Marine Machinery Systems - Tools and Architecture

A M.Sc. thesis in collaboration with the Institute of Marine Technology at NTNU Trondheim and STX Europe Brevik.

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Preface

The M.Sc. thesis is mandatory for all master students attending the Institute of Marine Technology at NTNU in Trondheim. The thesis accounts for 100 % of the workload in the tenth semester, consisting of 30 study points.

The subject of the thesis was developed in collaboration with the Institute of Marine Technology at NTNU in Trondheim and the Shipyard STX Europe in Brevik. The collaboration with STX in Brevik is a direct consequence of my summer job during the summer of 2009.

The thesis' focus is set to enlighten important aspects regarding the design of marine machinery systems (MS) for offshore support vessels (OSV) based on a research study, and to propose a design methodology consisting of tools and architecture.

I would like to thank Eilif Pedersen, Associate University Professor at the Institute of Marine Technology, and Geir Sæther, Technical Manager at STX Europe in Brevik, for mentoring and providing technical assistance throughout the project.

In addition, I would also like to thank my fellow students; Daniel Melingen, Thomas Stavenes, and Magnus Underland Berntzen, for motivation and keeping a good work atmosphere at office C. 1.058.

Egil Christoffer Sandbakken, Trondheim 14.06.2010

Executive Summary

The thesis presents tools and architecture regarding design of marine MSs in OSVs. It enlightens important aspects regarding the design based on a research study, and proposes a design methodology consisting of tools and architecture.

From the research studies in chapter 2 it becomes clear that the most common propulsion system today for platform supply vessels (PSV) is the diesel-electric (DEL) propulsion system. Other concepts such as; dual fuel engines, Voith Schneider Propellers (VSP), hybrid systems, fuel cell power, wind power, nuclear power, and jet propulsion exist today but is not yet considered typical solutions.

The research study in chapter 5, regarding current status on tools and architecture, shows that it exist very few dedicated and sophisticated tools and methodologies regarding early-design of MSs onboard OSVs. However, exceptions such as the software package GES, developed by TNO in Holland, were found and it is considered the most promising tool yet based on this study.

GES share the same design philosophy as the proposed tool in chapter 8, which is regarding the MS as an energy system where power flow through components is modeled with respect to the bond graph theory. By utilizing the bond graph theory, unified interfacing is introduced. This approach is applicable in any energy domain and the variables describing the energy or power are kept in a general form; effort and flow.

The proposed methodology, in chapter 7, presents structure and methods regarding the design process such as; concurrent engineering, hierarchical MS breakdown structure, component library scheme, and model documentation framework.

The thesis presents, in chapter 8, a MS mock-up with a hierarchical system structure and unified interfacing between components. The mock-up is flexible in terms of sub-system or component reconfigurations and it allows for energy domain-independent performance analysis which is exemplified in chapter 8.5 and 8.6.

The MS mock-up is considered far from complete in terms of user-friendliness, sub-system description, and component description, but it portraits trend lines regarding performance which are similar to what one may find by analyzing real MSs, which is considered the goal for developing this mock-up.

The presented mock-up and methodologies are meant to exemplify how one can approach this challenge.

Problem Description

The trend today shows that marine MS designs tend to head for more complex solutions as more decisive factors are implemented such as the operational profile, higher investment costs, stricter rules and regulations, and increasing amount of available optional configurations and solutions regarding system and component selection.

From a designer's point of view, in the early phases of the design, it is important to narrow down the amount of concept solutions and to present the best ones or the best one for further evaluation. This is a challenge designers are facing now and if not, in the near future. What tools and methodologies can be utilized to overcome this challenge?

The purpose of this thesis is to establish an outline for the current situation on methodologies and tools for early-design of multi energy domain MSs for OSVs and to propose a tool and architecture for how such procedures can be handled.

To approach this task one must enhance the understanding of, and answer the following questions:

- *What MSs are common in today's OSVs?*
- *What MSs are available?*
- *What tools and methodologies are utilized in MS design?*
- *What available methodologies exist which can be used to handle such a challenge?*

In addition to answer these questions, the thesis shall include:

- *A proposed MS design methodology and architecture covering:*
    - *The design process, system structure, component interface, component library, and component documentation framework.*
- *A MS description, describing a set of sub-systems and components.*
- *A MS mock-up which shall include:*
    - *Flexible model re-configuration possibilities, simulations, results from simulations, and a sensitivity analysis.*

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Nomenclature

Abbreviations:

AC	Alternating Current
ACSL	Advanced Continuous Simulation Language
AVR	Automatic Voltage Regulator
CATIA	Computer Aided Three-Dimensional Interactive Application
CBP	Class-Based Programming
CFD	Computational Fluid Dynamics
COD	Context Object Diagram
CPP	Controllable Pitch Propeller
CRP	Contra-Rotating Propeller
CS	Cooling System
CSI	Current Source Inverter
DC	Direct Current
DE	Diesel Engine
DEL	Diesel-Electric
DOL	Direct-On-Line
DP	Dynamic Positioning
DRA	Dynamic Response Analysis
EM	Electric Motor
FFT	Fast Fourier Transform
FOMM	Function and Object Mapping Model

FORTRAN	FORmula TRANslation
FPP	Fixed Pitch Propeller
FT	Function Tree
GenSet	Generator Set
GES	Geïntegreerde Energie Systemen
HB	High Bound
HOOM	High Order Object Model
HT	High Temperature
I/O	Input/Output
LB	Low Bound
LNG	Liquefied Natural Gas
LT	Low Temperature
MS	Machinery System
OO	Object-Oriented
OOD	Object-Oriented Design
OSV	Offshore Support Vessel
PI	Proportional-Integral
PSV	Platform Supply Vessel
RPM	Rounds Per Minute
RRM	Rolls-Royce Marine
SI	Systéme International
SIDOPS	Structured Interdisciplinary Description of Physical Systems
SFC	Specific Fuel Consumption
SPPM	Smart Propulsor Product Model
VSI	Voltage Source Inverter
VSP	Voith Schneider Propeller

Uppercase:

C	[-]	Bond graph capacitive element
E	[Wh]	Energy
GY	[-]	Bond graph gyrator element
I	[-]	Bond graph
I	[A]	Current
MSe	[-]	Bond graph modulated source of effort
P	[W]	Power
P	[Pa]	Pressure
$\mathbf{P_e}$	[W]	Nominal power
$\mathbf{P_e^*}$	[W]	Power at 100% MCR
$\mathbf{P_t}$	[W]	Theoretical power
R	[-]	Bond graph power dissipation element
R	[Ω]	Resistance
Se	[-]	Bond graph source of effort
Sf	[-]	Bond graph source of flow
T	[K]	Temperature
T	[Nm]	Torque
TF	[-]	Bond graph transformer element
$\mathbf{T_i}$	[Nm]	Indicated torque
Tt	[Nm]	Theoretical torque
$\Delta\mathbf{T_{ti}}$	[Nm]	Torque loss relative to the theoretical torque
U	[V]	Voltage

Lowercase:

$\mathbf{b_e}$	[g/kWh]	Specific fuel consumption
$\mathbf{b_{e100}^*}$	[g/kWh]	Specific fuel consumption at 100% MCR
e	[-]	Bond graph effort
f	[Hz]	Frequency

f	[-]	Bond graph flow
$\mathbf{f_s}$	[Hz]	synchronous frequency
hn	[MJ/kg]	Lower heating value for fuel
k	[-]	Pressure-temperature factor
m	[-]	Bond graph transformer modulus
$\mathbf{\dot{m}_B}$	[kg/s]	Mass fuel flow
ms	[kg]	Mass fuel injected per cycle
n	[RPM]	Engine speed
$\mathbf{n_\alpha}$	[-]	Number of rounds per cycle
$\mathbf{n_s}$	[RPM]	Synchronous speed
p	[-]	Pole number
p	[-]	Bond graph generalized momentum
r	[-]	Bond graph gyrator modulus
s	[-]	Slip
t	[s]	Time

Greek:

$\boldsymbol{\alpha}$	[-]	Switch for 2-stroke or 4-stroke
$\boldsymbol{\eta_m}$	[-]	Mechanical efficiency
$\boldsymbol{\eta_i}$	[-]	Indicated efficiency
$\boldsymbol{\omega}$	[rad/s]	Angular speed

1 Introduction

1.1 Background and Motivation

In a competitive marked, such as the offshore industry, it is important for the shipowners to own vessels which are slightly better than the competition. There are many variables which combined describe the performance of an OSV in terms of efficiency, or in other words; the resulting economic cost.

The trend today shows that marine MS designs tend to head for more complex solutions as more decisive factors are implemented such as the operational profile, higher investment costs, stricter rules and regulations regarding emissions, and increasing amount of available optional configurations and solutions regarding system and component selection.

As the MS becomes more complex, the consequence is that more system parameters and variables appear which leads to more uncertainties and challenges regarding optimization, and it becomes difficult to obtain performance predictions in an early phase which may result in poor design.

The MS performance is related to the vessel's ability to utilize the available amount of energy onboard. Hence, one can view the MS as an energy system, where power is generated from an energy source and distributed and consumed within the boundaries of the system.

1.2 Scope of the Work

The work has been carried out individually with counseling from supervisor, Associate University Professor Eilif Pedersen.

The goal for this thesis is to establish an outline for the current situation on methodologies and design tools for early-design of multi energy domain MS for OSVs and to propose a tool and architecture for how such procedures can be handled.

This goal has been obtained by doing the following:

- *Research study on:*
    - *today's design tools, design methodologies, and typical MS configurations onboard platform supply vessels (PSV).*
    - *model design approach for multi energy domain systems.*
    - *sub-systems and components in a MS.*
- *Propose a design tool and architecture for MS design based.*
- *Establish a MS mock-up with performance analysis.*

The focus is set on energy flow and component interfacing. The performance of the MS is directly related to how the energy onboard is utilized. Unified interfacing between components of different energy domains allow for easy sub-system or component re-configurations without having to correct and re-configure the remaining parts of the systems.

The proposed methodology and system architecture based on methodologies found in the research study are not yet considered common in MS design today.

The MS is considered the propulsion system and all the auxiliary energy systems combined throughout the thesis.

1.3 Structure of the Thesis

Chapter 2 presents the typical MS configuration for PSV's today.

Chapter 3 explains how a diesel-electric (DEL) MS works and why it is selected for many of today's OSVs by considering the pros and cons.

Chapter 4 presents alternative propulsion systems for OSVs, describing functionality and commenting on the feasibility for selecting such systems.

Chapter 5 presents design tools and methodologies utilized in designing marine MSs today and also introduces other conceptual methodologies utilized today in other types of system design such as software development.

Chapter 6 presents sub-systems and components found in a MS, and additionally how to monitor fuel consumption and effects of emissions to air. This chapter is meant to enlighten parameters and variables for the sub-systems and components to be modeled in the mock-up in chapter 8.

Chapter 7 proposes a system design and architecture for the marine MS based on discussions with supervisor and ideas and concepts found in chapter 5.

Chapter 8 proposes a mock-up of a MS, including structure and a performance and sensitivity analysis by simulation, by applying the bond graph method and dedicated software (20-Sim).

Chapter 9 presents the thesis' conclusions and proposes further work.

Appendix A presents a detailed description of the sub-systems and components found in the MS mock-up.

Appendix B presents the parameters for the performance analysis of the mock-up.

Appendix C is a CD which contains the modeling files in .emx-format which can be opened in the software tool 20-Sim.

2 PSV Propulsion Machinery System Configurations Today

Most of today's MS designs are based on prior known configurations. This chapter presents a typical propulsion MS configuration for operating PSVs in order to exemplify what is common today. This research is meant to show that many PSVs are using a complex machinery configuration such as the DEL MS, and also the low variation in the design. The focus in this chapter is set on the main part of the MS, the propulsion system.

The PSVs in table 1 are ships built in the last three years. These designs were developed by the following leading naval architect companies in the offshore segment; STX Europe, Ulstein Group and Wärtsilä. The current shipowners of the listed PSVs are; Island Offshore, Farstad Shipping, Bourbon Offshore Norway, DOF Offshore and Siem Offshore.

NoV:	Type:	Yard:	Built:	Machinery:	Propulsion Units:
M/S Island Challenger	UT-776 CD PSV	STX Europe Brevik	2009	Diesel Electric Power, 4x Gen. (Tot: 6.960 kW), 2x Em. Gen. (335 kW + 300 kW)	2x Azipull (Tot: 5.000 kW), 2x Tunnel Thrusters (Tot: 1.766 kW), 1x Swing-up Thruster (883 kW)
M/S Far Seeker	UT-751 E PSV	STX Europe Brevik	2008	Diesel Electric Power, 4x Gen. (Tot: 6.620 kW), 1x Em. Gen. (199 kW)	2x Azipull (Tot: 4.400 kW), 2x Tunnel Thrusters (Tot: 1.766 kW), 1x Swing-up Thruster (883 kW)
M/V Bourbon Sapphire	Ultstein P105 PSV	Zhejiang Ship-building Co. China	2008	Diesel Electric Power, 4x Gen. (Tot: 7.300 kW), 1x Em. Gen (250 kW), 1x Harbour gen. (315 kW)	2x Azimuth Thrusters (Tot: 5.000 kW), 2x Tunnel Thrusters (Tot: 1.766 kW), 1x Swing-up Thruster (883 kW)
M/S Skandi Flora	STX PSV 06 CD	STX Europe Aukra	2009	Diesel Electric power, 4x Generators (Tot: 7.920 kW), 1x Em. Gen. (360 kW)	2x Azimuth Thrusters (Tot: 4.400 kW), 2x Tunnel Thrusters (Tot: 1.766 kW), 1x Swing-up Thruster (883 kW)
M/S Siem Sailor	VS 485 PSV	Karmsund Maritime Service	2007	Diesel Electric power, 4x Generators (Tot: 7.300 kW), 1x Em. Gen. (320 kW)	2x Azimuth thrusters (Tot: 4.900 kW), 2x Tunnel Thrusters (Tot: 2.000 kW), 1x fwd Azimuth thruster (880 kW)

Table 1: Typical propulsion systems in operating PSVs today [5], [6], [7], [8], [9].

These PSVs range in length from 85,00m to 94,90m, beam approximately 20,00m, and the weight range from 4.000 GT to 4.500 GT. The PSVs listed, have a very similar propulsion MS configuration, both in selected power generation and selected propulsion units. The figure below is a simplified sketch which shows the typical propulsion system configuration found in many PSVs today.

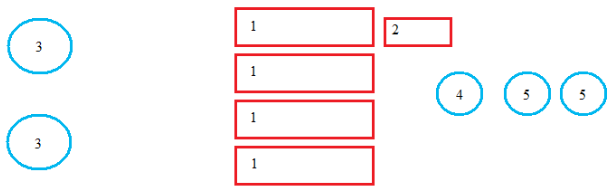


Figure 1: Typical propulsion machinery system configuration

Components in fig. 1:

1. *DE generator sets*
2. *Auxiliary emergency/harbor generator*
3. *Azimuth thruster/pull with electric motor*
4. *Swing-up thruster with electric motor*
5. *Tunnel thrusters with electric motor*

3 Diesel-Electric Propulsion Machinery System

An introduction to the DEL propulsion MS is given in this chapter in order to understand why it is selected for most of the PSVs and also other offshore support vessels (OSV) built in the recent years.

3.1 Background

DEL propulsion was introduced in 1920 to reduce the time crossing the Atlantic for passenger liners. A turbo-electric MS with steam turbine generators powering the electrical motors giving rotational speed by the electrical frequency was utilized. Typically the generators would run one propulsion motor each, but it was also possible to have one generator running several propulsion motors at low cruising speeds. Due to more economical diesel engines (DE), DEL propulsion systems more or less vanished from the marine merchant vessels only to reappear in the 1980's after the development of variable electric speed drives and a higher focus on the environment [10].

3.2 What is a Diesel-Electric Propulsion Machinery System?

DEL propulsion is a drive where the ship's propellers are driven by electrical motors, not conventional main DEs. The electrical motors are powered by prime movers; diesel/gas engines or gas turbines, giving rotational speed controlled by the electrical frequency given by the engine. Therefore the speed can be controlled stepless from zero to max. The figure below shows the principles of such systems.

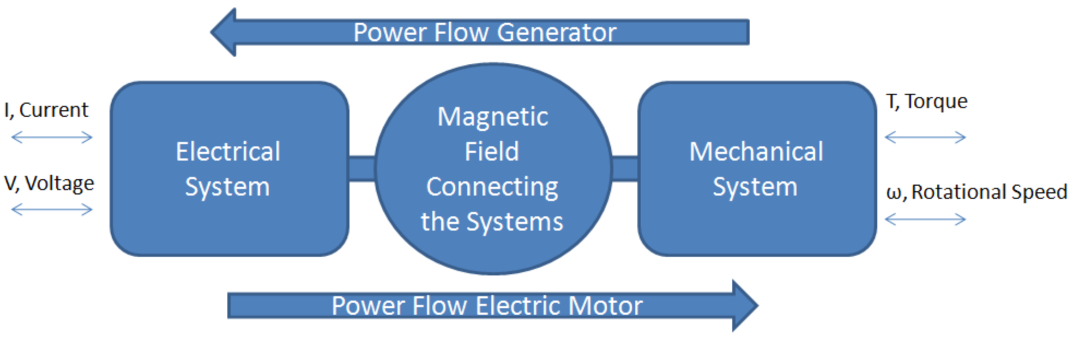


Figure 2: Principles of a Diesel-electric propulsion system [10].

The number of generators in use is dependent on speed, torque or thrust demand, and the redundancy of the system provides the option of using one or all generators [11]. Azimuth thrusters are preferred for PSVs, due to power required for running, size, and attributes regarding DP. The thrusters receive power from the electric motor via a gear located on top of the unit [10]. Alternatively podded propulsion can be used, where the electric motor is directly coupled to the propeller, though it's typically used for larger ships such as; cruise ships or ice-breakers. The propulsor units in both solutions are providing thrust by having propellers either pushing or pulling the water.

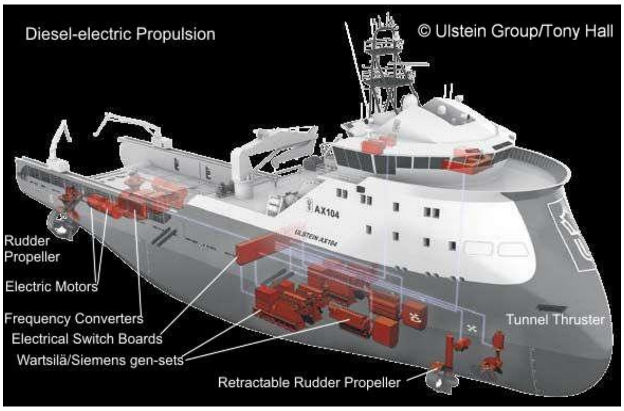


Figure 3: Diesel-electric propulsion system in offshore supply vessels [12].

3.3 Why Diesel-Electric?

Prior to the selection of a DEL MS one must consider the advantages and disadvantages.

Advantages	Disadvantages
Increased reliability	Hight capital investment
Reduced Maintenance work	Higher fuel consumption rates than low speed DE at the optimum point
Better manoeuvrability	Higher technical complexity
Considerable energy savings	Generator set operating under part load
Improved enviroment	
High adaptivity	
Generator location	
Reduced noise and vibration	
Better cargo handling	
Podded propulsion	

Table 2: Diesel-electric propulsion: Advantages & Disadvantages[11], [12].

A DEL propulsion system provides a high degree of reliability due to the possibility of sharing the load on the generator sets. When power or thrust is needed, the power is given by a generator set (genset) or a combination of gensets in accordance with operator’s demand. This allows some gensets to be switched off during operations and offers the availability for maintenance work, or to remove part loads. In addition, more optimized use of the gensets will reduce wear and tare and therefore reduce maintenance costs due to increased service intervals [12].

Azimuth propulsion is desired for its high degree of maneuverability in operation modes, such as dynamic positioning (DP) [10].

The DEL system also offers considerable energy savings due to its flexibility and redundancy in distributing the load on the gensets. The gensets may therefore vary in size in accordance with the power needed for the vessels operation profile [11]. Optimizing the use of the gensets will have a positive effect in reducing the fuel consumption and also consequently reducing emissions. The gensets are not mechanically connected to the to the propellers like the conventional mechanical systems and therefore offers the designer less restrictions when deciding where the gensets are placed regarding interference with cargo spaces. In addition the system will offer a lower level of noise and vibration due to the absence of shafted propulsion [12].

The advantages outnumber the disadvantages compared to conventional mechanical systems, but they must be taken into consideration in order to reveal the total performance.

A DEL propulsion system is a high capital investment, but is expected to pay off during the vessels lifetime. When considering the operation mode, in transit, a shafted propeller mechanically connected to a low speed engine running at optimal speed would be preferable, so one must weigh the different modes in the operation profile in order to make a decision. Commonly a PSV spends much time in standby mode and therefore in need of good maneuverability, resulting in varying engine loads, hence a DEL propulsion system is preferable [12].

A DEL propulsion system is more complex and has more components than the conventional mechanical system. This will require more from the crew handling and maintaining the system concerning knowledge and equipment. The high degree of redundancy will require a good system for monitoring and controlling propulsion and other auxiliary loads. When the complexity increases, this will become harder to obtain. An increase in components such as generators, switchboards, transformers, frequency converters and electrical motors will reduce the efficiency at full load, typically by 9-11 % from prime mover shaft to electric motor shaft [10].

Even though the generators can be switched on and off for a given amount of power, one or more generators may experience part loads [12]. Part loads leads to one or more DEs running below optimal point regarding the fuel consumption-power ratio, which is not desirable.

The main and commonly obvious reason why a DEL propulsion system is preferred for PSVs, is the fact that these ships often run at low speeds and spend a great deal of time in standby mode due to its operation profile. To optimize the system one must choose the configuration, in terms of size and number of generator sets and type of propulsion, best suited the operation profile.

4 A Brief Introduction to Alternative Propulsion Systems

Even though the typical DEL propulsion system, as described in chapter 2, is considered the most common propulsion system in today's offshore segment, other concepts appear due to the constant pursuit for more fuel efficient and more environment-friendly OSVs. This chapter presents some of the existing and future potential concepts. The concepts presented are part-systems of the propulsion MS. This implies that an option for potential combinations can be obtained and that a need for a modeling tool for complex multi energy domain system design exists.

4.1 Dual Fuel Engines

The dual fuel engine system is able to run on both diesel and liquefied natural gas (LNG). If running on LNG, the emissions of NO_X and CO_2 can be considerably reduced. According to the article; Unique design solution wins DOF contract for Aker Yard, in Skipsrevyen 11. March 2008 [13], the emission of NO_X can be reduced by 85-90 %. This system is more complex and requires more space than the DEL system.

4.2 Voith Scneider Cycloidal Propulsion

The design of a Voith Schneider propeller (VSP), also known as a cycloidal drive, is quite different from the conventional propulsion systems. The propulsion unit consists of parallel sets of vertical rotating hydrofoils on a rotating circular plate. The internal gear changes the angle of attack so that each hydrofoil gives thrust in any given direction [2]. This propulsion system is powered by DEL gensets [4].

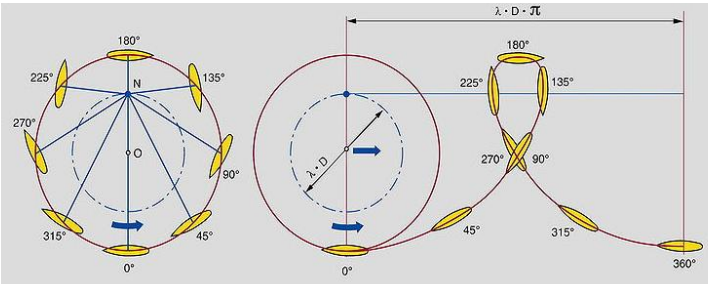


Figure 4: Path of hydrofoils in the water for Voith Schneider Proppellers [2].

The propulsion system offers a high degree of redundancy and maneuverability. This propulsion unit can also be used to reduce roll. According to Voith Schneider, tests done at Marintek in Trondheim have shown that the power needed with a VSP-system requires roughly 10 % less than for a contra-rotating propeller (CRP) set [4]. The complexity of this system will be higher than the complexity for the azimuth thrusters. This results in more challenges for operating and maintaining the vessel. These propulsion units are driven by electric motors and typically powered by DEL gensets.

Figure 5: Voith Schneider Propellers fitted on ST216 Edda Fram [4].

4.3 Hybrid Propulsion System

The hybrid propulsion system is a combination of a diesel-mechanical and a DEL system. Due to the increased mechanical complexity in the hybrid propulsion system, it is harder to optimize the configuration of the power plant and the propulsion units. This means that it is more difficult to operate at optimal conditions without manual interactions, though it provides more configuration possibilities for the operation modes. The azimuth thrusters are typically retractable in order to reduce the resistance and change in flow pattern during transit. The system provides a higher maximum bollard pull and lower fuel consumption during transit than a pure DEL system, and is therefore seen more often in anchor-handling vessels and also in high speed PSVs [14].

4.4 Fuel Cells

The fuel cell technology is not yet considered viable due to the lack of testing and development, but it has been implemented in the supply vessel Viking Lady and is currently subject to testing. The goal of this project is to significantly reduce CO_2 emissions, improve energy efficiency, and provide zero emissions of harmful substances relative to the today's engine technology [15].

A fuel cell works as an electrochemical conversion device where it produces electricity from fuel and an oxidant. For hydrogen fuel cells, as implemented in Viking Lady, the hydrogen acts as the fuel and oxygen as the oxidant. The fuel efficiency tend to decrease when more power is drawn, since drawing more power means drawing more current, which leads to increased voltage drop in the fuel cell. In addition a large amount of the energy produced is converted into heat [16]. One must also consider the process of producing hydrogen. If the side effects of producing hydrogen are equivalent or close to the same as using DEs, then this energy source is no better than the other.

4.5 Wind Power

Wind power is a free, but hard to utilize, energy source for OSVs. One way of utilizing this energy source is by having one or more kites towing the vessel and thereby reducing the amount of thrust needed. This solution can be considered as a measure of reducing emissions and fuel consumption but contains many dependencies like; wind and heading direction, wind speed and durance, crew knowledge, cruise speed, equipment, and operational complexity. In some cases the effort might be larger than the reward.

Figure 6: Skysail on a container ship [3].

Another way of utilizing wind power is by using The Magnus Effect. The Magnus Effect is a phenomenon where a rotating object in a fluid creates a resulting force perpendicular to the direction of the flow, due to the pressure differential [1]. Implementing a set of rotating cylinders on an OSV will then give an optimal force in the vessels heading if the wind flow is perpendicular. The issue then is where to put these cylinders and how much this effect will contribute to the overall propulsion.

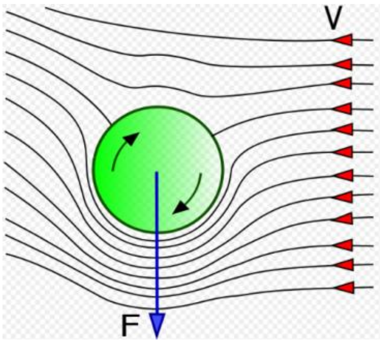


Figure 7: The Magnus Effect [1].

4.6 Nuclear Power

In order to create power from a nuclear propulsion system, nuclear fission takes place, producing heat which converts water into steam by using heat exchangers. The steam enters gas turbines which produces power [17].

A nuclear propulsion system provides a more or less unlimited cruising range for a ship considering fuel consumption, due to its endurance. This system will additionally cause no dangerous emissions to the environment during operation, which is a major advantage for propulsion systems today. It offers a high power density but the reactor is big and heavy, which isn't optimal for a OSV. In addition the system has a high capital investment cost and requires specialized trained men for handling and disposing the nuclear materials. There is also always a danger of radiation even though the reactor is shielded by special material to protect the crew. As for today it is the larger vessels, typically military vessels, and icebreakers which will benefit such a system the most [18].

4.7 Jet Propulsion

The principle of the jet propulsion system is having water pumped into the vessel and obtaining propulsion by distributing the water flow out of the vessel through a number of fixed or adjustable nozzles creating pressure differences.

The system has so far been implemented in a small, 14,5 m long and 3,0 m wide, research vessel named Ty. The water is pumped in through the bow by a DEL driven centrifugal pump and blown out through 60 nozzles providing directed thrust by adjusting the water flow of the nozzles.

According to tests performed by Tyvik AS, the jet propulsion system is comparable in efficiency and is more likely to be more efficient after further development than conventional propellers. The tests have additionally shown that the propulsion system provides a better maneuverability and shorter braking distance than for conventional propelled vessels [19].

5 Design Tools and Methodology for Marine Machinery Systems

The design of MSs in the offshore segment is subject to continuously optimization due to the constant effort imposed by shipping companies and governments to reduce fuel consumption and emissions. The consequence of this is increased complexity in the design such as combining mechanical and electrical power for a propulsion system. In order to solve new problems related to this, the engineer needs to expand his or her toolbox. These types of systems are too expensive, time-consuming and complex to make a full-scale model of in every new design.

The reason for this is that many of the ships build in the offshore segment have different designs, due to operational profiles, different working areas, and special requirements given by the shipping company.

Often, the design is not final until far into the building process. The design flexibility required in making complex and new designed ships is what makes ship-building profitable in a country such as Norway. A software tool for building and simulating large and complex multi energy domain dynamic systems, such as MS found in today's OSVs, should help the design engineers developing even more efficient designs.

5.1 Machinery System Design Tools and Methodology in Use Today

This chapter presents design tools and methodology used in today's design of MS for OSVs such as supply and anchor handlers.

Prior to this research study some ideas and thoughts around the status on this subject was shared and discussed. It was suspected that very few dedicated and sophisticated software tools exists or are utilized for solving problems concerning MS design and dynamic behavior in the early phases. Some of the thoughts and ideas on the subject are listed below:

Today's MS designers utilize:

- *Software such as Microsoft Excel for simple calculations on power demand based on prior hydrodynamic calculations.*
- *Previous estimations from previous designs.*
- *Simple estimations with corrections based on previous designs.*

Today's MS designers do not utilize:

- *Detailed operational profiles as basis for the selected machinery. This may be a result of insufficient input from shipowner due to uncertainties or availability.*
- *Software which allows for easy setup of new configurations, based on predefined components and sub-systems, with a dynamic performance analysis.*
- *Software with unified interfacing (domain-independent) allowing for reconfigurations in any energy domain without having to manually correct for it in the rest of the system.*
- *Software which allows for analysis of time domain specific events.*
- *Software with optimizing functions based on the result of a performance analysis.*

The following research study presents tools and methodology which are publicly available on the websites for the yard company STX Europe in Norway, the machinery manufacturers Rolls Royce

Marine and Wärtsilä. All of the presented companies are considered large, influential, and leading in this area of design. As result of this, the following should be able to represent a status of what is utilized today.

5.1.1 STX Europe Design in Ålesund and Machinery Design

STX Europe Design in Ålesund is currently not using any dedicated MS simulation software for selecting and configuring MS in their design. However, they have a method for the selection process. The method was explained by Machinery Chief Engineer Arnstein Rødset at STX Design in Ålesund [20] and it is described in the next paragraphs.

The MS design is based on prior hydrodynamic calculations in order to estimate vessel service speed and required power for DP operations. According to Mr. Rødset; the number of optional gensets for offshore vessel is low, which then makes the decision fairly easy. It is possible to categorize the engines into three groups based on the engine speed: 720 rpm, 900 rpm, and 1800 rpm. The engine manufacturers have a pretty similar portfolio of engine types which make such categorization helpful.

Based on previous designs, the hotel loads range approximately from 300 kW to 1200 kW and the deck load approximately 1500 kW. The difference in performance from one engine to another varies a lot i.e.:

$$4 \text{ x Wärtsilä 8L32:} \quad 4 \text{ x } 3\,690 \text{ ekW} = 14\,760 \text{ ekW} \tag{5-1}$$

$$4 \text{ x Wärtsilä 9L32:} \quad 4 \text{ x } 4\,150 \text{ ekW} = 16\,600 \text{ ekW} \tag{5-2}$$

$$\text{Difference} = 1\,840 \text{ ekW} \tag{5-3}$$

The difference between the two types of engines is as much as 1 840 ekW. This is twice as much as the hotel load can be.

The selected engine is also based on the desired engine speed. The relation between engine speed and engine size is important. Low speed engines tend to be larger and heavier than high speed engines, but lower speed engines means lower specific fuel consumption (SFC). The shipowner needs to decide which comes first.

The power estimation and a balancing of the electric system combined, are according to STX Europe Design sufficient for today's design of the MS [20].

The method described is based on product limitations from supplier, but what if the flexibility increases? How can the design process be improved and be more efficient when design based merely on previous experience is no longer enough?

5.1.2 Rolls-Royce Marine and Dynamic Response Analysis

The method Rolls-Royce Marine (RRM) is using to describe the dynamic behavior of the ship and its components is called Dynamic Response Analysis (DRA). The DRA is generating a set of equations for the components and combining them in a unified computer simulation which can predict the transient and steady state response of the complete system. The simulation quantifies performance and exposes potential problems. The DRA is used to verify MS design and selection prior to placing equipment orders, and is supported by an extensive mathematical model library. Additionally the DRA can be used as a tool to analyze normal operation and failure modes to help determine causes of problems and to help designing corrective actions throughout the systems service life.

The DRA is using both standard programming language (C, C++, Ada, FORTRAN) and sophisticated simulation environments such as ACSL and Simulink. The selected programming tool may vary and is based on customer requirements and special system design considerations [21].

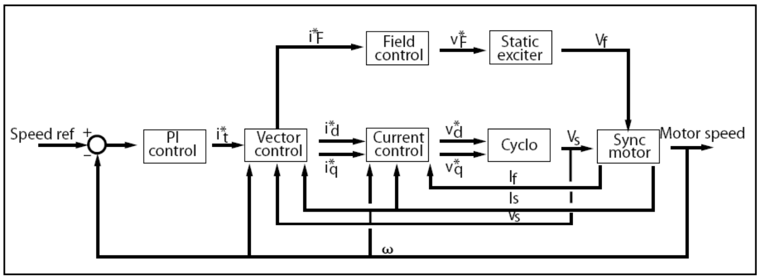


Figure 8: Dynamic Response Analysis in controller design [21].

RRM have additionally developed an integrated design environment, called Smart Propulsor Product Model (SPPM), which uses web-based software technology in order to link software tools used for propulsion design, development, life-cycle cost analysis, performance simulations, manufacturing, and field support. The SPPM has proven to be a factor in reducing design cycle time and offering trade-off analyses throughout the product life-cycle [22].

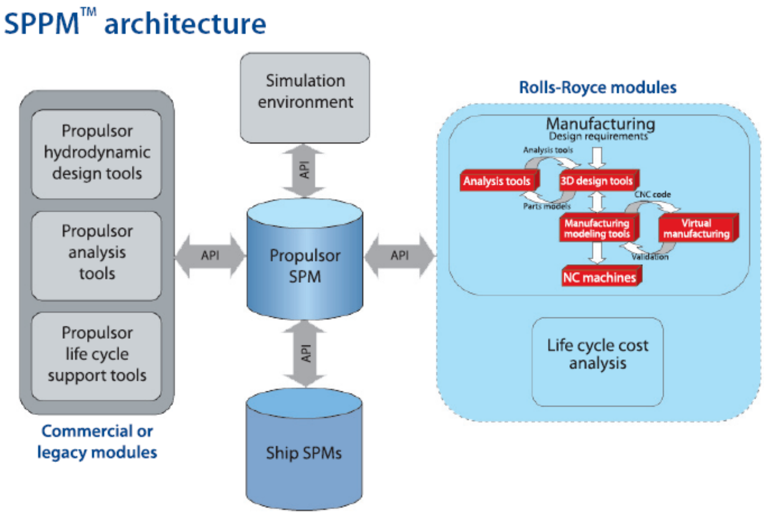


Figure 9: Smart Propulsor Product Model flow chart [22].

5.1.3 Wärtsilä, Simulink, and Real-Time Workshop Embedded Coder

Wärtsilä use Mathworks tools, such as Simulink and Real-Time Workshop Embedded Coder, as core tools for applying model-based design. The tools help to structure and represent complex functions and algorithms using hierarchical block diagrams and state machines. These softwares combined offer an integrated dynamic simulation for system testing to such a high degree of accuracy that when the application is run on a real engine, there are very few issues. The softwares use symbolic programming with automatic code generation. The simulations are based on a component library with applications such as speed/load controller [23].

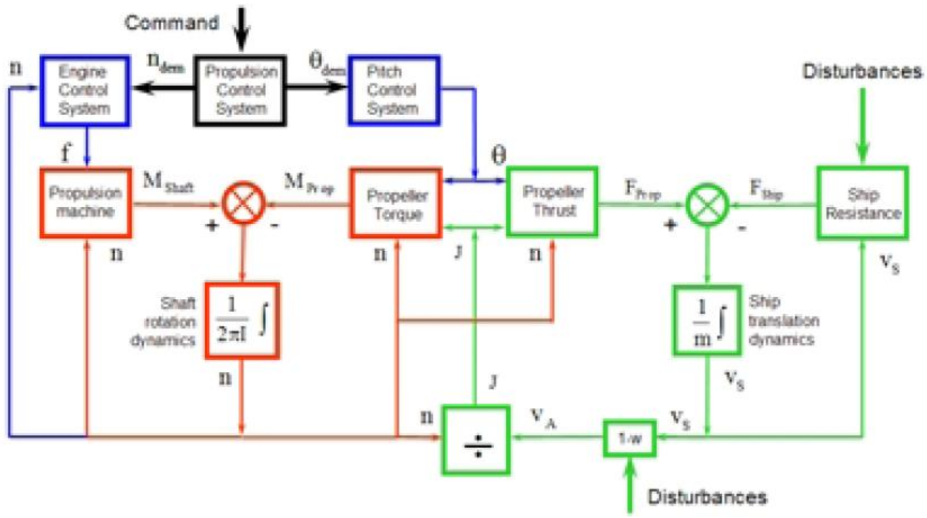


Figure 10: Propulsion system flow chart [24].

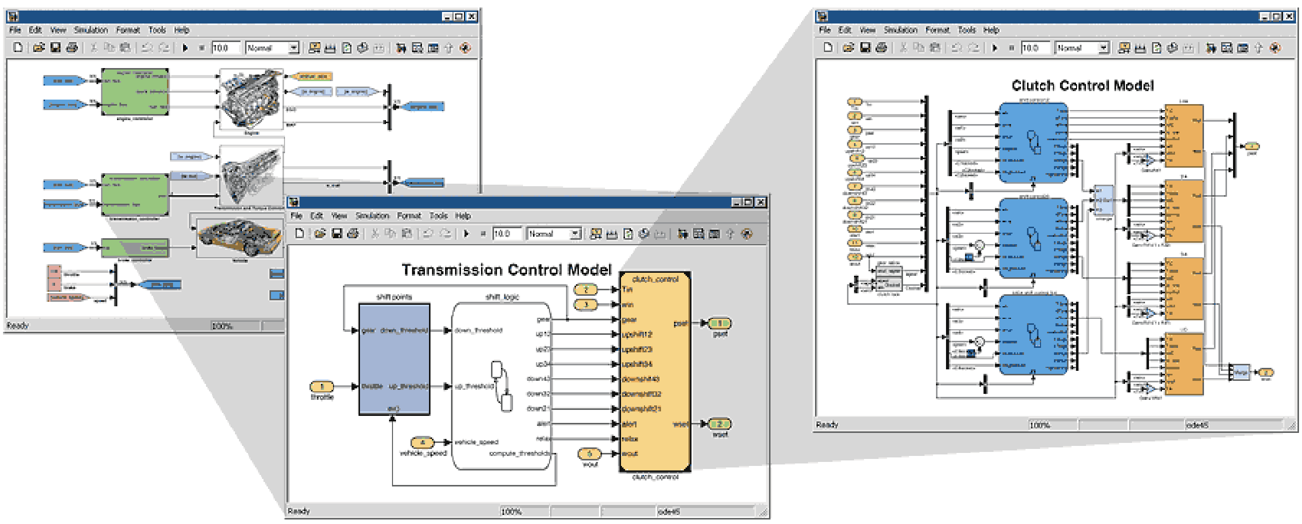


Figure 11: Simulink interface [25].

5.1.4 Comments on Today's Status

The result from the research shows that STX Europe Design is outsourcing the design of the MS to the manufacturer which is not completely surprising. Though, the restrictions apposed on the industry due to limited amount of configurations and large performance variations in the manufacturer's portfolio, may imply that there is a low level of flexibility to new design in today's design tools.

RRM and Wärtsilä both present software tools which seem to be able to perform integrated dynamic analysis for a complex MS model. Due to limited access in the description of the utilized software tools, it is hard to find examples with results and core conditions for underlying methodology.

After discussions with supervisor, who has been involved in the development of these software tools, it is questionable if the presented design tools are able to perform as well as presented, and that the software tools are more a framework and a design philosophy which cover less sophisticated underlying design methods. This is a statement which is made without discussions with neither of the manufacturers and reflects the author's point of view, due to no replies on sent e-mails.

5.2 General Energy Systems (GES - Geïntegreerde Energie Systemen)

In the research study it was discovered a tool for modeling and simulating energy systems onboard vessels for the Dutch navy developed by TNO in Holland. The design philosophy, methodology, energy flow, and unit interfacing in the integrated energy system; GES, seem to match many of the ideas and thoughts which were made prior to writing of this thesis and is therefore further reviewed in this chapter.

After contacting M.Sc. Hans Van Vugt at TNO with questions about the functionality and structure of the software via e-mail, a demonstrative version GES Lite, was sent and received. Based on GES Lite and the software description found on The GES website, a review and evaluation is made in the next paragraphs.

5.2.1 GES Software Description

The GES is a modeling and simulation software package based on object-oriented design (OOD) which derives from the bond graph method and therefore makes it domain-independent. Bond graphs will be introduced in chapter 5.3.3. The development of the software started in 1993 and was created to act as a preliminary design tool for simulation of stationary energy systems onboard naval vessels due to increasingly more integration of equipment into the propulsion system. The figure below depicts the user-interface of GES.

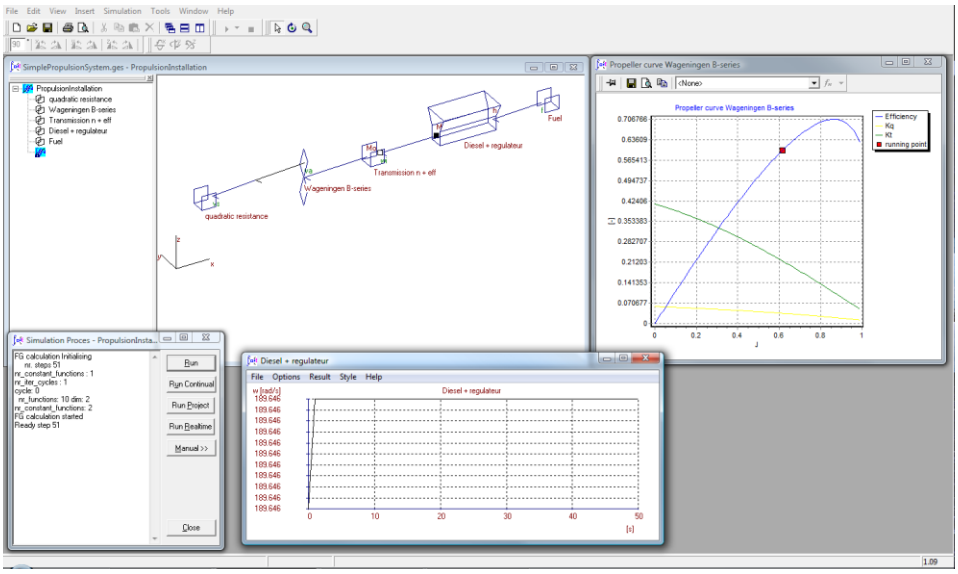


Figure 12: GES interface [26].

The architecture of the software package makes it possible to model and modulate all kinds of physical energy systems. It is possible to store and re-use components and sub-systems. The GES has a block-diagram structure, but the description is textual and based on an equation editor. GES consist of two types of components, energy components and signal components. The energy components are used for modeling the physical system and the signal components are used for controlling the energy components. The component description consists of several flexible inputs and outputs, which are called gates. Each gate is considered the energy flow either in or out of the component.

The energy or power flow is described by variables based on the bond graph approach. This allows for replacement and import of other components without losing system structure. GES also allows for grouping of components adding a hierarchical structure to the modeled system. A standard component library comes with the software package; containing a number of standard components found in MS onboard ships which the user can add to his/her model. Additionally, TNO has made external large model libraries which can be accessed by user and implemented in the model.

The philosophy of GES is to unite developers from different fields independently by assembling modules together in a larger system. This is obtained by describing the edges of the sub-models by variables which describe the ideal exchange of energy in between [26].

Typical areas in design for application of GES [27]:

- *Preliminary design calculations of ship installations*
- *Static and dynamic system analysis*
- *Innovative ship design, e.g. electrical*
- *Fuel consumption*
- *Determining the optimum voltage levels of the ship installation*
- *Emission calculations*
- *Energy transitions*
- *Tank flow calculations*
- *Dredging installations*

5.2.2 GES Lite A Brief User Evaluation

This evaluation is based on testing and exploring of the GES Lite software package. It has not been possible to review the available user manual since the only available version is written in Dutch.

The GES Lite's software package contains a number of pre-modeled examples of systems found onboard ships such as the propulsion system. By opening the model-file SimplePropulsionSystem.ges in GES Lite and exploring it by clicking on components and browsing through the drop-down menus, it becomes evident that redefining parameters and running a simulation for a predefined model is rather intuitive. The physical components are easy to recognize by name and physical appearance and the energy flow is displayed by arrows from one component to another or more. It is possible to plot the component variables in the time domain by right-clicking on the outgoing gate and selecting the plot function. The resulting plot shows the component's performance for the predefined parameters and variables.

Modeling a new system based on predefined is also rather intuitive if one has first explored a predefined system and understood how it is put together. Predefined components can be selected from the insert menu and is automatically dropped into the workspace. By clicking the component, the gates are revealed. By clicking the gate, one can connect one component to another by dragging the cursor and releasing it over the other component's gate. The component itself can also be moved around the workspace by left-clicking, dragging, and releasing.

However, creating new components is not as intuitive as building a model based on predefined components. Adding a new component is obtained by clicking the insert menu and selecting general then user defined. By right-clicking the component it is possible to define parameters, variables, and equations. Defining the equations requires some basic knowledge about the dedicated programming language.

There is only one brief tutorial file in the software package explaining how to add a user-defined component, so it is expected for the user to either have read the manual or to have some basic knowledge about similar software in order to achieve this implementation.

Overall, the GES Lite seems to be a helpful tool for early design and reviewing performance of the MS, though a more thorough demonstration or a basic introduction course would be very helpful in understanding how to best use the program. It should also be mentioned that the GES architecture and functionality is very similar to the MS mock-up presented in chapter 8, though the latter should be considered less sophisticated due to simplifications made in order to exemplify. This becomes clearer in chapter 7 and 8 when comparing the two.

5.3 Model Design Approach

The MS onboard offshore vessels are often DEL. This means that the power flow changes domain from origin to end consumer or sink, by changing between mechanical- and electrical power. System design, handling dynamic multi energy domains such as mechanical-, electrical-, control-, and computer engineering is categorized as mechatronics [28].

Mechatronic system design can be considered a synergistic approach. This implies that optimal solution is obtained by optimizing every domain simultaneously, and not by sequential optimization due to increased number of variables and more complex equations [29]. A consequence of this may be that the optimized solution is found in another domain than in a traditional sequential design. The traditional sequential ship design process is presented below.

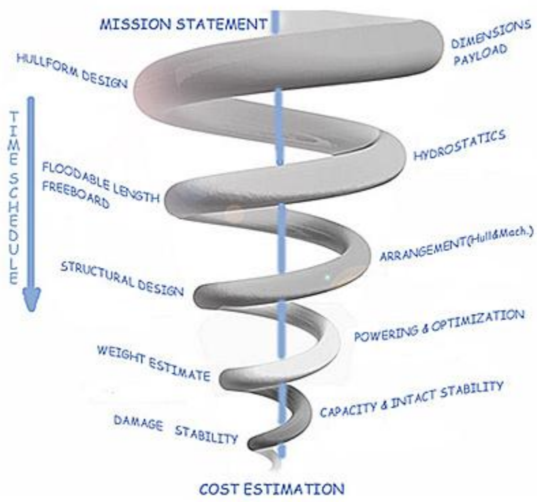


Figure 13: Traditional ship design spiral [30].

A mechatronic design process will require an early involvement by control- and software engineers to prevent problems in later stages of the design, which has been common when the design is done too sequentially. This approach is called; concurrent engineering, and is considered more complex than the traditional sequential approach [28]. Hence, coordination, communication, and integration between the different engineer disciplines are the key to success in this design approach in order to obtain the correct interfacing of the sub-systems and its components.

The information flow in concurrent engineering is bidirectional, meaning it allows for both up- and downstream flow in contrast to sequential engineering which flows in one direction only [31]. In a concurrent design, most of the early decisions are based on soft information, meaning information based on judgment, experience, and derived scientific principles. This allows for more freedom to make changes as the knowledge about the object designed increases. There will then be a progression from soft to hard information which will contribute to improvement of the quality in the final design.

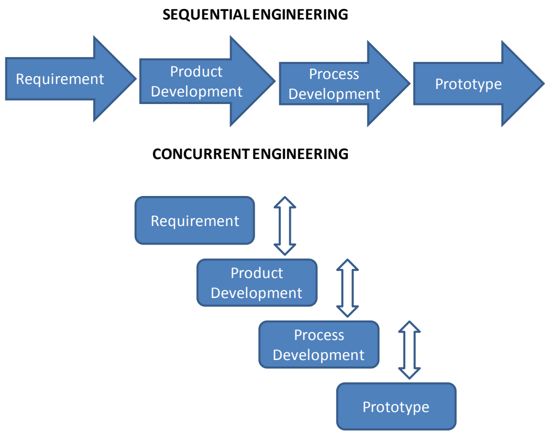


Figure 14: A comparison of sequential and concurrent engineering [31].

For a better understanding of the general basics and the way of thinking in mechatronic system design, the next paragraphs will describe underlying methodology and approaches.

5.3.1 Object-Oriented Design

Object-oriented design (OOD) can be described as a process of planning a system of interacting objects for the purpose of solving software or system problems. This method or approach is common in the general software design. The model is a graph with objects connected, sharing relations. The object is an entity with data, functions, and parameters encapsulated, which can represent a component in the system. The object needs a defined interface in order for interaction between other objects.

The most common OOD model is the Class-Based Programming (CBP) which shows static structure and dynamic behavior. The object is defined by a class which ensures a unique existence among other objects. The class defines an object's state, behavior, and identity. The system is simulated by input and output for each object where dependencies between the objects are imposed. Hence, correct interfacing is important since output from one object serve as an input for the next.

Additionally the objects may have functions and properties, allowing them to override or replace functionality of another object. Beyond the basics explained, there are many possible ways of describing the class in order to model the desired system [32].

5.3.2 A Hierarchical Object-Oriented Functional Modeling Framework

This framework is made as a support for both functional and object-oriented (OO) methods for designing a system, sub-systems, components and their functionalities.

The framework starts with a top-level function model in the functional domain and a top-level object in the physical domain. The relation between these two is represented and mapped by a top-level flow model. The top-level functions, objects, and models are decomposed down to lowest component level, where the objects become “primitives”. All engineering aspects, including electrical, mechanical, and software should be included at each level. This prevents the common problem where software is being left out in the conceptual design process. In addition, the interfacing between the components in all domains should be identified and specified.

The decomposition reveals the system’s structure and inter-relations. This level of structure allows for a concurrent design paradigm where engineers from different disciplines can co-design and co-analyze the system. The framework is based on the high order object model (HOOM) for the physical and software decomposition, a function tree (FT) for the functions, and the function and object mapping model (FOMM) for information flow and integration in between.

First off, a FT is created. The FT is a hierarchical presentation of the systems functions with a system behavior analysis. Located on the top is the prime function which is decomposed down to the lowest sub-function, the “primitive” function.

The next step is to create the HOOM. A context object diagram (COD), which is a top-level object model, is derived first. The COD defines the scope of the top-level object and describes the interactions between other external objects .The object then generates operational methods based on the functional requirements from the functional domain. The top-level object is then decomposed to sub-objects with operational methods. This step is repeated for all the sub-objects, down to the lowest sub-object, the “primitive” object.

The final step is to create the FOMM; a verification and an analysis technique. The FOMM describes the mapping relations and implementation parameters between the functions and the object models, making sure the functions are served by one or more objects. The analysis of the implementation parameters refers to what kind of information flow required by the object. There are three types of flow between the objects and the functions: material, energy and signal. This step is repeated for all the sub-flows, down to the lowest sub-flow, the “primitive” flow [33].

The graph below shows the decomposition process and the principle of the framework [33]:

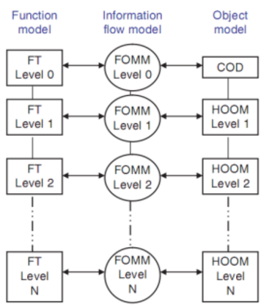


Figure 15: Level-by-level decomposition of the framework [33].

5.3.3 Bond Graph Modeling

Bond graph modeling is an approach where energy flow between components in a system is constructed, simulated, and analyzed. The components are considered energy manipulators which exchange energy through power ports. The power ports of a component can be divided into an input and an output. The component's ports are connected to other components by power bonds. A power bond is considered not to have any power or energy losses from one port to another.

The power ($P(t)$) flowing through a power bond is defined by two variables; the effort ($e(t)$) and the flow ($f(t)$).

$$\boldsymbol{P(t) = e(t) * f(t)} \quad \textbf{(5-4)}$$

Two other useful variables to describe the energetic relations are; the generalized momentum ($p(t)$) and the generalized displacement ($q(t)$).

$$\boldsymbol{p(t) = \int_0^t e(t)dt + p(0),} \quad \textbf{(5-5)}$$
$$\boldsymbol{q(t) = \int_0^t f(t)dt + q(0),} \quad \textbf{(5-6)}$$

Where:

- *$p(0)$ and $q(0)$ are the initial conditions at $t = 0$*

The energy ($E(t)$) which passes a port can be described as:

$$\boldsymbol{E(t) = \int_0^t P(t)dt = \int_0^t e(t) * f(t)dt + E(0),} \quad \textbf{(5-7)}$$

Where:

- *$E(0)$ is the initial condition at $t = 0$*

There are nine basic elements which can be utilized in a bond graph model. These elements make up the power supply (**Se**, **Sf**), energy storage (**C**, **I**), power dissipation (**R**), transformation (**TF**), gyration (**GY**), and junctions (**1**, **0**). The elements and their constitutive linear relations are shown below:

Se	Source of effort	$e = e(t)$	**(5-8)**
Sf	Source of flow	$f = f(t)$	**(5-9)**
C	Capacitor	$q = Ce$	**(5-10)**
I	Inertia	$p = If$	**(5-11)**
R	Resistor	$e = Rf$	**(5-12)**
TF	Transformer	$e_1 = e_2 m$	**(5-13)**
		$f_1 m = f_2$	**(5-14)**
GY	Gyrator	$e_1 = f_2 r$	**(5-15)**
		$f_1 r = e_2$	**(5-16)**
0-junction	Equal effort in bonds	$e_1 = e_2 = e_3$	**(5-17)**
		$f_1 - f_2 - f_3 = 0$	**(5-18)**
1-junction	Equal flow in bonds	$f_1 = f_2 = f_3$	**(5-19)**
		$e_1 - e_2 - e_3 = 0$	**(5-20)**

Table 3: Bond graph basic elements and their constitutive linear relations [34].

One important aspect regarding bond graphs is the causality. Flow- and effort variables exist at every port, but only one can be controlled. The controlled variable is defined by the casual stroke, which defines the direction of the effort [34]. A bond graph representation of a mass-spring-damper system is depicted in figure 16.

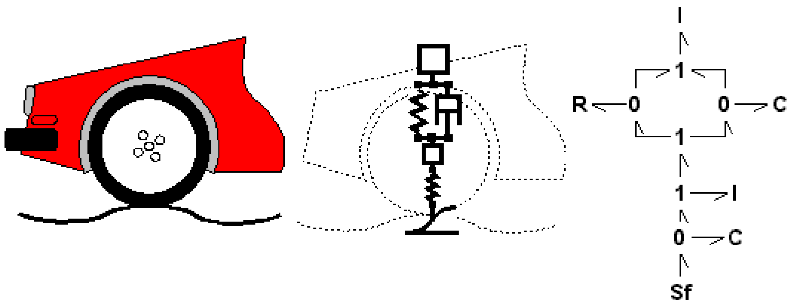


Figure 16: Bond graph representation of a mass-spring-damper system [35].

5.3.4 Automated Design Using Genetic Programming and Bond Graphs

Genetic programming is based on Darwinian concepts of evolution and natural selection, and is considered a promising technique in soft computing. Evolution is simulated for individuals in a population of hierarchical structure. The individuals are automatically generated or given computer programs or computer code. A fitness criterion is specified in order to filter out non-feasible solutions.

Bond graphs are combined with genetic programming through generative encoding. The bond graph elements (R, C, I, etc.) are encoded into functions and terminals which are used to grow genetic programming trees (genotypes). Mapping of these trees will result into bond graph models (phenotypes) which are feasible candidates for physical design. Genotype and phenotype are expressions with origin in biology and means respectively constitution of a cell and characteristic of an organism.

Jiachuan Wang proposed in 2005 a methodology which is a description of what goes into a constituting scheme for automated design of mechatronic systems using bond graphs and genetic programming [29]. The methodology introduces a dynamic knowledge library which is capable of storing information about initial and final stages of the automated design and additionally able to learn from the design experience. This is then used as reference in further designs making it possible to reuse previous generated individuals. The methodology is depicted in figure 17 [29].

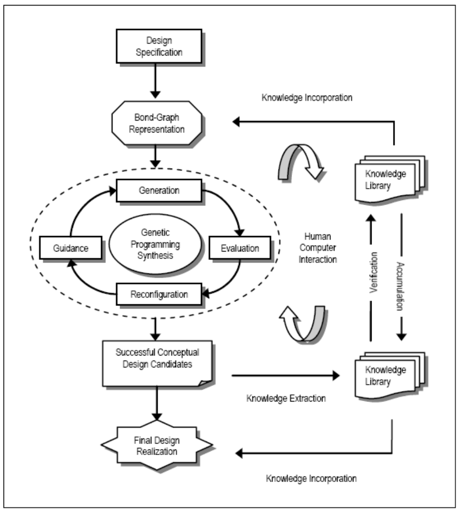


Figure 17: A methodology for automated design of mechatronic systems [29].

The reusability of the individuals stored in the knowledge library contributes to increased efficiency in a design process. In order to reach the full potential of this methodology, an integrated design environment with knowledge library supporting features required for handling all the elements of the automated design methodology must be established. This should include the bond graph coding, the genetic programming based search, and the mapping of the genotypes and phenotypes.

5.3.5 Intelligent Agent Technology

Intelligent agents are software objects which are capable of communicating and make decisions under negotiation about received input information. The technology was developed based on the demand for intelligence in increasingly complex systems rather than automated systems. The agents may be single- or multi functional. This technology is applicable in mechatronics and can be found in systems such as; robots and autonomous vehicles.

The agent's decisions are based on a dynamic knowledge library. The performance of the agents depends heavily on the quality of the domain knowledge stored. This information can be used in eliminating useless or poor components, functions, or processes. The agents are run algorithmically for proper functioning. This is done by a complex multitasking operating system; a runtime engine. The agent is interfaced to other agents and responding software in order to communicate and perform resulting actions. The agents are restricted by rules, guidelines and constraints stored in the dynamic knowledge library [36]. Figure 18 displays the architecture of the agent system.

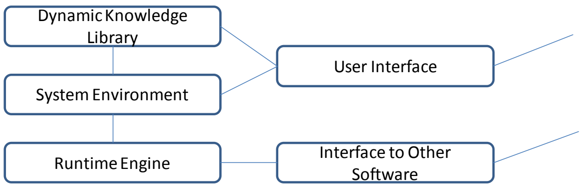


Figure 18: Architecture of Intelligent Agent Systems [36].

Agent-based design systems are mostly used as support for engineers for better simulations in conceptual and concurrent design [37].

5.4 Modeling Language

This chapter presents two modeling languages, Modelica and SIDOPS, which are available today and used in modeling of multi-energy domain systems such as mechatronic systems. Both modeling languages focus on energy flow in a dynamic system and are based on the bond graph modeling approach. There is not yet a common standard for describing such systems in the available modeling softwares. This can make importing models from one program to another difficult. A common standardized modeling language still remains a challenge.

5.4.1 Modelica

Modelica is an object-oriented, equation based modeling language for complex physical systems. It is designed to be domain neutral energy flow based, and as a result is used in a variety of applications such as; mechanical-, mechatronic, hydraulic-, electronic, thermal-, control-, electrical power systems or process-oriented sub-components. The language is non-proprietary and The Modelica Association, a non-profit organization, is working to develop the open standard Modelica and the free open source Modelica Standard Library [38]. From a user's point of view, the models are described as schematics or object diagrams as seen in the figure below:

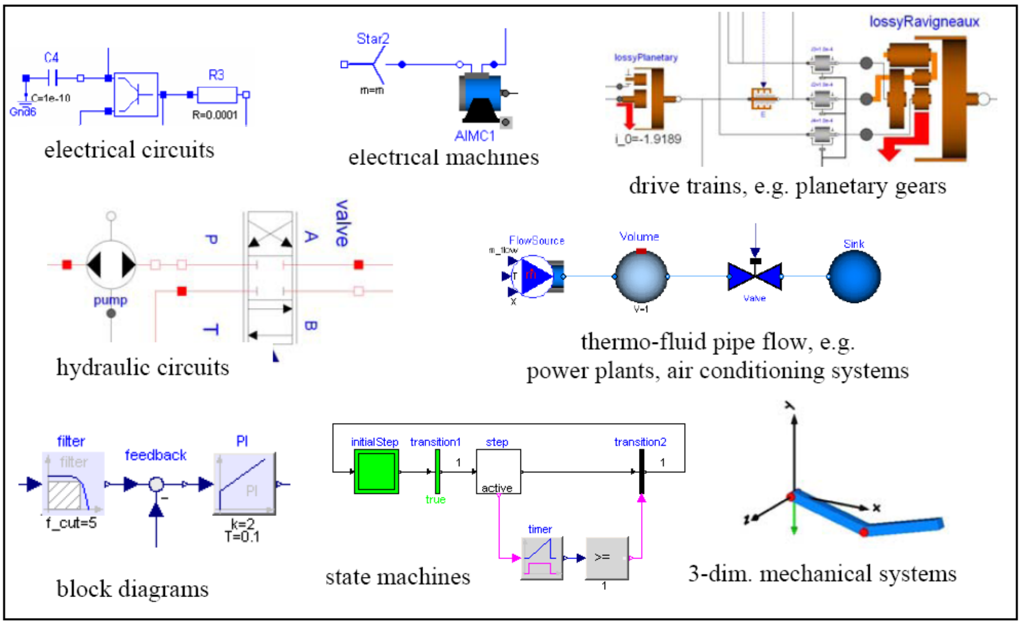


Figure 19: Model schematics based on the Modelica modeling language [38].

The industry is increasingly using Modelica or similar modeling language for model based development. Modelica has grown well-known and some of the companies using this modeling language are: Audi, BMW, Daimler, Ford, Toyota, VW, ABB, EDF, and Siemens [38].

Modelica Model Behavior

The Model behavior in the Modelica language is described by differential, algebraic, and discrete equations. There is no description by partial differential equations, i.e., no finite element method (FEM) and computational fluid dynamics (CFD), but usage of results from such dedicated programs [39].

Modelica Simulation Environment

Free or commercial graphical editors exist for Modelica models, such as; CATIA Systems, Dymola, MapleSim, MathModelica, SimulationX, OpenModelica, and SCICOS. The modeled system is divided hierarchically in levels by block diagrams. The blocks (components or sub-systems) are given a textual description which can be a set of equations. Next, the model is translated to C-code, simulation and interactive scripting (plot, frequency, response etc.). The process is depicted in figure 20.

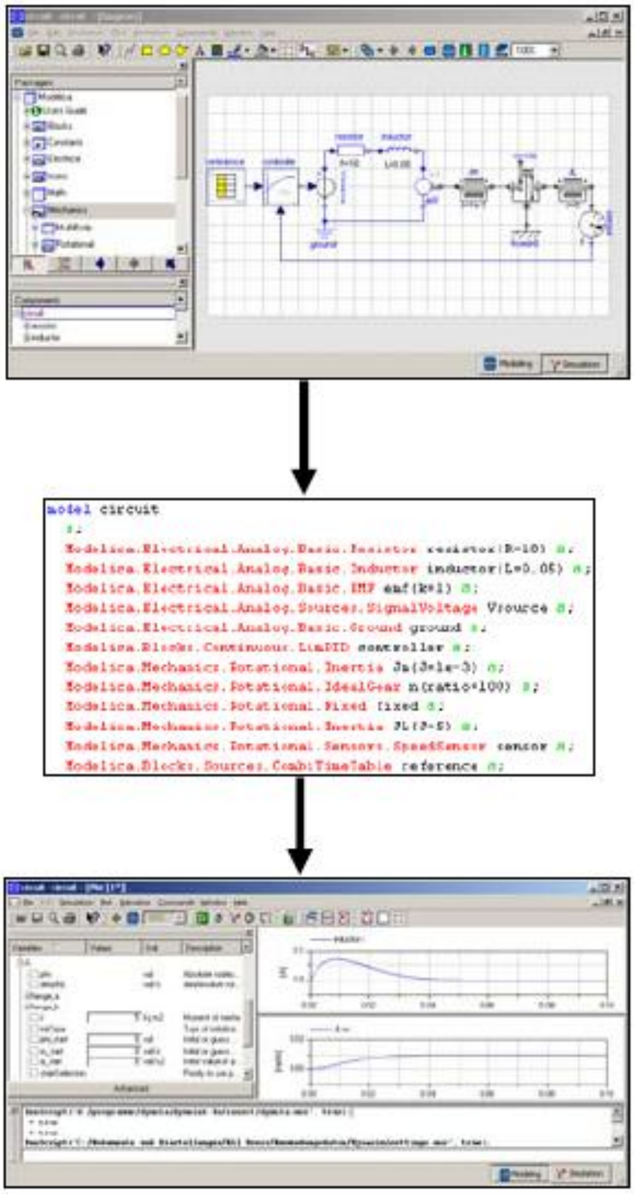


Figure 20: Modelica language and simulation environments [39].

Modelica Library

The Modelica Standard Library is developed by the Modelica Assocoation and is available for free in source code and can be modified and used in commercial programs. The library was initiated in 1998 and has since then been modified and updated every six to twelve months. The latest version (v3.1) of the Modelica library contains the following:

Blocks	Continuous, discrete, and logical I/O blocks
Constants	Mathematical and physical constants (pi, eps., h etc.)
Electrical	Electric and electronic components (digital, analog, machines, Multiphase)
Fluid	Components to model 1-dimensional thermo-fluid flow in networks of vessels, pipes, fluid, machines, valves, and fittings
Icons	Icon definitions
Magnetic Flux Tubes	Components to model magnetic devices based on the magnetic flux tubes concepts
Math	Mathematical functions for scalars and matrices such as; sin, cos, solve, eigenvalues, singular values
Mechanics	Mechanical components (rotational, translational, multi body)
Media	Media models for liquids and gases (about 1250 media, including high precision water model)
SI units	SI-unit type definitions such as voltage (V),torque (Nm)
State graph	Hierarchical state machines
Thermal	Thermal components (fluid heat flow, heat transfer)
Utilities	Utility functions for scripting (files, streams, strings, system)
Modelica services	New top level package that shall contain functions and models to be used in the Modelica Standard Library that requires a tool specific implementation.

Table 4: Sub-libraries in the Modelica Library [39].

5.4.2 SIDOPS (Structured Interdisciplinary Description of Physical Systems)

SIDOPS is a modeling language especially designed for bond graph-based system modeling. It uses the class concept, as described in chapter 5.3.1. Classes in SIDOPS are used to describe the unchanging, characterizing properties of a model. The Bond graph method is described in chapter 5.2.3.

SIDOPS Model Description

Model classes may contain sub-classes, which can form a class in a modularized combination. SIDOPS supports reuse of models, encapsulation of knowledge, and the development of modular hierarchically structured models. On a component level, models may be described using bond graphs. On the physical level bond graphs or block diagrams may be used. Bond graphs may be multi-bond graphs.

There are separate hierarchically descriptions for the interfacing between objects. At the component level, the interface elements are called plugs. At the physical process level, there is an interface distinction between power ports and signal ports.

Figure 21 illustrates the description of a one-port C-element. The interface part of the model class shows that the language supports bond graph by specifying the reference direction of the power flow oriented towards a port (fixed in p). The two conjugate power variables are, as explained in chapter 5.3.3, effort and flow. Preferred causality at a port of C-store means that effort is the output, which is expressed by preferred effort p [40].

```
class C1 version 1
# C1: Eintor-C-Element mit 1-dimensionalem Bond
interface
  ports: p
    causality restrictions
      preferred effort p
    orientation restrictions
      fixed in p
  outputs: real state
parameters
  real C
equations
  state = int(p.f)
  p.e   = (1/C) * state
```

Figure 21: SIDOPS description of a one-port C-element [40].

SIDOPS Simulation Environment

SIDOPS is implemented in the dynamic domain-independent modeling software 20-Sim which will be described in chapter 8.1.

SIDOPS Library

SIDOPS has predefined models, sub-system, and component library. The library is hierarchically structured and it supports various model representations, such as block diagrams, bond graphs, and iconic diagrams. In addition The user may add components to the library and have them stored for re-usage [40].

6 Machinery System Description

This chapter presents sub-systems and components in an exemplified marine MS based on a research study. Each component or sub-system has a description and a diagram which shows the energy or signal flow in and out. This is considered the basic theory for component description in the model mock-up in chapter 8. The sub-systems, components, and energy flow for the exemplified complete MS is depicted in figure 22.

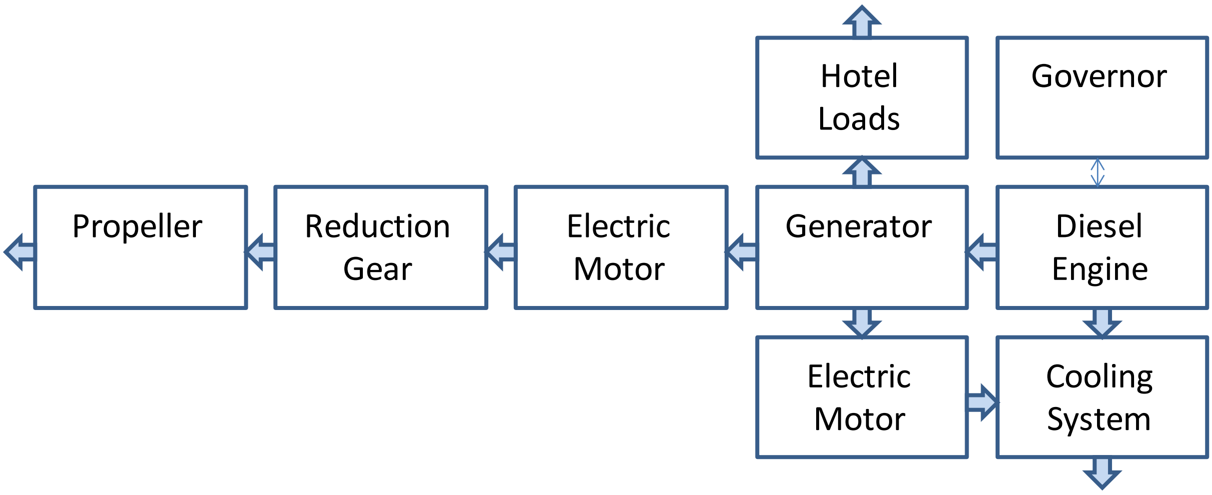


Figure 22: Energy flow in the machinery system.

6.1 Machinery Sub-Systems and Components

This chapter presents the components in a simplified marine MS configuration and it should be noted that a complete MS configuration will contain more components. The research study enlightens the component's important parameters and variables, and additionally adds structure to the model.

The model is not focusing on redundancy in order to simplify and easier exemplify, but it is important to mention that it can be included at a later stage and it is considered a very important and crucial aspect of the MS design.

In order to simulate and analyze the MS, a parameterization and setting of variables for the sub-systems and components is required. The sub-systems and components are later to be implemented in a dynamic multi-domain model mock-up, which handles simulation for mechatronic energy systems based on bond graphs. The bond graph approach which is applied for the mock-up in chapter 8 requires a unified interface between components which means that the variables; effort and flow for each sub-system or component must be determined based on the following research.

6.1.1 Diesel Engine

The internal combustion DE is categorized as a compression ignition engine. This means that gas is compressed, resulting in increase of temperature, according to Gay-Lussac's pressure-temperature law which states that the temperature and the pressure are directly proportional [41], which causes combustion when fuel is injected into superheated air.

The pressure-temperature law:

$$\frac{P}{T} = k, \qquad (6\text{-}1)$$

Where:

- *P is the pressure of the gas*
- *T is the Temperature (measured in Kelvin)*
- *k is a constant*

Air is compressed in a cylinder by a piston, generally to a compression ratio of 16:1 to 23:1. When the compressed air reaches a superheated state, around 538°C [42], diesel fuel is injected and ignites. The ignition causes an internal combustion which forces the current cylinder volume to expand. The expansion in the cylinder volume forces the piston down transforming some of the heat energy into mechanical power. This is explained by the pressure-temperature law; the cylinder volume increases, hence the gas temperature decreases. The higher the compression ratio, the greater the expansion of the gases on the power stroke .The average thermal efficiency is typically 30-40%, due to heat loss through the exhaust gas, cooling systems, and engine surface. Since DEs have higher compression ratios than gasoline engines, it means they are more thermal efficient.

The DE cycles are either 4-stroke or 2-stroke. The cycles are presented in the next paragraphs [42]:

4-stroke cycle diesel engine

1. The inlet valve opens. The piston starts at the top of the cylinder descending down drawing air into the cylinder. When the piston reaches the bottom of the cylinder the inlet valve closes.
2. The piston travels upwards compressing the enclosed air to 31 to 48 bars. The compression causes the temperature of the air to rise to 538°C or more.
3. At the top of the compression stroke fuel is injected. The temperature increases rapidly to 2 760°C and the pressure increases to 58 to 69 bars. This reaction forces the piston down causing a sudden drop in both temperature and pressure.
4. When the piston reaches the bottom, the exhaust valve opens. The piston travels up forcing the gases out. When the piston reaches the top, the exhaust valve closes and the cycle is repeated.

2-stroke cycle diesel engine

1. The piston starts at the top of the cylinder on its compression stroke. The cylinder is filled with pressurized, superheated air. Diesel is injected and ignites. The cylinder is forced down. When it is close to the bottom the exhaust valve is opened and most the gases rush out of the cylinder. As the piston continues to descend it uncovers a series of ports in the cylinder wall. Air is blown through these ports by a supercharger or a turbocharger, pushing the rest of the gases out of the cylinder and refilling it with a fresh air charge. The exhaust valve closes and piston moves upwards.
2. As the piston moves up it closes the air inlet ports and compresses the fresh air. When it reaches the top of the cylinder the fuel is injected and the cycle is repeated.

For any given size, a 2-stroke DE has two power strokes per cycle which means it will provide considerably more power than a 4-stroke DE. However, the 2-stroke DE has a lower thermal efficiency, higher levels of polluted exhaust, experiences higher loads which leads to a shorter lifetime, and are noisier than the 4-stroke DE. This has forced the manufacturers into more or less putting an end to the 2-stroke DEs [42].

In a DEL machinery, the DEs are typically medium speed or high speed with lower weight and costs than similar rated low speed engines which are used in direct mechanical propulsion. The engine configuration must be redundant with respect to faults and downtime for repair, since power availability is crucial in offshore related vessels.

When running a set of DEs, it is important that engine load is kept at optimum operating conditions. This is achieved by starting and stopping gensets dependent on load. The reason is that the efficiency drops rapidly when the load becomes lower than 50% of max continuous rating (MCR). In addition to low fuel efficiency, levels of NO_X, SO_X, and sooth becomes high which results in a higher emission rate and increased need for maintenance [10].

Figure 23 shows the energy flow in a DE.

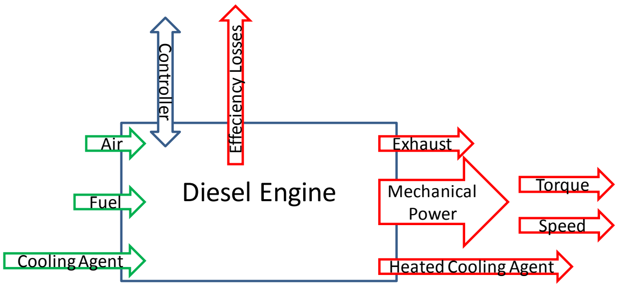


Figure 23: Diesel engine energy flow.

6.1.2 Generator

The typical generators in an AC power plant for DEL machineries are synchronous machines with a magnetizing winding on a rotor which carries DC current, and a three-phase stator winding where the magnetic field from the rotor current induces a three-phase sinusoidal voltage when the rotor is rotated by the prime mover. The frequency, *f*, for the induced voltage is proportional to the rotational speed of the DE, *n*, and the pole number, *p*, in the synchronous machine [10]:

$$f = \frac{p*n}{2*60}, \qquad (6\text{-}2)$$

where:

- *f [Hz] is the frequency*
- *p is the pole number*
- *n [RPM] is the the speed of the DE*

A large medium speed DE will normally work at 720 RPM for a 60 Hz network (10 pole generator). The DC current is transferred to the magnetizing windings on the rotor by slip rings, brushes or brush-less excitation. The latter reduces downtime and maintenance.

The brush-less excitation machine is an inverse synchronous machine with DC magnetization of the stator, rotating three-phase windings, and a rotating diode rectifier. The rectified current is then feeding the magnetization windings. Copper damper windings are installed in order to introduce an electromagnetic damping to the stator and rotor which removes large oscillations in frequency and load sharing for any variation of the load.

The automatic voltage regulator (AVR) controls the excitation. It senses the terminal voltage of the generator and compares it to a reference value. The controller has PI characteristics with stationary limited integration effect that results in a voltage drop depending on the generator load. This effect ensures equal distribution of reactive power in parallel-connected generators. Boundaries are set to define what voltage variations are acceptable. This applies for stationary voltage variations and voltage variations due to large transient loads. The AVR assures these requirements by a feed-forward control function based on measuring the stator current [10].

Figure 24shows the energy flow in a generator.

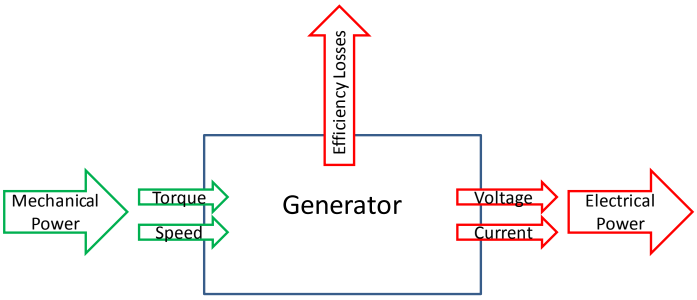


Figure 24: Energy flow in a generator.

6.1.3 Electric Motor

Electric motors are the most common drive in DEL machineries for transforming electric power to mechanical power such as propulsion, winches, pumps, etc. There exists many types of electric motors, but the most common is the asynchronous (induction) motor which is considered the workhorse of the industry.

The asynchronous motor is rugged and simple in design which results in a long lifetime, minimum of break-down and maintenance. The motor can run at constant speed directly connected to the network or at variable speed with feed from a static frequency converter. The three-phase stator windings are constructed similar to a generator. The cylindrical rotor has an iron core and a short-circuited winding similar to the damper winding in a synchronous machine.

When the motor is run as a constant speed, direct-on-line (DOL) motor, at no load, the voltages imposed to the stator winding will set up a magnetic field in the motor. The magnetic field crosses the air gap and rotates with a speed given by the frequency of the imposed voltages, which is called synchronous frequency, f_s. The synchronous speed, n_s, in RPM is given by:

$$n_s = \frac{f_s * 60}{p/2}, \qquad (6\text{-}3)$$

where:

- *n_s is the synchronous speed*
- *f_s [Hz] is the synchronous frequency*

- *p is the number of winding poles*

Currents are induced in the rotor windings as the shaft gets loaded since they are rotating relatively to the synchronous rotating magnetic field from the stator windings. The lag of the motor speed to the synchronous speed is defined as slip, *s*:

$$s = \frac{n_s - n}{n_s}, \tag{6-4}$$

Where:

- *s is the slip*
- *n_s is the synchronous speed*
- *n is the motor speed*

The slip varies from 0, no load, to 1 which is blocked rotor. The slip at rated load is normally below 5% for most motors or even lower.

Frequency dependencies must be regarded in order to obtain accurate results from the motor. The rotor parameters are dependent on the slip, i.e. frequency of the rotor currents.

Soft starters are adapted to the load characteristics of the motor. It reduces the current from the locked rotor from 5 times to 2-3 times the nominal current. This results in a reduced voltage drop for the start-up. Some of the soft starters are DOL, wye-delta coupling, autotransformer start, and semi-conductor soft-starters.

For propulsion and pumps there is a potential for saving power by reducing the no-load dependent losses in operations. This can be achieved by variable speed drives. The variable speed drives have a high capital cost but a lower operational cost than the constant speed drive.

The most common variable speed drives are voltage source inverter (VSI), current source inverter (CSI), cycloconverter, and DC converter. Most of the variable speed drives use AC motors. Most of the variable speed drives, except the cycloconverter, consist of a rectifier, which rectifies the line voltage, and an inverter, which generates the variable frequency and variable voltage source for the motor.

The motors are controlled by a controller which contains speed control and a controller for switching elements of the rectifier and inverter. The motor controller measures motor speed and current or voltage based on signals and feedback signals from sensor [10].

Figure 25 shows the energy flow in an electric motor.

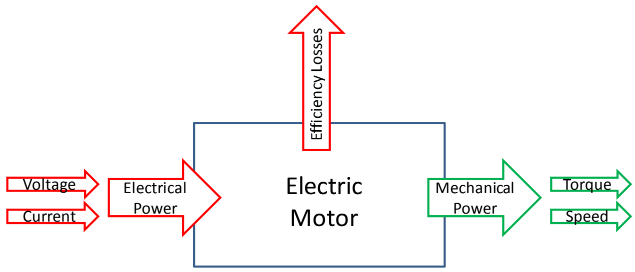


Figure 25: Energy flow in an electric motor.

6.1.4 Cooling System for Diesel Engine

This chapter presents a simplified description of a cooling system for the DE in a marine MS based on a cooling system description from the compendium in the course Marine Machinery, by Eilif Pedersen and Harald Valland [43].

What Is a Cooling System?

The cooling system's primary objective is to remove heat energy from a system or a component. It consists mainly of heat exchangers, pumps, pipes, valves and filters. The system configuration varies with different engine configurations, desired effect, and economic- and environmental restrictions. The cooling process in the cooling system originates in the heat exchangers.

Due to energy utilization concerns, it is desirable for the heat exchanger to operate with the lowest possible temperature difference. On the other hand it is desirable to reduce the pressure loss for cooling agents and as a result reduce the energy demand for the pumps. This indicates that there are dependencies in the system configuration, which means that one component not only have to be effective by itself, but contribute to a total effectiveness of the whole system, also regarding the economic aspect.

A cooling system for a DE can in many cases be relatively large and complex with a high number of components such as listed above which can be controlled both automatically and manually. As a result, a lot of different system solutions emerge with different technical and economic properties.

A cooling system has at least two circuits for hot and cold cooling agents. I.e.: One circuit for sea water and one for fresh water.

In this thesis, a simplified cooling system will be developed in order to exemplify.

Cooling System Requirements

The work load on the pumps is significant due to possible large and complex systems. This results in a set of requirements which the cooling system must comply with. Some of these requirements are described below:

- *Remove heat from engine cylinders, cylinder head, turbo-charger, and pistons. The coolant in the high temperature (HT) circuit, in the range 65-90 °C, must be fresh water. Sea water will cause corrosion and fouling.*
- *Remove heat from the charge air cooler after the turbo charger. The charge air is cooled down to 40-50°C, hence the coolant must be relatively cold. Sea water or cooled fresh water is used for this process.*
- *The sea water circuit's, the low temperature (LT) circuit's, main objective is to circulate through the heat exchangers and cool the fresh water and lube oil. The temperature in LT circuit should be kept below 50°C, due to risk of fouling.*
- *The cooling system should also in some designs remove heat from auxiliary components such as; auxiliary engines, compressors, and condensers, if there is not already established a separate cooling system.*
- *Valves introduce a risk of corrosion due to turbulence in the flow. In order to reduce the risk, limitations for maximum flow velocities must be established.*
- *Only treated fresh water may be used for cooling the engines in order to prevent corrosion. A corrosion inhibitor can be added to the fresh water in order to prevent this [44].*

Cooling System Description

The sea water circuit is an open circuit. Sea water is pumped through the sea chest by a sea water pump and at the end pumped over board back into the ocean. The sea water is first run through a de-aerator in order to avoid low vacuum levels. When run through the charge air coolers, sea water flow at low temperatures needs to be choked to avoid low temperatures which would cause the water to condensate. The next component is the lube oil cooler.

The sea water temperature will rise as it passes a heat exchanger and it is the temperature difference which allows for heat energy removal. It is important that the cooling of components at the lowest temperatures comes before coolers such as the fresh water coolers with high temperatures. After the sea water is run through the coolers, it is pumped over board or to the sea water pump if the sea water is very cold.

The fresh water circuit is a closed circuit. The fresh water is pumped through the circuit at a constant flow rate cooling the engines. If the temperature in the fresh water becomes too low there is a risk of creating sulfur compounds which will cause corrosion on the cylinder sleeve. It is possible to bypass the coolers, by a three-way valve, to obtain the desired temperature. Due to required redundancy in the cooling system, double sets of lube- and freshwater coolers are built.

The heat exchangers may be arranged in series, parallel, or a combination of the two. The different configurations will have different pressure losses over the heat exchangers which must be taken into account in the design process.

In order to reduce the size of the sea water circuit it is also possible to introduce a large central cooler which removes the heat energy from the fresh water circuit.

Piping is not discussed in order to simplify. Figure 26 and 27 shows the energy flow in the cooling system.

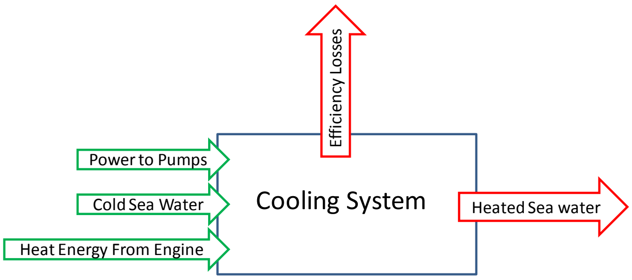


Figure 26: Energy flow in a simplified cooling system for a diesel engine.

Figure 27 shows the components in a simplified cooling system. The simplified cooling system consists of two pumps and a heat exchanger. Piping, which is an important aspect of the component design, is not depicted in order to simplify.

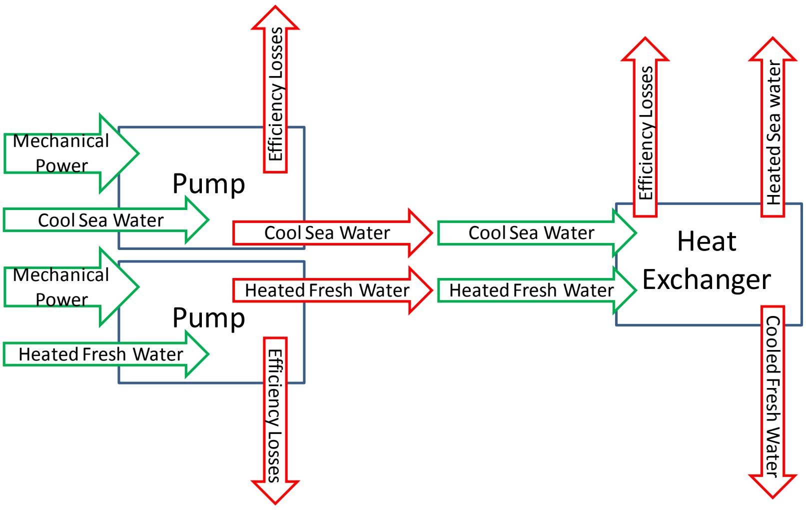


Figure 27: Energy flow in cooling system components.

6.1.5 Governor

The governor controls the engine speed by controlling the fuel injection. It provides the engine with the feedback mechanism to change speed and most important to maintain a desired speed, dealing with load variations [45].

A governor for a DEL power plant has mainly two operation modes; droop and isochronous mode. The droop mode, also called speed droop, allows for the steady-state frequency to drop proportionally to the active load. This mode is common in load sharing between generator sets. The isochronous mode keeps the frequency at a set point by utilizing a regulator with an integral effect. A hardwired signal between the gensets ensures proper load sharing [10].

For an isochronous governor, the main parameter is the reference speed for what the prime mover's set speed.

The governor will provide fuel injection to the prime mover in such matter that the reference speed or torque is acquired. This is obtained by comparing the actual speed to the desired reference and adjusting the fuel injected.

Figure 28 shows the signal flow in a governor.

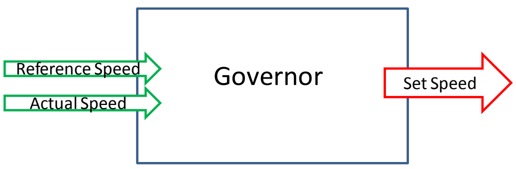


Figure 28: Governor signal flow.

6.1.6 Reduction Gear

A reduction gear is a mechanical gear where shaft speed is decreased and torque is increased. This device will be able to supply a direct mechanically driven propeller with sufficient torque with a medium or high speed engine. The engine would, without the reduction gear, be able to provide sufficient power but the torque would be too low.

The torque and speed is determined by the gear ratio. The gear ratio is determined by the diameter ratio between the two gear wheels in interaction, i.e.; 2:1, where one wheel has twice the diameter of the other [46].

The input variables for a reduction gear are torque and speed. The output variables are also torque and speed but with a shift in value due to the transformation.

Figure 29 shows the energy flow in a reduction gear.

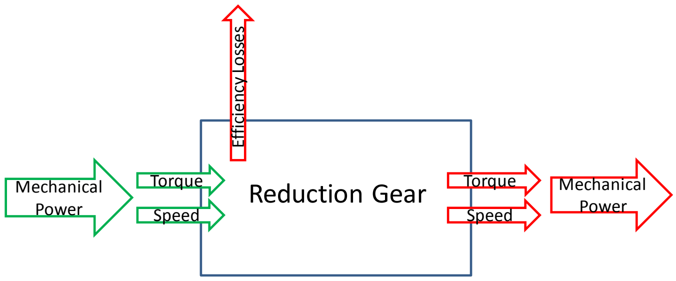


Figure 29: Reduction gear energy flow.

6.1.7 Propulsor

The most common propulsor is the propeller which obtains thrust by screw-motion. The propeller can be divided into fixed and controllable pitch (respectively FPP and CPP).Other types of propulsors are; waterjets and Voith-Schneider propulsors. In a waterjet, thrust is given by water being pumped out of fixed or controllable nozzles. The Voith-Schneider propulsor use vertical rotating foils, resulting in cycloidal movement underneath the ship. Further on, the focus will be on the propeller.

The propeller is converting rotational mechanical power, originated from the prime mover (typically a DE) to translating mechanical power by thrust. In order to achieve translating motion, the thrust force must overcome the hull resistance at the desired vessel speed. The hull resistance can be divided into; frictional or viscous resistance, form or pressure resistance, wave resistance, and wind or air resistance [47].

The forces induced by the propeller are given by the speed of the shaft, the torque, the propeller geometry, the advanced velocity, the viscous forces, the pitch angle, and the angle of attack [34, 47].

The thrust and the torque estimations on a propeller are based on coefficients found in open-water tests performed in a cavitation tunnel or a towing tank; respectively K_T and K_Q. A propeller diagram from tests is required in order to find the thrust for a given propeller speed. This diagram only applies for steady flow.

Figure 30 shows the energy flow in a propeller.

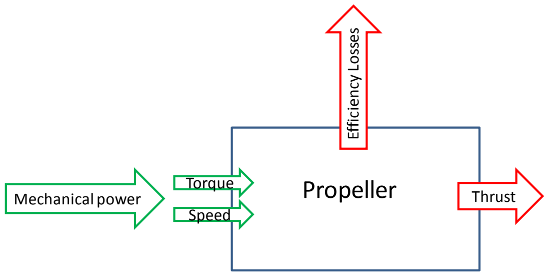


Figure 30: Propulsor energy flow.

6.1.8 Hotel Loads

The hotel load is the power required for housing personnel such as lighting, heating, ventilation etc. In this thesis, the hotel load is considered a sub-system with characteristics of a power sink.

Figure 31 shows the energy flow to the hotel loads.

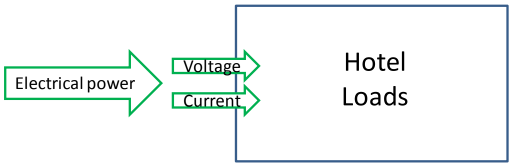


Figure 31: Hotel loads energy flow.

6.2 Monitoring of Fuel Consumption

The fuel consumption for a DE can be monitored by regarding the specific fuel consumption (SFC) diagram and the nominal and maximum continuous rating (MCR) ratio in percent:

$$\frac{P_{nominal}}{P_{rated}} = X\%\ MCR, \tag{6-5}$$

Where:

- *$P_{nominal}$ [W] is the power load*
- *P_{rated} [W] is the maximum rated load (MCR)*
- *X is the power ratio*

A SFC diagram for a DE with assumed values for different engine loads is presented in figure 38.

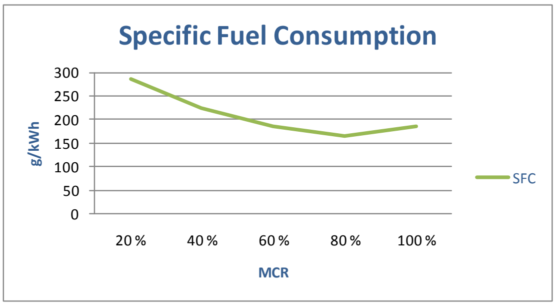


Figure 32: Example of a SFC diagram for a diesel engine.

6.3 Monitoring of NO_X and SO_X Emission Cost Factors

An important and restrictive aspect of the MS design is the emissions to air by gases such as NO_X and SO_X. The gases are mainly dependent on the combustion temperatures and sulphur content in the fuel respectively.

The emissions may be considered an operational cost contributor when designing the MS as they are representing restrictions to the final design in terms of legislative rules and regulations. According to the equation found in Damir Radan's thesis; Ingrated Control of Marine Electrical Power Systems on page 57 [48], trend lines by the effect of emission costs can be shown if other more accurate equations are not available or required:

$$C_e = 1 - e^{-e_0 \frac{1}{\% MCR}}, \tag{6-6}$$

where:

- *C_e is the emission cost coefficient*
- *e_o is an emission cost constant for a specific exhaust gas*
- *% MCR is the ratio of nominal engine load over rated engine load*

When applying this approximation in an exemplified manner by assuming values for the parameter e_o, it is possible retrieve the following estimation for the emission cost factor:

- Assuming that e_o for NO_X is 0,45 and e_o for SO_X is 0,65.

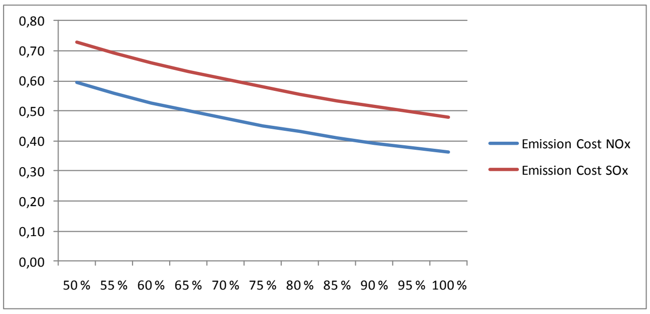


Figure 33: Emission cost factor plot for NO_X and SO_X.

The graph in figure 33 indicates that the emission costs are reduced as the nominal load approaches the rated engine load.

7 Proposed Machinery System Design Methodology and Architecture

This chapter presents a proposed methodology and architecture for the design process of MSs onboard OSVs. The methodology and architecture is kept in a general form and may be applicable for other marine vessels as well.

7.1 System Design Process

Many of today's and future design methods are focused on concurrent engineering. As stated in the chapter 5.3 this means involvement of all engineering principles from the very start. Figure 34 describes the overall flow of the proposed design paradigm. It becomes clear that this is not a sequential process but a continuously back-and-forth collaborative process with all engineer disciplines such as; electrical, structure, and software.

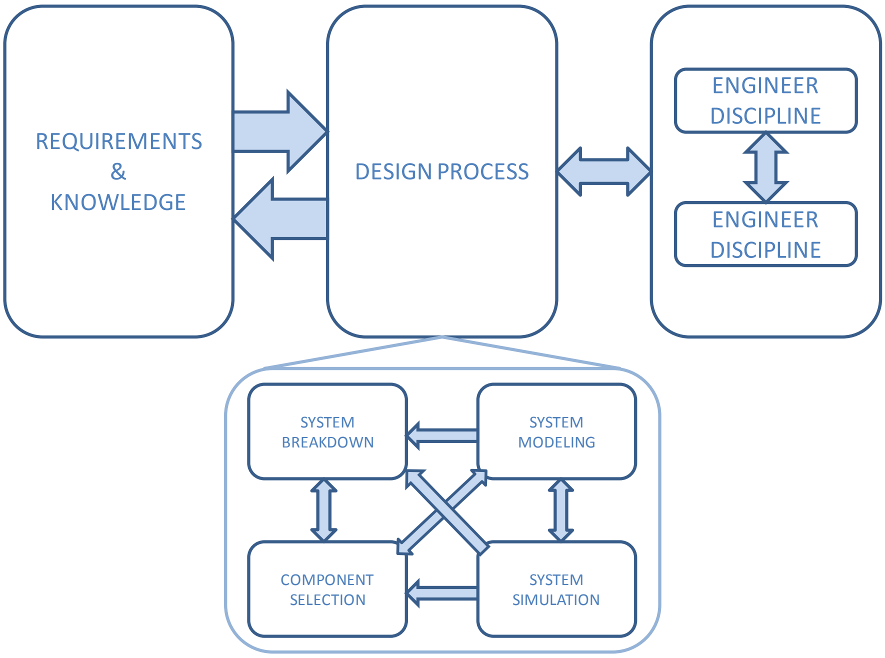


Figure 34: Flow and relationship for the proposed design process method.

Initially the design team is given a set of restrictions or requirements from the shipowner and the government. Combined with the knowledge from previous designs, this forms the starting point for a new design. The early progress will be based on soft solutions, due to flexibility to change in the design later in the process.

This flexibility is required in concurrent engineering and will allow for better solutions later on compared to traditional sequential processes where each phase imposes restrictions which accumulate and create problems for engineering processes in the final stages. These problems might then result in an unnecessary uneven distribution of time spent designing in the different engineering disciplines and perhaps more expensive components, sub-systems or total design solutions due to the forced restrictions by early decisions.

7.2 Machinery System Breakdown

In order to organize and understand the relation between sub-systems and components, a MS breakdown scheme is presented. This will support the structural design of the modeled system.

Figure 35 is an example of a hierarchical representation of a MS. The MS is arranged in levels which represent the break-down structure and its functions down to the lowest component.

The system, sub-system, and components are linked to a dynamic component library embedded in a knowledge database. The dynamic component library represents the available components for the system to be designed. It is dynamic in the sense that it will expand due to re-usage of method and implementation of new components. The system selection is based on accumulated knowledge from all engineer disciplines. This is a dynamic process where components may be proposed and changed throughout the process in order to optimize all aspects of the design. The development of algorithms for dealing with these challenges is not discussed further in this thesis. The presented MS breakdown scheme is meant to present a structural example.

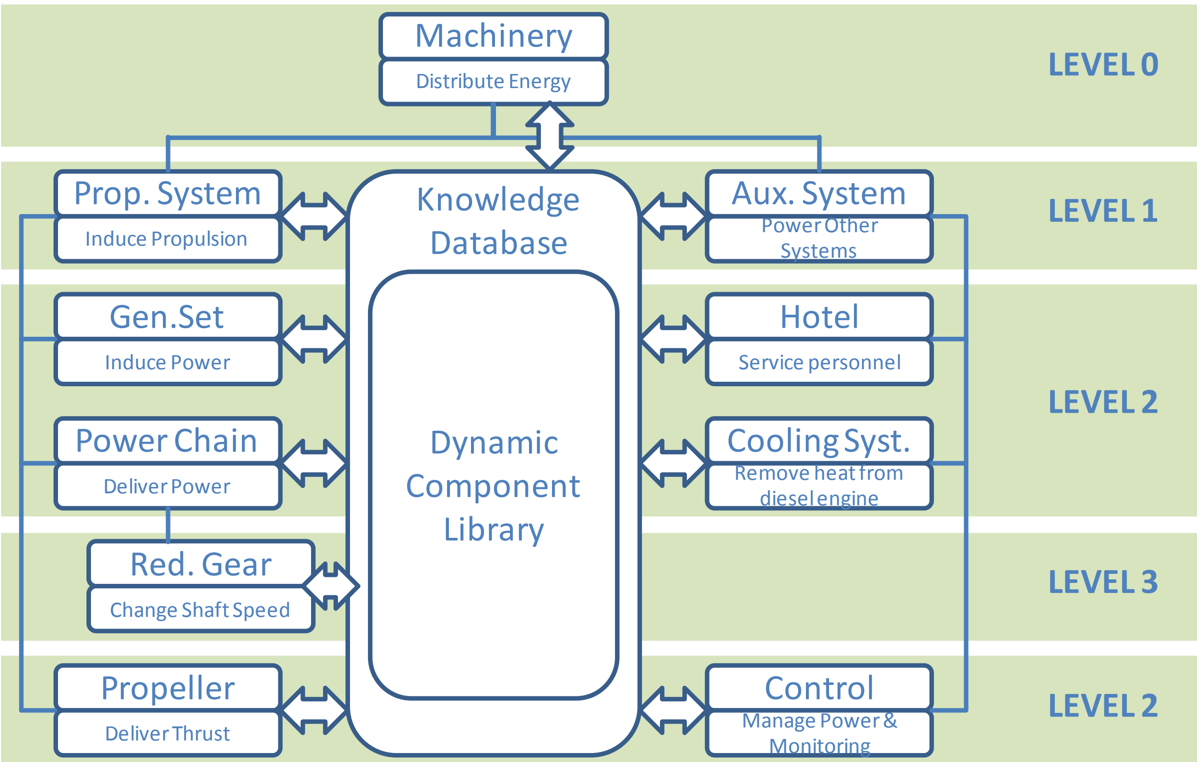


Figure 35: Hierarchical machinery system breakdown.

7.3 Technical Model Structure

The modeled MS is hierarchically structured as exemplified in figure 36. The two top layers depicts the component relations and the energy flow. The physical and mathematical layer shows how the component is modeled regarding structure, methodologies, mathematical equations, and restrictions.

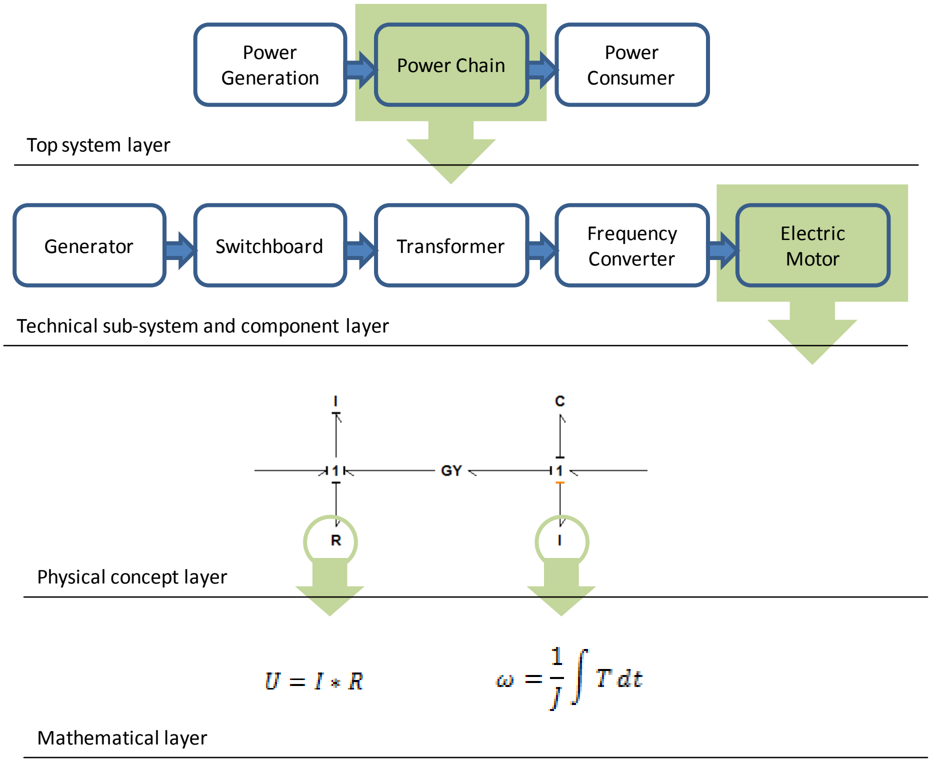


Figure 36: Machinery system model structure [33].

7.4 Sub-System and Component Unified Interface

A dynamic model with unified interfacing of sub-systems and components will allow for sub-system and component swapping or reconfigurations between energy bonds without having to reconfigure the sub-system's or component's environment.

The unified interfacing allows for reconfiguration of the system units in a simple manner where sub-systems or components can be predefined and implemented in the system by following the principles of the bond graph method as exemplified in figure 37 and explained in chapter 5.3.3.

Sub-systems and components are linked to the system via power and/or signal bonds and may be swapped for other units by breaking and rebuilding these bonds. The writing of the differential equations may be obtained automatically by means of built-in algorithms in a software package such as 20-Sim. This allows for a multi energy domain performance analysis of the model's variables.

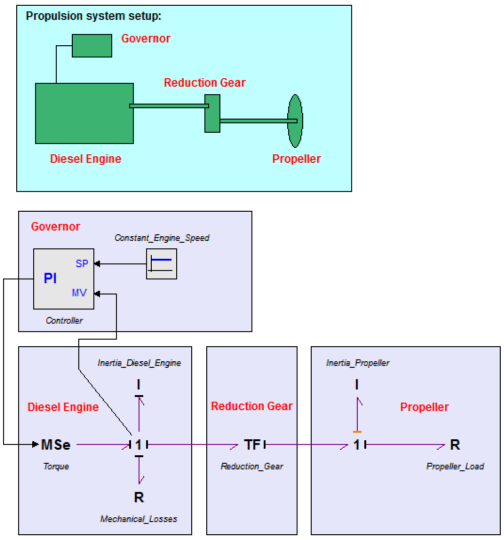


Figure 37: Bond graph representation of a simplified machinery system in 20-Sim.

7.5 Sub-System and Component Library Breakdown Scheme

The proposed library in this chapter is a suggested method for selecting sub-systems and components for a marine MS. The scheme presented is only an example of how it can be done and it is also expandable.

The proposed sub-system and component library breakdown scheme, depicted in figure 38, shows a marine MS divided into four top categories; the power controller, the power generation, the power chain, and the power consumer, which sums up the top overall functions. The next level is the component or sub-system class, where allocation is based on the component's or the sub-system's main function with respect to the suitable category. The lowest level is the specified component available for the vessel type.

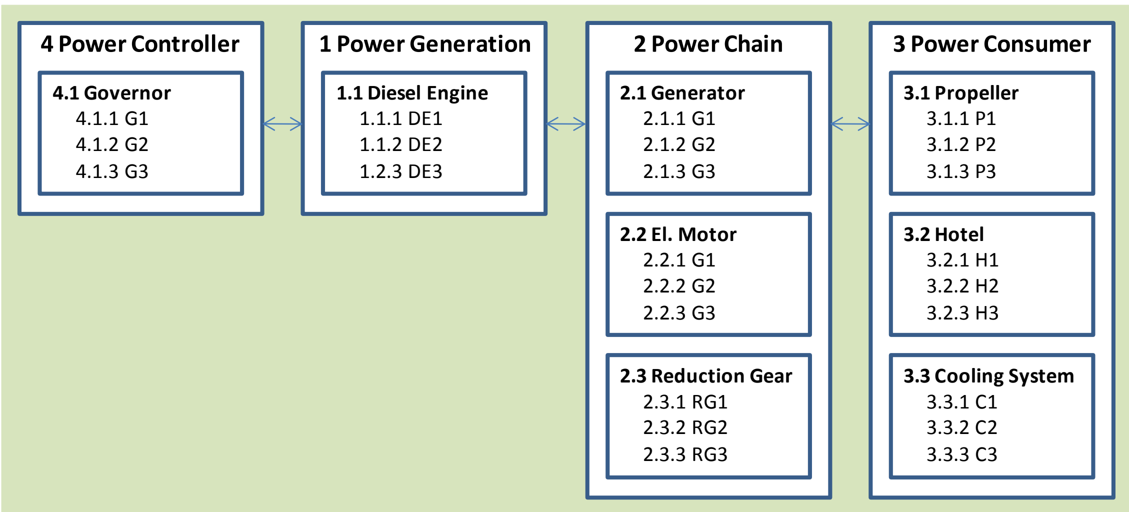


Figure 38: Component library scheme.

Every previous MS design configurations are to be stored in the library. This function together with intelligent agent technology (optimization algorithms), described in chapter 5.3.5, will allow for a dynamic knowledge-based selection and ranking based on a prior specified set of components. This is exemplified in the figure 39.

The red arrows shows the initially specified components, the green numbered arrows shows ranking, and the combined green and red numbered arrows shows the highest ranked and proposed component. The quality of the selection and ranking is dependent on the type and amount of components and sub-systems which are initially specified and the quality of the intelligent agents.

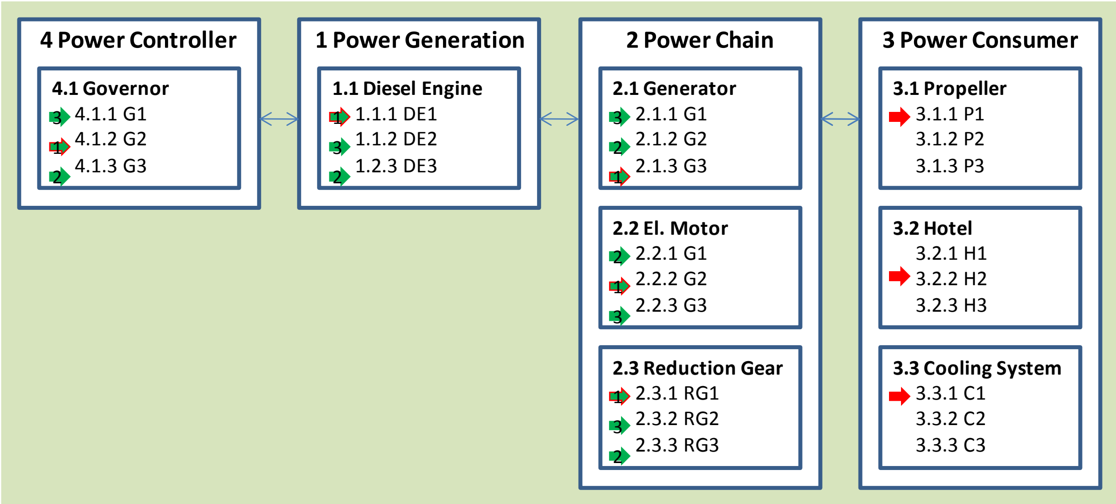


Figure 39: Component knowledge-based selection and ranking based on system constraints.

A development of a component library will not be pursued in this thesis. The scheme presented above is merely a structural suggestion.

7.6 Model Documentation Framework

When sub-systems and components are stored in a library it is important that relevant and sufficient documentation is stored along with it. The model documentation for sub-systems and components should consist of the following [34]:

Model name	Name and a short
Description	Mathematical and bond graph representation
Parameters	Model parameters
Input	Input interface and variables
Output	Output interface and variables
Limitation	Assumptions and constraints
Validation	Validation information
Comments	General comments
Reference	All references from the model development

Table 5: Model documentation for sub-systems and components [34].

8 Machinery System Mock-Up in 20-Sim

This chapter presents a mock-up of a marine MS in order to demonstrate and exemplify the modeling of a multi energy domain system and simulations with respect to unified interfacing between components. Both 20-Sim and the bond graph method are utilized in exemplifying the design philosophy and to reveal the benefits of unified interfacing. Before describing the mock-up, a brief introduction to 20-Sim is given below.

8.1 A Brief Introduction to 20-Sim

20-Sim is a modeling and simulation software developed by Controllab Products B.V., that runs in Microsoft Windows. The software provides tools for simulation of dynamic systems such as electrical, mechanical and hydraulic systems or any combination of these.

20-Sim is an interactive tool, where model entry and model processing are fully integrated. Models can be checked for consistency throughout the modeling process. 20-Sim use numerical integration methods from accepted international numerical libraries. Before simulation, the model is debugged and compiled in order to increase the simulation speed.

20-Sim has in addition a built-in library for block diagram components, iconic diagram components, and bond graph elements. The models are hierarchically constructed which allows for level specification within.

The modeling can be done by equations, block diagrams, bond graph, iconic diagrams or a combination of these. The simulation may be run by various tools such as FFT-analysis, optimization, tolerance analysis and more. It is also possible to generate ANSI c-code in order to export models or sub-models to other similar software [35]. Figure 40 shows the user interface of 20-Sim.

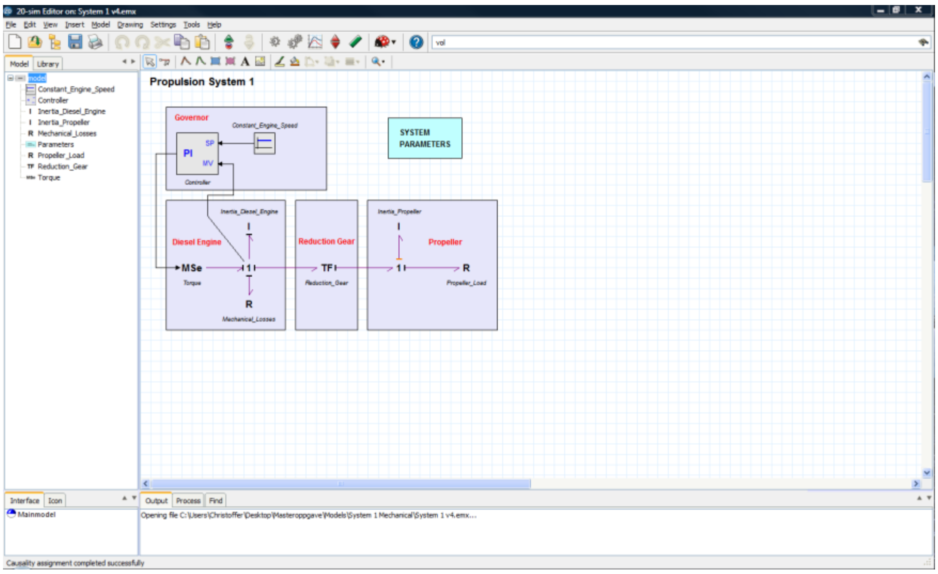


Figure 40: 20-Sim user interface.

8.2 General Model Description

The modeled MS is considered domain-independent due to implementation of the bond graph method. The mock-up consists of a high level of simplifications in order to exemplify. The level of complexity varies from component to component. This is not of great relevance in terms of exemplifying the functionality of the mock-up. The presented mock-up can be simulated and analyzed for mainly steady-state operations due to simplifications in modeling the system.

The mock-up is flexible to expansions and modifications in terms of adding or changing sub-systems or components. This is obtained by breaking the respective system connecting power bonds for the sub-system or component to be swapped, and then reconnecting them afterwards.

8.2.1 Model Structure

The machinery model's hierarchical structure is shown in figure 41, 42, and 43. The top level, level 1 depicted in figure 40, displays the main sub-systems described by functions of the exemplified MS divided into four categories; control, power generation, power transmission, and power consumption. Each category contains the sub-systems of respective relevance. The figures also show how the main functions are connected.

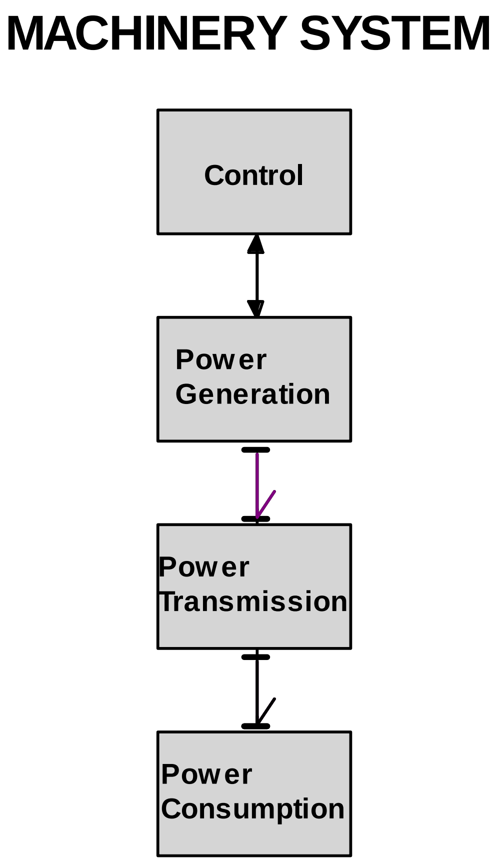


Figure 41: Model mock-up machinery system level 1.

Level 2, depicted in figure 42, displays the sub-systems and their interconnections within the top level main functions.

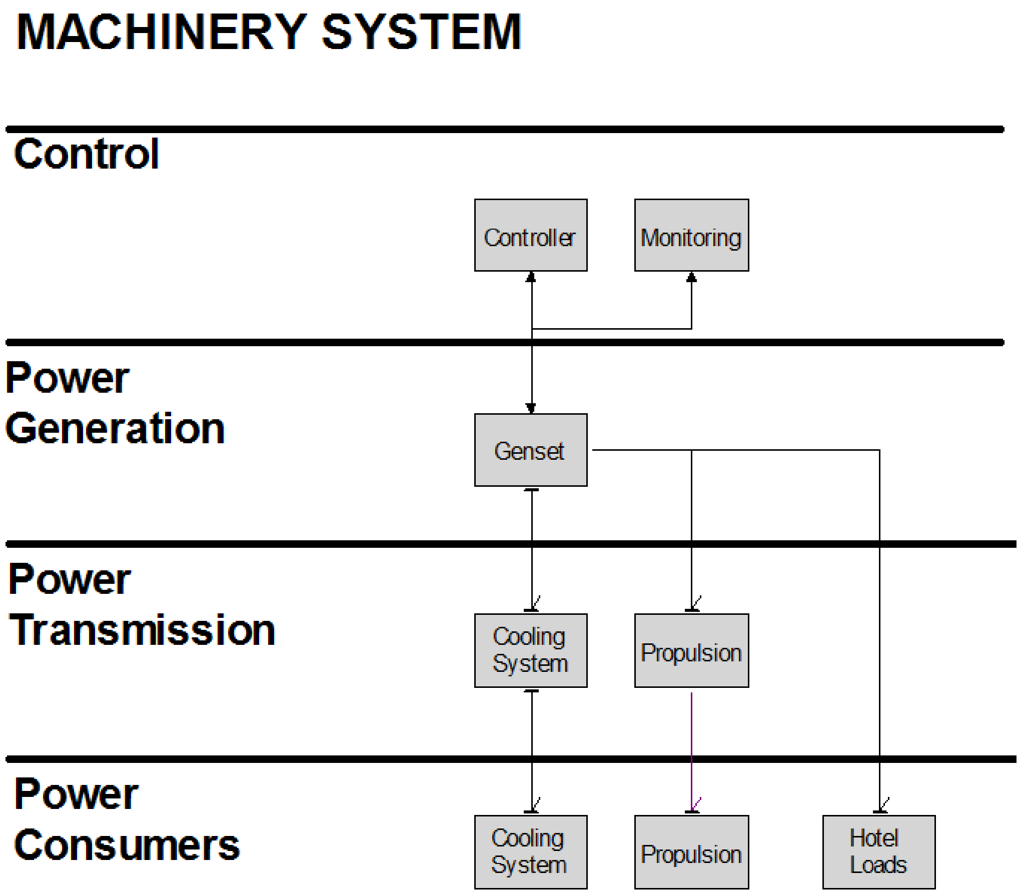


Figure 42: Model mock-up machinery system level 2.

Level 3, depicted in figure 43, displays the components within the respective sub-system and main function. The mathematical description of each component is available in appendix A and is accessed by clicking on the respective component. The system parameters box contains the parameters of all components in a similar hierarchical structure as presented for the division of the levels for the main functions, sub-systems, and components.

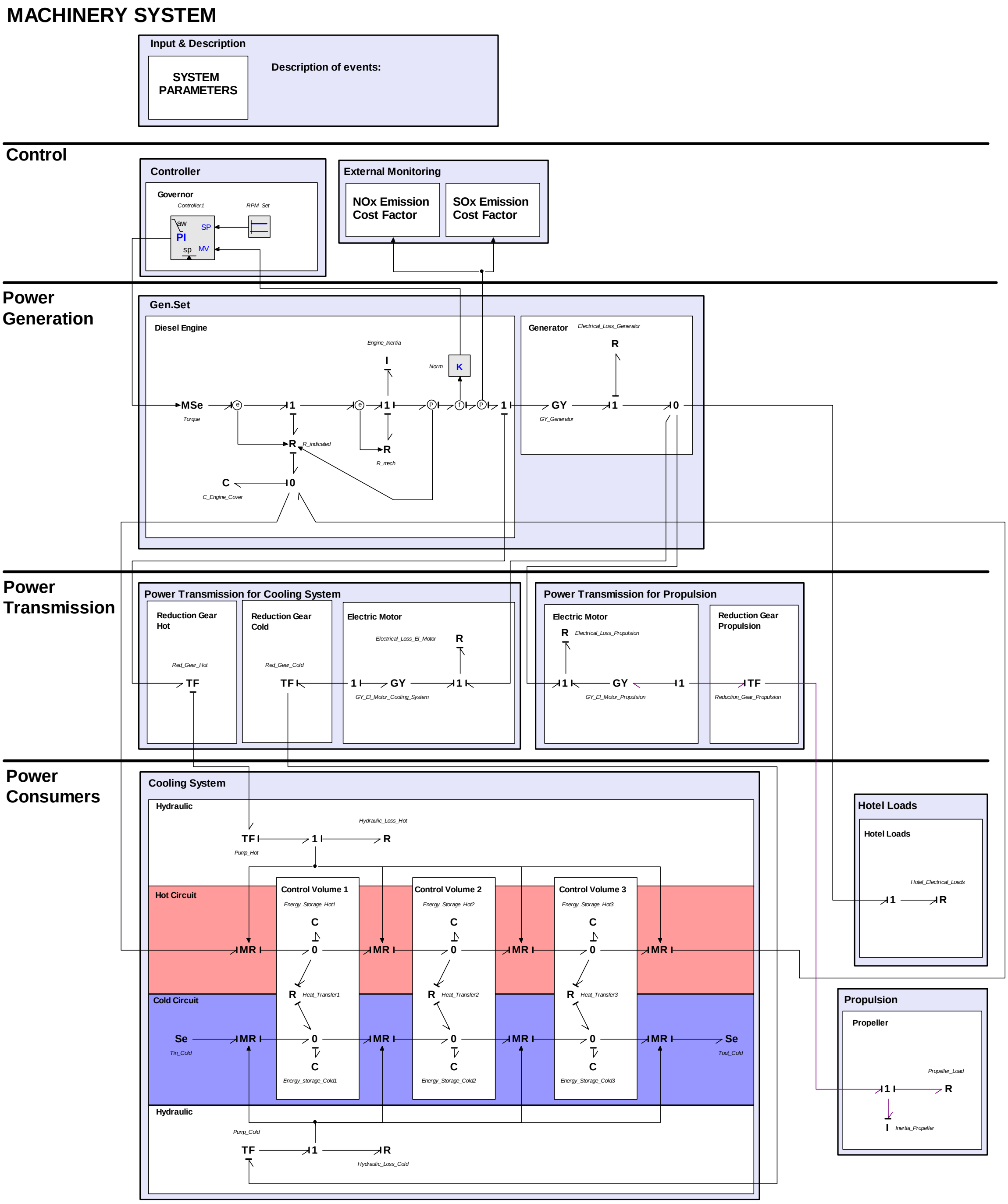


Figure 43: Model mock-up machinery system level 3.

8.2.2 General Component description and interrelations

This chapter presents a brief functional description of the components in the MS mock-up and how they interact. A more detailed description regarding parameters and variables can be found in appendix A and B.

Control

The control group contains three components; the governor and external monitors for emission cost factors for NO_X and SO_X.

The governor, a PI-controller, sets the speed of the DE to a constant speed by controlling the fuel input and correcting for load variations imposed on the shaft by the rest of the system. This is obtained by a speed signal input from the DE shaft and by setting a fixed reference speed. The DE will experience some speed variations during speed corrections due to load variations.

The external monitoring components are able to plot trend lines, based on equations given in appendix A, for emission cost factors of NO_X and SO_X by receiving a power signal from a power sensor located on the bond between the DE and the generator. The SFC is monitored internally by the DE component.

Power Generation

The power generation group contains two components; the DE and the generator.

The DE runs the generator by imposing torque on the generator shaft based on the fuel injected from the governor. The modeled DE has two types of energy efficiency losses; mechanical losses and thermal losses. The mechanical losses are represented by a power dissipative *R*-element. The thermal losses are connected to the cooling system by two two-port dissipative *R*-elements. The modeled DE is described in detail in chapter 8.2.3. in order to show how a component is constructed in the mock-up.

The generator transforms mechanical power to electric power. The electric power is distributed by power bonds to two electric motors and the hotel loads. The electrical losses are represented by a power dissipative *R*-element.

Power Transmission

The power transmission group contains five components; three reduction gears and two electric motors.

The two electric motors are each powering the cooling system and the propeller by transforming electrical power to mechanical power. The electrical losses are represented by a power dissipative *R*-element.

Two of the reduction gears are connected to the cooling system and the last one is connected to the propulsion system. The reduction gear is basically reducing the shaft speed and increasing the torque by a set gear ratio.

Power Consumers

The power consumer group contains two components and one sub-system; hotel loads, propeller with loads, and the cooling system containing two hydraulic pumps and two thermal circuits.

The hotel loads are considered all other electrical losses and are represented by a power dissipative *R*-element.

The propeller is modeled as a rotating mass with exponential loads of second order imposed by the propelled water.

The cooling system is divided into two circuits; hot and cold. Both circuits consist of a hydraulic pump and a thermal flow. Hydraulic losses are represented by a power dissipative *R*-element. The heat exchange is represented by a multi-port power dissipative *R*-element where heat is transferred from the hot circuit to the cold circuit through three control volumes. The pumps receive mechanical power directly and indirectly from the DE. The hot circuit is directly driven by the DE and the cold circuit is driven by an electric motor.

8.2.3 Detailed Component Description of Diesel Engine

A detailed description of the DE is given in order to show and to better understand how a component is built in the mock-up. The DE component is modeled and verified by supervisor Eilif Pedersen. A more detailed description regarding mathematical element description is found in appendix A. Figure 44 shows the DE's original structure before it is implemented in the MS mock-up.

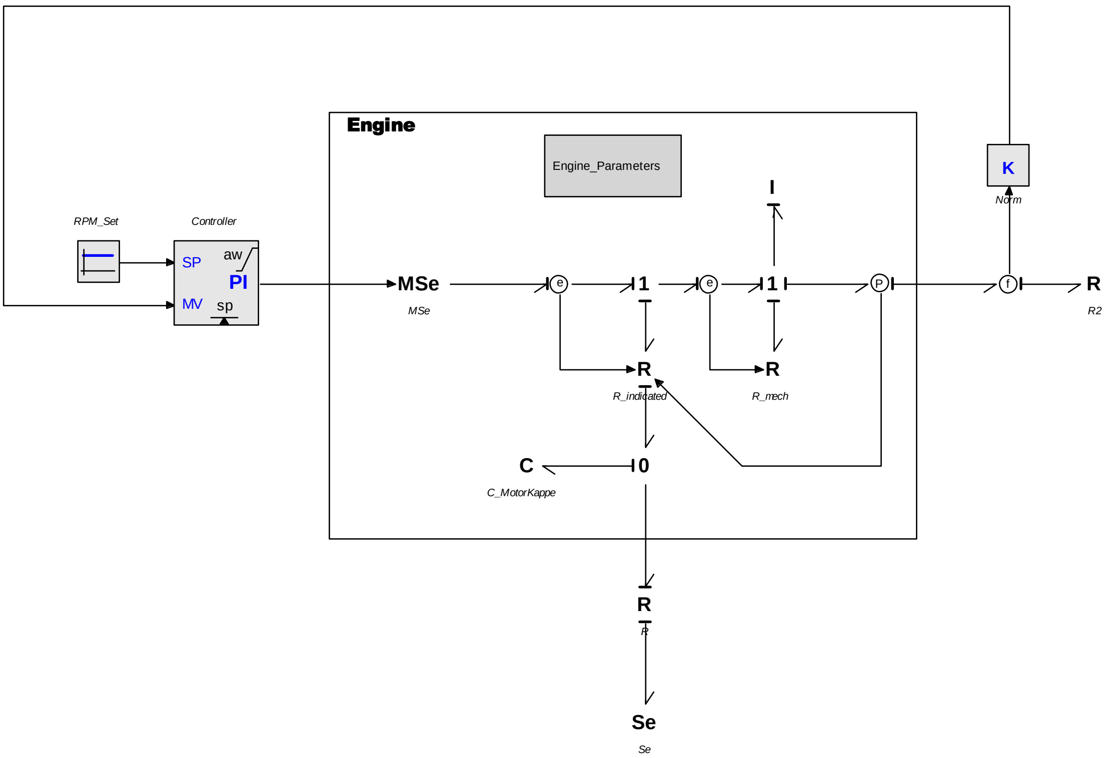


Figure 44: Model of diesel engine in 20-Sim.

In addition to the DE, the developer has included the governor, thermal losses and system loads in order to run simulations for the component isolated from the system. The bond graph structure shows that the DE consists of a rotating mass with mechanical and thermal losses. The generated power is distributed to an external load.

The modeled DE dynamics can be described as follows:

- *Torque is initiated by fuel input controlled by the governor, as described in chapter 8.2.2.*
- *The engine shaft rotates and mechanically powers a load.*
- *Due to mechanical power transmissions and the combustion process within the engine, mechanical and thermal efficiency losses are induced.*
- *Engine cooling water around the cylinders absorbs and temporarily stores the heat energy before it is transported away by the cooling system.*

The DE is modeled with respect to a set of global parameters which the user can easily access and reconfigure in order to obtain the desired specifications.

DE global parameters:

- *Rated engine power at 100% MCR:* *Pe100*
- *RPM at 100% MCR:* *RPM100*
- *SFC at 100% MCR in g/kWh:* *be100*
- *Mechanical efficiency (including pump work):* *neta_m*
- *Rotational inertia for rotating mass:* *J_motor*
- *Lower heating value for fuel in MJ/kg:* *hn*
- *DE cycle variable (2-stroke=1, 4-stroke=2)* *alfa*

In addition to the global parameters, there exist internal parameters which are bound to the respective bond graph element such as the factors for calculating SFC found in the two-port dissipative *R_indicated*-element. These internal parameters can be accessed by all, but should be controlled by more advanced users.

Diesel engine mathematical description

The next paragraphs present the development of the mathematical equations for the modeled DE's power calculation. These equations can be found in most learning books for combustion engines such as; Internal Combustion Engine, by J.B. Heywood [49].

In order to describe the work done by the DE one needs to obtain the indicated torque (T_i), which can be described as the direct work load on the pistons. The indicated torque is described by the following equation:

$$T_i = T_t - \Delta T_{ti}, \tag{8-1}$$

Where:

The equation for the theoretical torque (T_t) is initially given by the theoretical power (P_t) divided by the angular speed (ω), which leads to:

$$T_t = \frac{P_t}{\omega} = \frac{\dot{m}_B * h_n}{\omega} = \frac{\frac{\dot{m}_B}{n\alpha} * h_n}{\omega} = \frac{m_s}{2\pi\alpha} * h_n, \tag{8-2}$$

This is also valid for the indicated torque (T_i) and the relative torque loss (ΔT_{ti}):

$$T_i = \frac{P_t * \eta_i}{\omega} = \frac{m_s}{2\pi\alpha b_e(P_e) * \eta_m}, \tag{8-3}$$

where:

$$P_e = P_t * \eta_i * \eta_m, \tag{8-4}$$

and the relative torque loss:

$$\Delta T_{ti} = \frac{m_s}{2\pi\alpha}\left(h_n - \frac{1}{b_e(P_e)*\eta_m}\right), \tag{8-5}$$

where:

- *P_t is the theoretical power*
- *P_e is the nominal power*
- *T_t is the theoretical torque*
- *T_i is the indicated torque*
- *ΔT_{ti} is torque loss relative to the theoretical torque (T_t)*
- *η_m is mechanical efficiency*
- *η_i is indicated efficiency*
- *ω is the angular speed*
- *m_s is the fuel injected per cycle*
- *α is a parameter with value 1 for 2-stroke and value 2 for 4-stroke*
- *$b_e(P_e)$ is fuel consumption as a function of the nominal power*
- *$\dot{m}_B$ is mass fuel flow*
- *h_n is lower heating value for the fuel*
- *n_α is number of rounds per cycle*

The fuel consumption ($b_e(P_e)$) is estimated by the normalized SFC presented in matrix-form where the equation for nominal fuel consumption is obtained by regarding SFC at 100% MCR. Estimations by normalizing factors are based on three points on a given SFC-curve accordingly to the engine data:

$$b_e = b^*_{e100}\left[a(1) + a(2) * \frac{P_e}{P^*_e} + a(3) * (\frac{P_e}{P^*_e})^2\right], \tag{8-6}$$

based on:

$$a[3] = inverse(Abe) * beT, \tag{8-7}$$

where:

$$Abe = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 0,8 & 0,8^2 \\ 1 & 0,5 & 0,5^2 \end{bmatrix},$$

$$beT = [1,00 \quad 0,98 \quad 1,30],$$

- *b_e is nominal fuel consumption*
- *b^*_{e100} is fuel consumption at 100% MCR*
- *P_e is nominal power*
- *P^*_e is power at 100% MCR*

- *$a[3]$ is a normalizing factor matrix for obtaining the fuel consumption*
- *Abe is a matrix describing the engine loads at the three points on the SFC-curve*
- *beT is normalized SFC as a function of P_e for engine with speed variations*

The fuel injection and consumption is limited to a lower bound at 50% MCR. Engine loads below this will be considered loads at 50% MCR.

8.3 Model Parameters and Variables

The system parameters are based on assumed values and component data considered typical and can be found in appendix B. Some of the components such as the governor and the DE have internal parameters which can be found in appendix A.

The modeled system variables are found in appendix A in the description column for each component.

8.4 Assumptions and Simplifications

The mock-up of the MS is based on assumptions and simplifications in order to demonstrate the functionality. The main assumptions and simplifications are presented below:

General assumptions and simplifications:

- *The number of components in the mock-up is reduced compared to a real DEL MS.*
    - *No modeled shaft lines, switchboards, or frequency converters.*
    - *No three-phase currents.*
    - *No redundancy measures.*
- *Both high and low level of complexity in the component description.*
- *Simplifications in the mathematical description of components due to relevance, limited component data, and component knowledge.*
- *The mock-up is developed mainly for steady-state operations.*
- *The system parameters are based assumed and typical values.*

Specific assumptions and simplifications:

- *The governor is a pre-modeled PI controller from 20-Sim's component library, setting the engine speed.*
- *The monitoring equations for emission costs are simplified examples for obtaining emission effect by trend lines.*
- *The DE is modeled as a single rotating shaft.*
- *The generator transforms mechanical power to electric power via a GY-element.*
- *The generator is modeled as a reversed electric motor.*
- *The cooling system is reduced to two circuits, two pumps, and heat exchange through three control volumes.*
- *The hotel loads are modeled as a single power sink.*
- *The propeller is modeled as a rotating mass with a load modeled as a function of the propeller speed.*
- *The load on the propeller is considered a simple exponential function of second order.*
- *The input and output temperatures in the cold circuit of the cooling systems are fixed.*

It should be noted that one component may be modeled in more than one way by applying bond graph elements. The variation in level of detail and complexity shows flexibility in the model by allowing for different levels of accuracy and is not considered a crucial factor in the mock-up. Though, it is a factor that needs to be taken into consideration when analyzing the result from the simulations. In order to construct and validate a component properly, consultancy with engineers with special competence should be obtained.

8.5 Simulations

This chapter presents two simulations done with the MS mock-up in order to demonstrate functionality. The simulations are run by the simulator engine in 20-Sim in the time domain. The following set of variables is chosen in order to present the MS's performance:

- *DE speed [RPM]*
- *SFC [g/kWh]*
- *Fuel injected per cycle[kg]*
- *DE Nominal power [W]*
- *Propeller load [Nm]*
- *Propeller speed [RPM]*
- *Emission cost factors for* NO_X *and* SO_X
- *Control volume temperatures in the cooling system [K]*
- *Heat transfer in the cooling system [W]*

Every variable in the mock-up can be chosen for a performance analysis and it is up to the user to decide and choose which ones to be presented.

Due to several assumptions for many of the components in the mock-up, the result from the simulations may for some components deviate from values which are considered typical. The simulations are meant to show how one can monitor performance and obtain trend lines for different conditions with main focus on steady-state operations.

The reading of variable values in the presented graphs is obtained by utilizing the numerical-value tool in the 20-Sim simulator which presents values by left-clicking on the graph.

8.5.1 Simulation 1

Simulation 1 is run by initial parameters and variables which can be found in appendix A and B respectively.

From the graph in figure 45 the following steady-state performance data can be collected:

- *Engine speed:* *720 [RPM]*
- *SFC:* *260 [g/kWh]*
- *Fuel injected per cycle:* *0,00042 [kg]*
- *Nominal power:* *35 000 [W]*

This result shows that the power out of the engine, the nominal power, is low compared to the rated power, which is 1 000 kW. This is a major effect which can easily be identified in other component's behavior. The SFC will however not drop below the SFC for 50% load (as explained in chapter 8.2.3), hence 260 [g/kWh] is considered maximum SFC.

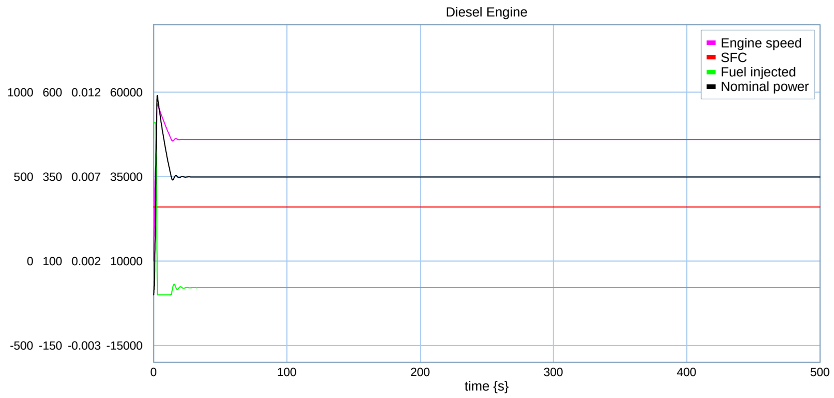


Figure 45: Engine speed, SFC, fuel injected, and nominal power from simulation 1.

From the graph in figure 46 the following steady-state performance data can be collected:

- *Propeller load:* *-168 [Nm]*
- *Propeller speed:* *-23 [RPM]*

The negative sign may be induced due to the simplified electrical components in the power transmission, but is not considered to have any significant effect in this simulation and will not be discussed further.

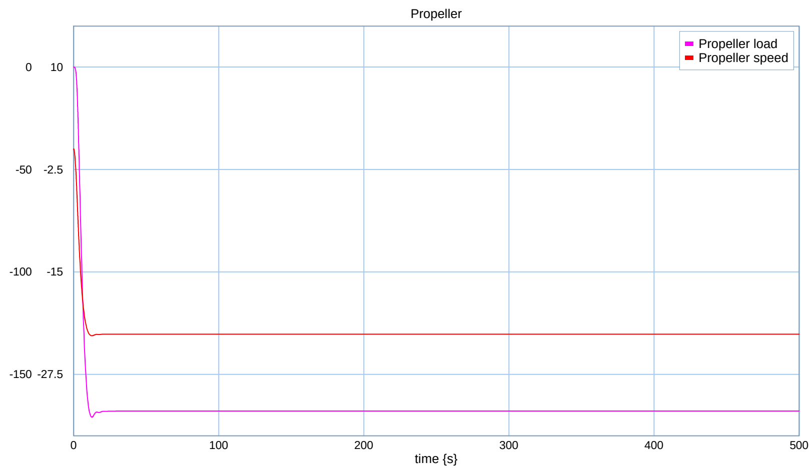


Figure 46: Propeller load and speed from simulation 1.

From the graph in figure 47 the following steady-state performance data can be collected:

- *Emission cost factor for NO_X emission:* *0.9999*
- *Emission cost factor for SO_X emission:* *0.9999*

The result shows a high emission cost factor for both NO_X and SO_X which directly indicates low nominal power according to chapter 6.3.

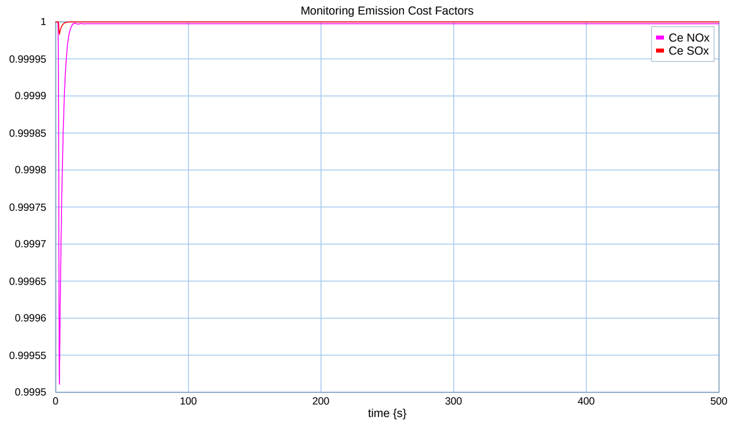


Figure 47: Emission cost factors for NOx and SOx from simulation 1.

From the graph in figure 48 the following steady-zstate performance data can be collected:

- *Cooling system control volume temperature hot circuit:*
  - *T1: 428 [K]*
  - *T2: 421 [K]*
  - *T3: 414 [K]*
- *Cooling system control volume temperature cold circuit:*
  - *T1: 320 [K]*
  - *T2: 317 [K]*
  - *T3: 315 [K]*

The result shows a higher temperature variation through the control volumes in the hot circuit compared to the cold circuit. This indicates that the mass flow in the cold circuit is greater than in the hot circuit since both sides are equally modeled.

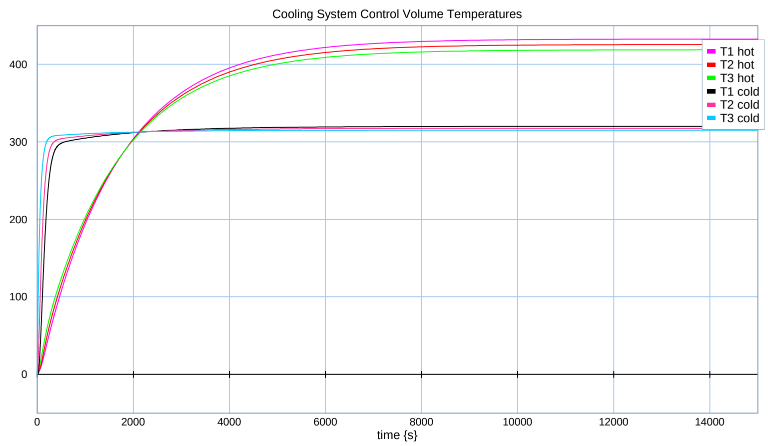


Figure 48: Cooling system control volume temperatures from simulation 1.

From the graph in figure 49 the following steady-state performance data can be collected:

- *Cooling system control volume heat transfer:*
  - *Qp1:* *14 000 [W]*
  - *Qp2:* *13 400 [W]*
  - *Qp3:* *12 800 [W]*

The result shows that the heat transfer from hot to cold circuit decreases as the hot control volume temperature decreases. According to the signal input for the mass flow in both circuits, which are of opposite direction, the heat exchanger operates by counter-flow.

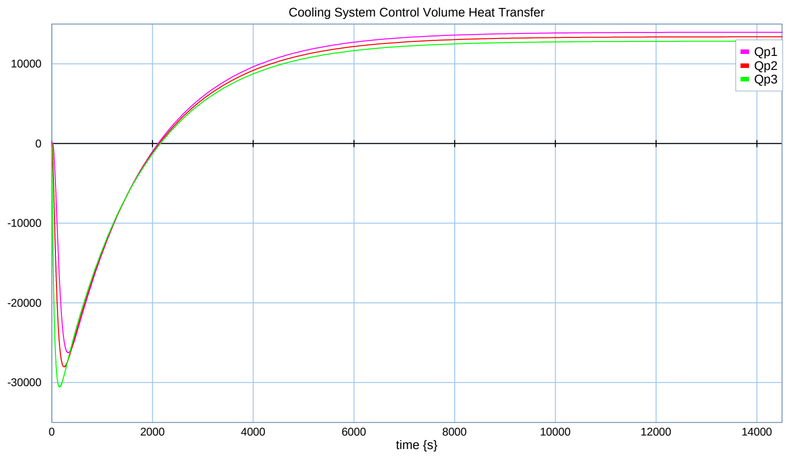


Figure 49: Cooling system control volume heat transfer from simulation 1.

8.5.2 Simulation 2 (Time-Specific Events Included)

Simulation 2 is initially run as simulation 1 but with two new reconfigured components; Propeller and Hotel Load with additional time-specific events in order to monitor the variation in performance. The time-specific events are introduced when MS is considered to operate at steady-state. The time-specific events in simulation 2 is presented below:

- *Propeller load halved at 10 000 seconds*
- *Hotel load doubled at 12 000 seconds*

From the graph in figure 50 the following performance data, including the effects of added events, can be collected:

- *Before 10 000 seconds:*
  - *Engine speed:* *720 [RPM]*
  - *SFC:* *260 [g/kWh]*
  - *Fuel injected per cycle:* *0,00037 [kg]*
  - *Nominal power:* *30 396 [W]*
- *After 10 000 seconds (propeller load halved):*
  - *No measurable fluctuations in the engine speed*
  - *No change in SFC*

- *No measurable change in fuel injected*
- *Nominal power decreased by:* *-303 [W]*

- *After 12 000 seconds (hotel load doubled):*
  - *Small fluctuations in engine speed:* *±1 [RPM]*
  - *No change in SFC*
  - *A small increase in fuel injected:* *+0,00012 [kg]*
  - *Nominal power increased by:* *+4328 [W]*

The result shows that the halving of the propeller load has a low effect on the DE. The doubling of the hotel load shows a significant rise in the power output.

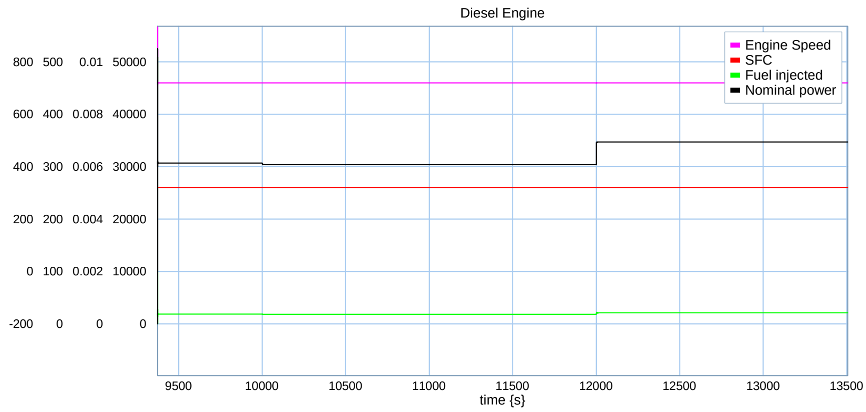


Figure 50: speed, SFC, fuel injected, and nominal power from simulation 2.

From the graph in figure 51 the following performance data, including the effects of added events, can be collected:

- *Before 10 000 seconds:*
  - *Propeller load:* *242 [Nm]*
  - *Propeller speed:* *27 [RPM]*
- *After 10 000 seconds (propeller load halved):*
  - *Propeller load is halved for a few seconds, then increases to and stabilizes at:* *229 [Nm]*
  - *Propeller speed is increased by:* *+10 [RPM]*
- *After 12 000 seconds (hotel load doubled):*
  - *Propeller load is reduced by:* *-74 [Nm]*
  - *Propeller speed is reduced by:* *-7 [RPM]*

The propeller load is halved for a few seconds but then increased to a load of 229 Nm which is below 242 Nm but higher than half load. The propeller speed follows the same initial trend as the load, but it stabilizes at a higher speed than for previous condition.

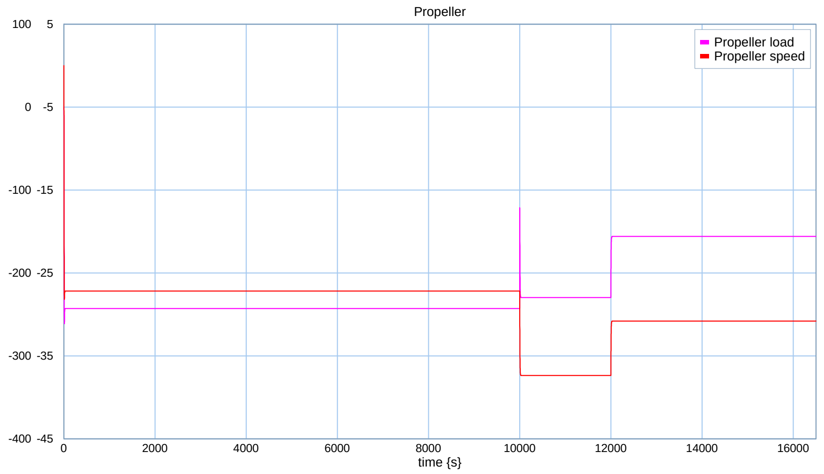


Figure 51: Propeller load and speed from simulation 2.

From the graph in figure 52 the following performance data, including the effects of added events, can be collected:

- *Before 10 000 seconds:*
    - *Emission cost factor for NO_X emission:* *0.9999*
    - *Emission cost factor for SO_X emission:* *0.9999*
- *After 10 000 seconds (propeller load halved):*
    - *Emission cost factor for NO_X and SO_X emission increased but by an insignificant amount*
- *After 12 000 seconds (hotel load doubled):*
    - *Emission cost factor for NO_X and SO_X emission decreased but by an insignificant amount*

The result shows an insignificant variation in the emission cost factors, which is expected at low engine loads.

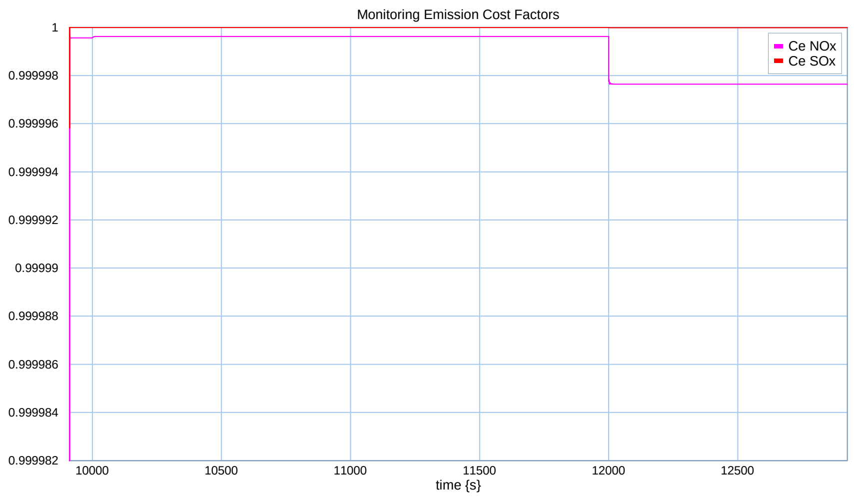


Figure 52: Emission cost factors for NO_X and SO_X from simulation 2.

From the graph in figure 53 the following performance data, including the effects of added events, can be collected:

- *Before 10 000 seconds:*
    - *Cooling system control volume temperature hot circuit:*
        - *T1: 417 [K]*
        - *T2: 410 [K]*
        - *T3: 404 [K]*
    - *Cooling system control volume temperature cold circuit:*
        - *T1: 317 [K]*
        - *T2: 316 [K]*
        - *T3 314 [K]*
- *After 10 000 seconds (propeller load halved):*
    - *Cooling system control volume temperature hot circuit:*
        - *No measurable temperature variations*
    - *Cooling system control volume temperature cold circuit:*
        - *No measurable temperature variations*
- *After 12 000 seconds (hotel load doubled):*
    - *Cooling system control volume temperature hot circuit:*
        - *T1 increased by: +15 [K]*
        - *T2 increased by: +14 [K]*
        - *T3 increased by: +14 [K]*
    - *Cooling system control volume temperature cold circuit:*
        - *T1 increased by: +2 [K]*
        - *T2 increased by: +2 [K]*
        - *T3 increased by: +1 [K]*

The result shows that the engine temperature increases as the load increases.

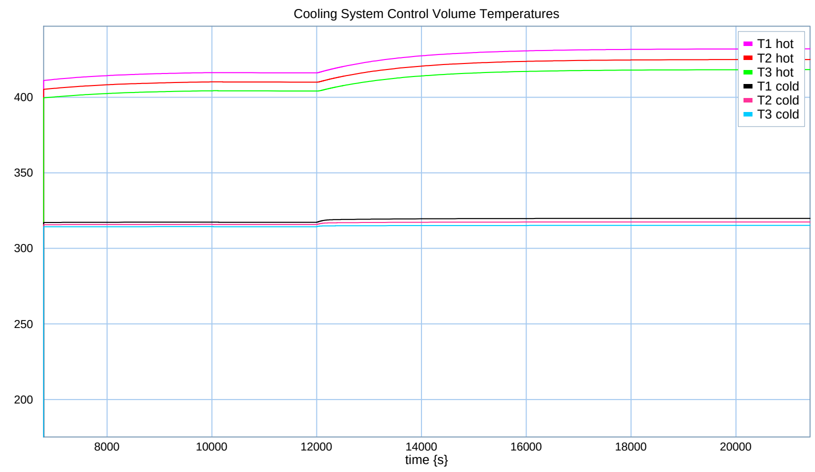


Figure 53: Cooling system control volume temperatures from simulation 2.

From the graph in figure 54 the following performance data, including the effects of added events, can be collected:

- *Before 10 000 seconds:*
    - *Cooling system control volume heat transfer:*
        - *Qp1: 12 262 [W]*
        - *Qp2: 11 687 [W]*
        - *Qp3: 11 139 [W]*
- *After 10 000 seconds (propeller load halved):*
    - *Cooling system control volume heat transfer:*
        - *No measurable heat transfer variations*
- *After 12 000 seconds (hotel load doubled):*
    - *Cooling system control volume heat transfer:*
        - *Qp1 increased by: +1 650 [W]*
        - *Qp2 increased by: +1 653 [W]*
        - *Qp3 increased by: +1 651 [W]*

The result shows that as the engine temperature rises, the heat transfer is increased due to a higher temperature difference between hot and cold circuit.

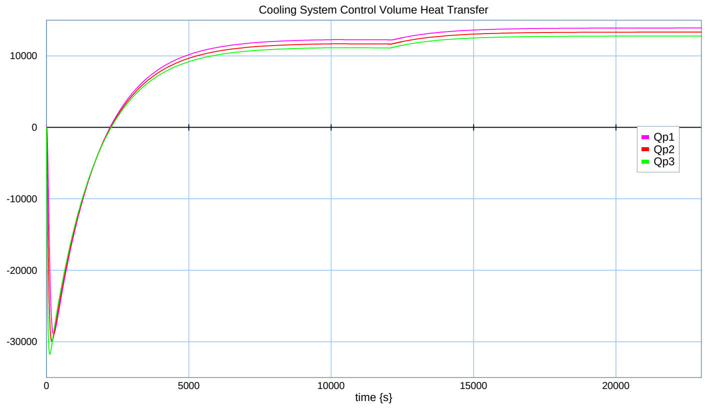


Figure 54: Cooling system control volume heat transfer from simulation 2.

8.5.3 Summary of Simulations and comments

The result from simulation 1 and 2 is presented in table 6. The table presents values from graphs presented by the simulator engine in 20-Sim, which are obtained by selecting a set of variables prior to the simulation.

Summary of MS Simulations							
Variables:	Simulation 1:	Simulation 2:			Deviations:		Units:
	Steady-state:	Before 10000 s:	After 10000 s (propeller load halved):	After 12000 s (hotel load doubled):	After 10000 s:	After 12000 s:	
Engine speed	720	720	720	720	0	±1	[RPM]
SFC	260	260	260	260	0	0	[g/kWh]
Fuel injected per cycle	0,00042	0,00037	0,00054	0,00066	0,00017	0,00012	[kg]
Nominal power	35000	30396	30699	35027	303	4328	[W]
Propeller load	168	242	229	155	-13	-74	[Nm]
Propeller speed	23	27	37	30	10	-7	[RPM]
Emission cost factor for NOx emissions	0,9999	0,9999	0,9999	0,9999	0	0	
Emission cost factor for SOx emissions	0,9999	0,9999	0,9999	0,9999	0	0	
Cooling system control volume temperature hot circuit:							
T1	428	417	417	432	0	15	[K]
T2	421	410	410	424	0	14	[K]
T3	414	404	404	418	0	14	[K]
Cooling system control volume temperature cold circuit:							
T1	320	317	317	319	0	2	[K]
T2	317	316	316	318	0	2	[K]
T3	315	314	314	315	0	1	[K]
Cooling system control volume heat transfer:							
Qp1	14000	12262	12262	13912	0	1650	[W]
Qp2	13400	11687	11687	13340	0	1653	[W]
Qp3	12800	11139	11139	12790	0	1651	[W]

Table 6: Summary of machinery system simulations.

When viewing the results from each selected variable it becomes clear that the nominal power load on the engine compared to the rated engine power is much lower than for typical real steady-state operation conditions. However, the objective of the simulations is not the obtained values but the behavior of the MS. Hence, the data from the simulations will not be discussed further in detail. The data from the simulations is considered set points for the sensitivity analysis in chapter 8.6. which is a more thorough analysis of the MS mock-up behavior.

8.6 Sensitivity Analysis

A sensitivity analysis is made in order to evaluate the MS mock-up. A set of parameters for the selected DE and the presented variables from the simulations in chapter 8.5 found the baseline for the sensitivity analysis. Parameters from other components may additionally be selected in order to obtain a more extensive sensitivity analysis. It should be mentioned that the presented MS mock-up consists of several uncertainties due to simplifications in many of the component's parameter and variable descriptions. Hence, the focus is set on the DE which has been validated by supervisor Eilif Pedersen.

Selected DE parameters and initial value:

- *Rated engine power at 100% MCR:* *Pe100* = *1000 [kW]*
- *RPM at 100% MCR:* *RPM100* = *720 [RPM]*
- *SFC at 100% MCR:* *be100* = *200 [g/kWh]*
- *Switch for 2-stroke or 4-stroke engine:* *alfa* = *2*

The selected DE parameters are set to a low and high bound (LB and HB respectively) and presented together with the result from simulation 1 and the respective result of variable values due to the parameter change. Only one parameter is changed at the time with respect to the set parameters from simulation 1. It should be mentioned that only variables with significant variations will be discussed. The DE parameters are presented with their original nametag. The sensitivity analysis for each selected DE parameter is presented in the next chapters.

8.6.1 Sensitivity Analysis for MS Mock-Up: Pe100

Changing the rated engine power by ± 500 kW has, according to the sensitivity analysis in table 7, a low effect on the modeled MS. The reason for this is most likely the small load, as presented in simulation 1, imposed on the engine. Small variations are found, but none worth further investigation.

Sensitivity Analysis for The MS Mock-up: Pe100						
Variables:	**Simulation 1:**	**Pe100:**				**Units:**
	Set points:	LB: 500	HB: 1500	Deviations LB:	Deviations HB:	
Engine speed	720	720	720	**0**	**0**	[RPM]
SFC	260	260	260	**0**	**0**	[g/kWh]
Fuel injected per cycle	0,00042	0,00042	0,00042	**0**	**0**	[kg]
Nominal power	35000	34900	34896	**-100**	**-104**	[W]
Propeller load	168	168	168	**0**	**0**	[Nm]
Propeller speed	23	23	23	**0**	**0**	[RPM]
Emission cost factor for NOx emissions	0,9999	0,9984	0,9999	**-0,0015**	**0**	
Emission cost factor for SOx emissions	0,9999	0,9999	0,9999	**0**	**0**	
Cooling system control volume temperature hot circuit:						
T1	428	432	433	**4**	**5**	[K]
T2	421	426	425	**5**	**4**	[K]
T3	414	419	419	**5**	**5**	[K]
Cooling system control volume temperature cold circuit:						
T1	320	320	320	**0**	**0**	[K]
T2	317	318	318	**1**	**1**	[K]
T3	315	315	315	**0**	**0**	[K]
Cooling system control volume heat transfer:						
Qp1	14000	13980	13978	**-20**	**-22**	[W]
Qp2	13400	13406	13404	**6**	**4**	[W]
Qp3	12800	12856	12854	**56**	**54**	[W]

Table 7: Sensitivity analysis for machinery system mock-up: Pe100.

8.6.2 Sensitivity Analysis for MS Mock-Up: RPM100

By reducing the rated engine speed the following variables are reduced:

- *Fuel injected per cycle*
- *Nominal power*
- *Propeller load and speed*
- *Emission cost factors for NO_X and SO_X*
- *Temperatures in the hot circuit of the cooling system*
- *Heat transfer in the cooling system*

The similar trend, but in the opposite direction, is found by increasing the rated engine speed.

Sensitivity Analysis for The MS Mock-up: RPM100						
Variables:	**Simulation 1:**	**RPM100:**				**Units:**
	Set points:	LB: 220	HB: 1220	Deviations LB:	Deviations HB:	
Engine speed	720	220	1220	**-500**	**500**	[RPM]
SFC	260	260	260	**0**	**0**	[g/kWh]
Fuel injected per cycle	0,00042	0,00013	0,00071	**-0,00029**	**0,00029**	[kg]
Nominal power	35000	3227	100488	**-31773**	**65488**	[W]
Propeller load	168	44	297	**-124**	**129**	[Nm]
Propeller speed	23	11	30	**-12**	**7**	[RPM]
Emission cost factor for NOx emissions	0,9999	1	0,9886	**1E-04**	**-0,0113**	
Emission cost factor for SOx emissions	0,9999	1	0,9984	**1E-04**	**-0,0015**	
Cooling system control volume temperature hot circuit:						
T1	428	326	644	**-102**	**216**	[K]
T2	421	324	632	**-97**	**211**	[K]
T3	414	322	621	**-92**	**207**	[K]
Cooling system control volume temperature cold circuit:						
T1	320	315	325	**-5**	**5**	[K]
T2	317	314	321	**-3**	**4**	[K]
T3	315	313	317	**-2**	**2**	[K]
Cooling system control volume heat transfer:						
Qp1	14000	1402	39602	**-12598**	**25602**	[W]
Qp2	13400	1234	38624	**-12166**	**25224**	[W]
Qp3	12800	1087	37669	**-11713**	**24869**	[W]

Table 8: Sensitivity analysis for machinery system mock-up: RPM100.

8.6.3 Sensitivity Analysis for MS Mock-Up: be100

By reducing the SFC at 100% MCR for the DE the following variables are reduced:

- *SFC*
- *Fuel injected per cycle*
- *Temperatures in the hot circuit of the cooling system*
- *Heat transfer in the cooling system*

The similar trend, but in the opposite direction, is found by increasing the SFC.

Sensitivity Analysis for The MS Mock-up: be100						
Variables:	**Simulation 1:**	**be100:**				**Units:**
	Set points:	LB: 180	HB: 220	Deviations LB:	Deviations HB:	
Engine speed	720	720	720	**0**	**0**	[RPM]
SFC	260	234	286	**-26**	**26**	[g/kWh]
Fuel injected per cycle	0,00042	0,00038	0,00046	**-0,00004**	**0,00004**	[kg]
Nominal power	35000	34896	34896	**-104**	**-104**	[W]
Propeller load	168	168	168	**0**	**0**	[Nm]
Propeller speed	23	23	23	**0**	**0**	[RPM]
Emission cost factor for NOx emissions	0,9999	0,9999	0,9999	**0**	**0**	
Emission cost factor for SOx emissions	0,9999	0,9999	0,9999	**0**	**0**	
Cooling system control volume temperature hot circuit:						
T1	428	413	451	**-15**	**23**	[K]
T2	421	408	443	**-13**	**22**	[K]
T3	414	402	436	**-12**	**22**	[K]
Cooling system control volume temperature cold circuit:						
T1	320	319	321	**-1**	**1**	[K]
T2	317	317	318	**0**	**1**	[K]
T3	315	315	316	**0**	**1**	[K]
Cooling system control volume heat transfer:						
Qp1	14000	11774	16187	**-2226**	**2187**	[W]
Qp2	13400	11291	15523	**-2109**	**2123**	[W]
Qp3	12800	10828	14887	**-1972**	**2087**	[W]

Table 9: Sensitivity analysis for machinery system mock-up: be100.

8.6.4 Sensitivity Analysis for MS Mock-Up: alfa

By switching from 2-stroke to 4-stroke the fuel injected per cycle is doubled.

Sensitivity Analysis for The MS Mock-up: alfa						
Variables:	**Simulation 1:**	**alfa:**				**Units:**
	Set points:	LB: 2	HB: 4	Deviations LB:	Deviations HB:	
Engine speed	720	See simulation 1	720	**None**	**0**	[RPM]
SFC	260		260		**0**	[g/kWh]
Fuel injected per cycle	0,00042		0,00084		**0,00042**	[kg]
Nominal power	35000		34897		**-103**	[W]
Propeller load	168		168		**0**	[Nm]
Propeller speed	23		23		**0**	[RPM]
Emission cost factor for NOx emissions	0,9999		0,9999		**0**	
Emission cost factor for SOx emissions	0,9999		0,9999		**0**	
Cooling system control volume temperature hot circuit:						
T1	428		433		**5**	[K]
T2	421		426		**5**	[K]
T3	414		419		**5**	[K]
Cooling system control volume temperature cold circuit:						
T1	320		320		**0**	[K]
T2	317		318		**1**	[K]
T3	315		315		**0**	[K]
Cooling system control volume heat transfer:						
Qp1	14000		13980		**-20**	[W]
Qp2	13400		13407		**7**	[W]
Qp3	12800		12857		**57**	[W]

Table 10: Sensitivity analysis for machinery system mock-up: alfa.

8.6.5 Comments on the Sensitivity Analysis

The purpose of the sensitivity analysis is to evaluate the strength of the mock-up. The analysis shows that the mock-up is able to describe many of the dynamic characteristics of a MS for different imposed parameter or variable variations. As mentioned earlier in thesis, this is a simplified model but the mock-up is still able to portrait trend lines which correspond with performance of a real MS.

Listed below are some of the possible source of errors for the MS mock-up and simulations:

Possible source of errors

- *Misreading graphs from 20-Sim simulator*
    - *Not reached completely steady-state at measure point*
- *Complexity level of the modeled components*
- *Simplifications regarding component structure and functionality*
- *Errors in mathematical component description*

9 Conclusions and Recommendations

9.1 Conclusions

The thesis focuses on the design of MSs for OSVs regarding tools and architecture. The main intention for writing this thesis was to enlighten today's status and to present and propose new tools, methodologies, and architecture.

From the research study, in chapter 2, it becomes clear that the most common propulsion system in PSVs today is the DEL propulsion system. There are slight variations in the configuration, but it typically consists of four gensets, one emergency/harbor generator, two azimuth thrusters or pull, two tunnel thrusters, and one swing-up thruster. As for generating power, the typical prime mover is a DE. DEL MS is mainly selected due to imposed high load variations on the system and the operational profile which commonly shows that these vessels often run at low speeds and spend a great deal of time in standby mode.

Due to the constant pursuit for more fuel efficient and environment friendly MS solutions, new concepts are emerging, such as; dual fuel engine, VSP, hybrid propulsion systems, fuel cell power, wind power utilization, nuclear power, and jet propulsion. These alternative concepts are not yet considered typical or common solutions due to the current size-, weight-, cost-, efficiency-, and complexity limitations for today's OSVs.

The research study in chapter 5 shows that the design department in a yard company, such as STX Europe in Norway does not have any dedicated model or simulation tools for selecting and configuring new MS designs. Based on the estimated power requirement, a MS manufacturer like RRM or Wärtsilä is offered the challenge of designing the system. These MS manufacturers have tools for analyzing and testing MS configurations, but due to limited information and access on the tool description and the architecture of the software, it is hard tell how sophisticated and well utilized they are.

However, there exist some companies like TNO in Holland, who has developed a rather sophisticated tool for designing energy systems onboard marine vessels. The software tool is called GES and is domain-independent, flexible in terms of system and component reconfigurations, and applicable for most of the energy systems onboard marine vessels such as the MS. The GES has in this thesis been subjected to further research and review, and is considered the most promising tool found in the research study. It also shares many of the ideas, thoughts, and philosophies regarding MS design which were made prior to writing this thesis.

There are many approaches for modeling multi-domain energy systems. The research study in chapter 5.3 presents methodologies which has been utilized in the design of both software and mechatronic systems. Most of the methodologies present a tool for mapping and analyzing components and respective functions in a hierarchical structure by regarding energy and signal flow. Many of these methods such as OOD originate from the bond graph method which is described in chapter 5.3.3. They also present the concept of having a sub-system and component library to store previous concepts.

The thesis presents in chapter 7 a proposed methodology and structure based on the result of the research study. Concurrent engineering, which means optimizing the design in more than one domain simultaneously is different from previous sequential engineering and is considered a promising approach in future design of MSs. This statement is based on the requirements for flexibility throughout the design phase. In addition, a transition from soft to hard decision-making is obtained by not imposing hard decisions at an early stage of the design which could prevent good part-design solutions in some engineer principles, such as software developers.

A hierarchical MS breakdown structure is presented in order to organize, describe functionality, and to understand the component relations in a MS. It is proposed to develop optimizing algorithms for selecting components in a library based on previous known configurations. This challenge is merely presented and is not pursued in this thesis. The importance of unified interfacing between components becomes clear when it comes to flexibility and number of different energy domains found in a marine MS. In addition there is also presented a structure for a hierarchical component library and model documentation.

The mock-up in chapter 8 is built with a hierarchical structure and describes domain-independent energy flow in a simplified marine MS with unified interfacing by utilizing the bond graph approach and the software 20-Sim. The level of complexity varies within the modeled components. This is not of great relevance in exemplifying the functionality of the mock-up. The mock-up is flexible in terms of changing or adding sub-systems or components to the system.

In order to test functionality of the MS mock-up, two simulation scenarios were made. The first simulation describes the modeled MS's performance for a steady-state operation. The second simulation includes two time-specific events; propeller load halved at 10 000 seconds and hotel load doubled at 12 000 seconds. The results, from 20-Sim, show that the load on the DE, in both simulations, is very low compared to the rated engine power. The effects of this seem to be handled well by the mock-up as seen in the sensitivity analysis. As stated previously, this is not of great concern regarding the analysis, since the focus is set on the MS behavior rather than specific values for different sets of parameters and variable changes.

In order to determine strengths and weaknesses of the MS mock-up a sensitivity analysis were made. By regarding a set of parameters for the DE and by adjusting one parameter value at the time to a lower and higher bound with respect to base line parameters and variables from simulation 1, the dynamic behavior of the MS mock-up was obtained. The MS mock-up is considered far from complete in terms of user-friendliness and sub-system and component description, but it portraits trend lines in performance which are similar to what one may find by analyzing real MSs which is considered the goal for developing this mock-up.

The thesis is, as previously stated, focused on tools and architecture regarding early design of MSs in OSVs. The methodologies and the mock-up presented are meant to exemplify how one can approach this challenge.

9.2 Recommendations for Further Work

An ongoing project at The Institute of Marine Technology at NTNU in Trondheim, called SHIP 4C, is currently looking into how one can efficiently design complex MSs based on a complex operational profile in the tendering phase. After discussions with one of the participants, Henrique M. Gaspar, it became obvious that one of the challenges are how to swiftly evaluate MS concept design solutions and how to include decisive factors such as the operational profile into an integrated design tool and methodology. The purpose of this thesis share to some extent the same goal as a partial suggestion to the stated problem but not as complete and integrated as described above.

Listed below are challenges which has been discussed but not pursued due to various limitations and the extent of the thesis.

- *A detailed library with component type variations and optimizing functions/algorithms for selection based on other selected components already inserted into the model.*
- *More complex and detailed components.*
- *Expansion of the modeled MS with respect to number of components in order to match a real size MS.*
- *Add redundancy measures to the modeled MS.*
- *Emission monitoring of NO_X and SO_X in g/kWh.*
- *Inclusion of the operational profile as a simulation parameter for performance analysis.*

Bibliography

[1] MathPages.com. *The Magnus Effect*. Available: http://www.mathpages.com/home/kmath258/kmath258.htm

[2] Voithturbo.de. (2010, *Voith Schneider Propeller*. Available: http://www.voithturbo.de/vt_en_pua_marine_vspropeller.htm

[3] Skysails. (2009, *Towing Kite Wind Propulsion*. Available: http://www.skysails.info/fileadmin/user_upload/Pressespiegel/2009/International/090306-Ship_and_Port-Towing_kite_wind_propulsion.pdf

[4] OSJ_Online, "Long relationship puts PSV at the forefront," September/October 2007.

[5] Skipsrevyen. (2007, *M/S "Island Challenger"*. Available: http://www.skipsrevyen.no/batomtaler/batomtaler-4-2007/998.html

[6] Skipsrevyen. (2007, *M/S "Far Seeker"*. Available: http://www.skipsrevyen.no/batomtaler/batomtaler-6-2007/1174.html

[7] Ulstein_Group. (2009, *Ulstein P105 Bourbon Sapphire*. Available: www.bourbon-offshore.no/prod_images/doc_2_165.pdf

[8] DOF_ASA. (2009, *PSV-111*. Available: http://www.dof.no/PSV-111.aspx

[9] Skipsrevyen. (2007, *M/S "Siem Sailor"*. Available: http://www.skipsrevyen.no/batomtaler/batomtaler-6-2007/1176.html

[10] A. K. Ådnanes, *Maritime Electrical Installations And Diesel Electric Propulsion*: NTNU Institute of Marine Technology, 2004.

[11] R. Skjetne, "Priniciples of Electric Machinery (Lecture notes in TMR 4290 Diesel Electric Propulsion Systems)
" 2009.

[12] Siemens. (2010, *Electric Propulsion*. Available: https://www.nwe.siemens.com/norway/internet/no/produkter/energy/marine/Pages/electrical_propulsion_systems0.aspx

[13] Skipsrevyen. (2008, *Unique design solution wins DOF contract for Aker Yard*. Available: http://www.skipsrevyen.no/nyheter/1286.html

[14] Siemens. (2007, *Hybrid Propulsion Systems*. Available: http://www.nwe.siemens.com/norway/internet/no/produkter/energy/marine/Pages/hybrid_propulsion_systems.aspx

[15] FuelCellsWorks. (2009, *Supply Vessel Viking Lady Passes Important Milestone With Installation of Full Scale Fuel Cell*. Available: http://fuelcellsworks.com/news/2009/09/15/worlds-first-marine-fuel-cell-installed/

[16] HowStuffWorks. (2010, *Fuel Cell*. Available: http://auto.howstuffworks.com/fuel-efficiency/alternative-fuels/fuel-cell.htm

[17] S. Dhulipala. (2007, *Propulsion Using Nuclear Energy*. Available: http://engineering.suite101.com/article.cfm/propulsion_using_nuclear_energy

[18] Royal_Belgian_Institute_of_Marine_Engineers. (2003, *Marine Fuels and Engines*. Available: http://www.gallois.be/ggmagazine_2009/gg_03_05_2009_112.pdf

[19] I. Nefstad. (2005, *Forskningsskip levert fra Ekstrand*. Available: http://www.varden.no/nyheter/forskningsskip-levert-fra-ekstrand-1.189714

[20] A. Rødset, "E-mail Interview," STX Design in Ålesund2010.

[21] Rolls-Royce_Marine. (2004, March 8.). *Modelling and Simulation, Dynamic Response Analysis*. Available: http://www1.rolls-royce.com/marine/downloads/power_management/model_fact.pdf

[22] Rolls-Royce_Marine. (2004, March 8.). *Systems Engineering*. Available: http://www1.rolls-royce.com/marine/downloads/power_management/model_fact.pdf

[23] MathWorks. (2005, March 8.). *Wärtsilä Accelerates Engine Control Development Using Production Code Generation*. Available: www.mathworks.com

[24] W. Corporation. (2009, March 8.). *Hercules Beta*. Available: www.teknologiateollisuus.fi

[25] MathWorks. (2005, March 8.). *Simulink*. Available: www.mathworks.com

[26] TNO, "GES Software Content file," ed: TNO.

[27] TNO. (2010, March 4.). *GES - Integrated Energy Systems*. Available: http://www.tno.nl/content.cfm?context=markten&content=product&laag1=184&laag2=214&item_id=1353&Taal=2

[28] J. V. Amerongen. (2007, 09.03.2010). Mechatronic Design - A Port Based Approach. Available: http://doc.utwente.nl/64403/1/SharjahVanAmerongen.pdf

[29] S. A. Kayani. (2007, 09.03.2010). On Automated Design of Mehcatronic Systems through Bond-Graphs and Genetic Programming. *Vol. 2(No. 4)*. Available: http://ewh.ieee.org/soc/e/sac/meem/public/old_issue/vol02iss04/MEEM020404.pdf

[30] Naval_Architecture_Progress. (2010, *Design Spiral Image*. Available: http://www.nap.gr/ship-design.html

[31] W. F. S. F. Mistree, B.A. Bras, J.K. Allen, D. Muster, "Decision-Based Design: A Contemporary Paradigm for Ship Design," ed, 1990.

[32] Object_Mentor. (2010, March 4.). *Object-oriented Design*. Available: http://www.objectmentor.com/omSolutions/oops_what.html

[33] J.-C. Wu, *et al.* (2009, 09.03.2010). A Hierarchical Object-oriented Functional Modeling Framework for Co-Design of Mechatronic Products. *17(4)*. Available: http://cer.sagepub.com/cgi/content/abstract/17/4/245

[34] T. A. Pedersen, "Bond Graph Modelling of Marine Power Systems," Phd, Cybernetics at the Institute of Marine Technology, NTNU, Trondheim, 2009.

[35] 20-Sim. Reference Help [Online].

[36] G. Rzevski. (2003, On Conceptual design of intelligent mechatronic systems. Available: http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6V43-48JK0WY-1&_user=586462&_coverDate=12%2F31%2F2003&_rdoc=1&_fmt=high&_orig=search&_sort=d&_docanchor=&view=c&_searchStrId=1251626942&_rerunOrigin=google&_acct=C000030078&_version=1&_urlVersion=0&_userid=586462&md5=89234952cd19fcdab8b79f680900fcf4

[37] W. S. L. Wang, H. Xie, J. Neelamkavil, A. Pardasani. (2001, Collaborative conceptual design - state of the art and future trends. Available: http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6TYR-43T2MGW-1&_user=586462&_coverDate=11%2F30%2F2002&_rdoc=1&_fmt=high&_orig=search&_sort=d&_docanchor=&view=c&_searchStrId=1251635392&_rerunOrigin=google&_acct=C000030078&_version=1&_urlVersion=0&_userid=586462&md5=2dc4e71c423b3215736ac3de79968eaf

[38] The_Modelica_Assocoation. (2010, *Modelica and the Modelica Assocoation*. Available: http://www.modelica.org/

[39] M. Otter. (2005, *Modelica Overview*. Available: http://www.modelica.org/education/educational-material/lecture-material/english/ModelicaOverview.pdf

[40] W. Borutsky. (1999, 5-6). *Bond graph modeling from an object oriented modeling point of view* Available: http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6V19-3YB1T4C-4&_user=586462&_coverDate=12%2F15%2F1999&_rdoc=1&_fmt=high&_orig=search&_sort=d&_docanchor=&view=c&_searchStrId=1302276870&_rerunOrigin=google&_acct=C000030078&_version=1&_urlVersion=0&_userid=586462&md5=4957883dfddec1190df409809494a278#toc6

[41] K. Potger. (2010, February 10.). *physics & Chemistry Gas Laws*. Available: http://www.anzcp.org/CCP/Physics&Chem/Physics-pdf/Gas%20laws.pdf

[42] N. Calder, *Marine Diesel Engines* vol. 3rd Edition, 2007.

[43] E. Pedersen and H. Valland, *TMR 4222 Marine Machinery* 2008.

[44] Wärtsilä, "Project Guide for the Early Design of Marine Engine Installations," ed, 2004.

[45] US_Departement_of_Energy. (1993|). *DOE Fundamentals Handbook - Mechanical Science. 1/2*. Available: http://www.artikel-software.com/file/mech-v1.pdf

[46] K. Nice. (2000, April 12.). *How Gears Work*. Available: http://www.howstuffworks.com/gear.htm

[47] H. K. Woud and D. Stapersma, *Design of Propulsion and Electrical Power Generation Systems*, 2002.
[48] D. Radan, "Integrated Control of Marine Electrical Power Systems," philosophiae doctor, Departement of Marine Technology, NTNU, Trondheim, 2008.
[49] J. B. Heywood, *Internal Combustion Engine*, 1988.

Appendices

Appendix A – Sub-System and Component Documentation

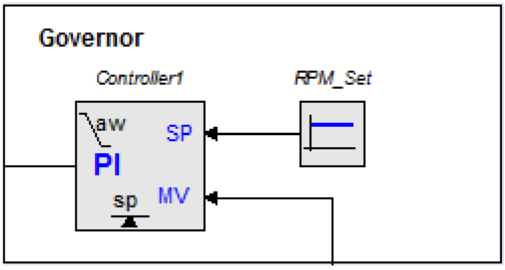
Appendix B – Machinery System Parameters

Appendix C – Model Files From 20-Sim (CD)

A. Sub-System and Component Documentation

Appendix A contains documentation and description for selected components in the presented marine MS mock-up. The set component parameters are described in appendix B. The inputs and outputs for components described by bond graphs are given by the causality imposed by the structure of the system and is either flow or effort in both cases. In this description both effort and flow will be considered.

A.1 Governor



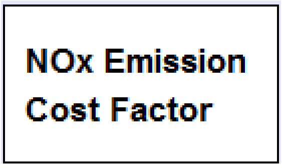
Model name	Governor

Description	**Controller:**
	// Created by C. Kleijn, 22 Sep 1999
	// Created by C. Kleijn, 22 Sep 1999
	parameters
	real K = 1.0 {}; // Proportional gain
	real Ti = 0.3 {s}; // Integral time constant: Ti > 0
	real b = 1.0 {}; // Proportional set point weighting
	parameter: 0 <= b <= 1
	real Ta = 0.1 {s}; // Tracking time constant.t: Ta > 0
	real minimum = 0.0 {}; // Minimum controller output
	real maximum = 1.1 {}; // Maximum controller output
	variables
	real error,PB_high,PB_low;
	real hidden uP,uI,ideal_output;
	equations
	error = SP - MV;
	uP = K * (b * SP - MV);
	uI = int ((K / Ti) * error - (ideal_output - output) / Ta);
	ideal_output = uP + uI;
	output = limit (ideal_output, minimum, maximum);
	PB_low = b * SP + (uI - maximum)/K;
	PB_high = b * SP + (uI - minimum)/K;
	RPM_Set:
	parameters
	real global C; // output value
	equations
	output = C;

Parameters	Diesel engine speed set point [RPM]
Input	Speed [RPM] from shaft of diesel engine Reference Speed [rad/s]
Output	Fuel injection

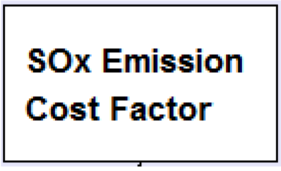
Limitation	None
Validation	Associate University Professor Eilif Pedersen
Comments	Modeled as PI-controller
Reference	Associate University Professor Eilif Pedersen

A.2 Monitoring of NO_X Emission Costs



Model name	NOx Emission Costs Factor
Description	parameters real global e0_NOx, Pe100; variables real Ce, s; equations s=(r+1^-10)/(Pe100*1000); Ce=1-exp(-e0_NOx/s);
Parameters	e0_NOx, emission cost constant for a specific DE
Input	Power signal [W] from DE
Output	Emission cost factor for NOx
Limitation	None
Validation	None
Comments	Monitors an emission cost factor for NOx in order display trend lines regarding the emission rate
Reference	Doctoral thesis: Integrated Control of Marine Electrical Power Systems by Damir Radan [48]

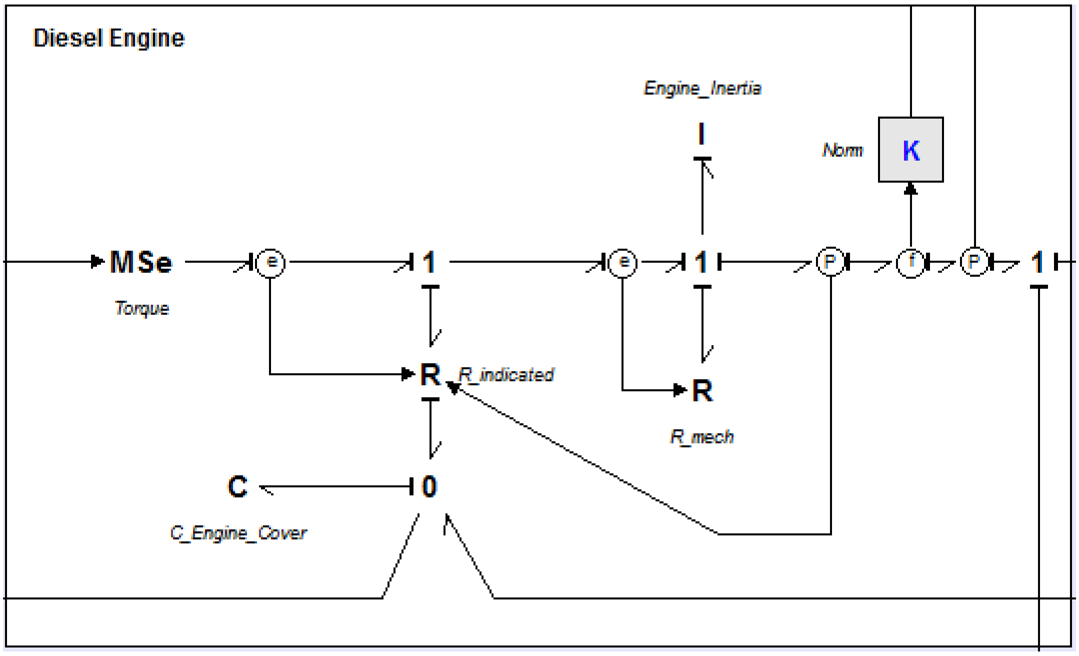
A.3 Monitoring of SO_X Emission Costs



Model name	SOx Emission Costs Factor
Description	parameters real global e0_SOx, Pe100; variables real Ce, s; equations s=(r+1^-10)/(Pe100*1000); Ce=1-exp(-e0_SOx/s);
Parameters	e0_SOx, emission cost constant for a specific DE

Input	Power signal [W] from DE
Output	Emission cost factor for SOx
Limitation	None
Validation	None
Comments	Monitors an emission cost factor for SOx in order display trend lines regarding the emission rate
Reference	Doctoral thesis: Integrated Control of Marine Electrical Power Systems by Damir Radan [48]

A.4 Diesel Engine



Model name	Diesel Engine

Description	**MSe:**
	parameters
	real global Pe100;
	real global RPM100;
	real global be100;
	real global neta_m;
	real global J_motor;
	real global hn;
	real global alfa;
	
	variables
	real hidden E, Tt, ms_s, omega;
	
	equations
	// Beregn innsprøytet mengde fuel pr syklus
	ms_s = s*Pe100*be100*(1e-3/3600.0)/(RPM100/(60.0*alfa));
	// Beregn teoretisk moment på akselen
	Tt = ms_s*hn*1e6/(2*pi*alfa);

```
		p.e = Tt;
		omega=p.f;

		E=Tt*omega;
```

R_indicated:

```
parameters
		real global Pe100;
		real global RPM100;
		real global alfa;
		real global neta_m;
		real global hn;
		real global be100;

// Spesifikt brennstofforbruk som funksjon av Pe, i.e. be=a1+a2*Pe+a3*Pe^2
(normalisert)

		real hidden beT[3] = [1.0,0.98,1.3];			//For dieselmotor ved
variabelt turtall
//		real hidden beT[3] = [1.0,1.0,1.1];			//For dieselmotor ved
konstant turtall (generatormotor)

variables
		real be, Abe[3,3], a[3], x, dTi;
		real Qvarme;

initialequations
		Abe=[1,1,1;1,0.8,0.8^2;1,0.5,0.5^2];
		a=inverse(Abe)*beT;

equations

// Beregn spesifikt brennstoff forbruk

		x   = sPe/(Pe100*1000);
		be  = min([be100*(a[1] +a[2]*x + a[3]*x^2),be100*beT[3] ]);

// Beregn tap i moment relativt til teoretisk moment som gir indikert moment
produsert
		dTi = s*(1-1/(neta_m*hn*be/3600.0));

// NB! be ovenfor er begrenset til 1.3*be100

		p.e = dTi;
		Qvarme = p.f*dTi*0.6;
		pThermal.f=Qvarme;
```

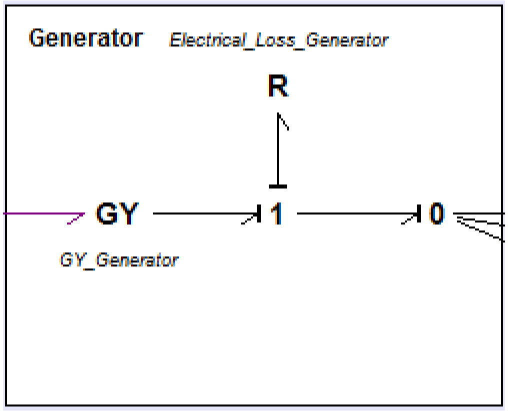
C:

```
parameters
		real cv = 4200;
		real rho = 1000;
		real vol = 0.1;
variables
		real Q;
equations
```

```
   Q = int(p.f);
   p.e = Q / (rho*vol*cv);
I:
parameters
           real global J_motor;
variables
           real RPM;
equations
   state = int(p.e);
   p.f = state / J_motor;

           RPM=p.f*30/pi;
R_mech:
parameters
           real global neta_m;
equations

// Beregn mekanisk tap utrykt vha moment, i.e. T_e=T_i*(1-neta_m), hvor T_i
indikert moment

           p.e = s*(1-neta_m);
K:
parameters
           real global RPM100;
equations

           output = input/(pi*RPM100/30.0);
```

Parameters	Pe100, Effective engine power at 100% MCR in kW RPM100, RPM at 100% MCR be100, Specific fuel consumption at 100% MCR in g/kWh neta_m, Mechanical efficiency (including pump work) J_motor, Rotational inertia for rotating mass hn, Lower heating value for fuel in MJ/kg alfa, 2-stroke=1, 4-stroke=2
Input	Fuel injection
Output	Temperature Heat flow [J/s] Torque [Nm] Speed [rad/s]
Limitation	None
Validation	Associate University Professor Eilif Pedersen
Comments	Modeled as a rotating shaft with inertia and mechanical and thermal losses.
Reference	Associate University Professor Eilif Pedersen

A.5 Generator

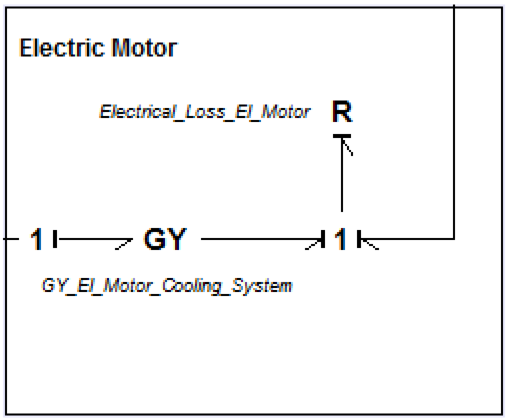


Model name	Generator

Description	**GY:**
	parameters
	    real global gy_gen;
	equations
	    p1.e = gy_gen * p2.f;
	    p2.e = gy_gen * p1.f;
	R:
	parameters
	    real global el_loss_gen;
	equations
	    p.e = el_loss_gen * p.f;

Parameters	Gyrator Modulus Electrical Losses
Input	Torque [Nm] Speed [rad/s]
Output	Voltage [V] Current [A]
Limitation	The model does not include 3-phase current.
Validation	None
Comments	Modeled as gyrator for energy transformation with efficiency losses.
Reference	None

A.6 Electric Motor (Cooling System)

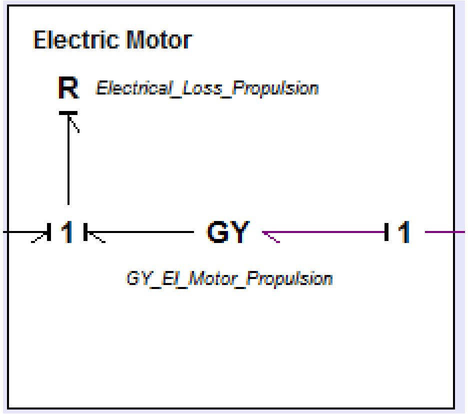


Model name	Electric Motor

Description	**GY:**
	parameters
	real global gy_EM_CS;
	equations
	p1.e = gy_EM_CS * p2.f;
	p2.e = gy_EM_CS * p1.f;
	R:
	parameters
	real global el_loss_EM_CS;
	equations
	p.e = el_loss_EM_CS * p.f;

Parameters	Gyrator Modulus Electrical Losses
Input	Voltage [V] Current [A]
Output	Torque [Nm] Speed [rad/s]
Limitation	Modeled as a reversed version of a generator.
Validation	None
Comments	None
Reference	None

A.7 Electric Motor (Propulsion)

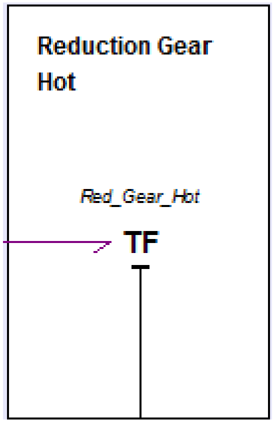


Model name	Electric Motor

Description	**GY:**
	parameters
	real global gy_EM_prop;
	equations
	p1.e = gy_EM_prop * p2.f;
	p2.e = gy_EM_prop * p1.f;
	R:
	parameters
	real global el_loss_EM_prop;
	equations
	p.e = el_loss_EM_prop * p.f;

Parameters	Gyrator Modulus Electrical Losses
Input	Voltage [V] Current [A]
Output	Torque [Nm] Speed [rad/s]
Limitation	Modeled as a reversed version of a generator.
Validation	None
Comments	None
Reference	None

A.8 Reduction Gear Hot

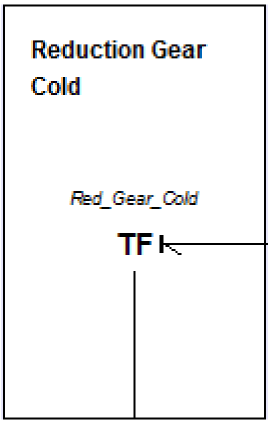


Model name	Reduction Gear

Description	**TF:**
	parameters
	real global red_ratio_hot;
	equations
	p1.e = red_ratio_hot * p2.e;
	p2.f = red_ratio_hot * p1.f;

Parameters	Gear ratio, n
Input	Torque [Nm] Speed [rad/s]
Output	Torque [Nm] Speed [rad/s]
Limitation	None
Validation	None
Comments	Reduction of shaft speed for hydraulic pump input
Reference	None

A.9 Reduction Gear Cold

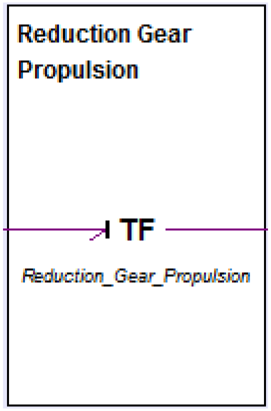


Model name	Reduction Gear

Description	**TF:**
	parameters
	real global red_ratio_cold;
	equations
	p1.e = red_ratio_cold * p2.e;
	p2.f = red_ratio_cold * p1.f;

Parameters	Gear ratio, n
Input	Torque [Nm] Speed [rad/s]
Output	Torque [Nm] Speed [rad/s]
Limitation	None
Validation	None
Comments	Reduction of shaft speed for hydraulic pump input
Reference	None

A.10 Reduction Gear Propulsion

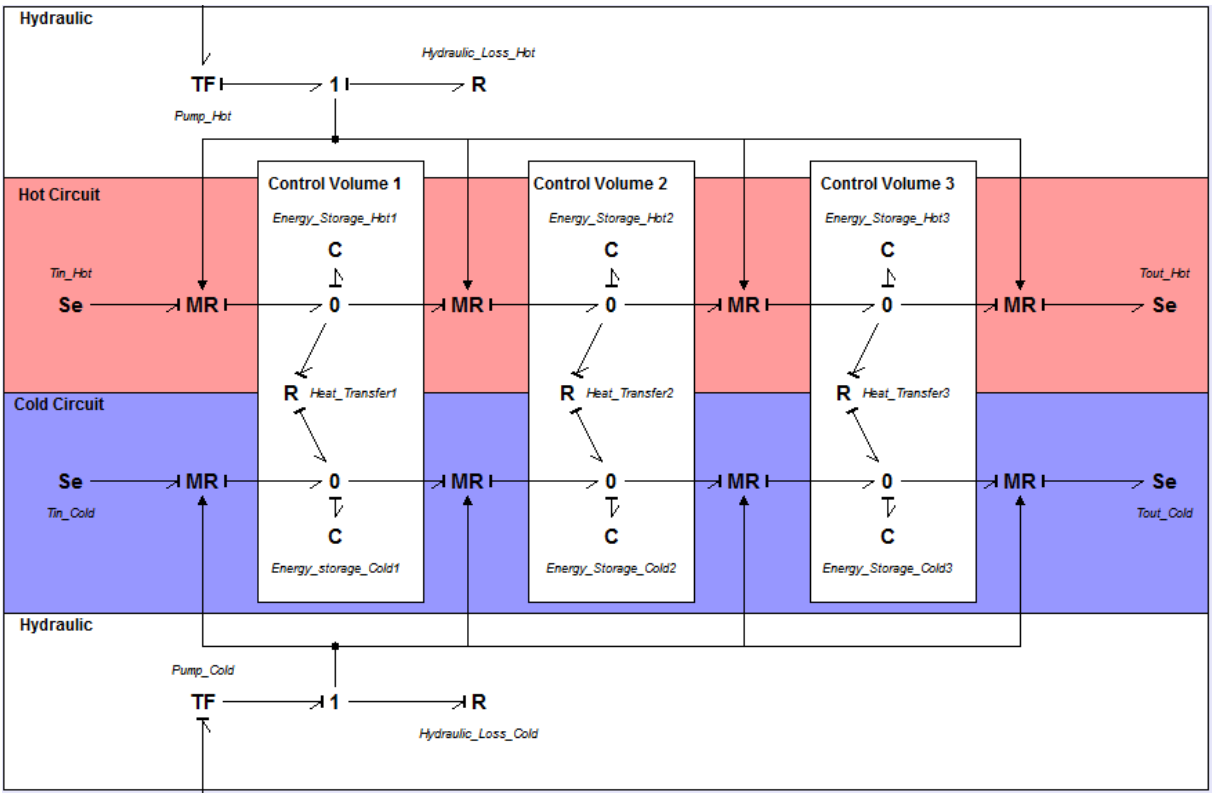


Model name	Reduction Gear

Description	**TF:**
	parameters
	real global red_ratio_prop;
	equations
	p1.e = 1/red_ratio_prop * p2.e;
	p2.f = 1/red_ratio_prop * p1.f;

Parameters	Gear ratio, n
Input	Torque [Nm] Speed [rad/s]
Output	Torque [Nm] Speed [rad/s]
Limitation	None
Validation	None
Comments	Reduction of shaft speed for propeller input
Reference	None

A.11 Cooling System For Diesel Engine



Model name	Cooling System For Diesel Engine

Description	**TF (Pump_Hot):**
	parameters
	real global pump_ratio_hot;
	equations
	p1.e = pump_ratio_hot * p2.e;
	p2.f = pump_ratio_hot * p1.f;
	R (Hydraulic_Loss_Hot):
	parameters
	real global hydr_loss_hot;
	equations
	p.e = hydr_loss_hot * p.f;
	Se (Tin_Hot):
	parameters
	real global T_in_hot;
	variables
	real Q;
	equations
	p.e = T_in_hot;
	Q= p.f;
	MR (Hot):
	parameters
	real global rho_hot, cp_hot;
	variables
	real Q;

```
equations
        if r>0 then
        Q = rho_hot*r*cp_hot*p1.e;
        else
        Q = rho_hot*r*cp_hot*p2.e;
        end;
        p1.f=Q;
        p2.f=Q;
```

C (Energy_Storage_Hot):

```
parameters
        real global vol_control_hot, rho_hot, cp_hot,T0_hot;
variables
        real Qt, Qt0;
initialequations
        Qt0=rho_hot*vol_control_hot*T0_hot;
equations
  Qt = int(p.f,Qt0);
  p.e = Qt / (rho_hot*vol_control_hot*cp_hot);
```

Se (Tout_Hot):

```
parameters
        real global T_out_hot;
variables
        real Q;
equations
        p.e = T_out_hot;
        Q= p.f;
```

R (Heat Transfer):

```
parameters
        real global A, h;
variables
        real Qp;
equations
        Qp=h*A*(p1.e-p2.e);
        p1.f=Qp;

        p2.f=Qp
```

TF (Pump_Cold):

```
parameters
        real global pump_ratio_cold;
equations
        p1.e = pump_ratio_cold * p2.e;
        p2.f = pump_ratio_cold * p1.f;
```

R (Hydraulic_Loss_Cold:

```
parameters
        real global hydr_loss_cold;
equations
        p.e = hydr_loss_cold * p.f;
```

Se (Tin_Cold):

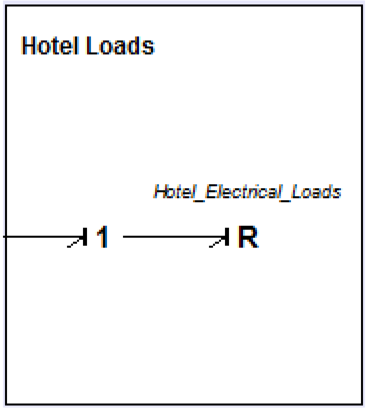
```
parameters
        real global T_in_cold;
variables
        real Q;
equations
        p.e = T_in_cold;
```

	Q= p.f;
	MR (Cold):
	parameters
	real global rho_cold, cp_cold;
	variables
	real Q;
	equations
	if r>0 then
	Q = rho_cold*r*cp_cold*p1.e;
	else
	Q = rho_cold*r*cp_cold*p2.e;
	end;
	p1.f=Q;
	p2.f=Q;
	C (Energy_Storage_Cold):
	parameters
	real global vol_control_cold, rho_cold, cp_cold,T0_cold;
	variables
	real Qt, Qt0;
	initialequations
	Qt0=rho_cold*vol_control_cold*T0_cold;
	equations
	Qt = int(p.f,Qt0);
	p.e = Qt / (rho_cold*vol_control_cold*cp_cold);
	Se (Tout_Cold):
	parameters
	real global T_out_cold;
	variables
	real Q;
	equations
	p.e = T_out_cold;
	Q= p.f;

Parameters	Pump ration cold Hydraulic losses hot Hydraulic losses cold Pump ration hot Surface area for heat exchanger [m²] Heat transfer coefficient [W/m²K] Inlet temperature hot circuit [K] Outlet temperature hot circuit [K] Density hot agent [kg/m³] Specific heat capacity hot circuit [J/kgK] Inlet temperature cold circuit [K] Outlet temperature cold circuit [K] Density coolant [kg/m³] Specific heat capacity hot circuit [J/kgK]
Input	Temperature [K] Heat flow[J/s] Torque [Nm] Speed [rad/s]
Output	Temperature [K] Heat flow [J/s]
Limitation	The cooling system is based on assumed input and output temperatures for the two circuits

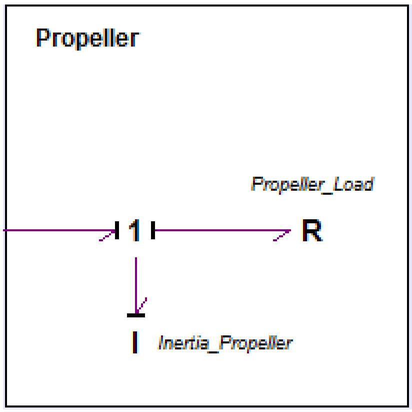
Validation	None
Comments	The number of control volumes is expandable
Reference	None

A.12 Hotel Loads



Model name	Hotel Loads
Description	**R:** parameters real global hotel_load; equations p.e = hotel_load * p.f;
Parameters	Electrical Losses
Input	Voltage [V] Current [A]
Output	None
Limitation	Modeled as a single R-element and is considered as pure electrical losses
Validation	None
Comments	None
Reference	None

A.13 Propulsor



Model name	Propeller

Description	**I:**
	parameters
	real global inertia_propeller;
	equations
	state = int(p.e);
	p.f = state / inertia_propeller;
	R:
	parameters
	real hidden global load_propeller;
	variables
	real k;
	equations
	if time > 500 then
	k=0.5;
	else
	k=1;
	end;
	p.e = k*load_propeller * abs(p.f)*p.f;

Parameters	Inertia [kg] Propeller Load [Nm]
Input	Torque [Nm] Speed [rad/s]
Output	None
Limitation	Modeled as rotating mass with opposing loads
Validation	None
Comments	Exponential load of second order on propeller
Reference	None

B. Machinery System Parameters

```
parameters

//________________________________________________CONTROL________________________________________________\\

	//GOVERNOR
		real global C = 1.0;						//Normalized engine set speed
	//NOx Emission Cost Factor
		real global e0_NOx = 0.45;					//emission cost constant for NOx
	//SOx Emission Cost Factor
		real global e0_SOx = 0.65;					//emission cost constant for SOx

//____________________________________________POWER_GENERATION____________________________________________\\

	//DIESEL ENGINE (DE)
		real global Pe100	= 1000;				//Effective engine power at 100% MCR in kW
		real global RPM100	= 720;				//RPM at 100% MCR
		real global be100	= 200;				//Specific fuel consumption at 100% MCR in g/kWh
		real global neta_m	= 0.9;				//Mechanical efficiency (including pump work)
```

```
        real global J_motor      = 250;                        //Rotational inertia for rotating mass
        real global hn           = 42;                         //Lower heating value for fuel in MJ/kg
        real global alfa         = 2;                          //2-stroke=1, 4-stroke=2

    //GENERATOR (gen)
        real global gy_gen = 20;                               //Gyrator modulus generator
        real global el_loss_gen = 50.0;                        //Electrical losses in generator

//________________________________POWER_TRANSMISSION________________________________\\
    //COOLING SYSTEM (CS)
        //ELECTRIC MOTOR (EM)
            real global gy_EM_CS = 10;                         //Gyrator modulus electric motor
            real global el_loss_EM_CS = 50.0;                  //Electric losses in electric motor
        //REDUCTION GEAR HOT CIRCUIT
            real global red_ratio_hot = 6;                     //Gear reduction ratio
        //REDUCTION GEAR COLD CIRCUIT
            real global red_ratio_cold = 4;                    //Gear reduction ratio
```

```
//PROPULSION SYSTEM (prop)
    //ELECTRIC MOTOR
        real global gy_EM_prop = 10;                    //Gyrator modulus electric motor
        real global el_loss_EM_prop = 50.0;             //Electric losses in electric motor
    //REDUCTION GEAR
        real global red_ratio_prop = 3;                 //Gear reduction ratio

//__________________________________________POWER_CONSUMERS__________________________________________\\
//COOLING SYSTEM DIESEL ENGINE
    //MECHANICAL
        //HOT CIRCUIT
            real global pump_ratio_hot = 1e-6;          //Pump ration hot
        //COLD CIRCUIT
            real global pump_ratio_cold = 1e-5;         //Pump ration cold
    //HYDRAULIC
        //HOT CIRCUIT
```

```
            real global hydr_loss_hot = 40.0;                    //Hydraulic losses hot
        //COLD CIRCUIT
            real global hydr_loss_cold = 40.0;                   //Hydraulic losses cold
    //THERMAL
        real global A = 0.62  {m2};                              //Surface area for heat exchanger
        real global h = 200       {W/m2.K};                      //Heat transfer coefficient
        //HOT CIRCUIT
            real global T0_hot = 273{K};
            real global T_in_hot = 373 {K};                      //Inlet temperature hot circuit
            real global T_out_hot = 323 {K};                     //Outlet temperature hot circuit
            real global vol_control_hot = 0.009 {m3};            //Control volume hot circuit
            real global rho_hot = 1000 {kg/m3};                  //Density hot agent
            real global cp_hot = 4200 {J/kg.K};                  //Specific heat capacity
        //COLD CIRCUIT
            real global T0_cold = 273{K};
            real global T_in_cold = 293 {K};                     //Inlet temperature cold circuit
            real global T_out_cold = 313 {K};                    //Outlet temperature cold circuit
```

```
        real global vol_control_cold = 0.075 {m3};          //Control volume cold circuit
        real global rho_cold = 1024 {kg/m3};                //Density coolant
        real global cp_cold = 4000.0;                       //Specific heat capacity

//PROPULSION
    real global inertia_propeller = 500 {kg};               //Propeller inertia
    real global load_propeller = 30;                        //Propeller load factor

//HOTEL LOADS
    real global hotel_load = 20;                            //Auxilliary electric loads
```

C. Model Files from 20-Sim (CD)