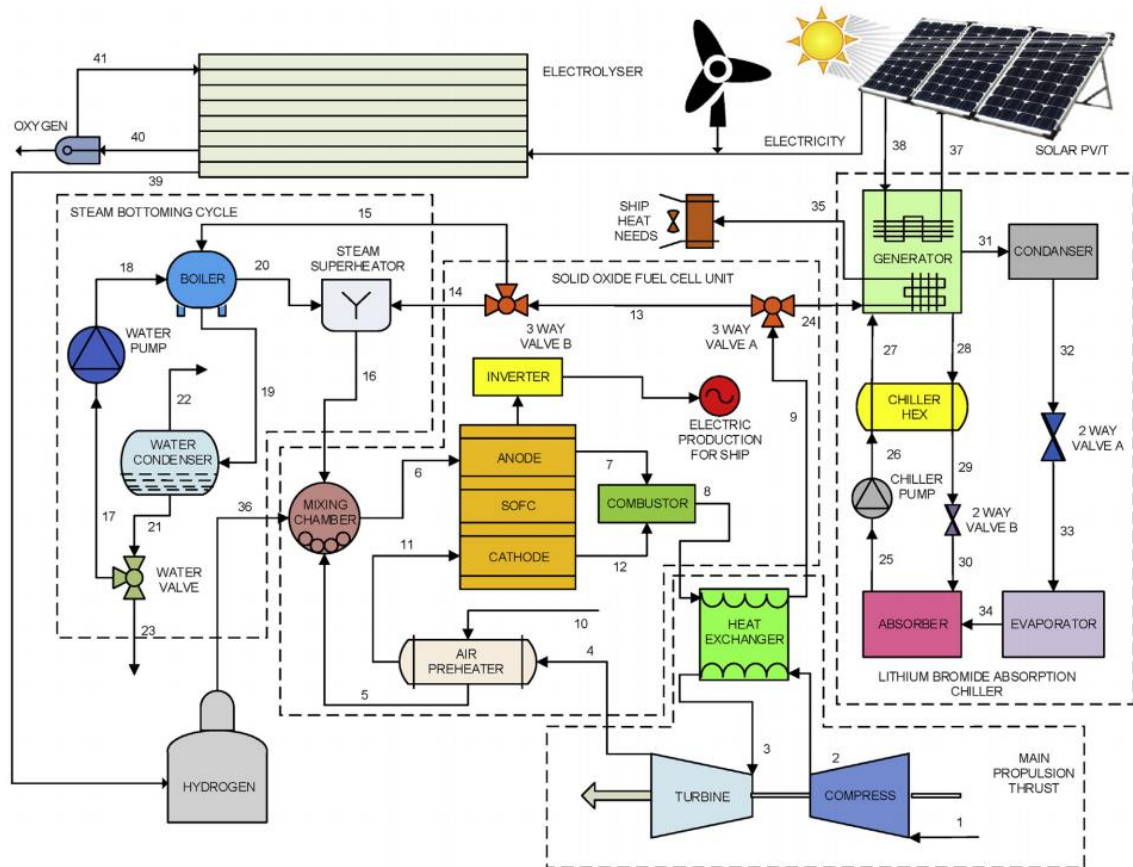
**Figure 2:** Concept system diagram of hydrogen fuelled SOFC powered ship. (Evrin and Dincer, 2021, p.6921).

The popularization of ammonia as shipping fuel is still in a small-scale research stage and there is a variety of issues to solve before ammonia becomes a competitive fuel in the industry. The main reasons are ammonia's current use as mainly in the fertilizer industry, which might lead to a situation where global fuel and food prices are increased due to higher competition and also the production of green ammonia requires that renewable energy generation increases substantially from the current state. Hansson et al., 2020).

A techno-economic assessment of advanced fuels and propulsion systems in future fossil-free ships analyses 18 different options for close future energy options in shipping to replace LNG / MGO / HFO operation for 2030 (Figure 3). The most cost-efficient options are internal combustion engines using biofuels and battery-electric propulsion of which the latter is very dependent on ship's operational profile and suits for example for large ferries where

the voyage is relatively low compared to the charging times at the harbour. (Korberg et al., 2021).
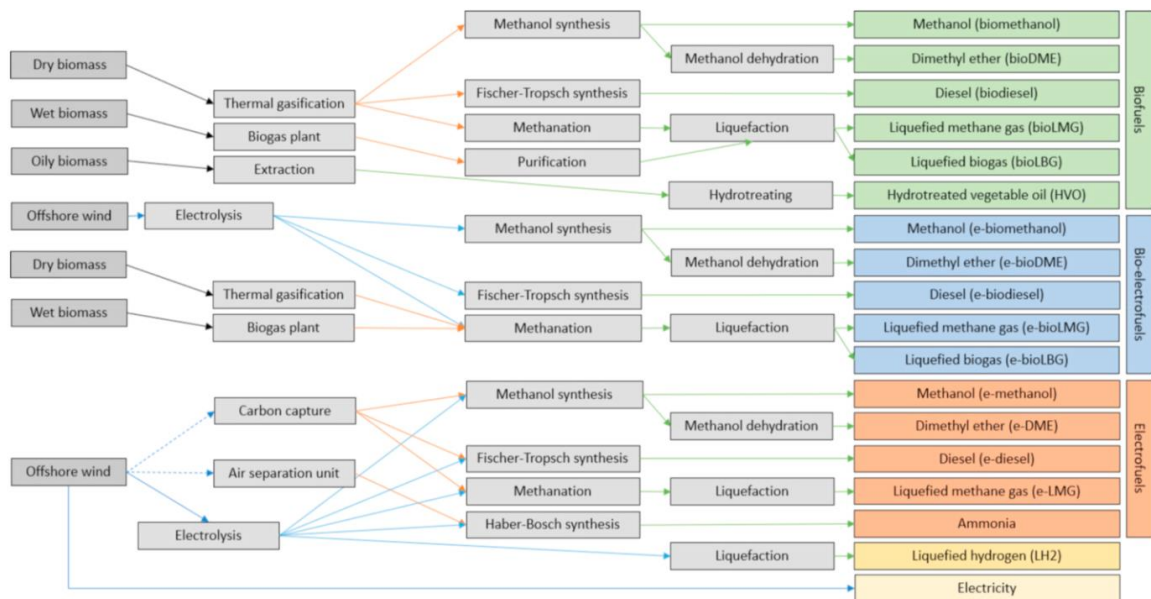


**Figure 3:** Production pathways for fossil-free fuels in shipping. (Korberg et al., 2021, p.142).

The analysis lead to a wide range of fuel prices, where e-fuels and hydrogen are estimated as 158 €/MWh and 153 €/MWh respectively compared to estimated cost of wind electricity in 2030 33 €/MWh. As a comparison some of the biofuel prices are 69 €/MWh for biomethanol and 85 €/MWh for HVO (hydrotreated vegetable oil). Results are shown in Figure 4. (Korberg et al., 2021).
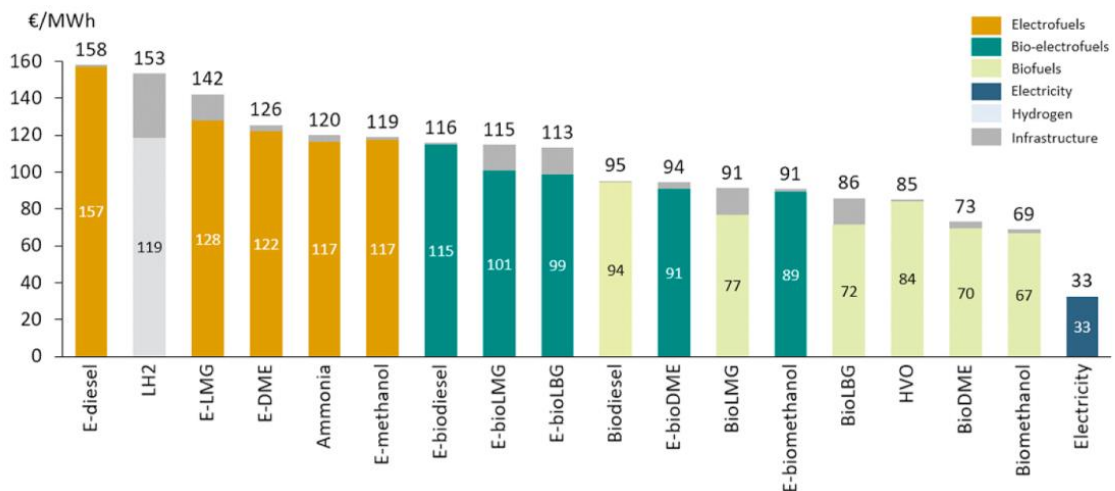


**Figure 4:** Fuel costs in 2030 in the base case (without sensitivity analysis). (Korberg et al 2021).

The price range for 2030 prime mover technologies (Table 1) and fuel options (Table 2) gives indication of the feasibility of different future ship energy solutions. Fuel cells are seen as 2-5 times as expensive as the traditional internal combustion engines (ICE).

In addition to cost consideration it is pointed out that all fuel options to replace MGO will have lower density that might bring further challenges for onboard configuration and fuel flexibility but is subject to case-by-case consideration. (Korberg et al., 2021).

**Table 1:** Investment cost of different prime mover technologies. (Korberg et al., 2021, p.142).

| Component | Cost (€/kW) |
| --- | --- |
| ICE Diesel, HVO | 240/460[a] |
| ICE Methanol | 265/505[a] |
| ICE DME, Ammonia | 370/600[a] |
| ICE LMG, LBG | 400/700[a] |
| ICE Hydrogen | 400/700[a] |
| Fuel reforming and evaporation | 360 |
| PEMFC (LT and HT) | 730 |
| SOFC | 1280 |
| Electric motor | 250 |
| Gearbox | 85 |

[a]4-storke/2-stroke engine

**Table 2:** Investment cost of different prime mover technologies. (Korberg et al., 2021, p.142).

| Component | Cost$_a$ (€/kW) | Cost$_b$(€/kW) | Lifetime (years) |
| --- | --- | --- | --- |
| Diesel, HVO | 0,09 | 0,07 | 30 |
| Methanol | 0,14 | 0,12 | 30 |
| DME, Ammonia | 0,29 | 0,23 | 25 |
| LMG, LBG | 0,94 | 0,72 | 20 |
| Hydrogen | 1,71 | 1,29 | 20 |
| Battery | 250 | 250 | 15 |

Cost$_a$ is for large ferries, Cost$_b$ is for general cargo, bulk carriers and container ships

The most cost-efficient option of these fuels for today's shipping fuel market is HVO that is already supplied by Neste. HVO is a renewable option for diesel and the combustion process is the same as for MGO. Operation on HVO will require SCR exhaust aftertreatment for $NO_x$

reduction and optimization of engine injection time for reduced fuel consumption and $CO_2$ emissions. (Neste, 2020).

The usage of HVO blends as an alternative fuel has been already studied on passenger cars and the results conclude that there are no major performance differences between fossil diesel and different HVO blends. (Suarez-Bertoa et al., 2019).

Finnish project "Clean Propulsion Technologies" aims to make Finland the global technology leader in sustainable shipping solutions. The roadmap for technology solutions for 2030 Finnish emission goals includes:

- Development of intelligent digital twins,
- 20 % reduction in GHG emissions and ultra-low $NO_x$ particle emissions with combination of engine and aftertreatment measures,
- optimal control architecture for e.g. battery hybrid systems for various characteristics and energy sources, and
- 30 % reduction in GHG emissions with a full-scale hybrid propulsion system.

An example of related research is use of Reactivity Controlled Compression Ignition (RCCI) in dual-fuel engines, which can potentially increase engine efficiency and reduce GHG emissions (Mikulski et al., 2019).

A simulation-based study about optimization of hybrid ships shows that utilization of batteries, can lead to fuel savings as the power plant operation can be optimized to run more often at the best engine efficiency, especially at low engine loads. (Ritari et al., 2019).

## 2.2 Design and analysis

System-wide energy efficiency simulation in shipping is still a relatively new method, that has gained popularity during the previous decade (Baldi et al., 2018; Lepistö et al., 2016; JOULES, 2015; Dimopoulos et al., 2014). Optimization of complex technologies for ship's energy efficiency improvement requires detailed analysis of operational parameters by

means of dynamic simulation, which has shown prominent results in fuel consumption reduction. At the same time careful attention must be given to the potential weight increase due to installation of new equipment. New layout should be designed to ensure negligible or minor increases in total weight while improving the energy savings. (Barone et al., 2020).

Previously the most common computer aided design engineering methods (CAE) in marine industry have focused on ship's hydrodynamic performance or evaluation of a specific component by means of Computational Fluid Dynamics (CFD), ship strength, noise and vibration analysis with Finite Element Method (FEM). System-level simulation is suggested to be the next step for managing the increased complexity of a modern ship. (Dimopoulos et al., 2014).

Ship energy and exergy analysis provide different approaches to modelling the ship energy systems. Energy flow rates are calculated with an assumption that chemical energy flows always at its lower heating value and physical energy is equal to its relative enthalpy. Energy approach assumes that energy may be transformed from one form to another, but it can never be created or destroyed, as per $1^{st}$ law of thermodynamics. This approach provides very limited information about energy system inefficiencies. Another way to analyse a system is an exergy analysis. Exergy is the *"maximum theoretical useful work as the system is brought into complete thermodynamic equilibrium with the thermodynamic environment while the system interacts with it only"*. Unlike energy, exergy is not conserved in real energy conversion process and the amount of exergy destroyed irreversibly quantifies the systems exergy efficiency. (Baldi et al., 2018).

Limited amount of data is a common reason for lack of deeper analysis of ship energy systems. In the absence of real-life data, it is mandatory to make certain assumptions that lead to a generalized model that does not provide the best possible information about e.g. heat flows on board a ship. The absence of measurement data affects mostly the analysis of operative efficiency of HVAC systems and engine room cooling and ventilation systems. In addition, auxiliary heat demand and low-grade heat flow data are required for a detailed simulation of ship energy systems. (Baldi et al., 2018).

Analysis of cruise ship energy system analysis is still considered a novel technology in the shipping and shipbuilding industry. Conducting a dynamic simulation of cruise ship energy systems can show significant opportunities to redude fuel oil consumption and annual operational costs even up to 615 000 € per year. In this type of simulations take ship travel path and weather data, low, medium and high temperature heat recovery and energy, environmental, economic and weight optimization possibilities into consideration (Barone et al., 2020).

Classification society DNV GL utilizes Simulation X Ship Energy Systems -tool for analysis of energy-efficiency, reliability and cost-saving aspects of a large commercial freight ship Waste Heat Recovery Systems (WHRS). Thermodynamic model is created to predict different scenarios that happen or are expected to happen during the ship's voyage. It is concluded that using simulation-based approach for evaluation of alternative designs can be used for fast replication of different operational cases and this evidence-based method and selections done based on that can be utilized for making more cost-efficient choices when improving ship's energy system efficiency. Simulation can be used for predicting costs from repair and down time of various energy systems. (Lampe et al., 2018).

Recent changes in ship emission regulations have led to a situation where the ship owners have more detailed and difficult requests about the power plant of their new ship. These requests unavoidably impact the design of all other disciplines related to the shipbuilding process. Holistic assessment of different solutions requires systems engineering approach for inter-disciplinary ship design. Systems engineering is an approach for handling complex designs and simulation tools can be utilized with systems engineering to address the complexity of the ships of today. (Gianni et al., 2021)

## 2.3   Systems Engineering Principles and Practice

Systems engineering is a concept that emphasizes holistic understanding of different functions of a system over the traditional engineering discipline limits. This is explained by Kossiakoff et al. (2003) in a book called *Systems Engineering Principles and Practice*. The concept is summarized in the following paragraphs.

Systems engineering examines a system from its total operation perspective. This includes assessing the internal components of the system as well as its interaction with any external factors. The external factors can be understood as e.g. surrounding environment, logistic supply chain requirements, competence of the personnel operating the system and different requirements of the client. These must be taken into consideration during the system design and documentation. (Kossiakoff et al., 2003).

Traditional engineering disciplines are bridged with systems engineering. Complexity and diversity of modern engineering problems require involvement of multiple disciplines throughout various design stages. Correct function and operation of a system requires that different elements in various disciplines function in combination with each other. Successful implementation of these functions depends on their interactions between each other. This means that the elements cannot be considered independently without also focusing on the connection to other disciplines. (Kossiakoff et al., 2003).

The systems engineering concept was initiated by Bell Telephone Laboratories in 1940s (INCOSE, 2021) and after that utilized by for example US Department of Defence in World War II for gaining advantage in design and operation of complex systems of systems (MIT, 2021).

After World War II the US Department of Defence applied wider use of systems engineering practise to develop recommendations about strategic capabilities of ship, aircraft and weapon systems, locations of military bases and development of life-cycle cost estimation for budgeting, among other aspects. The continuous development of systems engineering principles allowed further advances in missile and missile defence systems during the Cold War. The US DoD has developed from procuring individual systems to wide utilization of complex, tightly integrated systems of systems. A system of systems contains tanks, ships, aircrafts, satellites and ground stations that collect, process and distribute large amounts of data in real time to ensure quick decision made by the decision-makers (MIT, 2021).

The importance of systems engineering thinking can be highlighted by using an electronic device as an example. The electronic device (system of systems) contains hardware and software, which are abstract concepts if considered separately. When the two are put together, it is possible to create complicated components that are capable of complex computations and also able to communicate the computation results to the surrounding environment. Thus, system of systems is more than a sum of its parts, the complete functions are realized only by careful integration of different disciplines. System of systems can be understood by a system where two or more separate systems are managed and governed individually. (Sommerville, 2016).

Systems engineering basic principle about connecting multiple engineering disciplines is shown Figure 5.
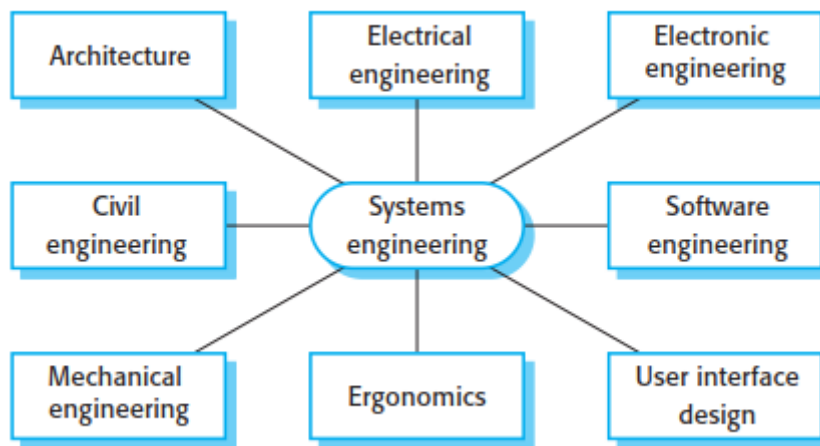


**Figure 5:** An example of disciplines that are required in systems engineering (Sommerville, 2016).

Systems engineering theory is also utilized by NASA for production of elegant systems. Elegant products provided or manufactured in modern world of engineering rely, to great extent, on systems engineering thinking. Systems engineering forms an analysis methodology and technique to manage systems that are used for integrating e.g. organizational structures, physics and information flow. Understanding of all these disciplines is required from a successful systems engineer. (Watson, 2017).

One of the key tasks of a systems engineer is to manage complexity. NASA Systems Engineering Consortium considers the following principles in their design of large scale systems. System complexity is *"a measure of a system's intricacy and comprehensibleness in interactions within itself and with its environment"* (Watson, 2017).

**Table 3:** Properties of complex systems by NASA Systems Engineering Consortium (Watson, 2017).

| |
|---|
| **Aggregation** |
| *Complex systems are aggregations of less complex systems* |
| **Emergence** |
| *Complex systems have a propensity to exhibit unexpected performance of intended function* |
| *Complex systems exhibit properties not present in the individual subsystems but present in the integration of subsystems (emergent property)* |
| **Interaction** |
| *Complex system interactions form networks within the system and with the system environments* <br> *Complex system interactions can be understood through control theory* |
| *Complex systems can be analyzed using two concepts:* <br> *laws (rules of interaction)* <br> *states (current state and prior history)* |
| **Nonlinearity** |
| *Complex systems exhibit nonlinear responses to system stimuli* <br> *Complex systems are difficult to predict* |
| **Optimality** |
| *Complex systems have local optimums* <br> *(Organizational Efficiency Determines ability to achieve local optimum)* |

The properties shown in Table 3 illustrate the different aspects of a complex system. Aggregation is seen as the most important of all the properties. This property ensures that the system can be split into smaller sub-systems that still function as one, despite being designed separately. Emergence indicates that the system is more than a sum of its sub-systems and each individual function can have large impact on the rest of the system and it is further reinforced by interaction property. System functions can be non-linear, and each system has its own optimal state. These two are handled in the big picture with the aggregation aspect. (Watson, 2017).

# 3   SIMULATION SOFTWARE INTRODUCTION

## 3.1   Simulation X

Simulation X Ship Energy Systems is a software by ESI ITI GmbH that specializes in simulation of ship energy flows on quasi-dynamic principle where dynamic behaviour of fluid flow is excluded, and the equations are based only on fulfilling the energy and mass balances. Simulation X contains dozens of other licences that can be used for e.g. in fault tree analysis, heat exchanger design or energy simulation of an entire city which, however, are not further discussed in this thesis.

## 3.2   Ship Energy Systems model architecture

Ship Energy Systems library in Simulation X is for analysing ship energy efficiency on system level, where component properties are used as an input for the calculation model. The focus is on the largest consumers onboard, e.g. main and auxiliary engine cooling and exhaust gas circuits and the related waste heat recovery systems.

The purpose of the simulation model is to create a holistic understanding of ship power plant behaviour under varying operating conditions and identify the best plant configuration. The model can be used for investigating a variety of ways to save fuel and to lower total life-cycle cost of the ship machinery, evaluation of different fuel types (e.g. LNG vs MGO) and optimizing different parameters of ship power plant process.

### 3.2.1   Simulation structure and logic

The starting point of creating a simulation model is to define the engine configuration, electrical consumption and environmental conditions. The simulation model is used for calculating the energy transfer and conversion losses for each component. Calculation results will give e.g. fuel consumption, heat rate and mass flows during different stages of simulation. The fluids used in the simulation are fresh water, sea water and steam. Simulation X standard governing equations are explained in the following chapters.

### 3.2.2 Operational conditions

Operational input parameters include air temperature, air pressure and sea water temperature. These values can be imported based on actual weather data or the standard annual conditions can be used. Simulation frequency $\tau$ is defined in the operating conditions as well. The standard simulation frequency is 5 seconds, which leads to long simulation times in extensive simulations, e.g. when evaluating ship operation over a period of one year.

### 3.2.3 Propulsion and electrical power

Power requirement for propulsion and onboard electrical power are used as basic information for deciding the power plant configuration. Propulsion power requirement comes from speed-power prediction curves as an input data from ship theory department. Some methods for definition of ship power requirement are manual calculations with ITTC guidelines (ITTC, 2002) or Computational Fluid Dynamics (CFD) (Coppedè et al, 2019).

Ship's electrical balance is used as an input value that needs co-operation with electrical department. The electrical balance covers power requirement during different operation modes and conditions. It can also contain the propulsion power requirement in case of electric propulsion ship.

### 3.2.4 Connector types

Connectors are used as interfaces between different elements in the model and they are a way for a model to exchange information with another model. These elements include various physical domains that cannot be connected directly with each other, e.g. water, steam or fuel connectors. There connectors are available in unidirectional or bidirectional types with different variables.

Bidirectional connectors consist of a pair of potential and flow variables. Potential variables are differences in the values across a component e.g. a valve, where differences in the quantities lead to dynamic behaviour of the system. Flow variables are quantities that follow the conservation laws like energy, mass and momentum. Unidirectional components are for information transfer from an output to input(s) in one direction without internal computations.

## 3.3 Pipe, pump and heat exchanger systems

### 3.3.1 Pipe system

The simulation is based on the energy balance principle and pipes between components are only connectors where the sum of flow variables is always zero. Basic dynamic behaviour of a pipe system is made by assigning throttle components between each component. The throttle component will act as a simplified version of pipe pressure losses and affects the flow that a centrifugal pump is able to supply to next boundary. The volumetric flows $q_v$ [m³/s] in the piping systems are calculated as

$$q_v = \frac{p_a - p_b}{|p_a - p_b|} \cdot k_{vs} \cdot \sqrt{\frac{p_a - p_b}{1\ bar} \cdot \frac{1000 \frac{kg}{m^3}}{\rho}} \qquad (1)$$

where $p_a$ is pressure before the throttle [bar], $p_b$ is pressure after the throttle [bar], $k_{vs}$ is the flow factor that and $\rho$ is fluid density [kg/m³].

Flow factor is an important value when considering energy saving potential of frequency controlled pumps. The magnitude of the flow factor affects the volumetric flow produced by the pump at certain point of pump curve, thus high flow factor will increase the pump power consumption at frequency controlled pump or decrease the pump capacity at fixed speed pump.

Flow factor is an input value to the model and it is calculated based on the assumed or actual pipe size of the piping system as

$$k_{vs} = q_v \sqrt{\frac{sg}{\Delta p}} \qquad (2)$$

where $q_v$ is the volumetric flow in pipe [m³/h], $sg$ is specific gravity of the fluid, which is a dimensionless unit that describes the ratio between the density of the system fluid to the density of fresh water at certain temperature ($sg_{water} = 1$), $\Delta p$ is the pressure drop over the

throttle (pipe system) [bar], thus in a piping system with water as a fluid with a pressure drop 1 bar $q_v = k_{vs}$.

### 3.3.2 Pumps

All pumps used in the simulation model are of centrifugal type and the operation is based on QH and PH curves (Figures 8 and 9). Pump operation is either fixed speed or by signal input which mimics the operation principles of a VFD controlled pump. Pump electrical energy can be added to the overall electrical consumption and can be used to assess initial feasibility of VFD controls in ship energy applications.

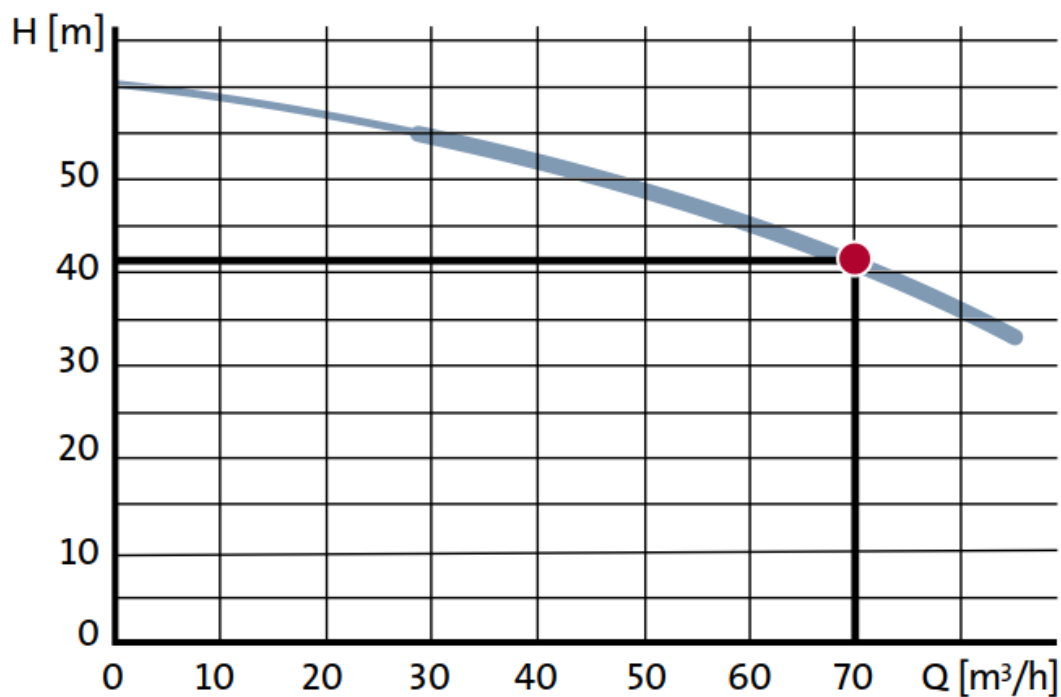

**Figure 6:** Typical centrifugal pump QH curve with different impeller diameters. (Grundfos, 2019).

Pump input parameters can be put manually, or it is possible for the software to calculate the unknown values based on the default pump curves.
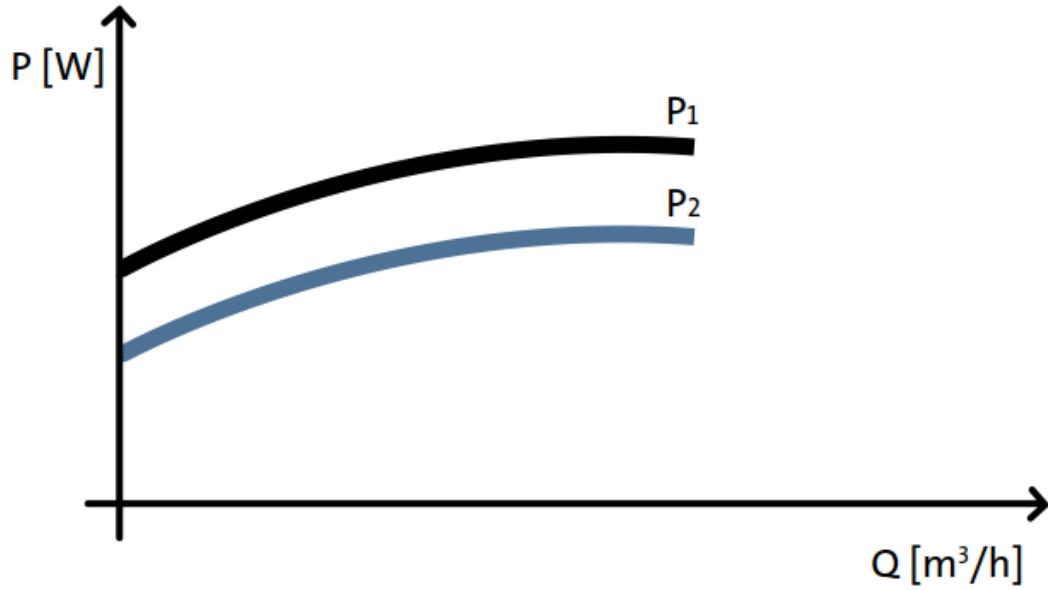
**Figure 7:** Typical centrifugal pump QH curve where $P_1$ is electrical power and $P_1$ is shaft power (Grundfos, 2019).

### 3.3.3 Heat exchangers

Heat flow rates through heat exchangers are calculated with $\varepsilon$-NTU method which requires less input values than Logarithmic Mean Temperature Difference (LMTD) method. NTU method in Simulation X is written as

$$NTU = \frac{k_A}{min(\dot{m}_{inlet1} \cdot c_{p,inlet1}, \dot{m}_{inlet2} \cdot c_{p,inlet2})} \tag{3}$$

where $k_A$ is heat transfer coefficient, $min$ is smaller heat capacity rate of two fluids, $\dot{m}_{inlet1}$ is mass flow of primary fluid, $c_{p,inlet1}$ is specific heat of primary fluid, $\dot{m}_{inlet2}$ is mass flow of secondary fluid, $c_{p,inlet2}$ is specific heat of secondary fluid.

Heat transfer in the heat exchanger is calculated as

$$\dot{Q} = \dot{Q}_{Max} \cdot \eta_{hx} \tag{4}$$

where efficiency of heat exchanger counter flow is

$$\eta_{hx} = \frac{1-exp[-NTU\cdot(1-c_r)]}{1-c_r\cdot exp[-NTU\cdot(1-c_r)]} \tag{5}$$

and where $c_r$ is heat capacity ratio.

$$c_r = \frac{c_{p,min}}{c_{p,max}} = \frac{min(\dot{m}_{inlet1}\cdot c_{p,inlet1},\dot{m}_{inlet2}\cdot c_{p,inlet2})}{max(\dot{m}_{inlet1}\cdot c_{p,inlet1},\dot{m}_{inlet2}\cdot c_{p,inlet2})} \tag{6}$$

Maximum heat flow rate of heat exchanger is

$$\dot{Q}_{Max} = min(\dot{m}_{inlet1}\cdot c_{p,inlet1},\dot{m}_{inlet2}\cdot c_{p,inlet2})\cdot(T_{inlet1}-T_{inlet2}) \tag{7}$$

### 3.3.4 Waste heat recovery from HT cooling water

HT cooling water waste heat recovery energy can be utilized in a variety of systems where water temperature of approximately 80 °C is needed, for example HVAC re-heating or potable water heating systems. The heat is recovered with a plate heat exchanger that is placed before HT-LT-mixing valve that controls the HT-water temperature in normal situations. Position of the Waste Heat Recovery (WHR) heat exchanger is shown in Figure 8. In the simulation model, the waste heat recovery potential is calculated as 85 % of the heat dissipated to sea water cooling system as per OEM recommendations.

Heat transfer to the cooling water is calculated as

$$\dot{Q}_{CW} = P_{fuel} - P - \dot{Q}_{EG} - \dot{Q}_C \tag{8}$$

where $P_{fuel}$ is the energy of fuel converted in the engine to mechanical work [kW], $P$ is the engine output power, $\dot{Q}_{EG}$ is the heat losses to exhaust as and $\dot{Q}_C$ are the convection losses of the engine.

Outflowing water temperature is calculated as

$$T_{CW,out} = T_{CW,in} + \frac{\dot{Q}_{CW}}{\dot{m}_{CW}\cdot c_{p,cw}} \tag{9}$$

where $T_{ce,in}$ is the cooling water temperature at engine inlet.
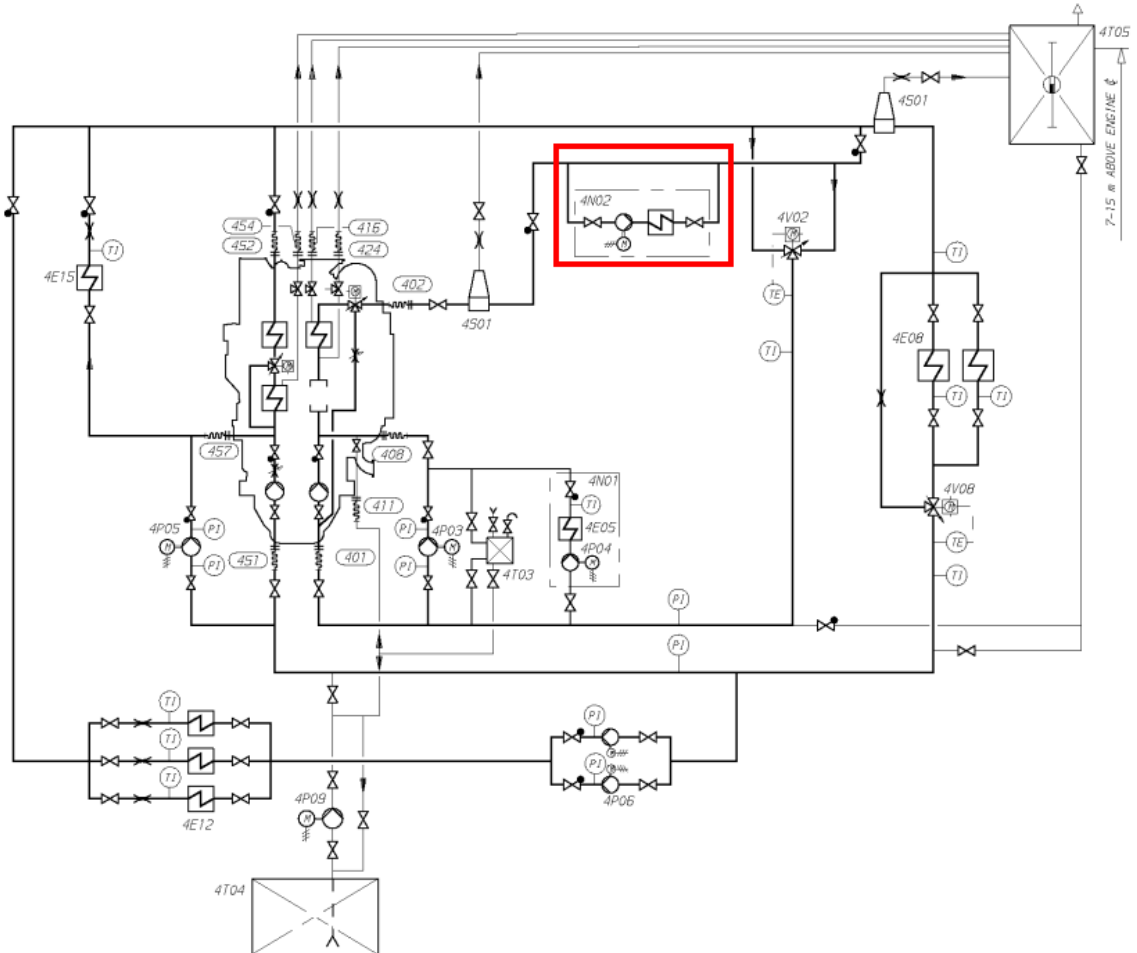


**Figure 8:** Example of positioning of WHR heat exchanger on marine power plant (Wärtsilä, 2016).

### 3.3.5   Waste heat recovery from exhaust gas

Exhaust gas waste heat recovery has the biggest potential on board due to the exhaust gas temperature after turbocharger being approximately 300 °C. This heat is recovered with exhaust gas boiler that generates either saturated steam or superheated steam. In shipbuilding industry this is most commonly 8-10 bar saturated steam. Superheated steam is usually not needed onboard a ship, one aspect where it could be utilized is a steam turbine generator that is evaluated in the case study.

The exhaust gas properties at engine outlet are based on temperature, specific mass flow and composition, which are input values based on engine manufacturer documents. Exhaust gas mass flow balance is $\dot{m}_{wg}$ is calculated as

$$\dot{m}_{eg} = \dot{m}_f + \dot{m}_{ca} \tag{10}$$

where $\dot{m}_f$ is fuel mass flow [kg/s] ($\dot{m}_f = \dot{m}_{NG}$) and $\dot{m}_{ca}$ is combustion air mass flow.

Exhaust gas heat flux $\dot{Q}_{eg}$ is calculated as

$$\dot{Q}_{eg} = \dot{m}_{eg} \cdot c_{p,eg} \cdot \left( T_{eg} - T_{ref} \right) - \dot{m}_{ca} \cdot c_{p,ca} \cdot \left( T_{ca} - T_{ref} \right) \tag{11}$$

where $c_{p,eg}$ is specific heat of the exhaust gas [kJ/kg], $T_{eg}$ is the temperature of exhaust gas, $T_{ref}$ is simulation model reference temperature 25 °C, $c_{p,ca}$ is specific heat of the combustion air and $T_{ca}$ is temperature of the combustion air.

# 4  CASE STUDY – EFFICIENCY OF A BATTERY-HYBRID SHIP

## 4.1  Introduction

The case study is conducted partly as a customer project and the results are protected by a Non-Disclosure Agreement (NDA). The case study presented in this thesis is a generalized version of the actual case study that is related to customer project with modified power plant parameters.

The ship's operational profile and characteristics are generalized to that of a platform supply vessel (PSV) or an anchor-handling tug supply vessel (AHTS). These types of ships generally require large maximum power available for short periods of time which can lead to situations where the ship power plant is running on much higher load than required. The simulation-based evaluation of the actual power requirement of a ship is expected to improve the design of new and existing ships' machinery systems optimization of energy consumption. This will lead to reduced generator loads and better energy efficiency, which means lower fuel consumptions and less GHG emissions.

The simulation model is built for multiple different scenarios where impact of engine load profiles, waste heat recovery utilization, pump variable frequency controls and energy storage systems (ESS) are evaluated against the baseline simulation that has no special measures to improve energy efficiency. The simulation model is used to study aspects that are seen as the most interesting for the client and all pilot-stage technology is excluded from the study. The generalized requirements for energy saving aspects are that it:

-   is easily scalable technology,
-   has no need for additional land-based infrastructure,
-   has proven track record in other ships,
-   has clear cost saving potential, and
-   has well-to-wake life-cycle GHG emission saving potential.

The reason for this is that based on experience the clients of Elomatic rarely want to pay for a study that demonstrates latest academic research or small-scale pilot projects that cannot

be utilized immediately. This means that e.g. hydrogen or ammonia-powered ships are left out of the study.

An exception for this is simulation of a fuel cell unit fuel consumption. However, this was only for additional information to compare how a fuel cell could perform onboard a ship and if it is feasible to consider installation of a fuel cell on a retrofit in the future. It should be noted that there are no feasible 500 – 1000 kW marine fuel cell units available at the moment. The biggest downside compared to a traditional internal combustion engine is the size of the unit.

The most important parameters of the case study ship energy efficiency analysis are explained in the following chapters.

## 4.2  Simulation library upgrades

The Ship Energy Systems library has good basic functions for the case study, but it is necessary to increase the existing component library to enable simulation of gas-fuelled battery-hybrid ship. The three main functions that are modelled are:

1. Gas engine fuel consumption
2. Battery energy storage system
3. Battery management system

The updating of Simulation X library is done in co-operation with the software company's technical support, as creating the components requires sound command of the Modelica programming language (Modelica, 2021). The distribution of work tasks was for the author to specify the required functions and operation principles while the software support added the components to the model library based on these requests.

The components are tested and adjusted according to the discoveries, for example charging logic of the batteries on an energy system simulation is done so that the batteries are only charging or discharging but never both at the same time. This limitation is required as more complicated logics are not needed at this stage and these are left for later development that

shall be done inhouse at Elomatic. In addition to smart battery functions, there is a requirement to model complete DC ship power systems, which is studied by Bijan Zahedi in their doctoral dissertation: *Shipboard DC Hybrid Power Systems* (Zahedi, 2014).

## 4.3 Modelling of gas engine fuel consumption

The most important parameter for the engine energy balance is an accurate calculation of fuel consumption. This is a basic function of the software that is included in the fuel tank component. Fuels available in the library are HFO, MGO, MDO and NG (natural gas in gas phase). Liquid Natural Gas (LNG) is not needed for the purpose of fuel consumption calculation as energy losses related to phase change from -162 °C cryogenic liquid to 30 °C gas at engine inlet are neglected for the sake of simplification. The fuel consumption is calculated as

$$\dot{m}_{NG} = P * SFOC(P/MCR) * LHV_{Fuel} / LHV_{Testrig} \qquad (12)$$

where $\dot{m}_{NG}$ is natural gas mass flow to engine at 30 °C in gas phase [kg/s], $P$ is mechanical engine power output [kW], *SFOC* is specific fuel oil consumption [g/kWh], which in case of gas engine is given by engine manufacturers as heat rate [kJ/kWh] on different engine loads 50, 75, 85 and 100 % of MCR. *LHV_{Fuel}* is lower heating value of natural gas [kJ/kg], *LHV_{Testrig}* is lower heating value of the fuel at engine and is calculated as

$$LHV_{Testrig} = \frac{hr_{OEM} \cdot P \cdot \frac{MRC}{100}}{\dot{m}_{EG,OEM} - \dot{m}_{CA,OEM}} \qquad (13)$$

where $hr_{OEM}$ is natural gas heat rate values from OEM datasheet (equivalent to specific fuel consumption in diesel engines) [kJ/kWh], $\dot{m}_{EG,OEM}$ is exhaust gas mass flow from OEM datasheet and $\dot{m}_{CA,OEM}$ is combustion air gas mass flow from OEM datasheet. Example of the values is shown on Table 4.

**Table 4:** Example of simulation model input values for $LHV_{Testrig}$

| Description | Unit | Value | | | | Information |
|---|---|---|---|---|---|---|
| MCR | kW | 3000 | | | | |
| $LHV_{Fuel}$ | kJ/kg | 49500 | | | | |
| Engine load | % | 50 | 75 | 85 | 100 | |
| $mdot_{CA}$ | kg/s | 2,87 | 3,86 | 3,91 | 4,55 | From Wärtsilä engine data |
| $mdot_{EG}$ | kg/s | 2,94 | 3,96 | 4,02 | 4,68 | From Wärtsilä engine data |
| $mdot_{NG1}$ | kg/s | 0,07 | 0,10 | 0,11 | 0,13 | Based on exhaust gas and combustion air mass flow |
| Specific exhaust gas flow | kg/kWh | 7,1 | 6,3 | 5,7 | 5,6 | Input value to simulation model |
| $T_{EG}$ | °C | 370 | 360 | 350 | 320 | From Wärtsilä engine data |
| Heat Rate GAS (total) | kJ/kWh | 8590 | 7850 | 7620 | 7460 | From Wärtsilä engine data |
| $P_{Fuel}$ | kJ/h | 12885000 | 17662500 | 19431000 | 22380000 | |
| $P_{Fuel}$ | kJ/s | 3579,2 | 4906,3 | 5397,5 | 6216,7 | |
| $mdot_{NG2}$ | kg/s | 0,07 | 0,10 | 0,11 | 0,13 | Based on lower heating value |
| SFOC | g/kWh | 173,54 | 158,59 | 153,94 | 150,71 | Input value to simulation model |
| $LHV_{Testrig}$ | kJ/kg | 51131 | 49063 | 49068 | 47821 | Input value to simulation model |

The fuel tank component in the model library calculates the fuel consumption of different fuels used in the simulation [kg/s], which can be used to calculate the total consumption of the simulation and further used for evaluation of profitability of payback time of different energy saving methods.

## 4.4 Modelling of battery energy storage system

The modelling of battery system starts by defining the required functions and equations to fulfil the purpose of energy model without adding unnecessary functions for the model. After reviewing some related research (Zahedi, 2014 and Ritari et al., 2019) it is concluded that battery chemistry is not needed, and electrical topology is made simple enough to cover only the absolute basic functions needed to evaluate the battery energy balance and conversion losses related to battery charging and discharging. These functions are explained in the following pages and the basic simulation input parameters shown in Table 5 below and Table 6 in the next chapter.

**Table 5:** Simulation input values for Battery Energy Storage System

| Description | Symbol | Unit |
|:---:|:---:|:---:|
| C-rate | Cr | 1/h |
| Minimum energy | Emin | kWh |
| Maximum energy | Emax | kWh |
| Efficiency | η | % |
| Initial energy | E0 | kWh |

The maximum power $P_{B,Max}$ is the maximum electrical power available from the battery [kW] and is defined as

$$P_{B,Max} = E_{Max} \cdot C_R \qquad (14)$$

where $E_{Max}$ is maximum capacity of the battery [kWh] and $C_r$ is the charge and discharge rate of the battery [1/h].

The battery charge and discharge clause are written as

$$\begin{aligned}
&\left(E \geq E_{Min} \ \vee \ P_{Charge} > 0\right) \wedge \left(E \leq E_{Max} \vee P_{Disharge} > 0\right) \\
&=> der(E) = \ P_{Charge} \cdot \eta \ - min(P_{Disharge}, P_{Max}) \cdot (2 - \eta) \\
&else \ der(E) = 0
\end{aligned} \qquad (15)$$

where $E_{Min}$ is minimum charge of the battery [kWh], $P_{Charge}$ is charging power of the battery, $P_{Discharge}$ is the battery discharging power, $\eta$ is the efficiency of the battery and $E$ is the state of charge.

The principle is that the battery supplies the power plant when the set point values are met and after power requirement becomes too low or too high the battery stops supplying the network and it turns into the charging mode. The battery charging power is an additional power requirement for the total power plant, which increases the fuel consumption of the generators.

## 4.5   Battery management system model

The battery management system is needed to ensure correct charging and discharging functions for the battery. The basic function is to distribute the electrical grid load i.e. power demand between the generator sets and battery system based on the pre-set values.

$$P_{Demand} = \sum P_{Usage}$$

$$P_{Set,min} < P_{Demand} < P_{Set,max}) \vee P_{Demand} > P_{Set,peak}$$

$$=> \begin{cases} P_{E,battery} = P_{Demand} \cdot y \\ P_{E,engines} = P_{Demand} \cdot (1-y) \end{cases} \tag{16}$$

$$else \begin{cases} P_{E,battery} = 0 \\ P_{E,engines} = P_{Demand} \end{cases}$$

where $P_{Set,min}$ is the minimum charge of the battery [kWh], $y$ is the signal between battery and battery management system about the state of the power plant and represents the state of current power demand that defines whether batteries or engines are prioritized for covering power plant electrical power demand $P_{Demand}$. Electrical power demand is covered by batteries when the power plant is operating within pre-set minimum and maximum values for battery operation, $P_{Set,min}$ and $P_{Set,max}$, or the power demand is higher than pre-set value for peak shaving $P_{Set,peak}$. If none of these conditions are met, the power utilized from the battery is zero and all electrical power demand is covered by the engines.

The basic layout of the created model is shown in Figure 9 and the input values for battery management system are shown in Table 6.
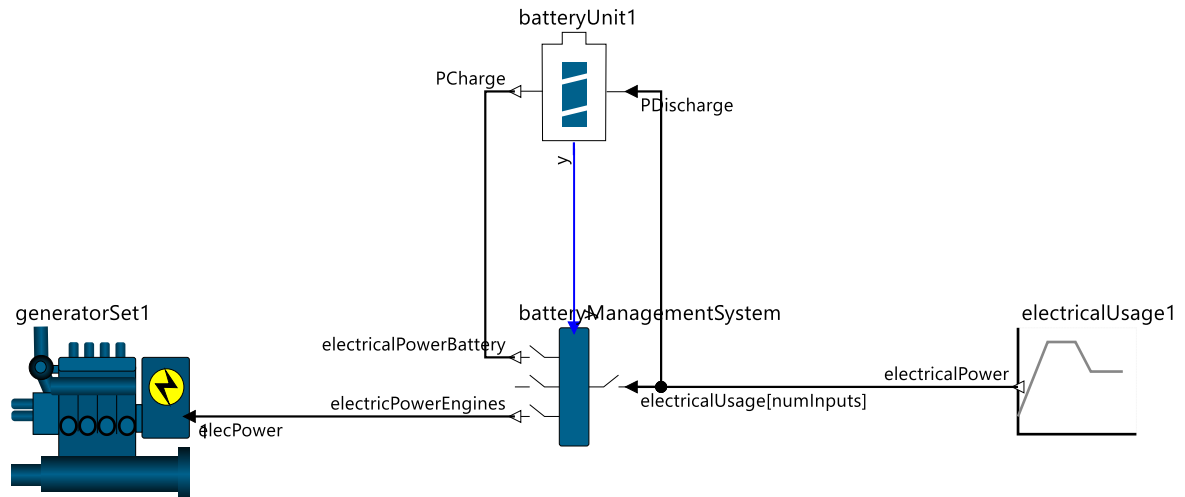
**Figure 9:** Simplified layout of a battery-hybrid model.

**Table 6:** Simulation input values for Battery Energy Storage System

| Description | Symbol | Unit |
|---|---|---|
| Minimum power to cover loads | Psetmin | kW |
| Maximum power to cover loads | Psetmax | kW |
| Peak power to cover loads | Psetpeak | kW |

## 4.6   Case study model layout

Simplified layout of the simulation model is shown in Figure 10. The main components used in the model are:

- Ambient conditions
- Fuel tank
- Generator sets
- Power demand loads: hotel, auxiliary, PM1 and PM2
- Battery ESS
- Battery management system
- HT and LT fresh water cooling systems
- Sea water cooling systems
- PI controllers for cooling water set points and pump speed
- Exhaust gas boilers

The Ship Energy System library has additional components for modelling of engine room fans and advanced technology for exhaust gas waste heat recovery, such as steam turbine generators.
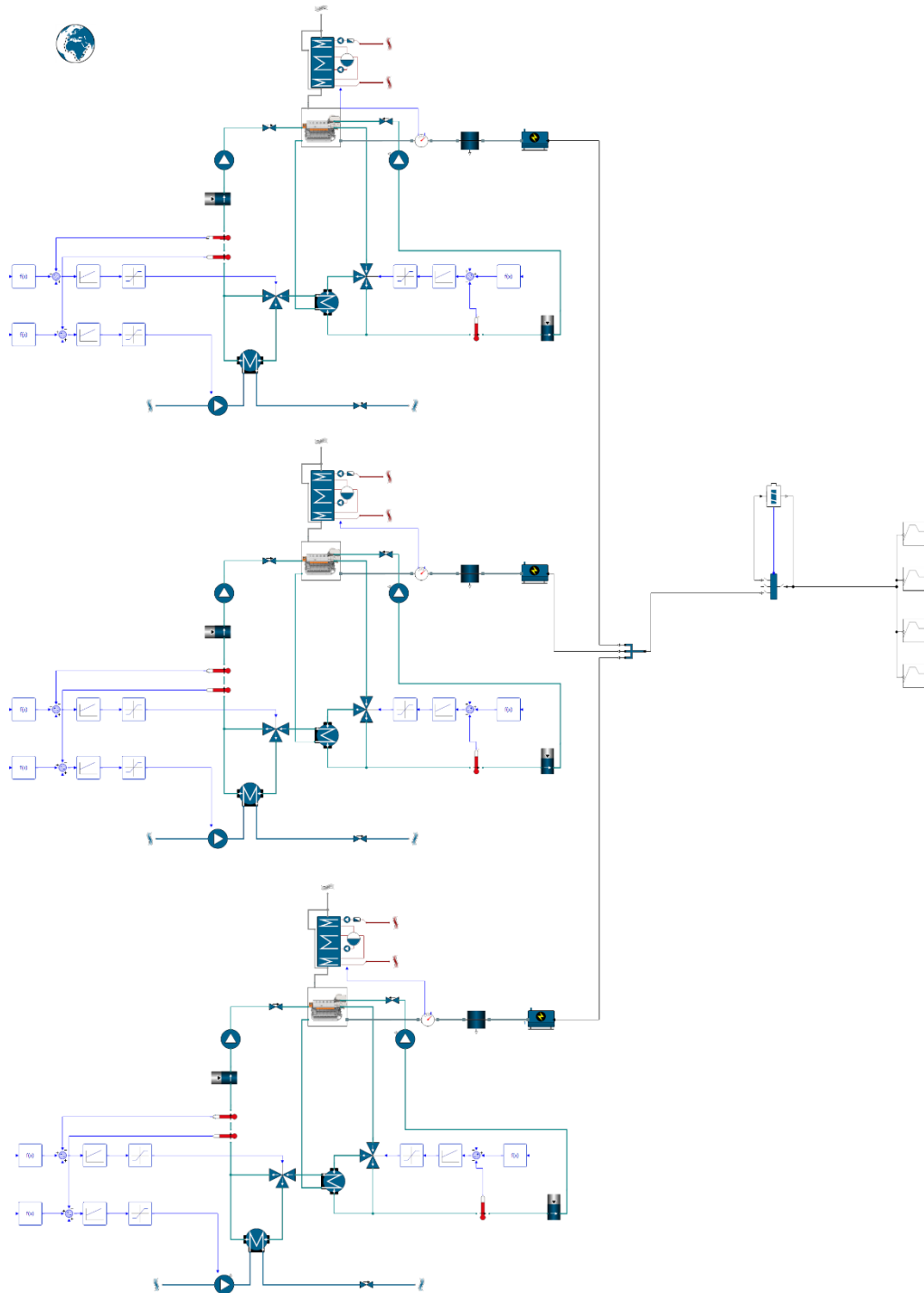


**Figure 10:** Example of the case study simulation model.

The generalized example results are shown in chapter 4.7 with an example about ships operation profile of one day (self-made operation profile).

## 4.7   Case study results

The example simulation shown in this chapter is about studying ship fuel consumption reduction by utilizing batteries for different operation scenarios. The ship is at port for 6 hours and power demand covers the hotel and auxiliary consumers. After 6 hours the ship leaves the port and extra power demand is due to propulsion and bow thruster power demand. The studied scenarios are:

- Simulation 1: All power demand is covered by diesel generators (Figure 11)
- Simulation 2: Battery is utilized for peak shaving (power demand > 1800 kW) (Figure 12)
- Simulation 3: Battery is utilized for covering harbour power demand (Figure 13)
- Simulation 4: Battery is utilized for both peak shaving and harbour demand (Figure 14).

Results of different simulation models are shown in Figures 11 - 16 The baseline for comparison of battery-hybrid modes is shown in Figure 11 where the power demand is covered only by the three-engine power plant. Engine power [kW] and battery charge [kWh] are on *y* axis and time [h] is on *x* axis.
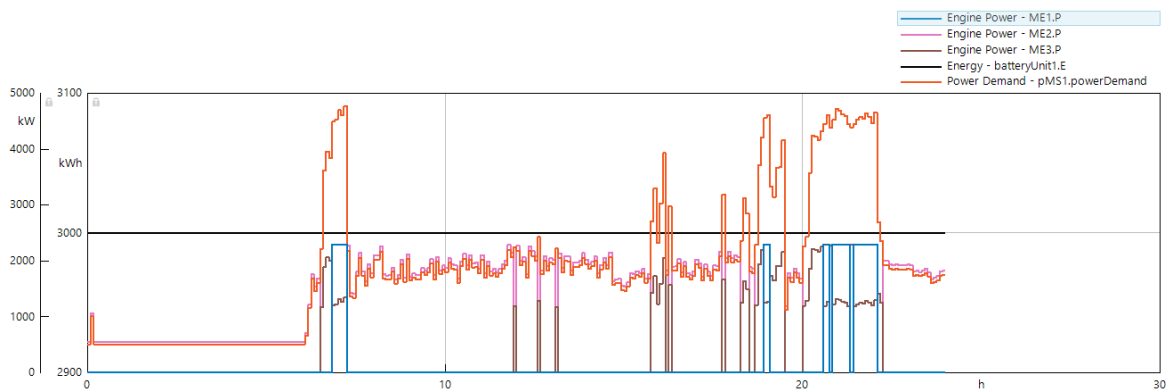


**Figure 11:** Simulation 1: Power demand and engine loads without battery utilization.

The simulation results show that most of the time the ship is operating with one engine running. Power consumption peaks lead to short starts of one or two additional engines which leads to uneven load sharing and engines operating with sub-optimal efficiency. The next model is done to cover loads above 1800 kW.
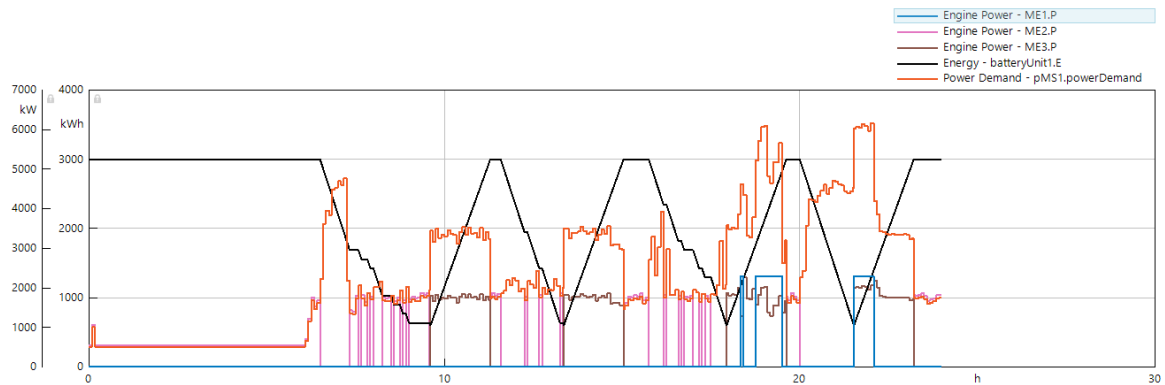


**Figure 12:** Simulation 2: Power demand and engine loads with battery set to peak shaving mode for power demand loads above 1800 kW.

The high load battery mode enables one engine to remain shut down at the small peaks compared to first simulation. This leads to 20,1 % reduction in fuel consumption compared to simulation 1.
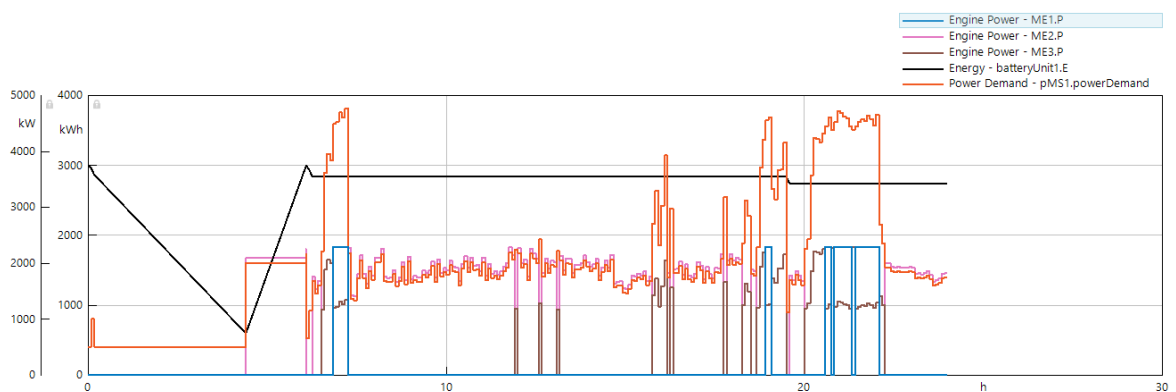


**Figure 13:** Simulation 3: Power demand and engine loads with battery set to cover power demand below 1200 kW.

Simulation 3 is set to cover harbour power demand by ESS until leaving the harbour and the ESS would be charged back to full capacity at sea with engine optimal load. This leads to increased fuel consumption by 1,9 % compared to baseline but this way it is possible to

prevent exhaust gas emissions at the harbour. The increase in fuel consumption is due to conversion losses to and from the ESS (battery). This highlights the smart use of the power plant – using batteries in every situation possible does not guarantee the best results in the fuel consumption as some of the energy is always lost.
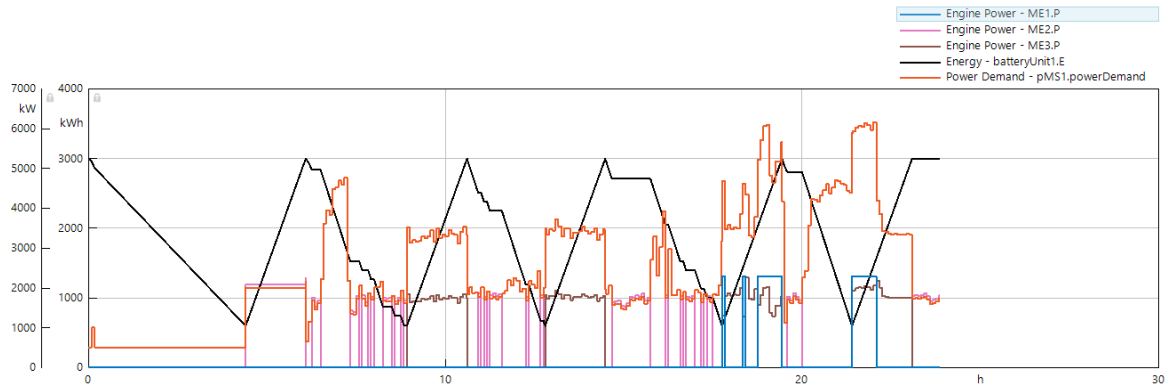


**Figure 14:** Simulation 4: Power demand and engine loads with battery set to cover power demand below 1200 kW and above 1800 kW.

The last simulation model is used to combine simulation models 2 and 3 for harbour battery mode and peak shaving. The fuel consumption is worse than in simulation 3 due to same reasons as bad results on simulation 3.

Table 7 presents the daily fuel consumption of different simulation models. Peak shaving yields good reduction in fuel consumption with both options with full battery $(E_0 = 3000\ kWh)$ and empty battery $(E_0 = 600\ kWh)$ at the beginning of simulation.

**Table 7:** Daily fuel consumption of different modes.

| Description | Fuel consumption | Unit | Reduction to no batteries |
|---|---|---|---|
| No batteries | 6823,4 | kg/day | |
| Peak shaving above 1800 kW, $E0 = 3000\ kWh$ | 5627,8 | kg/day | 17,5 % |
| Peak shaving above 1800 kW, $E0 = 600\ kWh$ | 6150,9 | kg/day | 9,9 % |
| Load load below 1200 kW | 6955,4 | kg/day | -1,9 % |
| Both modes | 5864,8 | kg/day | 14,0 % |

Simulation model is used for studying waste heat utilization onboard. The examples shown here are examples of how amount of waste heat recovery is dependent on the engine loads. The simulation result is taken from the different time period (10-110 hours) compared to simulations above (0-24 hours). This is as the model adjusts the cooling water loads at the start of the simulation. It can be seen that the loads start to even out after 20 h mark is passed.
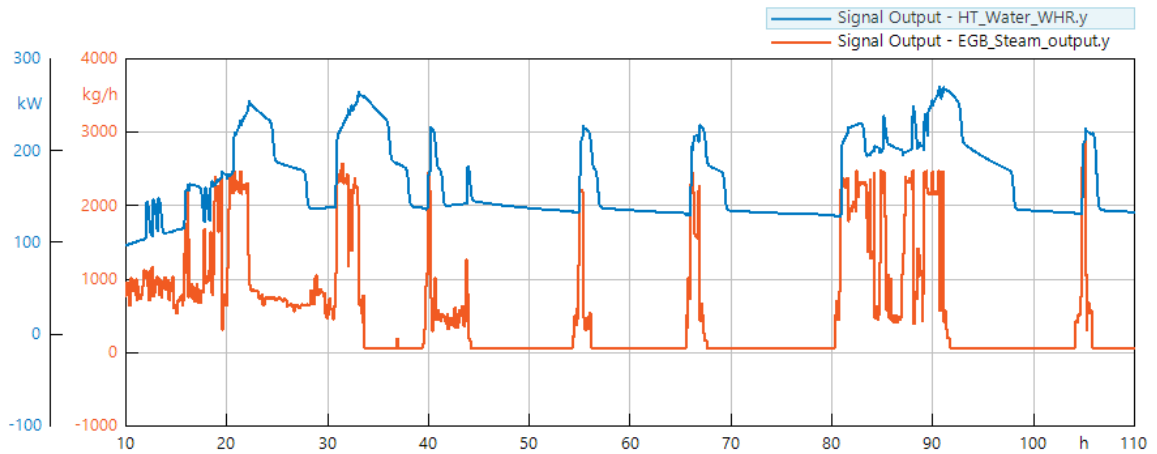
**Figure 15:** Exhaust gas boiler (EGB) and cooling water waste heat recovery (WHR) utilization potential examples.

Last part of the case study is to evaluate performance of commercially available marine diesel generators to a fuel cell unit of same capacity. The studied engines are Wärtsilä 12V14 (MGO fuelled) and Wärtsilä 6L20DF (LNG fuelled) and the fuel cell unit is based on Convion C60 (Convion, 2021) that is needed to be scaled as 700 kW fuel cell units are not yet commercially available. The purpose of this study is to determine how much fuel saving potential a fuel cell unit could yield after the units are commercially available as the options for small size dual fuel gas engines are limited to size of Wärtsilä 6L20DF that has rated output 960 kW (Wärtsilä, 2021).
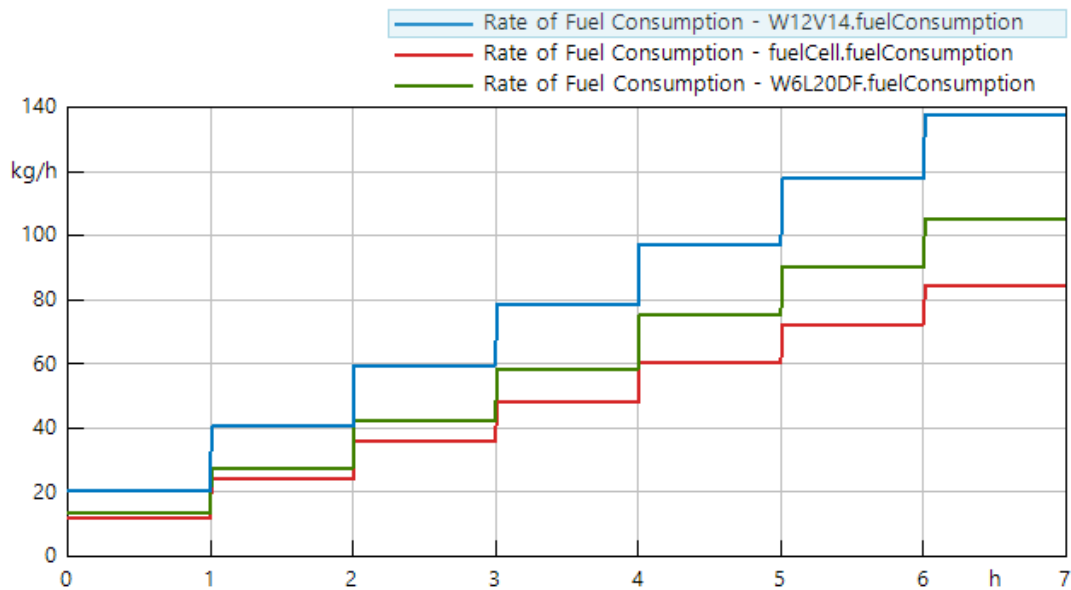


**Figure 16:** Comparison of fuel consumption between two commercially available engines and fuel cell.

## 4.8 Verification

The simulation results are always verified with manual calculations to ensure that the simulation model calculated correct results. There is also fuel consumption data available from different year (2007) than the power plant simulation input data (2020). When these values are compared it can be seen that the total fuel consumption of the simulation model is -10,4 % less than actual bunker data.

These values are not completely comparable between each other as there are differences between ship's operation years, but the basic profile of the ship is assumed to be similar enough as the ship's planned annual operational hours are same every year. The values shown in Table 8 are modified values, but the percentage difference remains the same.

**Table 8:** Comparison between bunkering values and simulation results.

| | | | | |
|---|---|---|---|---|
| 1 | Reference ship bunkering values from 2007 | MGO | 320,4 | [ton/a] |
| | | LNG | 1110 | [ton/a] |
| | | Total | 1430,4 | [ton/a] |
| 2 | Reference ship simulation values from 2020 | MGO | 587,28 | [ton/a] |
| | | LNG | 1008,96 | [ton/a] |
| | | Total | 1596,24 | [ton/a] |
| 3 | Reference and simulation value difference | MGO | -45,4 % | |
| | | LNG | 10,0 % | |
| | | Total | -10,4 % | |

The main difference between real life values and simulation model consumption is that the share between MGO and LNG consumption is different, which is explained by two assumptions. First one is the different operation year, as the difference in operational profile leads to difference in fuel consumption.

Second reason is the operation principles of LNG-powered dual fuel engines in real life and in simulation. The engine is switched to gas mode and back to liquid fuel mode depending on e.g. engine load. DF engine operation does not always mean it is consuming LNG, as the engine can be run on full MGO operation as well. Simulation model on the other hand always

uses LNG mode and MGO consumption is only the pilot fuel consumption that is assumed to be 1 % of the LNG mass flow.

The comparison table compares annual fuel mass, which is not completely accurate due to differences in fuel specific heat values. When the mass was converted to energy [MGO 42,8 MJ/kg, LNG 49,5 MJ/kg] the annual energy consumption difference was -8,4 %.

## 4.9 Validation

Fuel consumption of the new main engine component (chapter 4.3) is compared to the OEM documents during the component modelling process to ensure that the fuel consumption values are in line with the engine data. Further validation is done with an internal review at Elomatic and also based on customer feedback about how the simulation results satisfy the requirements of evaluating options for improving the efficiency of ship energy systems, thus decrease annual fuel consumption and ultimately reduce the emitted GHG emissions. The results are considered to be valid.

## 4.10 Other Simulation tools (Aveva Process Simulation)

The Waste Heat Recovery system of a ship is also modelled with Aveva Process Simulation (APS) for the purpose of studying the properties of the software. It is known at the beginning of the case study that APS is a process simulation software especially for chemical process industry. Expectation is that holistic simulation of ship's energy systems is not possible with APS, but it is important to study the extent of its properties due to APS links to Aveva Engineering, a software that is used during ship's basic and detail engineering phases for complete design and modelling of the ship.

The advantage of Aveva Process Simulation (APS) comes from the interconnection with Aveva Engineering software, which is a common tool used in Elomatic Marine & Offshore and it is used especially for detail design phase 3D modelling. There is a possibility to create piping and instrumentation diagrams (P&ID) based on simulation model, which means that all pipe flow and heat transfer related calculations are done directly on the software. The pipe system can be assessed as a steady-state or dynamic model based on the design requirements. Simulation results are used as a basis for 3D model and after the model is ready, the pipe geometry can be imported to APS for pipe system verification.

The communication between APS and Aveva Engineering is not tested and the results of the study are left out from this thesis as the results are not comparable to the actual case study requirements. The wider use of simulation-based design with APS will be piloted by Elomatic if or when a suitable project starts. The project needs to be done with Aveva Engineering and the definition of design software is usually client shipyard's responsibility. The project ship should also be large and complicated enough as the use of expensive and complicated simulation-based design is not profitable or worthwhile in small projects.

# 5 DISCUSSION

## 5.1 Simulation-based evaluation of ship energy systems

The purpose of this study is to evaluate the suitability of various simulation softwares for design engineering in marine industry. Implementing EEXI regulation to shipping in 2023 will most likely lead to a peak in environmental studies and retrofits, similar to how the new sulphur limits implemented in 2020 increased the number of exhaust gas scrubber retrofit-related offer requests at Elomatic. Simulation-based design will form the core for these studies and retrofits as fine-tuning the ship's performance for the most optimal new equipment installations will be more important than ever before.

It is likely that future customer embarking on a cruise ship voyage will select their preferred vessel largely based on its environmental aspects. This will hopefully mean that the least emitting, energy-efficient ships are the most preferred ones, despite the possibility for higher price.

Majority of zero-carbon operational fuels are yet to be viable for shipping, mostly due to incomplete shore infrastructure, energy-inefficient conversion processes or complex and expensive onboard equipment. Building of a zero-carbon ship with today's technology is expensive in both CAPEX and OPEX perspective. Thus, it is likely that biofuels in blue water shipping and electrification in short-voyage shipping compared with special attention paid to the energy-efficiency will become dominant topics in shipping for the upcoming decades.

Simulation-based design can be utilized throughout the ship's lifecycle to benefit both the builder and the customer. Optimized design leads to reduced material costs as components, e.g. pumps, are selected based on actual need without excessive design margins. Operator ends up paying less throughout the ship's lifecycle as operational costs are lower due to less weight onboard and lower fuel consumption.

Simulation tasks for different stages of design require selection of correct tool for the task. Simulation X Ship Energy Systems and Aveva Process Simulation can be used to fulfil most

of the requirements for a successful ship design project from concept drafting to planning commissioning activities of complex systems. However, these softwares are not the solution when design problems consider a specific component instead of a complete system. One of the more suitable methods for solving component-level problems of a fluid system is CFD based on Reynold-Averaged Navier-Stokes (RANS) equations (Ansys, 2017).

Simulation-based ship system design requires understanding of calculation models, system-level thinking and detailed knowledge of ship machinery equipment. Systems engineering practice has become of utmost importance for successfully conducting a modern large-scale ship design project. The complexity of modern ship machinery systems requires consideration over various disciplines. Various technical departments like machinery, HVAC, electrical and automation must function as a whole for a successful end result. Simulation-based design is not a complete solution for all challenges that emerge from complexity of modern energy-efficient ships, but it can be used as a tool to bridge the gaps between the disciplines and to help harmonizing the functions that require input from each other.

The use of simulation tools for ship design yields promising results for further development. It should be emphasized that the number of hours used within the scope of this thesis was very limited and despite that it was still possible to clearly distinct what type of softwares are the most promising for this type of work. Energy-efficiency simulation compliments multiple disciplines and should be used as an initial procedure for every concept ship project.

Some thoughts about utilization of simulation in different phases of design work are shown below in Table 9.

**Table 9:** Potential uses of Aveva Process Simulation and Simulation X in different phases of ship's life-cycle.

| Design phase | Software | Description |
|---|---|---|
| Concept Design | Simulation X | - Data input from expected or experienced ship's operational profile<br>- Evaluation of various engine and fuel types for most efficient operation<br>- Assessment of ROI for energy saving equipment and battery-hybrid drives |
| Basic Design | Simulation X | - Further evaluation of ship's energy, HVAC and electrical system modes<br>- Studying the interaction of different systems, such as Main Diesel Engine HT Cooling Water, Waste Heat Recovery and AC Reheating systems |
| | Aveva Process Simulation | - Initial heat transfer and pressure loss calculations of different pipe systems |
| Detail Design | Aveva Process Simulation | - Importing 3D model geometry to Aveva Process Simulation<br>- Verification of correct pipe dimensioning<br>- Planning of operation manuals |
| Startup and Commissioning | Aveva Process Simulation | '- Planning of commisioning procedures<br>- Implementing the results to function test documentation (HAT, SAT) |
| Operations throughout ship's lifecycle | Simulation X | - Ship's operation data is utilized in the Digital Twin<br>- Verification of onboard environmental upgrades and other machinery retrofits |

Carbon neutral shipping is a hot and popular topic in the industry seminars, but the actual large-scale projects are far and few between. One example of a pilot project is Ardmore Shipping's announcement about a joint venture that aims to bring hydrogen fuel to shipping. (Ardmore Shipping, 2021).

The shipping company Evergreen was recently on the headlines of all big newspapers about their ship blocking the Suez Canal (Wikipedia, 2021), but after the dust had settled a bit they published a building contract of 20 new HFO fuelled container ships from Samsung Heavy industries ship yard (Lloyds List, 2021). These ships can be expected to operate approximately for the next 25 years, which means the plans of many of the large shipping operators are very much different from the general public discussion. It might be so that the use of fossil fuels is only be limited once the taxies and emission levies become high enough that the operator will choose the new cheapest fuel, which by that time would be something else than fossil hydrocarbon fuel.

## 5.2  Future development ideas

The Ship Energy System model does not fulfil the requirements of evaluating various electrical grid options, e.g. differences between AC and DC grids, but that will a development aspect for the future together with electrical and software development specialists. The logic of battery management system charging, and discharge requires further development to enable more realistic evaluation of battery-hybrid ships.

Easier way to define load sharing topology of ship power plant configuration is needed as it is not accurate enough with the current state. The function of varying engine loads and steady engine loads will be implemented to the model in the future. Comparison of engine load sharing is done for at least two different scenarios to see which one has lower annual fuel consumption. These scenarios are:

- all running generators follow the load requirement, and
- one or two generators are running on constant load at the most optimum specific fuel oil consumption (SFOC) while other generators follow the load requirement.

Largest improvement topic for the future is to model complete ship energy system that will be built based on large amount of ship energy aspect requirements gathered from various projects and silent information of engineers at Elomatic. The simulation model will include the heat, cooling and electrical balance of at least the following systems:

- Bilge system,
- ballast system,
- fire-fighting system,
- cooling water systems (already included),
- potable water production and distribution system,
- sewage treatment system,
- heating, ventilation and air-conditioning (HVAC) system,
- fuel system, and
- lubricating oil system.

Building of these models is important for more accurate evaluation of voyage time energy consumption as the simulation model results are compared to basic energy and electrical calculations that are done for dimensioning of the ship power plant. These values can give unrealistic picture of the actual operating state of the ship. For example, if cruising speed power consumption of a ship is calculated to be 4000 kW it can be 2000 kW in the simulation model. This is because all consumers are not running continuously, and this is sometimes

handled by putting simultaneous factors to the electrical and energy balance, but this is very vague and inaccurate way and it can in worst case lead to over dimensioning of the ships power plant, which brings more expenses both to shipyard and the shipowner, but also brings additional load to the environment from extra material requirements and increased operation time emissions.

The purpose of this thesis was to find a suitable simulation tool for Elomatic's needs. When the results gotten from the use of Simulation X Ship Energy System are successful and the study conducted for the customer is more thorough than if it would have been done by means of spreadsheet calculations, it is safe to say that this requirement was fulfilled.

There are plenty of work for future development and possible topics for theses of different levels that could be done at Elomatic in the future. The building of complete simulation model of a ship is a complex, time consuming task that was only started during this thesis.

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