INTENS

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beyond
the obvious

Integrated Energy Solutions to Smart And Green Shipping

2019 Edition

Zou Guangrong (Editor)

VTT TECHNOLOGY 354

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Preface

Five years back in 2014 when we organized the first public project[1] seminar on ship energy efficiency technologies, it attracted high interest among the Finnish marine communities. Specifically, very positive feedback was received on the holistic modelling and optimization approach that the project group adopted to ship energy system design and operation. Two years later in 2016, we held another public seminar on the same topic, with several invited speeches from international top experts in the marine domain, which reached even wider interested audiences. During the seminar, it was also suggested to organize the public seminars on a regular basis in the future, as a kind of tradition for the Finnish marine communities and beyond, which we thought was a great idea, of course! Over the years of close collaboration with the marine industries, we also realized that there was a real need for a dedicated technology forum/symposium to regularly share, exchange, and follow recent progress on research, development and innovation in smart and green shipping, specifically regarding energy efficiency and emissions of ship energy systems. Thanks to the great support of all the involved colleagues, especially the INTENS project[2] group, we are able to continue the “tradition” to organize the third public seminar in March 2019.

The seminars have been project-based so far, which ensures that the events are with focused scope and topics, which we think are interesting and crucial to the decarbonization and digitalization of shipping, and free of charge for all interested participants. Besides, starting from this year, for those who were not able to attend the seminars, we prepare the proceedings of the seminars and make them publically available to interested colleagues worldwide.

This book is a collection of extended abstracts of the speeches and posters presented in the third public seminar, a.k.a. the first INTENS public project seminar held on March 13, 2019, which concerns specifically initial results of the INTENS project achieved in the first project year. This would hopefully give the readers a sneak peek at what we do in the INTENS project to address the major challenges

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[1] SET - Ship energy efficiency technologies (2013 - 2016), co-funded by Tekes’ (the Finnish Funding Agency for Innovation, now Business Finland) Arctic Seas Programme (2014 - 2017) and the SET project consortium.

[2] INTENS - Integrated energy solutions to smart and green shipping (2018 - 2020), co-funded by Business Finland’s (formerly Tekes) Arctic Seas programme (2014 - 2017) and the INTENS consortium.

of shipping, and showcase and promote the Finnish marine expertise in the decarbonization, digitalization and automation of shipping.

Acknowledgement

We gratefully acknowledge the great support of Business Finland, 19 INTENS consortium partners, including 14 industrial partners (3D Studio Blomberg Ltd, Deltamarin Ltd, Dinex Finland Oy, Jeppo Biogas Ab, JTK Power Oy, Meyer Turku Oy, NAPA Oy, Parker Hannifin Manufacturing Finland Oy, Protacon technologies Oy, Tallink Silja Oy, Vahterus Oy, Visorc Oy, NLC Ferry Ab Oy and Wärtsilä Oyj Abp) and 5 research institutions (Aalto University, LUT University, University of Vaasa, Åbo Akademi University, and VTT Technical Research Centre of Finland Ltd), and other INTENS supporting partners.

Special thanks are due to the INTENS steering group, advisory group and project group, especially to all the authors contributing to the proceedings of the public seminar. Without your great support, collaboration and hard work, it would not have been possible to make INTENS happen and to make the public seminar another success.

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1. INTENS Overview[1]

Zou Guangrong[2], Johannes Hyrynen[2]
VTT Technical Research Centre of Finland Ltd

1.1 Background

Smart and green is the megatrend in global shipping! Specifically, decarbonization, digitalization and automation have been transforming the shipping cluster. Novel technologies and innovations are continuously gaining momentum in the marine domain and enabling the mega-transition at a rapid pace. Major digital transformation trends, such as Artificial Intelligence (AI), Big Data, Digital Twin, Internet of Things (IoT) and Cloud/Edge Computing, are already shaping the future of shipping. In the foreseeable future, the shipping cluster will be radically different from what it is now, which poses both challenges and opportunities to the global shipping cluster.

Owing to the knowledge of cutting-edge digital technologies and expertise in the marine domain, Finland already has all the necessary ingredients to intensify the digital transformation of the marine sector globally. Taking both the challenges and opportunities, we were able to form a research-industry collaborative consortium (INTENS - Integrated energy solutions to smart and green shipping) striving to advance, promote and digitalize Finnish marine industries and beyond in 2018 - 2020, with special focuses on energy efficiency and emissions of ship energy systems.

1.2 INTENS Consortium

Collaboration and sharing is the future, which is especially true for the Finnish marine cluster since over 90% of the marine products are exported abroad. Given the increasingly fierce competition, it is crucial for the Finnish marine cluster to formulate an effective strategy to join forces together.

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[1] This chapter is excerpted and revised from the INTENS project plan and a conference paper presented in COMPIT 2018 [1].

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As shown in Figure 1, the INTENS project consists of 14 Finnish marine industrial companies, listed in the upper half of the graph, and 5 research institutions, listed in the lower half of the graph, to collaborate in seven important and trendy RDI topics of shipping now and in the near future, including emission reduction, data analytics, waste heat recovery (WHR), optimization, operations, hybridization and electrification and Arctic-specific solutions and innovations. The detailed partner list can be referred to in the end of the chapter. As one of the largest networked research project funded by Business Finland, the INTENS comprises nine industrial projects led by industrial partners, marked blue in Figure 1, and one public research project conducted by the research partners, marked orange in Figure 1. The volume of the INTENS project is over 13 million euros, over 10 million euros of which goes to the nine industrial projects.

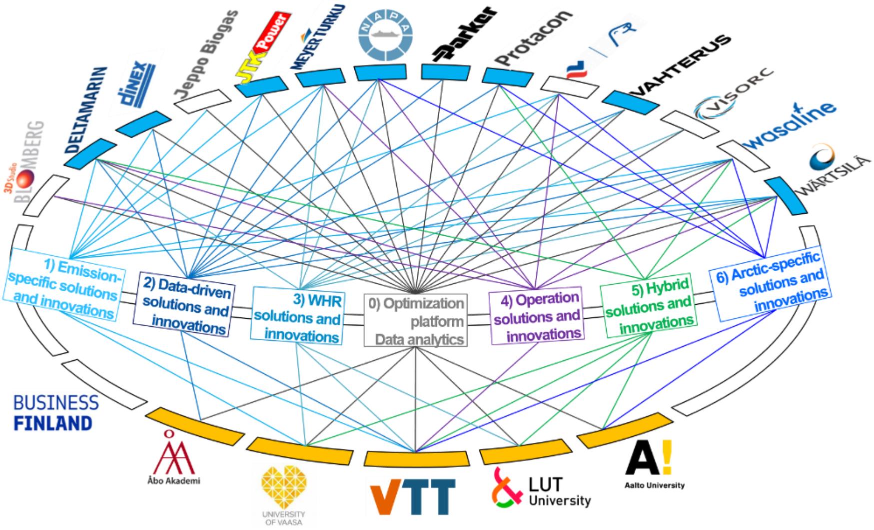

Figure 1. The INTENS consortium and selected RDI topics.

The INTENS partners cover the whole technical value chain of the marine cluster, including ship owners/operators, ship designer, ship builder, system/component suppliers, solution/service providers and technology innovators, which have decent knowledge and expertise in ship energy systems' design, construction or operation. As shown in Figure 1, the partners have mutual interest in the selected RDI topics, which laid the foundation for intensive collaboration within the consortium and with other Finnish and global shipping players outside of the consortium.

1.3 Objectives

The INTENS consortium aims to develop and utilize novel methodological and technological innovations and solutions to 1) integrate the INTENS consortium (mimicking different operational silos), 2) implement digital transformation (towards Digital Twin and “smart” shipping) and 3) improve ship energy efficiency and reduce emissions (towards “green” shipping). The specific focus of the entire INTENS consortium is on ship energy systems, covering all the component, system, ship and fleet levels.

To achieve the overall aims, there are four main specific objectives to pursue in the INTENS project.

1. Advance, digitalize and streamline novel research methodologies to enable effective research and development.
2. Work closely with consortium partners to enable efficient technology transfer, between the research groups and the consortium companies, to support them in acquiring and developing special knowledge about digital transformation, ship energy efficiency improvement and emission reduction.
3. Develop novel collaboration platform to enable and encourage the cooperation, information exchange and enrichment within the consortium partners efficiently and securely.
4. Promote public awareness and change mind-set of how decarbonization, digitalization and automation would transform the marine industries and the society, by actively sharing the consortium knowledge to the industries and the public nationally and globally. The digital transformation will only gain full speed after a critical mass of players are involved.

1.4 The RDI methodology

Thanks to its great potential and expected advantages, the Digital Twin concept has started gaining momentum and become more imperative to the business when the IoT starts emerging, and will continue playing a central role in industries’ digital transformation. Industrial leaders, such as General Electric [2] and IBM [3], have been introducing Digital Twin in their businesses. Specifically, DNV GL [4] has been promoting Digital Twin in marine industries as part of their digital asset ecosystem. Done properly, Digital Twin can bring IoT, Big Data, AI, VR/AR (virtual reality/augmented reality), Cloud/Edge Computing and dynamic simulation and optimization to one central place and communicate interactively with physical counterparts, which can potentially transform the industries and the whole society.

In INTENS, we adopt the Digital Twin concept as the main RDI methodology to study, develop and implement Digital Twins into the marine cluster, and to address the scientific and practical challenges hindering the wider utilization of the concept in the industries. Instead of identical twins of physical systems, we would rather build schematic twins with necessary details for desired purpose and focus more on developing the capacities of Digital Twin. As shown in Figure 2, the schematic twins of the case energy systems, including fleets, ships, systems and components, connect and run in parallel with their physical counterparts online or offline. Combined with AI and Big Data technologies, they learn and update themselves based on the available information, which includes multi-source data, generated by themselves or collected from the case systems or other sources (e.g. similar systems, environments …) in real time or in the past, and knowledge accumulated through the earlier experience during the long history of shipping. Thus, the roles of models can be redefined as

- information collector and carrier to collect and carry the information throughout their lifecycles,
- information enabler and transformer to enrich and transform the information to benefit the system design and operation, and
- information generator as large amount of information is generated when virtually running the models in parallel with their physical counterparts identically or for various scenario analyses.

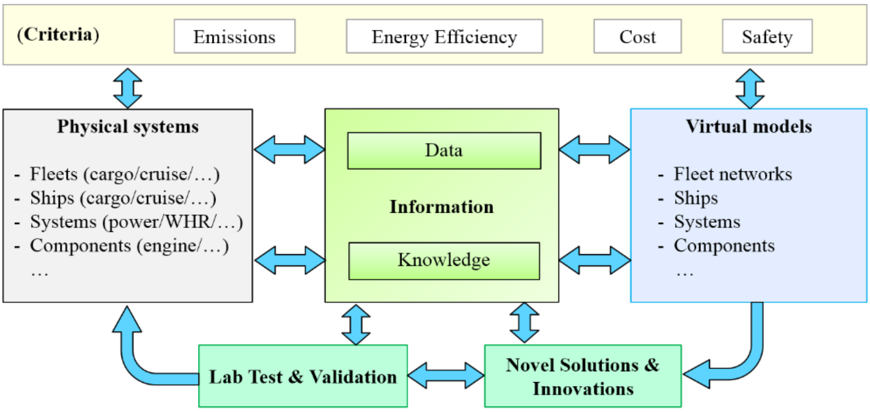

Figure 2. An illustrative diagram of the RDI methodology

Digital Twins are primarily built based on their physical counterparts. However, advanced digital design methods are commonly used in all engineering domains nowadays. The future twins will be *digital by design* before even having the physical counterparts. Different from identical twins that represent all the details of the physical counterparts, the schematic twins contain only necessary details and can be efficiently utilized for various purposes.

Figure 3 gives a brief overview of how we develop and utilize the virtual models to identify proper scenarios, novel solutions and innovations for design, operation and maintenance of ship energy systems throughout their lifecycles. The core of the conceptual framework is the three-layer platform built on top of an information (knowledge and data) base. The knowledge base includes various ship energy technologies, energy systems and their dynamic and/or data-driven models and libraries; the database includes measurement data, collected via ship onboard energy management systems (EMS) and on-site or lab experiments, and simulation data generated in the earlier work. The ship energy flow simulation and optimization platform provides a multi-domain dynamic simulation environment where ship energy systems are modelled based on first principles and data-driven methods and simulated under real operating conditions.

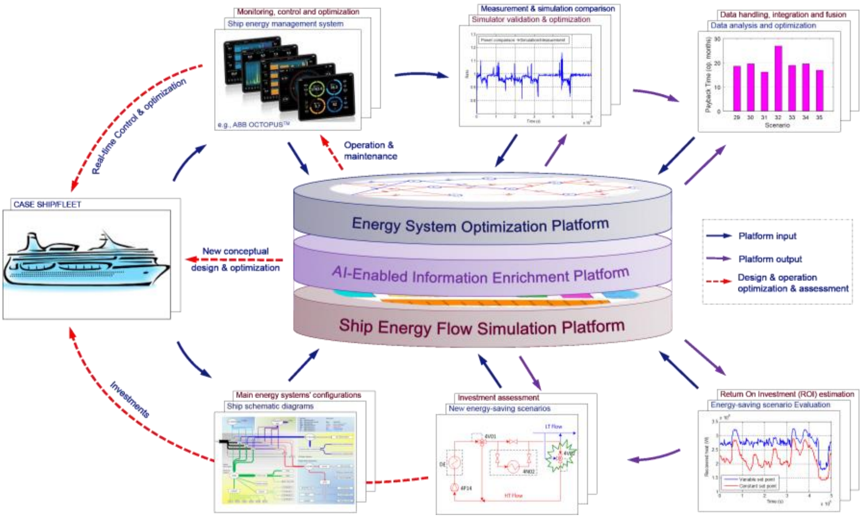

Figure 3. A multi-layer platform for the design, operation and maintenance of ship energy systems.

1.5 Expected impacts

As industry-wide collaborative efforts, the INTENS project and the generated novel solutions and innovations are expected to renew partners' businesses, to accelerate the digital transformation and to leap Digital Twin closer to reality in the marine industries, which could potentially change and disrupt the ways how the marine industries operate currently and pave the way of future shipping. Especially, the project will generate profound impacts not only to the consortium but also to the Finnish and global marine industries and even the whole society technologically, economically and socio-environmentally.

1. Technologically, the advanced R&D innovations will have the great chance to meet best practices, which will in turn speed up new technological innovations and achieve novel technological advancements. By leaping and implementing Digital Twin into the marine industries, significant scientific breakthroughs, innovations and solutions may be expected. Using the developed innovative collaboration and information exchange platform, we can encourage, enable and enhance efficient technology transfer and intensive technical cooperation, which can benefit the consortium and the Finnish industries socially and economically.
2. Economically, the enhanced expertise and collaborations will largely help the consortium and the marine cluster digitally transform their business, improve

ship energy efficiency and reduce emissions remarkably. Consequently, this will further help build up more competitive and sustainable businesses for the Finnish marine industries and hence gain the long-term competitive advantages globally, and even generate new momentous businesses, which will in turn gain good reputations to Finland for its high-level smart and green expertise.

3. Socio-environmentally, the more energy-efficient innovations and solutions will largely improve shipping efficiency, and help to achieve ambitious goal of GHG emission reduction globally. More importantly, by actively sharing the knowhow and promoting the public awareness of the potential impacts of digital transformation and green technology advancement to the marine industries and the public, we can strengthen the green and innovative global image of the consortium partners, the marine cluster and the country. Eventually, we can make global shipping more economic, energy efficient and environmentally friendly.

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Appendix - List of the INTENS consortium partners

Partner	Type
3D Studio Blomberg Ltd	SME
Deltamarin Ltd	Large company
Dinex Finland Oy	Mid-cap company
Jeppo Biogas Ab	SME
JTK Power Oy	Large company
Meyer Turku Oy	Large company
NAPA Oy	Mid-cap company
Parker Hannifin Manufacturing Finland Oy	Large company
Protacon technologies Oy	SME
Tallink Silja Oy	Large company
Vahterus Oy	SME
Visorc Oy	SME
NLC Ferry Ab Oy(Wasaline)	SME
Wärtsilä Oyj Abp	Large company
Aalto University	Research institution
LUT University	Research institution
University of Vaasa	Research institution
Åbo Akademi University	Research institution
VTT Technical Research Centre of Finland Ltd	Research institution, coordinator

2. Trashing design margins with smart data

Mia Elg[1], Ossi Mettälä[1], Jyri-Pekka Arjava[1]
Deltamarin Ltd

2.1 Introduction

Optimizing the lifetime fuel economics of the ships requires understanding the actual ship operation and applying this knowledge from the start of ship design, which is simple in theory but challenging in practice. One of the major challenges is that the most critical decisions considering ship efficiency are made during the early phases of the ship design process, when both available time and resources are limited.

2.2 Design margins

Considering ship design process from the concept phase to the detail engineering, various design margins may be applied on top of the preliminary system capacities. These margins can be utilized for describing some inherent variation of external conditions in the ship processes. The key to eliminating any unnecessary, static design margins is the capability to utilize suitable operation data.

For instance, the heat exchangers in ship auxiliary machinery are normally dimensioned for transferring heat from the ship machinery with full power, although the actual loading varies depending on the operating conditions, as shown in Figure 1. On top of this, it is the custom to add a notable fouling margin. It is clear that larger margins eventually also lead to larger costs and often considerable part-load operation of the equipment. This was one of the initial reasons for Deltamarin to start developing the ship energy flow simulation tool, as shown in Figure 2, which is applicable from the earliest concept designs to the final detail design phase. In our recent projects, our simulation tool has been utilized for evaluating the most economical way of arranging the ship machinery waste heat recovery or LNG

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evaporation, considering the LNG cold recovery in the total system. In this case, the measured operation data from the existing ship on the same route was utilized as the basis for the new project.

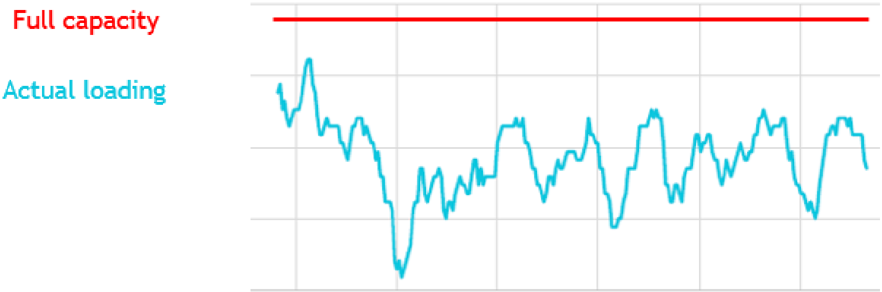

Figure 1. The difference between the nominal capacity and the actual loading of a heat exchanger.

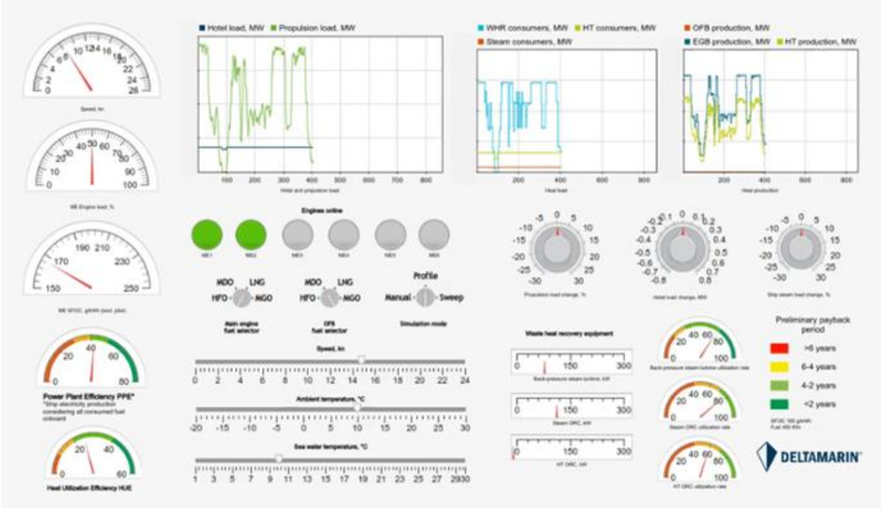

Figure 2. The Deltamarin ship energy flow simulation tool dashboard.

Another important example of design margins is the traditional way of evaluating the average loading of ships at sea, where ship designers model the ship in calm sea conditions and apply a figure called sea margin on top of this result. Considering the current CFD tools available, this approach introduces a fixed percentage of uncertainty on otherwise very accurate results.

2.3 DeltaSeas

In the offshore industry, using potential theory calculations for the effect of ocean waves, shown in Figure 3 as an example, is routinely used for accelerations, mooring forces, structural loads, defining lifting condition limits, dimensioning fenders etc. In addition to the ship hull design, this is another strong expertise area at Deltamarin, which we use in marine industry, for instance, for lashing or passenger comfort calculations. So far, in marine industry, the usage of wave load analysis has been limited and never applied to lifetime fuel economy evaluation. This understanding led us to the idea of combining these two. When we bring together worldwide increased understanding of weather and ship operations, improved calculation capabilities and our strong tradition of hull design in calm water and waves, the result is a holistic analysis we call DeltaSeas.

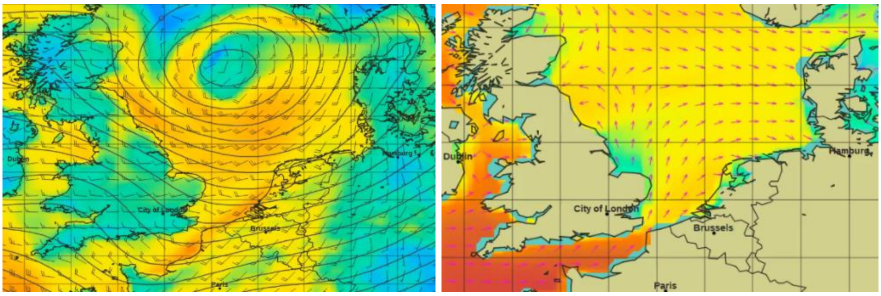

Figure 3. An illustration of the ocean wave and wind conditions in the North Sea.

For DeltaSeas analysis, ship hull characteristics can originate from calculations (Figure 4), model tests or sister ship measurements. Weather data can be received from onboard measurements, weather services or long-time statistics. Thus, DeltaSeas brings together everything we know about hydrodynamics, energy efficiency and weather, which, as a result, gives a lifetime power profile.

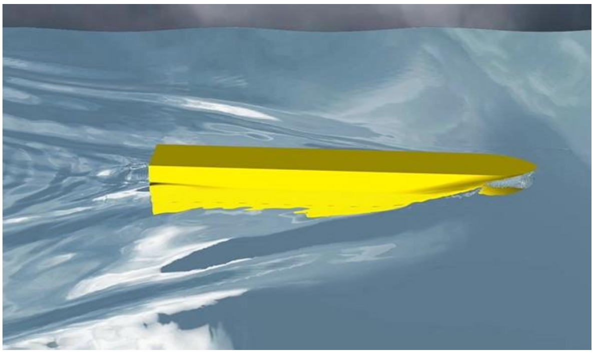

Figure 4. RANS CFD simulation of a ship hull.

The power profile from DeltaSeas analysis combined to our energy simulation tool enables designing an efficient machinery or studying various other improvements to the ship system. With DeltaSeas, we can estimate the ship fuel consumption with an accuracy far better than in the past. In our latest newbuilding project, this approach led to a main machinery solution with less installed power than traditional design approaches would have suggested, as shown in Figure 5. Consequently, 6% less fuel consumption was expected due to this new dimensioning only.

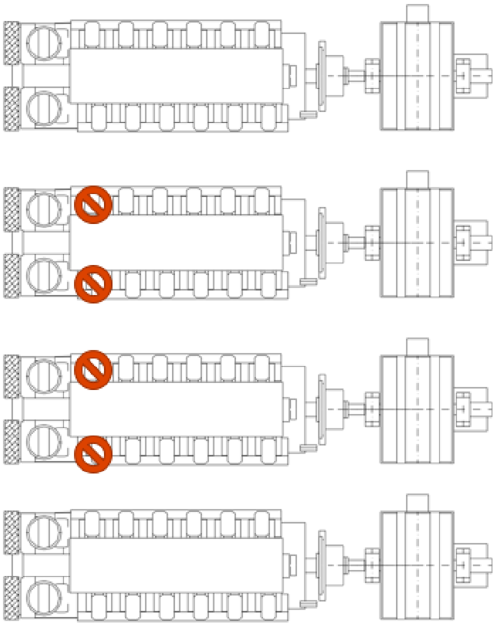

Figure 5. DeltaSeas reduces installed power of onboard main machinery.

2.4 Digital design at Deltamarin

Today, we have a large amount of data available from ships, and we can form a digital twin of an existing ship with our energy model. This approach we utilize in our retrofit projects. Nevertheless, with the same tools and partially with the same data, we can utilize this approach in the newbuilding process as well: before the ship and its digital twin, we form a digital prototype of the ship. For this, we have to carefully choose the relevant input signals from the various data sources available. This is what we call smart data, which combines databases from reference ships, statistical data, measured signals and pure engineering skills. The result is a ship optimized for its actual operation area or specific route already from the early phases of design, where the true energy savings are made.

Our concrete products that Deltamarin has recently developed all serve this purpose, as shown in Figure 6, and consist of **DeltaKey,** for energy simulation services, **DeltaSeas,** for holistic hydrodynamic analysis, and **DeltaWay,** which is a digital concept generation platform.

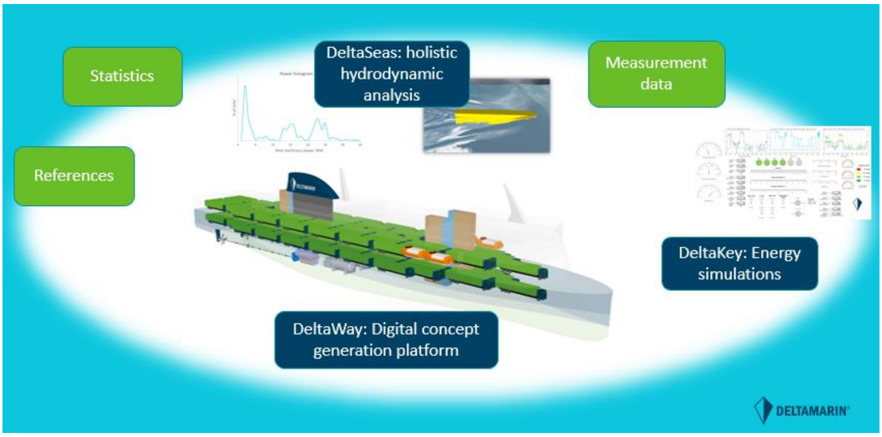

Figure 6. The Deltamarin digital design products.

3. Boosting the marine powertrain with system simulations

Juho Könnö[1], Ville Kumlander[1], Jonatan Rösgren[1]
Wärtsilä Finland Oy

3.1 Introduction

In this paper, we give the reader an overview of a simulation-driven design strategy for complex vessel powertrains, with a focus on battery hybrids in particular. Here, the traditional power management system is by definition tasked also with the function of energy management. From the system design point of view, a battery can be merely seen as yet another source of energy, but the efficient use of the battery in a way that provides the operator of the vessel with additional value, covering the cost of equipment and more, which is a topic intimately connected with the design of both the mechanical and automation systems on board.

Accordingly, we employ simulations not only to validate and design the system but also to demonstrate that the system fulfils the functional specification before having the physical assets connected on board – an approach which helps to avoid costly modification during, e.g., sea trials. Furthermore, we show the possibilities provided by simulation models to also assess the vessel performance as a whole which, in turn, drives the sizing and detailed design of the vessel system. Finally, we strive to connect the rather technical simulation models directly to customer value by demonstrating how such a modelling approach can be used to give the operator of the vessel information on the predicted performance of the vessel.

3.2 Hybrid systems

As mentioned, adding a battery to a vessel system has direct consequences to the vessel design in at least three different aspects. First and foremost, the vessel electrical system must be designed to accommodate a battery, which typically translates to a need for a DC bus and frequency drives. Secondly, the functionality

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of the automation system for the energy management on board is of paramount importance for the performance of the hybrid system. Finally, also the mechanical design is affected not only from the size reservation point of view but also from the different requirements imposed, e.g., on the load taking capability and maximum power of other sources of power on board.

Evidently, the system design gets rather complex when more components and functionalities are added, as is the case with a battery hybrid. Particularly in transient events, such as clutch-in, change of operational mode and intense manoeuvring, the effects of both the mechanical response of the system and the controls must be considered simultaneously. One also needs to pre-validate the functionality of the system with the virtual model in order to assure that the operator receives a vessel behaving in the desired manner and meeting the operational targets.

Next, we will look at a particular battery hybrid vessel system in more detail and use this further as a basis of our case study.

3.3 System simulation model

The system simulation model of an energy storage system (ESS) assisted hybrid vessel is developed to study the interactions between different components in the vessel powertrain. A MATLAB/Simulink simulation model helps to give requirements for a hybrid control system and control applications. The model enables the evaluation of system performance and, in general, increases the knowledge regarding the hybridization of vessels.

This chapter presents the vessel topology of an existing fish-process and transport vessel which is used as a base for the simulation model development. An introduction to the mechanical and electrical components is given and the control system is presented.

3.3.1 System topology

System simulation model of a battery-assisted vessel power train is built to replicate a diesel-mechanic, single main engine marine installation. The main engine, Wärtsilä 10V31, is coupled with a 2-speed reduction gearbox which applies power to a controllable pitch propeller (CPP). An electric motor/generator enables power take-in/power take-out (PTI/PTO, respectively). PTI/PTO is controlled by a motor inverter (MI) which is one part of the frequency converter system. DCDC-chopper and active front end (AFE), both part of the frequency converter, are interfaces towards an ESS, in this case a lithium-ion battery, and hotel grid, respectively. Figure 1 illustrates the topology of the installation modelled.

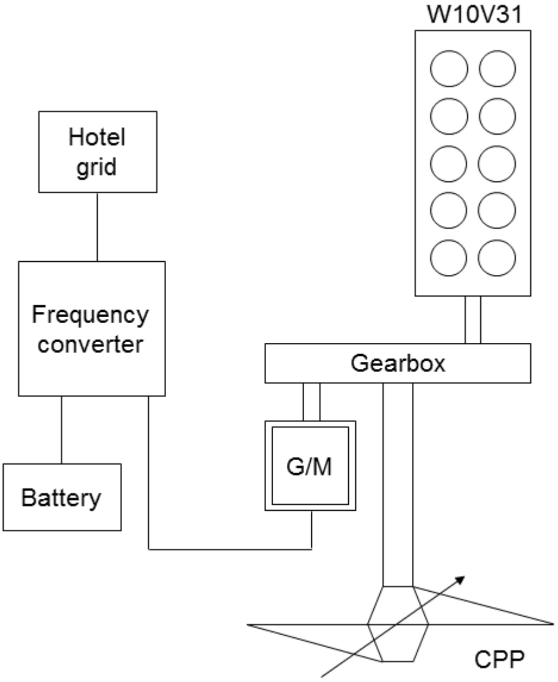

Figure 1. Single line diagram of modelled system topology.

3.3.2 Mechanical system modelling

Mechanical modelling, meaning the simulation models of the engine, gearbox, propeller and hull, uses one rotating mass modelling as a simulation fundamental. All rotating masses in the power system, for example the pistons, flywheel, gears and propeller, are reflected to the propeller shaft according to the gear ratios in the gearbox. All the reflected masses are then added together, and the propeller rotational speed is resolved according to Newton's second law for rotation (1),

$$\Sigma\tau = I\alpha \tag{1}$$

Where,

τ – torque on propeller shaft
I – sum of reflected rotational inertia
α– rotational acceleration

3.3.3 Hull

The hull model [2] resolves the vessel speed with Newton's second law of motion by using the speed-resistance relation presented in Figure 2.

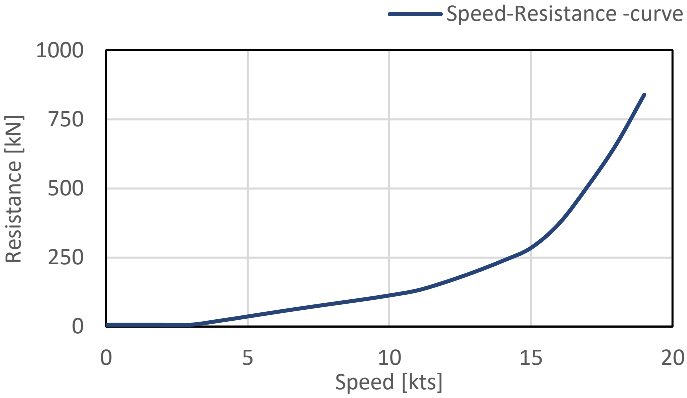

Figure 2. Speed-resistance curve of the hull model.

The following Figure 3 concludes the mechanical modelling principle. Torque from engine and PTI/PTO is scaled through gear ratios to one rotating mass calculation in the propeller model where the propeller rpm is resolved. This rpm is fed back to the gearbox where it is scaled to the engine and PTI/PTO. The hull model resolves the vessel speed. A pitch value is used as a controlling parameter.

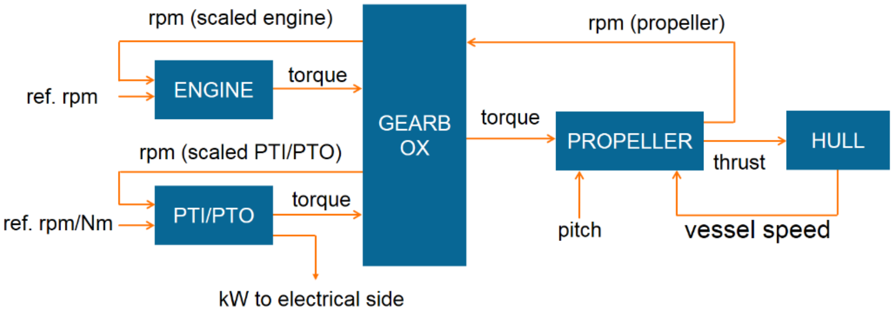

Figure 3. Principle of one rotating mass modelling on mechanical side simulation.

One rotating mass modelling provides enough accuracy to evaluate controls logics. If the study goal is more on vibrations or on very detailed transients, then each rotating mass in the powertrain should be separately modelled.

3.3.4 Electrical system modelling

Electrical system modelling, meaning the modelling of PTI/PTO, frequency converter, battery and hotel load, is done by power flow calculations. This means that there are no virtual components using voltages and currents. Power flow calculation enables a lighter model which was the aim during the developing process [1].

The Energy Management System (EMS) includes a Propulsion Control System (PCS) and controls of MI and DCDC-chopper, which combined are known as the Hybrid controller. PCS includes combinatory curves setting the propeller rpm and pitch references. PCS converts the rpm references for engine and PTI/PTO according to gear ratios. The Hybrid controller calculates the reference torque and speed of PTI/PTO, and these values are directed to MI model.

Figure 4 summarises the electrical modelling in simulation. If PTI is providing power to the gearbox, negative power flows towards the drive. This is then directed to the battery model which resolves the State-of-Charge (SOC) of the ESS. If PTO-operation is selected, meaning that power is taken from the gearbox, power flow towards the drive is positive. In this case, if there is no demand to deliver power to the hotel grid, the battery will be charged.

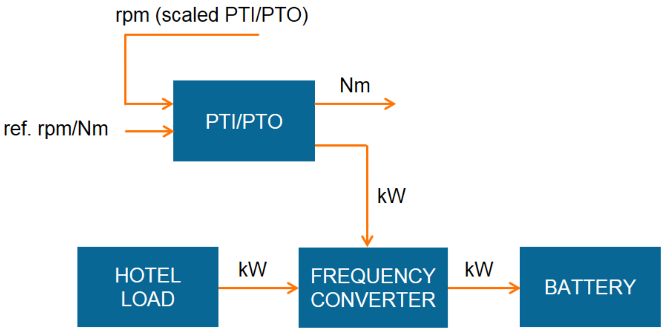

Figure 4. Principle of power flows in electrical modelling.

3.4 CASE STUDY: WAVE LOADING

Waves and disturbances in water flow to propeller causes the propeller rpm to fluctuate. Engine speed control keeps the rpm as close to a reference as possible, but PTI/PTO and ESS can be used to share the load and to balance a fluctuating engine load. The aim of this case study was to compare two different motor inverter control logics when wave loading occurs: torque and speed mode control. The goal was, by simulating, to find out which control strategy enables a more stable engine load.

In the simulation model, a sine wave was disturbing the propeller loading torque and this caused the system rpm to fluctuate. To have some understanding of engine load fluctuation during wave loading, measurement data of an existing vessel was studied. The data is from a diesel-mechanic, single main engine installation. Figure 5 illustrates the engine speed deviation from its reference value during the wave loading.

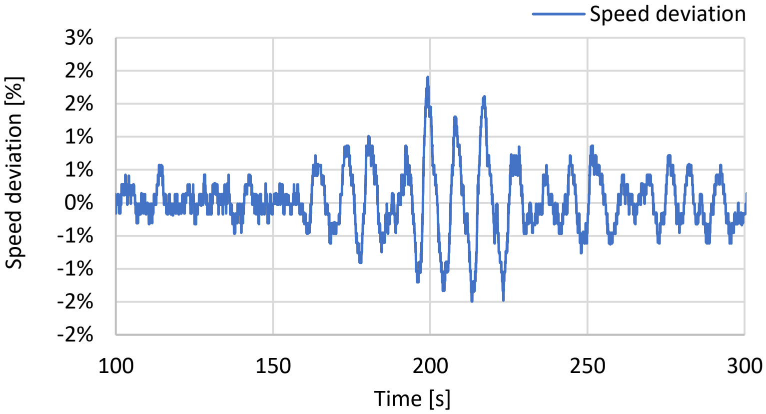

Figure 5. Engine rpm deviation during wave loading conditions on a vessel.

Apart from a couple of large spikes in the deviation, the engine rpm mainly fluctuated between -0.5% and +0.5% from the reference. The aim was to achieve the same engine load fluctuation in simulation during wave loading without PTI/PTO sharing the load. The period of the waves in the simulation was 12 seconds.

3.4.1 MI torque and speed control modes

PTI/PTO can be used to balance the loads in the powertrain with the help of the battery. A motor inverter, one part of the frequency controller, controls the PTI/PTO. Two different control modes can be used to adjust the torque output of the PTI/PTO. This chapter explains the differences between torque and speed mode controls.

3.4.1.1 MI torque mode

In torque control, the motor inverter PI-controller uses torque as a reference. Torque reference, during wave loading, is calculated by utilizing a torque flange located between the engine and gearbox. EMS receives the torque value from the flange and scales the value with the gear ratio so that the torque value corresponds to the torque on the PTI/PTO shaft. This signal is filtered with a transfer function. The filtered and unfiltered signals are subtracted, and the deviation is used as a reference torque value for the PI controller. To be noted is that there is also a delay of around 160 ms from the moment torque is measured to the moment when it reaches EMS.

The advantage of torque mode operation is that PTI/PTO can be set to deliver a constant torque. A disadvantage is that PTI/PTO reacts always after the engine has reacted to changes in rpm since, in this mode, the torque in the system changes only after the engine has changed its fuel input. This mode requires also a torque flange.

3.4.1.2 MI speed mode

In speed control, MI is controlling the rpm of the PTI/PTO with the PI-controller. The advantage of this strategy is that PTI/PTO will react faster than in the torque mode as it is controlling the rpm directly. In addition, this controlling mode does not require additional components, like the flange in the torque control mode. Since both engine and MI are in the speed control mode, tuning the parameters might cause issues in a real installation.

3.4.2 Case study – comparison of MI torque and speed mode control

In the simulation case study, a comparison between the control strategies was made. In the simulation, the vessel was accelerated to 14 kts and waves were initiated. The first system was operating without peak shaving. After this, MI was enabled and MI in torque control shared the load with the engine. Next, the MI control mode was changed to speed control. The engine was always in the speed control mode, maintaining its reference rpm. The following Table 1 illustrates the simulation schedule.

Table 1. Simulation schedule.

Sequence (seconds)	Vessel speed	Peak shave	MI mode
0–1000	Acceleration	OFF	-
1000–1200	Constant	OFF	-
1200–1400	Constant	ON	Torque
1400–1600	Constant	ON	Speed

Case 1 results present rpm and loads on both the engine and the PTI/PTO. In addition, battery power and SOC are shown. The results depict the simulation at the time of 1000–1600 s since the vessel was accelerating until 1000 s. Figure 6 shows the engine rpm during the simulation.

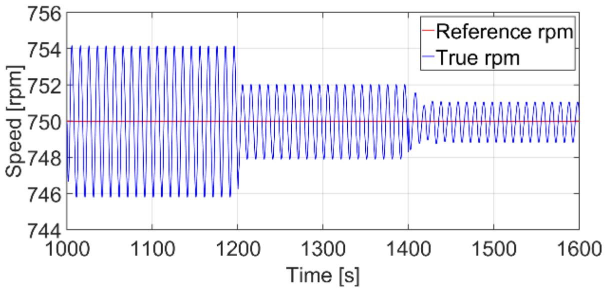

Figure 6. Engine rpm in Case 1.

The engine rpm fluctuated between 746 and 754 rpm, the reference value being at 750 rpm. Without MI shaving the peaks, ±0.5% speed deviation from the reference was gained, as learned, from the measurement data earlier. Rpm fluctuation decreased when load sharing was enabled at 1200 s. At this stage, MI was in torque mode. At 1400 s, the motor inverter mode was changed to speed mode and engine rpm fluctuation was further decreased. Next, Figure 7 illustrates the engine load. Engine load fluctuated between 56% and 67% without any load sharing. The load fluctuation was decreased when load sharing with PTI/PTO in torque mode was enabled. At 1400 second, when speed mode was enabled, the load fluctuation was on its smallest, 60 - 63%.

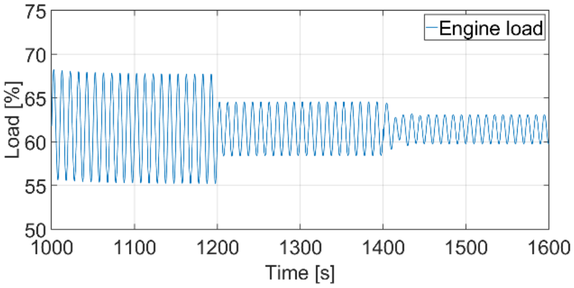

Figure 7. Engine load in Case 1.

The following Figure 8 shows the PTI/PTO rpm in the simulation. The motor inverter was started at 1200 s when load sharing was enabled. The rpm of the PTI/PTO fluctuated between 1196.5–1203 rpm in torque mode. When speed mode was enabled, the fluctuation was reduced to 1198–1201.5 rpm.

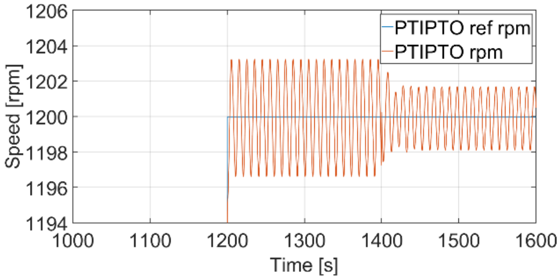

Figure 8. PTI/PTO rpm in Case 1.

The following Figure 9 depicts PTI/PTO load in the simulation. PTI/PTO load increased when the mode was changed from torque to speed, and the load ended up being between -28-% and 30-%. A negative load on PTI/PTO refers to PTO operation, meaning that power is flowing from the gearbox to the frequency converter. A positive load refers to PTI operation and means that torque is applied to the gearbox.

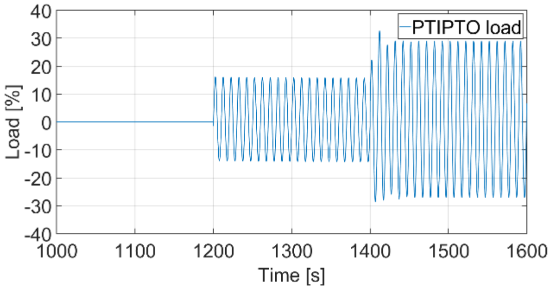

Figure 9. PTI/PTO load in Case 1.

Figure 10 depicts the battery power flow during the simulation. The battery was started at the same time as the frequency converter at 1200 s. The battery responded to the waves according to the changing output of PTI/PTO.

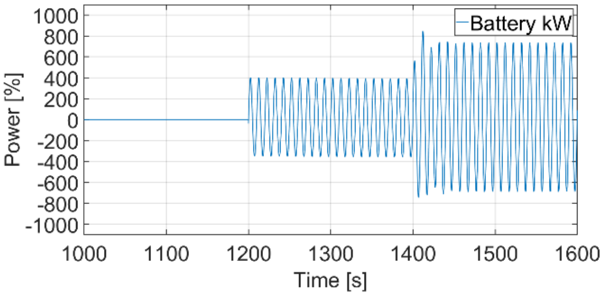

Figure 10. Battery power during Case 1 simulation.

Figure 11 illustrates the SOC of the battery. SOC was fluctuating as power was repeatedly flowing in and out of the ESS. The trend of the SOC was decreasing due to the internal battery losses.

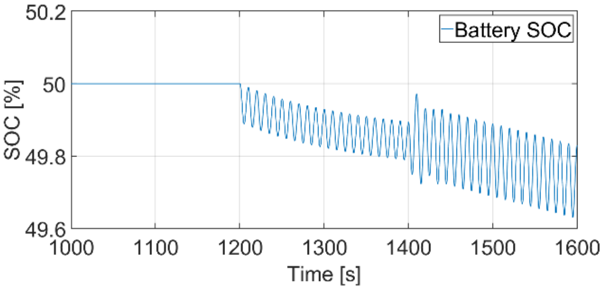

Figure 11. Battery SOC in Case 1 simulation.

3.4.3 Conclusion on speed control strategy

A set of simulations were run to study the difference between two motor inverter control modes. In simulations, the vessel was accelerated to 14 kts and waves were initiated. The first vessel was sailing without any load sharing, and this was followed by PTI/PTO sharing the load in torque mode. Finally, MI control mode was changed to speed mode. Simulations showed that MI in speed mode enabled the engine to run with a more stable load than MI in torque mode. The reason for this is that wave loading in the powertrain can be detected first from a measured speed. If torque information from the torque flange is used, the changes in torque can be witnessed only after the engine has altered the fuel input. System simulation offered a way to evaluate and to choose between two motor inverter control methods. In addition, with simulation, it is possible to test some extreme conditions that could not be tested onboard of a real vessel.

3.5 Conclusions

As shown by the use case studied, system simulation can offer great insight into the system performance and functionality way before the physical assets are commissioned on the actual vessel. More importantly, it allows one to include the functionality and performance in an integral way into the design and sales process of the vessel, giving the customer an opportunity to see and feel the performance beforehand.

Additionally, such models can be used during the vessel lifecycle to further improve and optimize the performance. For example, should the vessel move to a different route or adopt a new set of operating conditions, a system level model can be utilized to pre-tune the vessel. The same principle can be applied to new vessels, allowing one to virtually commission the ship system to work together as one functional entity and saving considerable amounts of cost during the commissioning and initial operation phase.

System level modelling also gives the possibility to assess the mechanical performance of the vessel in more detail. Such an approach has been previously demonstrated in a power generation setting in a fault ride-through scenario in [3, 4]. Similar analysis methodology combining controls with multibody dynamics can be applied to the hybrid vessel case presented here. Strasser et al. present a case study of a similar simulation workflow in [5].

Overall, system simulation provides an effective workflow for assessing performance not only on the system level, but also all the way down to component level, being a key component for providing valuable information both in the design phase, and also over the whole lifecycle of marine systems.

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4. Cloud-based collaboration platform for information sharing and enrichment[1]

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4.1 Introduction

Modern ships, especially large cruise ships, are of a collaborative nature due to their complexity and the involvement of large number of suppliers. However, in the current modus operandi, the same or similar operations still involve plenty of operation silos (ship design, build, operation, ship maintenance, supply, logistics, etc.). The limited collaborations and interactions between different silos result in the lack of systematic consideration and hence unnecessary inefficiency and waste of energy and resources, especially during the design and operation phases of ships. This becomes even more critical when the scale and the complexity of ship energy systems and shipping network increase. On the other hand, digital transformation will only gain full speed after a critical mass of players is involved.

The conventional approach, simply gathering a group of companies and institutions, will work for some specific purpose but not for the long-term collaboration and benefit. Some new try-outs, such as Zero Vision Tool (ZVT) [2] from Sweden, have been implemented in shipping with success. However, the ZVT is more a general project platform, which is good to catch a big picture of the general trend in shipping industries, but with only limited impact and benefit to the marine companies, which is the backbone of the industries.

4.2 Multi-level collaboration framework

In this chapter, we propose a network-based multi-level collaboration framework, aiming to enable and encourage the industry-wide cooperation, information

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[1] This chapter is excerpted and revised from the INTENS project plan and a conference paper presented in COMPIT 2018 [1].

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exchange and enrichment within the consortium during the project period and to the whole cluster afterwards. As shown in Figure 1, ship energy systems can be represented at multiple levels, with higher levels specifying the topology of the networks or ship energy plants and lower levels including more components with more detailed dynamic representation. It is not limited to four levels, however. For instance, on top of the fleet level, the framework can be expanded to the global shipping network level and even further extended to land-based energy and logistics networks related to shipping. Different companies are grouped to corresponding levels according to their main businesses. The INTENS consortium covers the whole value chain of the marine cluster, vertically across all the component, system, ship, and fleet levels, which offers ideal opportunities to research and demonstrate how to enable industry-wide collaboration and information sharing. Done properly, this could benefit different players in the domain and ensure the developed solutions and innovations can be feasible and applicable to the whole cluster later on.

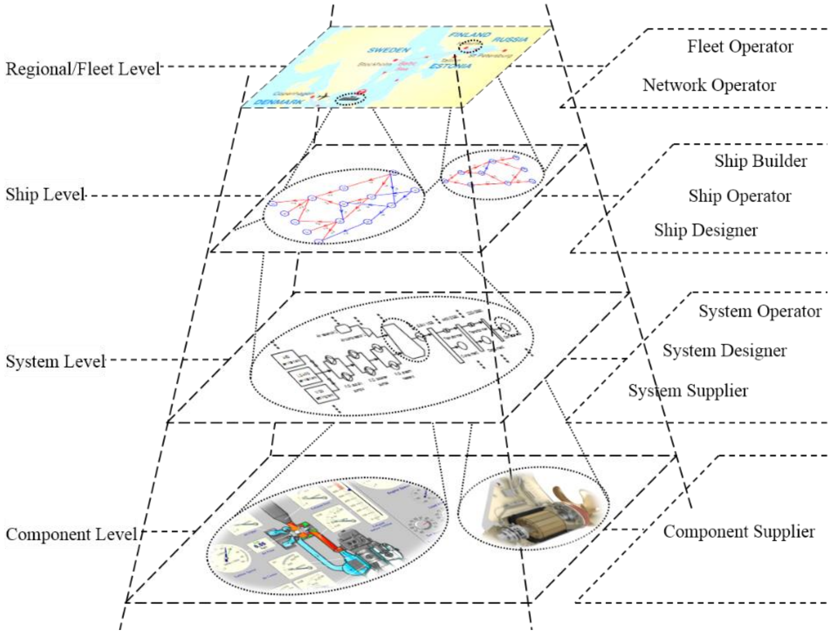

Figure 1. An illustrative figure of the multi-level collaboration framework.

4.3 Cloud-based collaboration platform

In INTENS, we propose a cloud-based collaboration platform to implement the aforementioned multi-level collaboration framework into practice so that it can be available for the consortium partners and for all interested players in shipping after the project. Figure 2 shows an illustrative software architecture of the proposed collaboration platform. Given that the potential users may come from different background with variable level of knowledge in ship energy systems, the external web frontend is designed concisely to communicate only necessary information with the cloud end. The user can send their request and necessary data needed for their specific purpose using the external web frontend, which is then processed by the web/API server before further processing and submitting the request to the cloud. After the job is done, the results will be pass to web/API server for processing and visualization before presented to the user.

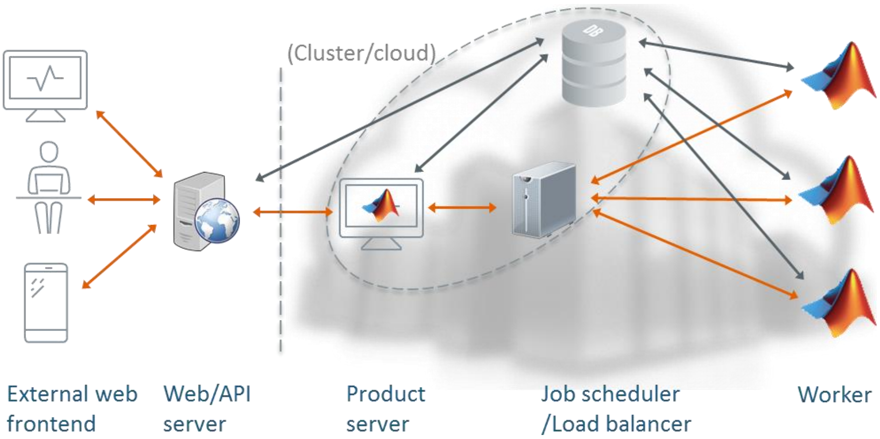

Figure 2. The architecture of the cloud-based collaboration platform.

Regarding the information enrichment in the cloud-based collaboration platform, the foundation is a multi-layer conceptual energy system platform shown in Figure 3, which runs as an information fusion reactor to generate added value, optimized solutions and innovations for the involved partners from the information they shared. Specifically, each partner can design and optimize their products in a true marine environment and evaluate system performances with operating profiles from real operating conditions, not just with single “design points”. Furthermore, the partners work together to offer a better-integrated product portfolio to their customers.

The advanced platform and its vast information base provide the collaboration framework with some unique features:

- Scalability – The energy systems of ships of different types, scales and complexities, can be systematically represented at one or more levels, with necessary details for specific purpose. At each level, the systems are shown as a network, and all levels together form an overall network.
- Flexibility – The energy systems can be modelled using physics-based, data-driven or hybrid approaches at one or more levels depending on the requirement and information available. During the optimization process, different concepts or scenarios of design, operation and maintenance can be formed and evaluated at each level or across all the levels of the overall network.

- Interactivity – The energy systems have to be taken into consideration as an integrated one and the interactions between different subsystems are key to the systems' performances. Huge data communication not only happens at each level, but more importantly, across the different levels, which is one of the key features of the framework.

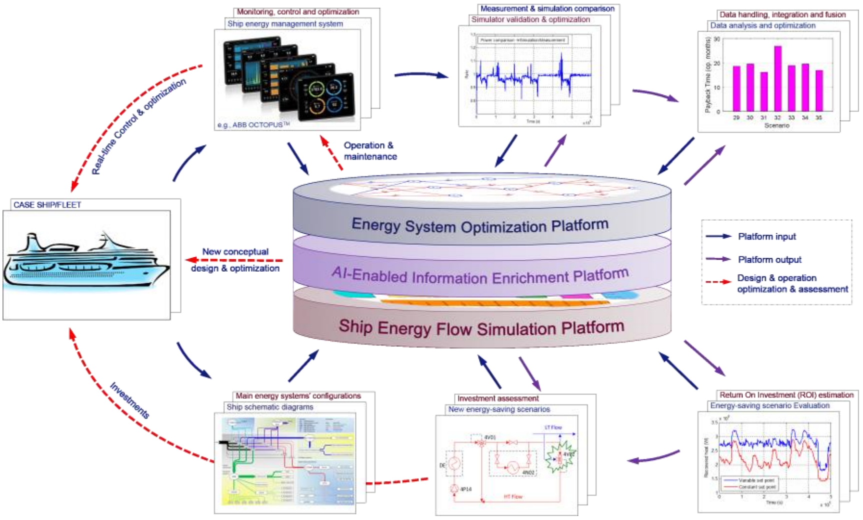

Figure 3. A multi-layer platform for the design, operation and maintenance of ship energy systems.

4.4 Challenges

Information sharing, including model, data, knowledge, etc., is the main challenge and opportunity for the collaboration platform. On the one hand, the platform could be a common place for different users to conveniently share, exchange and enrich information with others. On the other hand, how to enable and encourage the data sharing is a big concern, specifically how to ensure the safety and ownership to the information shared, which still remains under development. Another challenge is the interoperability of different information formats provided by different end users.

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5. Cloud-based framework for optimising complex systems including dynamic simulation

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5.1 Introduction

In this research, we develop methodology for agile utilization of optimization in the cloud to support decision making in complex maritime problems involving energy systems and operative aspects. The objective is to enable mathematical optimization with in-house dynamic simulators by developing a framework, which is capable to cope with the complexity and scalability issues. We present the architecture of the optimisation platform, which employs evolutionary algorithms, such as Genetic Algorithm.

5.2 Motivation

Faced by the tightening environmental regulations and the threat of global warming, it is necessary to explore novel methods and practises into the marine engineering workflow. Simulation aided engineering is a paradigm that provides a systematic approach for evaluating novel process and control concepts with respect to energy efficiency and operability. A contemporary need exists for good modelling tools and experienced simulation engineers, besides being acquainted with other state-of-the-art design methods. Equally, a crucial part in a company's simulation toolbox are best practises for promoting that models are efficiently and fully exploited. Regarding dynamic simulation, it is rather time consuming to perform various simulation scenarios. Consequently, there is an apparent need for supporting tools to enhance productivity. The need is emphasized by the iterative nature typical to the engineering projects. Without proper post-modelling tools, a

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significant risk exists that the simulator gets under-used. It would be beneficial to separate the model development activities from the model exploitation. This division of the modelling and simulation activities deserves more attention and motivates us in this research. Efficient means to exploit developed models are crucial for increasing the impact of dynamic system simulation in industrial engineering.

In system wide dynamic simulation, single simulation run provides time-variant behaviour of the system state within the scope of the model. One run enables only one scenario with a certain set of parameter values, such as heat exchanger surface area, number of parallel coolers, controller tuning parameters, control valve characteristics, limit value for a mode switching, etc. In many cases, it is possible to define objectives with the state and output variables, e.g. minimum deviation from a desired trajectory, minimum cumulative fuel consumption, maximum fresh water production, etc. Incorporating this simulation within an optimization loop is a natural direction to increase efficiency for simulation-aided engineering. This approach is known as simulation-based optimization [1] or simply simulation optimization [2] and it is in the core of our research task.

5.3 Research hypotheses

Here, we introduce seven hypotheses as the starting points of our work. The overarching hypothesis is as follows:

> *Today's cloud computing infrastructure enables an easy and flexible framework for taking out-of-a-box marine simulators and solving related optimization problems.*

We divide this further into a set of sub-hypotheses:

1. Engineering problems that arise within the in-house simulation activities can commonly be converted into simulation-based optimization form, without reformulation of the simulation model (i.e. using them as black box simulators).
2. The black box simulators can be transferred and run in the cloud in the form of containers.
3. Harnessing computing capacity in the cloud allows use of gradient-free optimization algorithms. Computation efficiency is achieved by parallel computing which the cloud provides on demand.
4. Evolutionary optimization algorithms provide a means to find adequate solutions to the engineering problems.
5. Machine learning can help in directing the search of the optimization algorithms to improve the performance.
6. The optimization framework allows changing the simulation model or the simulator, goals and constraints of the optimization, and the optimization algorithm. It allows the use of simulators built for different operating systems (especially Windows and Linux).
7. The optimization framework promotes the optimization-as-a-service approach.

In section 6, we will conclude the status related to these assumptions, while more thorough discussion can be found in [3].

5.4 Framework architecture

Optimisation can address both planning and operative decisions such as concept level strategic choices, detailed dimensioning problems, tuning of process automation parameters, or operation with existing equipment. Our framework aims at enabling optimisation for models not originally intended for this purpose. Thus, we have chosen evolutionary algorithms as the primary optimisation approach. They allow parallel computing to take advantage of even hundreds of computing cores easily and affordably available in the cloud.

Figure 1 presents a schematic view of the components and information flow in the optimization framework. We focus on the methods that are well suited for parallel computation. Thus, the framework is for running simulations in parallel. For this discussion, we assume that we have an optimization algorithm that needs lots of simulations that compute the objective function. The algorithm allows simulations in parallel batches of dozens at a time. As part of our sub-hypothesis 3, we assume that the overhead of managing the simulations over the network is small compared to the execution time of the simulation.

Kubernetes cluster is used to execute the simulations. They are nowadays available from major cloud providers. The main preparations for the cluster are that Helm (a Kubernetes package manager) and an ingress server must be installed. The user packages the simulation model as a Docker image. The image includes the server side software of our framework, typically as a base image, the simulator, any model data, and the implementation of a simple Python interface that the framework uses to access the model. The image is pushed to a container registry; the cluster can later retrieve it from there. The simulation service cluster application is deployed with Helm. The number of workers is specified as a parameter; it should match the number of parallel simulations expected. Upon deployment, a release name is assigned for the Kubernetes cluster.

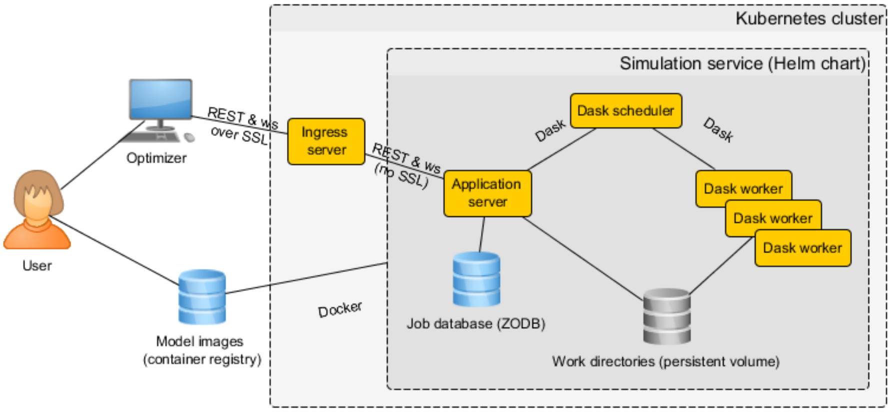

Figure 1. Schematic view of the optimization framework

The optimization software needs an evaluation plugin that can act as a client to the simulation service. In an earlier project [4], we have implemented such a plugin for Opt4J, which is an optimization framework for Java. Initially, we are using the NSGA-II algorithm [5] in the optimization.

An optimization problem is then defined: the optimizer evaluates solution candidates by computing simulation input parameters from the decision variables, posting them to the simulation service, which creates a simulation job there, waiting for the job to complete, fetching its results and computing the optimization objectives from them.

The simulation service is coded in Python; the web application is based on the Flask framework and distributes the execution of posted simulation jobs with the Dask library. Job inputs, state and results are stored in ZODB, a Python object database. Apart from the persistent volume, all communication inside the simulation service application is performed with the Dask library. The model interface consists of a Python function that receives the posted job inputs as parameters and returns a Dask task graph for computing the results. In simple cases, the user would write a function that computes the results and decorate it with @dask.delayed. Once the optimization run has finished and the user decides that the data stored in the simulation service are no longer needed (because the interesting parts have been fetched), the service can be deleted with Helm. This stops all components and releases all storage.

5.5 Simulation cases

One of the main objectives in this research is to lower the threshold of using optimization in engineering practice. Optimization can address both planning and operative decisions such as concept level strategic choices, detailed dimensioning problems, tuning of process automation parameters, or operation with existing equipment. If this kind of framework succeeded enabling optimization as a method for models not originally intended for this purpose, it would also facilitate the utilization of the simulation in the marine companies. Examples of potential optimization problems include:

- The lowest-emission alternative of given WHR strategies when the cruising route is given and cruised one average operation year
- The best structure of AC cooling systems for managing the most demanding operational situation
- The optimal way of running the main engines in a given operational situation
- The lowest-energy operation of the ship energy systems in given conditions
- The optimal dimensioning for a cooling/heating system for the given operational tasks
- Optimal calibration of a simulation model with the available measurement data

5.6 Conclusions and future prospects

So far, our experiences are mainly dealing with the framework design and implementation issues. Currently, we are focusing the development in the Linux environment. We have already been experimenting with toy simulators, while we are simultaneously discussing with partners and preparing the industrial cases too. We consider that the results gained so far provide valuable indications and insights on using cloud computing in this area. Readers are recommended to refer [3] for more details.

Our work continues by evaluating the framework with different industrial cases. They deploy different simulation platforms, which is one of the challenges. We will collect also numerical metrics on the performance. We will study applicability of different optimization variants in the cloud use. We will find out how our approach generalizes to different simulators and optimization problems. Future work will also emphasize the question, how the algorithms and the framework parameters should be tuned and modified to deliver the best performance in the cloud environment. We aim at using machine learning principles for speeding up the optimization sessions.

Apparently, there is plenty of future work left to make daily use of simulation-based optimization in the cloud easy. Our early results indicate that this is a promising direction. The future will show how much we need to compromise our original goals.

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6. On-ship data compression and cleansing using Digital Twins

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6.1 Introduction

In the current era of data deluge, the problem of managing, storing and analyzing data is becoming ever more difficult. At this point, data scientists and engineers are already spending a considerable amount of time processing and sorting data by hand. As the amounts of collected data will increase over time, this practice will not remain feasible. Thus, in this study, we introduce a sparse-optimization-based framework for automatic cleansing and compression of data that utilized a digital twin.

6.2 Digital Twin

A digital twin is a virtual model of a physical system that is used to simulate and test the behaviour of a true-world process [9]. Examples of such processes might be mechanical components, plants and manufacturing supply chains. In shipping industries, digital twins are predicted to have a key role in improving the overall energy efficiency of ships. A few potential areas of impact are in design of energy optimized control systems, optimal rout planning and in determining operation strategies of hybrid vessels. In this case study, a digital twin of a ship cooling system was created. Simple dynamical models of the unit processes, together with an automation system, form a digital twin of the waste-heat recovery system. A snapshot view of the digital twin model implemented in MATLAB & Simulink is presented is presented in Figure 1.

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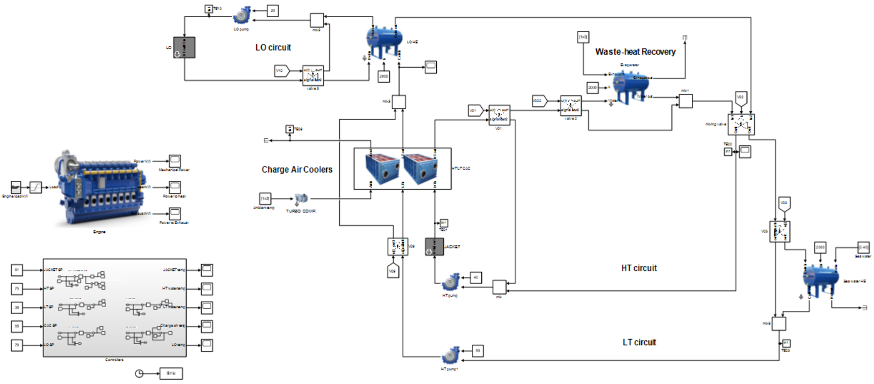

Figure 1. Digital twin implemented in MATLAB & Simulink.

A simple dynamical model of a heat exchanger, assuming perfect mixing, is given by the differential equations

$$\frac{dT_{\mathrm{H,out}}(t)}{dt} = \dot{m}_{\mathrm{H}}(t)\left(T_{\mathrm{H,in}}(t) - T_{\mathrm{H,out}}(t)\right) - \frac{h(t)A}{M_{\mathrm{H}}c_{\mathrm{p}}}\left(T_{\mathrm{H,out}}(t) - T_{\mathrm{C,out}}(t)\right) \qquad (1)$$

$$\frac{dT_{\mathrm{C,out}}(t)}{dt} = \dot{m}_{\mathrm{C}}(t)\left(T_{\mathrm{C,in}}(t) - T_{\mathrm{C,out}}(t)\right) + \frac{h(t)A}{M_{\mathrm{C}}c_{\mathrm{p}}}\left(T_{\mathrm{H,out}}(t) - T_{\mathrm{C,out}}(t)\right) \qquad (2)$$

where t is the time, A is the area of the surface where the heat transfer takes place, M_{H} and M_{C} are the masses of the medium in the hot and cold side respectively, $h(t)$ is the heat transfer coefficient, $\dot{m}_{\mathrm{H}}(t)$ and $\dot{m}_{\mathrm{C}}(t)$ are the mass flows at the hot and cold side respectively, $T_{\mathrm{H,out}}$, $T_{\mathrm{H,in}}$, $T_{\mathrm{C,out}}$ and $T_{\mathrm{C,in}}$ are the inlet and outlet water temperatures on the hot and cold side of the heat exchanger.

6.3 Automatic cleansing and compression of process data

When cleansing data collected from a physical process, it is important to ensure that physical properties such as mass and energy balances are satisfied. In practice, since different measurements are physically related, data from different sensors cannot be manipulated independently. If a correction is made in one signal, all signals should change accordingly so that physical laws are still satisfied. This feature of process data can be utilized to detect sensor faults and outliers by keeping track of how signals are related using a digital twin.

Assuming that the number of sensor faults is small compared to the total number of data, the cleansing problem can be formulated as an optimization problem which fits into a sparse optimization framework. Sparse optimization is a field of combinatorial optimization that has its roots in compressive sensing [1,2] and has been used in a wide range of applications, including image reconstruction [2,4], trend filtering [5,6,8] and model reduction [7]. Sparse optimization also plays a fundamental role in state-of-the art methods for compression of time-series. This is due to the fact that most signals have a sparse representation with respect to an orthonormal basis such as the Fourier transform or a wavelet basis.

6.3.1 Automatic cleansing of heat-exchanger data

To illustrate how sparse optimization and a simple digital twin model can be used to detect and correct sensor faults in data, twelve-hour data of a heat exchanger was generated with 60 seconds sampling time, and sensor faults (outliers and stuck values) were introduced. An algorithm that automatically identifies the faulty sensor values and corrects them using the digital twin, without a human interfering, was constructed.

The data was reconstructed in such a way that the smallest number of corrections needed to ensure that (1)-(2) are satisfied was made. Since this problem is combinatorial by its nature, it would often be infeasible to solve it exactly for large data sets. However, the problem can be relaxed using ℓ_1 regularization, resulting in a convex optimization problem that can be solved efficiently [2, 3]. In Figure 2, the sensor data and the reconstructed time-series are presented. Stuck sensor values close to 2, 4 and 8 hours and outliers were detected and corrected successfully.

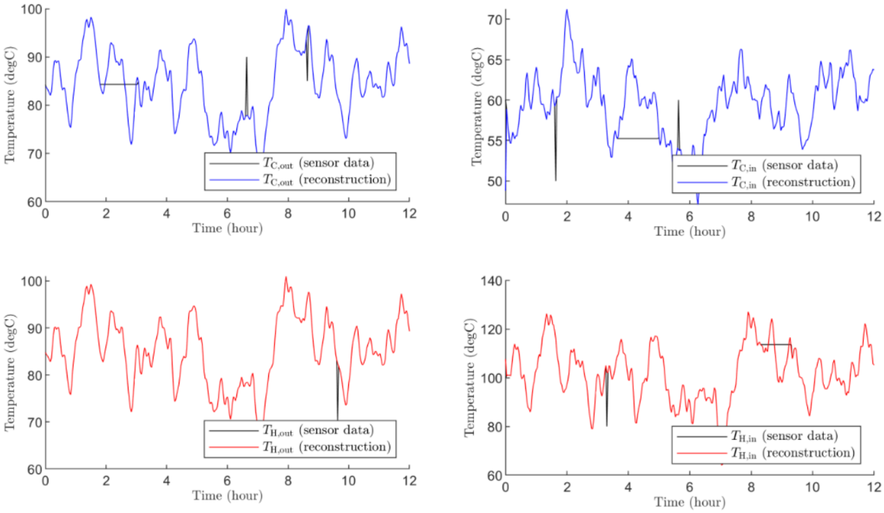

Figure 2. Reconstructed time-series.

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7. Effects of flow and oil properties on filter service life[1]

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7.1 Introduction

In fluid power systems, one of the most common causes of failure is contamination of the hydraulic fluid. In addition to its main function, i.e., to transfer energy, the fluid acts as a lubricant between moving parts in the components, enabling control of friction, wear and operating temperature.

In order to avoid machine downtime and loss of production, it is important to maintain adequate technical performance level of the fluid at all times. This is done by filtering, without which the fluid gets contaminated with harmful particles over time. Excessive concentration of particles in the fluid will cause excessive wear of components or block motion of parts in flow control valves. Wear can cause, e.g., insufficient efficiency or even failure of pumps, and jammed parts in control valves can cause unreliable and erratic motion in actuators. These potential detrimental effects stress the importance of maintenance of fluid filter units.

Filter elements are usually replaced according to pre-defined time-schedules, but this is inefficient as the maintenance actions are not based on the actual time-history of the filter unit and the fluid system. Time-based maintenance can either lead to premature replacement of filters, or lead to excessive contamination levels in the fluid due to unforeseen sudden increase of particle load during the presumed service period. Condition-based maintenance of filter elements can be made possible by continuously measuring the pressure drop over the filter element and using the measured value in a filter model to predict the remaining lifetime of the element.

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[1] This chapter is a synopsis of the work submitted for publication in [1] and [2].
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Comprehensive laboratory tests have been made in order to produce filtration performance data relating the effect of flow rate, contaminant particle concentration, and fluid temperature to the pressure drop measured over the filter element. This work demonstrates the mathematical correlation models derived from the experimental data.

7.2 Methodology

The study to create correlation models for the pressure drop across a filter element was twofold: perform laboratory tests at different fluid conditions, and develop a model based on said laboratory tests that could predict the pressure drop based on the different conditions.

7.2.1 Experimental

The experimental part consisted of measuring the filter pressure drop at different oil conditions. For this purpose, a test bench with multiple sensors monitoring the different conditions was constructed. The filter type used in the experiments was a 5 μm rated commercial filter with glass fibre media that has an effective surface area of 0.154 m2 through 57 pleats. The oil that was used was the standard ISO VG 32 hydraulic oil. [3]

The different oil conditions considered for this study were the oil flow rate, temperature, and gravimetric contamination level. For adjusting the gravimetric contamination level, the fluid was subjected to ISO medium test dust (ISO12103-1-A3) at different rates resulting in four different contamination levels at 2 mg/l, 5 mg/l, 8 mg/l and 10 mg/l. The flow rates were set to 40 l/min, 80 l/min and 120 l/min, and the fluid temperatures were adjusted to 30 °C, 40 °C, 50 °C, and 60 °C. Figure 1 showcases examples of different experiments, and illustrates the types of effect that the different oil conditions have on the pressure drop development over time.

7.2.2 Modelling

The main goal of this study was to establish models that will describe the development of the pressure drop across the filter element and the length of its service life. Based on the experimental data, the model will consist of an equation of physical variables:

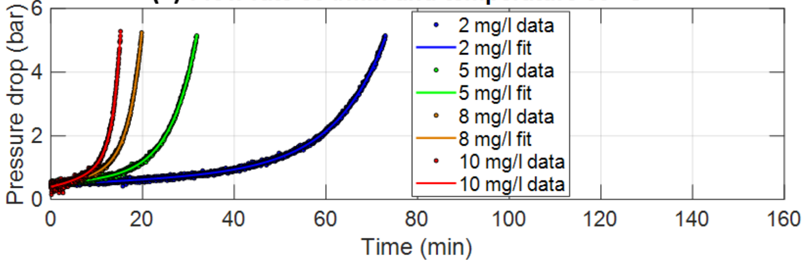
$$\Delta p = f(t, q_V,\ T,\ \rho_c) \tag{1}$$

where t is time, q_V is volumetric flow rate, T is temperature, and ρ_c is mass concentration i.e. the gravimetric contamination level. The approach used for constructing the model was regression analysis. Different models were experimented with, but the best fitting was discovered to be with an exponential function that has two exponential terms, resulting in a function:

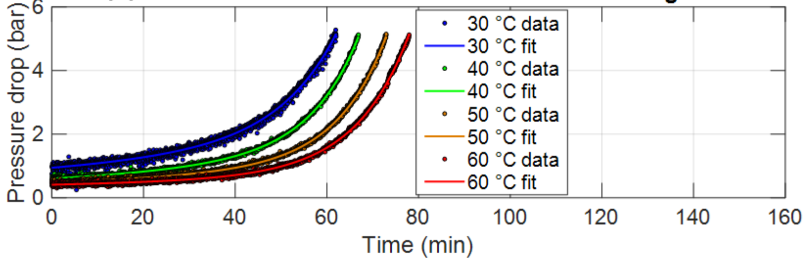
$$\Delta p = \left(\Delta p_0 - \left(\left(x_1 q_v \rho_c + x_2 q_v^{x_3}\right)\nu + x_4 q_v^{x_5}\rho_c + x_6 q_v\right)\right) e^{x_7 q_v \rho_c t} + \left(\left(x_1 q_v \rho_c + x_2 q_v^{x_3}\right)\nu + x_4 q_v^{x_5}\rho_c + x_6 q_v\right) e^{x_8 q_v \rho_c t} \tag{2}$$

where Δp_0 is the initial pressure drop, ν is kinematic viscosity (calculated from temperature), and x_1—x_8 are constants.

(a) Flow rate 80 l/min and temperature 50 °C



(b) Flow rate 80 l/min and contamination level 2 mg/l



(c) Contamination level 2 mg/l and temperature 50 °C

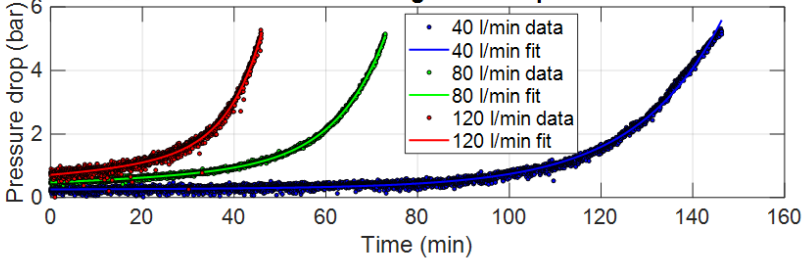


Figure 1. Example of effects of operating conditions on the pressure drop development during experiments.

In addition to deriving an equation for the entire pressure drop development, a simpler equation was derived that would only give the service life duration of a filter element. This was possible as the slopes of the different Δp curves were found to be extremely similar. Figure 2 demonstrates how the different oil parameters affect the total lifetime of a filter unit.

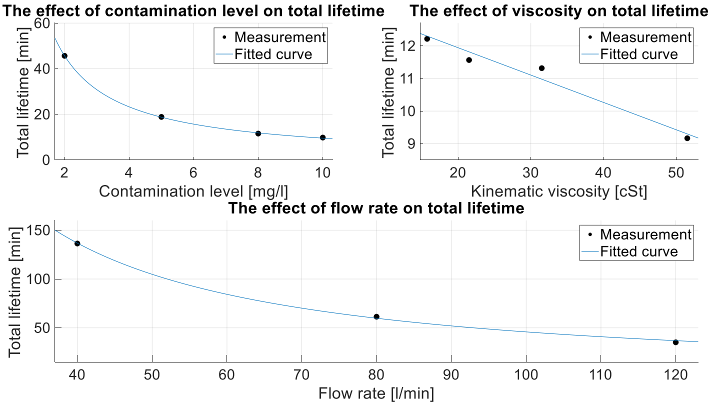


Figure 2. Examples of effects of operating conditions on the total lifetime. Cases 120 l/min and 50 °C (upper left), 120 l/min and 8 mg/l (upper right), 2 mg/l and 30 °C (bottom).

With regression analysis, the following equation was derived for the total lifetime of the filter element:

$$t = \left(x_2 \cdot \nu + x_3 \cdot q_V^{x_4}\right) \cdot {\rho_C}^{x_1} \tag{3}$$

where q_V is volumetric flow rate, ρ_c is contamination level, ν is kinematic viscosity, and x_1–x_4 are constants.

7.3 Results

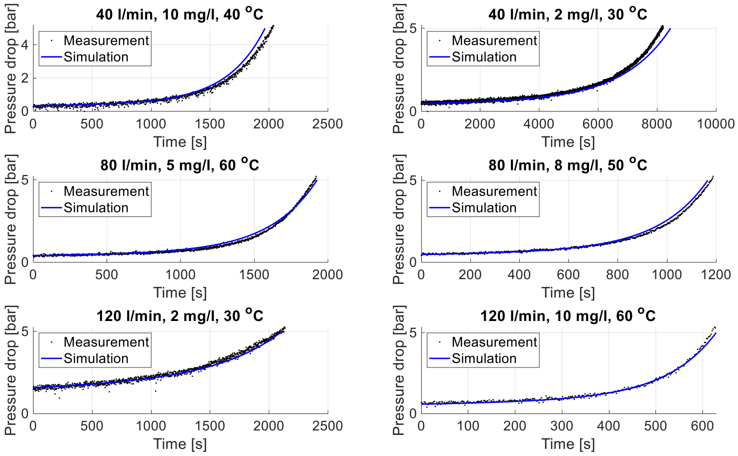


Figure 3. Comparisons of measured pressure drop curves and simulated with Equation (2).

Table 1. Comparing the lifetimes of experimental results and estimated that were calculated with Equation (3).

Flow configuration (q_V-T-ρ_c)	Actual lifetime (min)	Predicted lifetime (min)	Error (%)
40-30-2	136.3	138.3	1.5
40-40-10	31.7	33.8	6.1
80-50-5	30.5	31.7	3.5
80-60-10	16.3	16.5	1.3
120-50-5	19.4	18.9	3.0
120-30-8	9.0	9.2	2.1

7.4 Discussion

The model developed in this study can predict the development of Δp up to 5 bar with a high degree of accuracy (Figure 3). When comparing the simulation results with corresponding measurements, the coefficient of determination R2 typically had a value of over 0.98. The greatest variance between the simulated and measured results can typically be observed at the end of the simulation, though the greatest inconsistencies in the experimental results also occurred at the end, making the end of the Δp curve the greatest area of uncertainty. The simpler equation for the total filter lifetime can predict the service life accurately as well, with only a small percentage of error (Table 1).

The models can accurately describe the pressure drop evolution over the whole filter lifetime as well as give the total lifetime estimation, when the operating conditions remain stable. This situation is likely in many industrial applications with fluid power systems, or lubrication systems running continuously until the next service break. However, there is no guarantee that the models would work for applications with varying flow conditions. Another aspect is that the models are most likely media specific, and cannot therefore be directly applied for other filter types. The coefficients that were considered constants in this study would most likely vary based on the filter media. Though the effects of different oil conditions on filter service life as demonstrated in Figure 2 are likely similar across different types of hydraulic oil depth filters. As laboratory tests that were performed at careful conditions were the basis of this research, further confirmation of the accuracy of the developed models would require additional field-testing.

7.5 Conclusions

The objective of this study was to develop correlation models for the pressure drop across a filter element that is subjected to a stream of contaminated oil at different oil contamination levels, flow rates and temperatures. The resulted models were validated against experimental data and were found to match the data with high degree of accuracy.

This study has been done as part of an initial research in order to investigate correlations between oil conditions and filter service time. The ultimate goal of the research is to develop an intelligent oil filter that can predict its remaining lifetime. This information will be used in predictive maintenance to eliminate unnecessary filter replacements, and to prevent downtime due to a filter failure.

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8. Predicting remaining useful lifetime for smart oil filters

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8.1 Introduction

Oil filters are used for removing solid particles from fuel oils, lube oils and hydraulic oils. Oil filters are parts that needs replacement when the filter performance degrades. The main reason for decreased performance in clogging, i.e. the filtered particles builds up a filter cake. This can be observed by an increased pressure drop Δp over the filter when the filtrate is pumped through the filter.

To ensure proper filter function, the filters are replaced at regular intervals. However, if the replacement interval is to short, unnecessary resources go into the replacement activities. When the replacement interval is too long, the pressure drop over the filter might cause lost oil pressure in the system, causing emergency shutdown of the machinery. Hence, the target is to optimize the filter replacement time or interval. The optimal replacement interval is additionally dependent on a multitude of parameters, such are filtrate particle concentration, usage patters and ambient temperatures.

The objective in this work is to provide a methodology for building smart filters that have an inbuilt functionality of predicting their remaining useful life (RUL). One step in this process is to construct algorithms, which based on measured Δp over the filter, can make predictions on optimal filter replacement time, reducing unnecessary filter replacements, but avoiding filter malfunctions.

8.2 Methodology for predicting remaining useful filter lifetime

The basis for filter cake build-up can be given by a mass function for the filter

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$$M = \int_0^t q_v \, \rho_c dt$$

where q_v is the oil flow rate and ρ_c is the oil contamination level. Hence the mass M accumulated is the filter is just the integral over time over contaminations reaching the filter. The pressure drop over the filter can them be expressed using a function

$$\Delta p = f(M, q_v, \rho_c, T)$$

The objective is now to predict when Δp reaches a threshold value, indicating filter replacement requirement. However, the only measurements we have are previous samples of Δp measurements. In real life scenarios the flow rate q_v and contamination level ρ_c are hard to measure. The temperature T can however quite easily be measured.

To construct an algorithm predict the time when Δp reaches a threshold value, we have some options:

1. To base the prediction on previous historical time series of Δp, assuming that the Δp build-up will perform the same way as historically (profile mapping)
2. Use filtering techniques like a Kalman filter or a particle filter to estimate the internal state of the filter
3. To estimate oil contamination levels from historical data, and assume that these levels remain similar – use as input for integrating filter mass

The typical Δp over time is given in Figure 1.

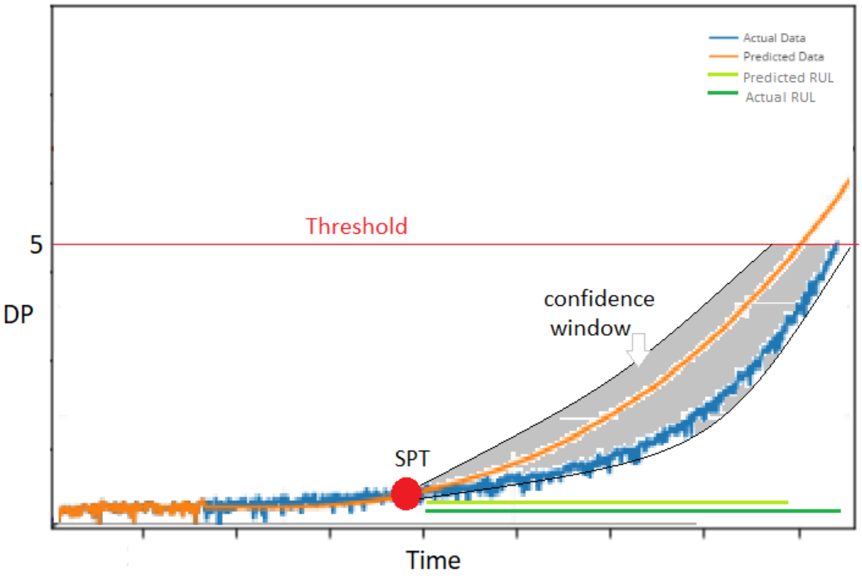

Figure 1. Pressure drop build-up predictions vs. actual

The poster shows some results of applying different methodologies to received lab data on pressure drop for some scenarios with given flow rates and contamination levels. In these results, measured lab data and prediction methodology data can be compared.

9. Data-enriched system fault diagnostics

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9.1 Introduction

Fault diagnostics, the problem of detecting faults in industrial systems and determining their cause by computational methods, has been well studied but remains challenging to implement in new applications (Isermann 2006). Faults can be detected and diagnosed either by a model-based approach, in which the expected behaviour of the system is described by a mathematical model, or by a data-based approach (Qin 2012, Dai and Gao 2013), in which the expected behaviour of the system is described by historical data of its operation. Hybrid approaches combining the two have also been developed (Tidriri et al. 2016). Similar methods can also be applied to compensate for detected faults in control engineering.

One of the challenges of data-based fault detection is that realistic data about faults in operation is both difficult and expensive to acquire, and so the vast majority of data is typically about system operation in normal, non-fault conditions. Yet even the same class of fault can develop and manifest in many different ways, depending e.g. on timing and operating point. One way to address this challenge is data-enriched system fault diagnostics: applying a model-based method to generate plausible data about a comprehensive variety of system fault situations.

We are working to apply data-enriched system fault diagnostics to a real-world application case: an electro-hydraulic valve-train system of an internal combustion engine (Herranen 2014). The focus of the case is in valve position sensors, the correct operation of which is essential to efficient and safe operation of the engine. The engine control system uses the valve sensor signal to avoid contact between pistons and valves, and is able to switch the engine to safe fallback mode in case of detected system faults, whether in the valve sensors or elsewhere.

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The valve sensors are magnetic quadrature sensors, which provide incremental position changes in discrete steps, indicating both speed and direction of movement of the valve. The sensors have been observed to experience intermittent signal loss depending on engine vibrations and the exact alignment of the magnetic strip with the quadrature sensor. Electromagnetic disturbances may also cause position errors. The goal is to devise a system to estimate the correct valve position despite intermittent signal faults, or to flag the sensor as faulty whenever the valve position cannot be reliably estimated. The fault correction and detection system should operate at sub-millisecond latency, as the engine speed can be on the order of 1200 rpm (50 ms per revolution), and the system should be reliable even in case of engine faults or abnormal operation.

We present our initial work focused on establishing a model-based baseline solution for sensor fault detection and correction.

9.2 Materials and methods

9.2.1 Measurement data

Wärtsilä has provided us with measured position data from two inlet valves of an electro-hydraulic engine. One of the inlet valve position sensors (valve A) suffers from intermittent loss of quadrature signal, which means that the decoded position signal may suddenly freeze for up to approx. 5 ms, and possibly take a step in the wrong direction at the beginning or end of a signal loss event. The other inlet valve position sensor (valve B) functions reliably, and can be used as relatively accurate reference data for the correct valve position, since the two cylinders are interlocked. There are two data sets for both valves: one measured at 200 MHz over 15 seconds, in which the engine is started, and another measured at 1 MHz over 5 seconds, in which the engine runs at steady rate.

9.2.2 Fault correction method

We have implemented a basic solution for fault detection and correction of a valve sensor, based on a Kalman filter and a heuristic for non-linear state transitions. The algorithm input is the position signal from the quadrature sensor, and the output is the estimated valve position.

The scope of the basic model includes only the position x and velocity v of the valve, which are assumed to vary continuously according to basic dynamics, and two discrete health states:

- Position sensor functional
- Drop-out of position signal

The observed position signal y is a function of the valve position x and the health state z: In the functional state, we have $y = x + f$ where f is an unknown position offset that stays constant as long as the sensor is functional. In the drop-out state, the observed position is assumed to stay constant. In a known health state, the continuous system state variables (x, v) can be estimated by a Kalman filter, under the assumption that the measurement errors in y are Gaussian white noise. Of course in the drop-out state the estimation is trivial, and we simply project the position forward at constant speed.

To better model the closing of a valve in the sensor functional state, we add a damped spring force to the valve dynamics whenever the estimated valve position $\tilde{x}$ is closed ($\tilde{x} < -0.01$ mm). In the drop-out state we simply stop the valve dead at closing position $\tilde{x} = 0$, since we have neither an accurate closing model nor measurement data to correct the estimate.

To keep the computational complexity of our algorithm low, we use a heuristic to determine a likely health state z, and then apply a Kalman filter to estimate the continuous state variables (x, v). In addition to the state variables, the Kalman filter produces an estimate $\tilde{y} = \tilde{x} + f$ of the observed position, and an estimate $\tilde{\sigma}_y$ of its standard deviation. Our fault detection heuristic is to compute the likelihood p that a sample from the Gaussian $N(\tilde{y}, \tilde{\sigma}_y^2)$ is as high or low as the observed position y (two-tailed test). As soon as the likelihood drops below a fixed threshold, we assume that the system has been in the drop-out state since the last observed change in the position signal, and re-estimate the current state accordingly. The transition back to the sensor-functional state is triggered by observed changes in the position signal as described below.

We also apply drift correction to the position signal: Whenever the position stays constant for a long enough time (10 ms), and the estimated position is near the closing position ($\tilde{x} < x_{LOW}$ where x_{LOW} is a fixed threshold), the position is corrected to closing ($\tilde{x} = 0$, $\tilde{v} = 0$). Correspondingly, the fault detection heuristic is only applied whenever $\tilde{x} \geq x_{LOW}$, so that the position signal staying constant can only lead to a single conclusion.

The algorithm updates the sensor offset f whenever the estimated position is closed ($\tilde{x} \leq 0$), or the system transitions to the sensor-functional state: at such times t we set $f(t) = y(t) - \tilde{x}(t)$.

As described, during longer drop-outs the estimated position can easily undershoot or overshoot the actual position, since the position $\tilde{x}$ is updated using the last estimated velocity before drop-out. To compensate, we have implemented a recovery stage after drop-out: the algorithm waits for 4 position steps before transitioning back to the sensor-functional state, collecting 3 velocity samples, and takes the median of the 3 velocities as the new velocity estimate $\tilde{v}$. The new position $\tilde{x}$ (and the new offset f) is then estimated by assuming constant acceleration for the duration of the drop-out state.

9.2.2.1 Compensating for drop-outs in closing position

Another complication is that the problematic valve position sensor has been observed to suffer from drop-outs when the valve is in closing position, extending for the first few mm of the valve lift. As the valve is moving but the observed position signal does not change, it is impossible to correct the position signal without additional input signals. However, in such situations the position signal transitions from closing position immediately to a relatively high rising speed, and we can use this abrupt velocity change to compensate for position error.

As can be seen in Figure 1, during the first 5 mm of valve B lift the valve position can often be deduced as a function of velocity. The exceptional trajectories are from the first cycles in the engine start-up phase. We have fit a cubic polynomial of the form $\tilde{x}_R = c_3\tilde{v}_R^3 + c_2\tilde{v}_R^2 + c_1\tilde{v}_R$ to describe the relationship, using a robust fit method that puts low weight on outliers.

Whenever the valve starts moving from the closing position, our algorithm waits for 6 position steps, collecting 5 velocity samples, and takes the median of the 5 velocities as the new velocity estimate $\tilde{v}$. The correct position $\tilde{x}$ is then estimated from the median velocity using the cubic polynomial.

When the valve is closing, a similar drop-out near the closing position does not require special compensation logic: the basic algorithm detects the drop-out, keeps projecting the position forward using the last estimated velocity, and stops at closing position $\tilde{x} = 0$. The result of this simple extrapolation is near the correct valve trajectory, since the valve is typically closed with force, applying only limited deceleration.

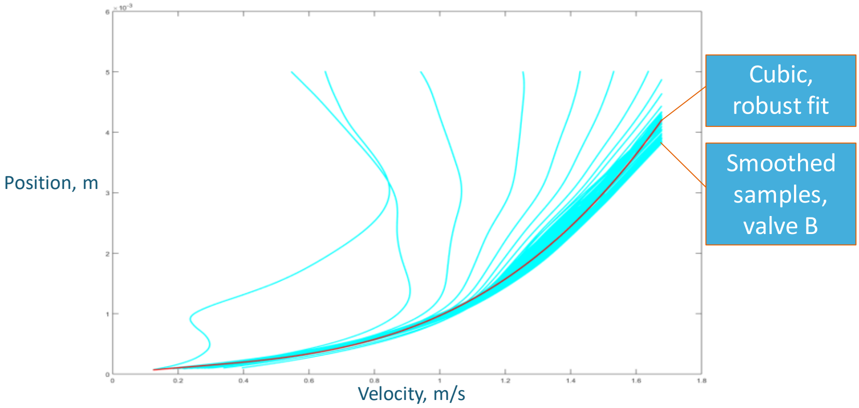

Figure 1. Valve position as a function of velocity over first 5 mm of valve lift, and a cubic polynomial fit to the data.

9.3 Initial results

We have tested the algorithm with the two available test data sets, on the position data of the problematic valve A. The algorithm successfully detects visually obvious drop-outs, and significantly reduces the differences between the decoded position signal and the correct position (indicated by valve B position signal).

If we run the algorithm without the compensation procedure described in Section 9.2.2.1, the top of the valve lift curve can differ by up to 4 mm from the correct position, i.e. about 15 % of the maximum valve offset of 27 mm. After introducing the compensation procedure, the difference in the top of the lift curve is reduced to 3 mm on one occasion, and on other occasions 2 mm or less. An overview of the results is shown in Figure 2, and Figure 3 shows a closer look at the results over a single valve lift. The rising edge compensation procedure of Section 9.2.2.1 can be seen in action at the lower left of Figure 3, as the corrected position signal jumps directly from 0 to 2 mm; however it is clear that the compensation is still somewhat inaccurate, as the correct position at that point would be closer to 4 mm.

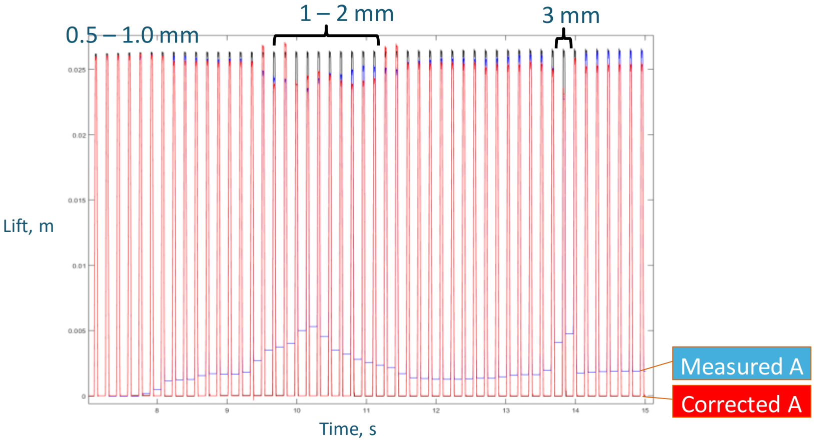

Figure 2. Original valve A position signal (blue), with corrected signal (red) overlaid and reference signal (black) from valve B on the background. Differences between the top of the corrected and reference curve are indicated at the top.

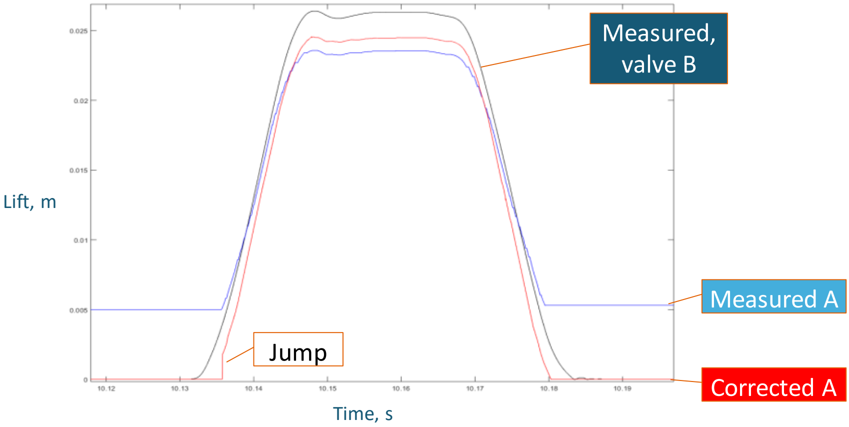

Figure 3. Original valve A position signal offset by significant drift (blue), signal corrected for drop-outs and drift (red), and reference signal from valve B (black). The jump in the corrected valve A signal due to the special drop-out compensation procedure of Section 9.2.2.1 is specifically marked.

9.4 Ongoing work

The presented algorithm is a somewhat ad-hoc solution with the advantage that it can be implemented with minimal computational resources. We are investigating solutions based on more general data-based fault detection methods.

As compensating for frequent sensor faults is turning out to be quite challenging, we are also investigating the use of additional input signals such as the crank angle; however adding sensors or using data from other engine subsystems remains outside the scope of the case study.

We have discussed the possibility to test the method with measurement data from controlled test situations that simulate real faults. We also have access to a simulation model of the valve-train system, and are working on simulation experiments to reproduce the test scenarios with different faults.

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10. Ship waste heat recovery scheme identification with machine learning

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10.1 Introduction

Ship energy efficiency has improved gradually. The main driver has been to reduce carbon dioxide and other related emissions as described by [1]. Despite of this, ships are rarely operated at maximum efficiency, and there is room for improvement, as evaluated by [2]. This is due to the limited consideration of dynamic operational conditions and constantly changing environment in ship design.

In addition, it is important to understand the operating environment and mission of the ships to optimise the efficiency. Development of virtual models of on-board energy systems has proven to be a key tool in understanding and monitoring ship operations and in making operational decisions. Several ship systems may be modelled, and finally the whole ship. Such systems may be fuel oil consumption, as studied by [3], fresh-water cooling systems and waste heat recovery by [4] and [5], and even the complete ship, as presented by [6].

To develop a virtual model it is necessary to identify the configuration of the respective energy subsystem of a ship. This may be available as prior information, but often the configuration is insufficiently known, or even completely unknown. In our study, we identify methods, which may be used to determine such configurations, and achieve some information about their operation. Such methods are usually in hybrid modelling category. Hybrid modelling idea for some other application areas has been presented by [7] and [8]. [7] concentrated mostly on the chemical engineering, and [8] for biological systems. Another approach is to process the unknown systems with reverse engineering, as presented in general by [9] and again for biological systems by [10].

To reduce the study complexity we concentrated on the Exhaust Gas Waste Heat Recovery system (EG-WHR). EG-WHR is a key element in an energy-efficient ship.

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A good presentation for the design of WHR in general is given by [11]. A simplified schematic figure of a typical EG-WHR system is in Figure 1. The hot exhaust gases from engine transfer energy in economisers. Economiser feed the wet steam to boilers as an auxiliary energy source. The return line from the boilers comes back to the economiser. We try to deduce WHR configuration by analysing system input and output values, signals and parameters.

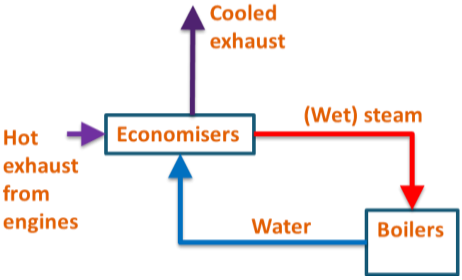


Figure 1. A simplified block diagram of an Exhaust Gas Waste Heat Recovery (EG-WHR) system.

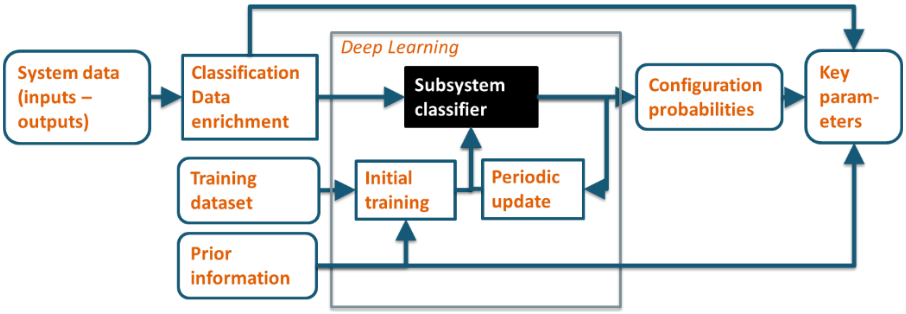


Figure 2. Non-parametric modelling principle.

10.2 Scheme identification concept testing

The principle of the learning-based modelling is shown in Figure 2. The objective is to obtain the subsystem configuration, existing with some probability, and key parameters of the subsystem. The classifier is initialized with a training dataset and prior information about the subsystem. The classifier is then updated periodically when new data is available.

The concept of a system configuration identification with a machine learning classifier was first tested with a simplified Simulink simulation model. It consisted of three subsystems - a gain, a delay and an averaging filter - as shown in in Figure 3. The subsystems were chained to create a single system with a combined transfer function.

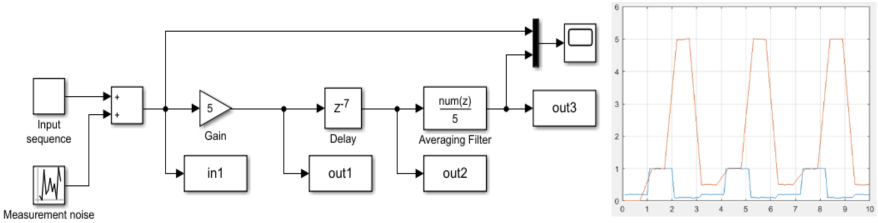


Figure 3. Simulation model for testing the machine learning classifier (left) and input (blue) and output (red) signals of the simulation model (right).

First, a set of training data was created for each individual subsystem. For creating the training data, subsystem parameters (gain, delay, and averaging length) were randomly varied and transfer functions of the subsystems were estimated by their inputs and outputs. In this step, the classifier was taught how each subsystem behaves, and labels for them were created. For example, transfer functions referring to the gain block were labelled as [1, 0, 0] indicating that the probability for that kind of response is 1 for gain, 0 for delay and 0 for averaging filter. For simplified simulation model, the key parameters were selected as the value of the gain and the length of the delay. These parameters can be extracted from the transfer functions after the classification.

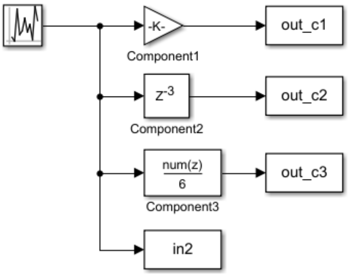
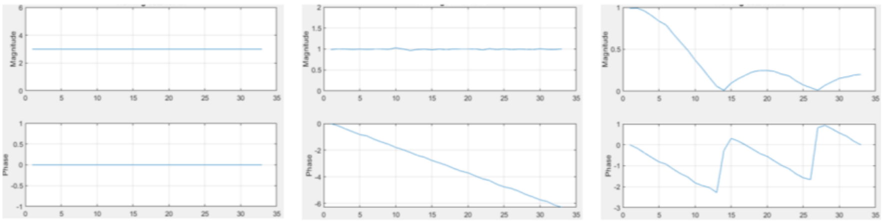


Figure 4. Simulation model for creating the training data.



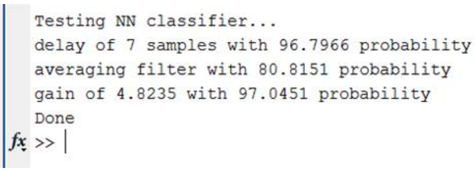
Gain

Delay

Averaging filter

Figure 5. Typical transfer functions (magnitude + phase response) of the subsystems.

The simulation model used for the training process is illustrated in Figure 4 and typical transfer functions of the subsystems are shown in Figure 5. The learning-based classifier was then initialized using the transfer functions and the corresponding labels indicating the type of subsystem. After the training, the classifier was tested so that the transfer function of the simulation model including all three subsystems was given as the input of the classifier. As the output, the classifier gives a probability for the type of the subsystem, as illustrated in Figure 6. The delay and gain blocks were easier to identify with a high probability whereas the more complex averaging filter was identified with a smaller probability. This concept testing gave an insight to probable results with real systems and real data, and showed what to expect.



```
Testing NN classifier...
delay of 7 samples with 96.7966 probability
averaging filter with 80.8151 probability
gain of 4.8235 with 97.0451 probability
Done
fx >> |
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Figure 6. The probabilities of the subsystems for the simulation model.

10.2.1 Machine learning with authentic ship data

The concept was then applied to measurement data obtained from a WHR system of a cruise ship. In the ship, there were four main engines and economizers were used to retrieve heat from the exhaust gases. Measurement data contained exhaust gas temperatures before and after economizers and the engine load information. To model the behaviour of an economizer, the energy balance equation was used:

$$\dot{m}_{eg} C_p \Delta T = \dot{m}_w \Delta h \tag{1}$$

Here $\dot{m}_{eg}$ and $\dot{m}_w$ are the mass flows of the exhaust gas and water, *C*p is the specific heat capacity of the exhaust gas, ΔT is temperature difference of the exhaust gas before and after economizer and Δh is the enthalpy difference between the steam leaving the economizer and feed-water entering it. Mass flow of the exhaust gas is proportional to the engine load and given in the engine specifications. Water mass flow can then be obtained as a function of engine load.

In Figure 7, water mass flow for one economiser is given. The scatter plot contains data from several days and shows large variation of mass flow values, which may be caused by different operating points.

In Figure 8, water mass flow curves are shown for all economizers. Since they differ from each other in shape and range, the learning-based modelling concept was applied to classify the water mass flow characteristics of the economizers. To train the learning-based classifier, several water mass flow curves are needed for each economizer. For that, the measurement data was divided to subsections and water mass flow for the subsections was computed. In Figure 9, training set for one economizers is shown. Load values are limited between 40 and 80 % because of missing data outside that range.

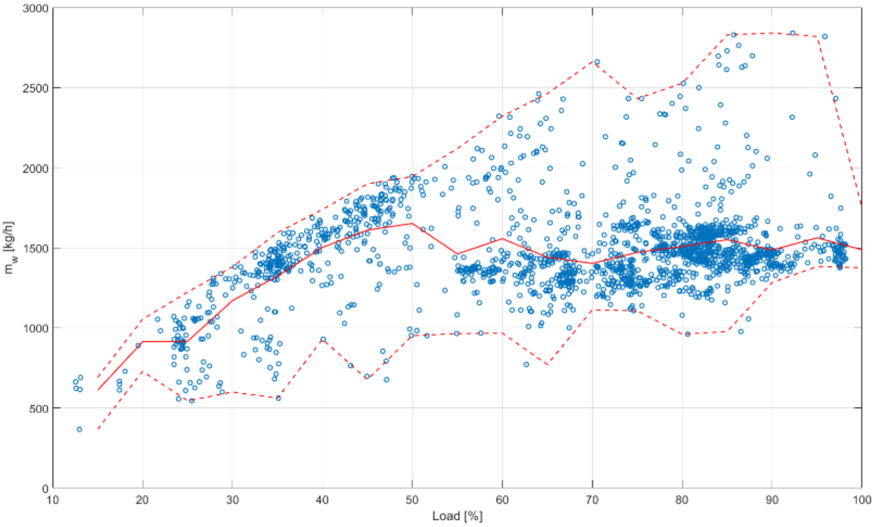

Figure 7. Scatter plot of water mass flow for one economiser. The solid red line indicates the mean value and the dashed lines indicate minimum and maximum values.

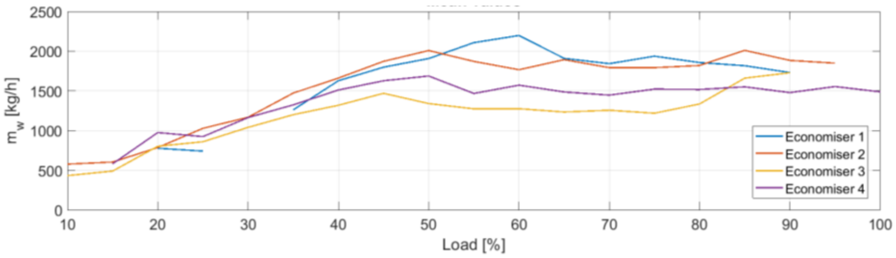

Figure 8. Mean values of water mass flow for all economizers.

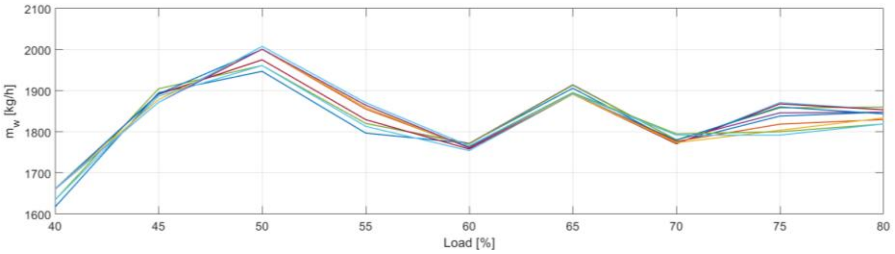

Figure 9. Training set of water mass flow curves for one economizer.

The classifier was then trained with the training data and tested with water mass flow curves chosen outside the training set for validating the classifier. In all cases, the classifier was able to identify the correct economizer with 100 % accuracy.

10.3 Conclusions and future work

A learning-based modelling concept for ship waste heat recovery systems was presented and tested. For validating the concept, both a simple simulation model and real-ship data were used. With the simulation model, successful classification of the subsystems were achieved. In the case of real measurement data, the classifier was able to separate the economizers based on their water mass flow. The concept can be further utilized to find different operating points of the ship. It can also be applied to data-driven modelling of other ship subsystems.

Acknowledgements

We would like to express our gratitude to Business Finland INTENS project for the support of this work. All consortium members are gratefully acknowledged. Our special appreciations go to Tallink Silja Oy and its several helpful employees who kindly provided us with the ship logging data and other useful information.

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11. Measurements and actual twin of micro-ORC for waste heat recovery

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LUT University

11.1 Introduction

The high importance of increasing the efficiency of energy production, transport sector and different industrial sectors have been highlighted in the recent times as an effective way for decreasing the global emissions and in tackling the threat of global warming. Different methods for increasing energy efficiency have been proposed, investigated and developed including systems capable for converting waste heat streams into electricity or other useful forms. At LUT, it was observed that waste heat recovery systems capable for converting the high temperature waste heat into electricity in small-scale systems, could offer several benefits and opportunities in increasing efficiency in the distributed power production and in the transportation energy systems. Among the different waste heat recovery (WHR) technologies, organic Rankine cycle (ORC) was selected as the most suitable technology for further investigations. A small-scale and high-temperature ORC system was designed and constructed at LUT for experimental investigations on the small-scale WHR system capable for converting exhaust gas heat from a diesel engine into additional electricity production. For this type of systems, fluids with high molecular weight and high expansion ratio have been identified as potential working fluid candidates [1, 2]. Specific investigations and analysis related to turbomachinery and heat exchangers are carried out as a non-conventional working fluid with significant real gas effects in the fluid dynamics and thermodynamics are presents in this type of systems. Within the INTENS-project, the experimental studies and model developments paving the way towards digital twin will be carried out to identify the potential for different waste heat recovery opportunities and to

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develop efficient waste heat recovery systems capable for increasing energy efficiency of shipping industry in the future.

11.2 Experimental micro-ORC system

The experimental ORC system was constructed at LUT in the laboratory of fluid dynamics. The hot exhaust gas heat from a 150-200 kW sized diesel engine is utilized in the ORC system to produce additional electric power. The system uses high molecular weight and high critical temperature siloxane MDM (octamethyltrisiloxane) as the working fluid. The key component of the experimental system is a high speed turbogenerator including supersonic radial turbine, permanent magnet generator and a barske type feed pump assembled on a single shaft. The rotational speed of the turbogenerator is controlled via frequency converter to reach optimal rotational speed for the respective waste heat load conditions and the system has working fluid lubricated bearings to remove the need for external lubrication oil system. A simplified process layout and picture of the experimental system are presented in Figure 1. The design values of the experimental ORC system are presented in Table 1. Temperature and pressure measurements have been added to the inlet and outlet of the main process components in order to carry out a thermodynamic analysis of the whole system and analysis on the each individual component operation. [3]

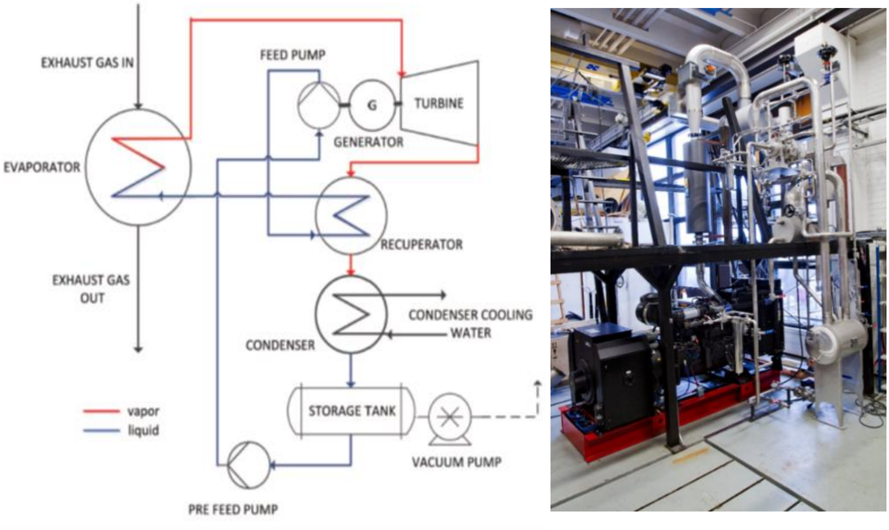

Figure 1. Simplified process layout and picture of experimental system at LUT laboratory of fluid dynamics.

Table 1. Experimental system design values [3,4]

Turbine mechanical power	12 kW
Max. electric power output	About 8 kW
Evaporator heat rate	67 kW
Evaporation pressure	7.9 bar
Temperature at turbine inlet	265 °C
Recuperator heat rate	40 kW
Condensing temperature	57 °C
Condensing pressure	0.03 bar
Turbine outlet pressure	0.07 bar

11.3 Results and conclusions

Several experiments have been carried out and the results have shown the capability of the ORC system to convert the high temperature exhaust gas heat into electricity. The power output is dependent on the system condensing conditions, waste heat load and turbogenerator rotational speed. The maximum measured electric power outputs from the system have been over 6 kW. The measured ORC electric power outputs are presented as a function of working fluid mass flow rate and turbine inlet pressure in Figure 2. An example of the turbogenerator loss and power distribution analysed based on the measurements is shown in Figure 3.

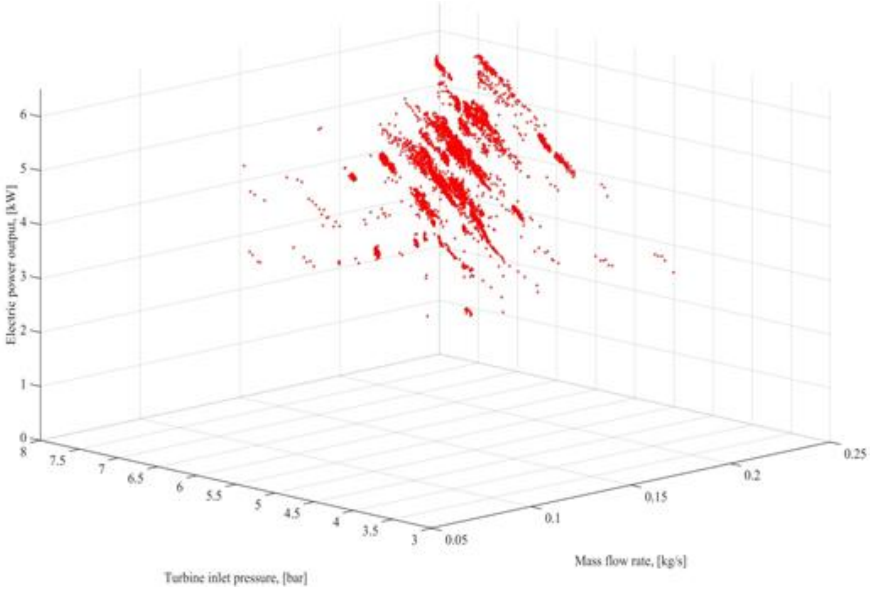

Figure 2. Measured electric power output of the ORC system as a function of working fluid mass flow rate and turbine inlet pressure.

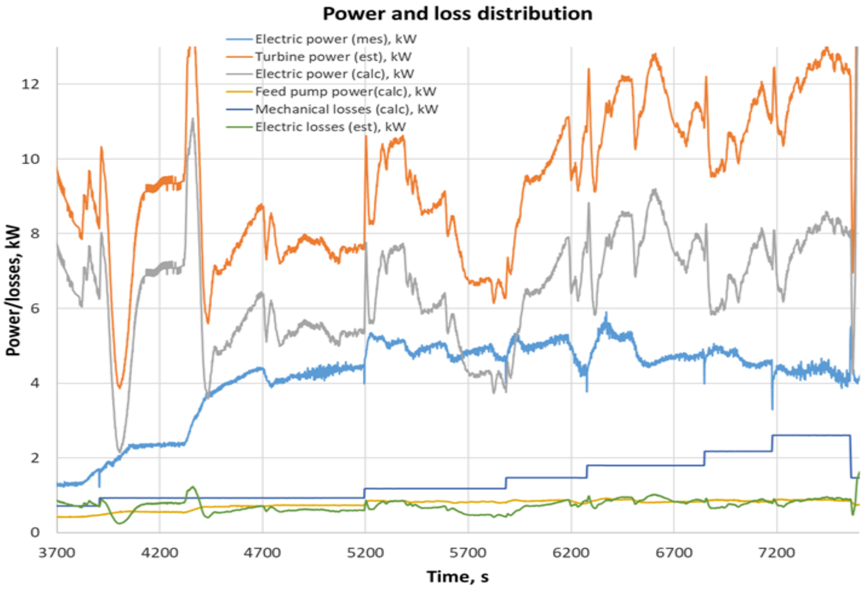

Figure 3. An example of turbogenerator power and loss distribution.

With the experiments using the high molecular working fluids in the small-scale and high temperature ORCs, the successful waste heat recovery have been identified and confirmed. The measured operation of the experimental system have shown that the ORC system can efficiently recover the high temperature waste heat of the exhaust gases to the system working fluid. The measurements also indicate that the designed supersonic radial turbine reaches a mechanical power outputs that are close to the design values. In addition, the cycle pressure levels, temperature levels, flow rate and heat exchanger heat rates are close to the values that were estimated in the systems design stage. However, the measured power output from the system is indicating about 1-2 kW higher losses inside the turbogenerator than were expected in the system design stage. Thus, it is important to concentrate on reducing the mechanical losses of small-scale high rotational speed turbogenerators in the future to increase the power output of small-scale waste heat recovery systems. The increased knowledge and understanding on the fluid dynamic effects and thermodynamics of high molecular weight and non-conventional fluids in waste heat recovery systems can be adopted in developing high efficiency waste heat recovery systems for future ships. The model developments will be concentrated on developing the digital twin for the waste heat recovery system at LUT by utilizing the knowledge gained from the experiments.

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12. System twin construction of an ORC system using dynamic modelling approach

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LUT University

12.1 Introduction

There is an increasing trend with demands for renewable energy systems with the depleting fossil fuel sources over the years. In the marine industry, the concept of green shipping is one such case, where waste heat utilization can be one of the most effective ways to achieve that. When it comes to low and medium, grade waste heat recovery (WHR) Organic Rankine Cycle (ORC) technology is a proven technique. Therefore, effective operation of the turbomachinery and heat exchanger components is necessary for an ORC plant to achieve the maximum possible cycle efficiency. System or digital twin is increasingly popular in the power-based industries with the aid of real-time data to construct a virtual demonstration of the physical model. It helps in better assessment of the system performance and therefore to present control methodologies for its operation. In addition, it is helpful to investigate the transient behaviour of the plant when operating in variable conditions. Dynamic behaviour is important, especially in small-scale WHR applications.

12.2 Dynamic modelling

12.2.1 Methodology

In the present work, an effort has been made to develop a dynamic model for the small-scale high-temperature ORC experimental test rig at the LUT University, which utilizes waste heat from a heavy-duty diesel engine exhaust. The schematic of the facility is shown in Figure 1. Octamethyltrisiloxane (MDM) is the chosen

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organic working fluid in this cycle. Matlab-Simulink environment along with the open-source thermodynamic and transport database CoolProp has been chosen for calculating the thermodynamic properties for the dynamic model. A lumped parameter model approach has been followed for each individual block component namely, Turbogenerator, condenser, recuperator, pre-feed & main-feed pumps and the evaporator by predefined input and output parameters. In addition, it is aimed at modelling the performance characteristics with a limited number of inputs for both design and off-design operations of the cycle. The dynamic model will be validated with the experimental data, which together will be helpful in building an optimized performance and control characteristics of the process.

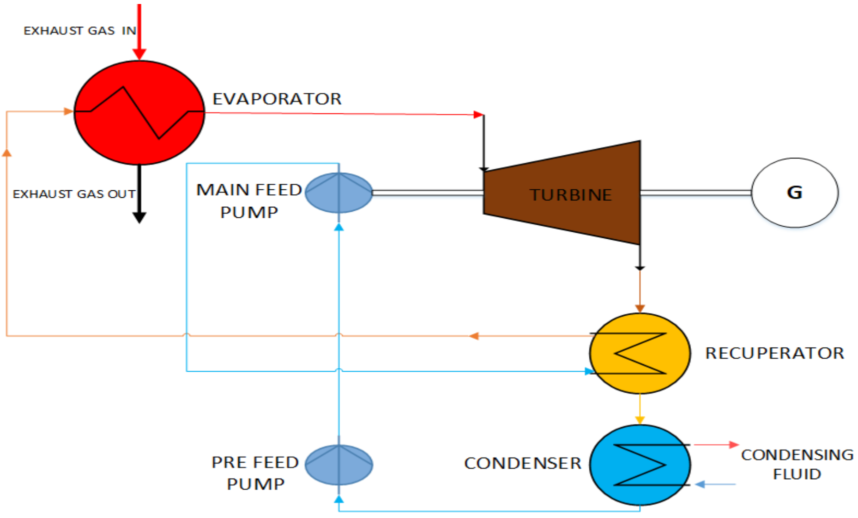

Figure 1. Schematic of the ORC Test Rig at the LUT University

12.2.2 1-D model construction

As a first step, a simplified 1-D model of the ORC cycle process is constructed in Simulink, using the embedded MATLAB function and CoolProp, as shown in Figure 2. The pre-feed pump is excluded and with the assumption of zero pressure loss in the heat exchanger components. The inputs are the turbine inlet pressure (P1) and temperature (T1), turbine outlet temperature (T2) and the turbine isentropic efficiency, pump efficiency for the pump block, condensing fluid and condenser outlet temperatures and mass flow (m_cw) and exhaust gas heat load (Q_in). The desired output values are the mass flow rate (m), turbine outlet temperature (T2), condenser inlet temperature (T3), recuperator inlet and outlet temperatures (T5 and T6) along with the state properties (enthalpy and entropy) of each component. This step serves important in acquiring a preliminary idea of the process. Additionally to ensure that the deviations with the calculated state properties using CoolProp are within the allowable limits.

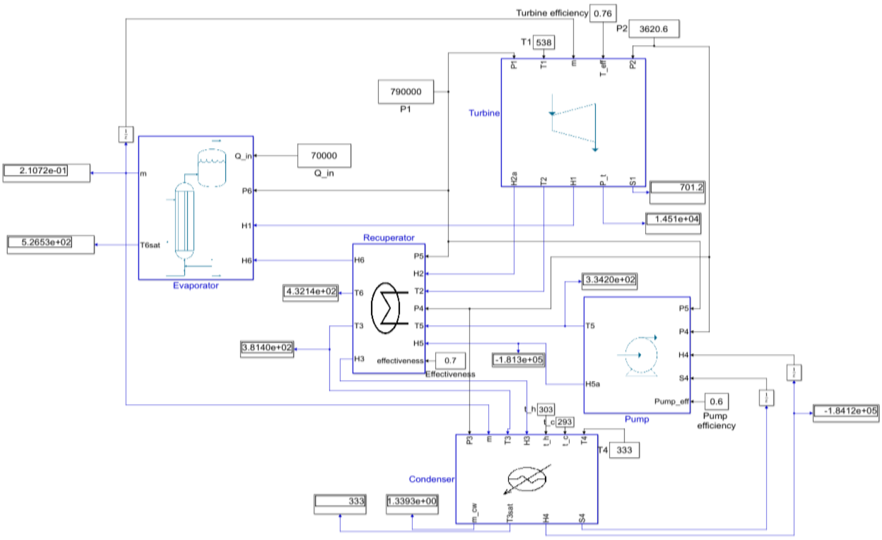

Figure 2. 1-D Simulation of the ORC model

12.2.3 Quasi 2-D model construction (current status)

Currently, dynamic modelling of a quasi-2-D model of the ORC system is being carried out with a more detailed modelling approach for each component. S-function is used to model the components in MATLAB-Simulink environment. The modelling process is divided into two parts as (i) turbo-pump (turbine, pre-feed & main feed pumps) and (ii) heat exchanger components (condenser, recuperator & evaporator). The turbine is assumed to be choked for all the operating conditions, which determines the mass flow of the cycle. Pressure loss in each component is considered. It is aimed at constructing the components with a lumped parameter modelling approach and to generate their performance characteristics for both design and off-design conditions. Table 1 shows the lumped parameters for each block.

Table 2. Lumped parameters for each block

Turbine block	Efficiency, $\eta_t(N, q_m)$, as a funtion of rotational speed (N) and mass flow rate
Main feed pump	Pressure increase, Δp (N, q_m), as a function of volumetric flow rate (q_v) & Rotational speed (N)
Pre-feed pump	Pressure increase, $\Delta p(q_v)$, as a function of volumetric flow rate (q_v)
Heat Exchangers (Condenser, Recuperator & Evaporator)	Based on heat exchanger area (A), heat transfer effectiveness (ε), energy balance (E_b) and pressure drop (Δp)

12.3 Results and discussions

12.3.1 Preliminary 1-D simulation

The preliminary results for the 1-D simulation (on-design working conditions) performed using Simulink is shown in figure 2. In addition, the values compared with the corresponding experimental data shown in figure 3, which implies that the maximum deviation is around 1.45%, which is in the accepted range.

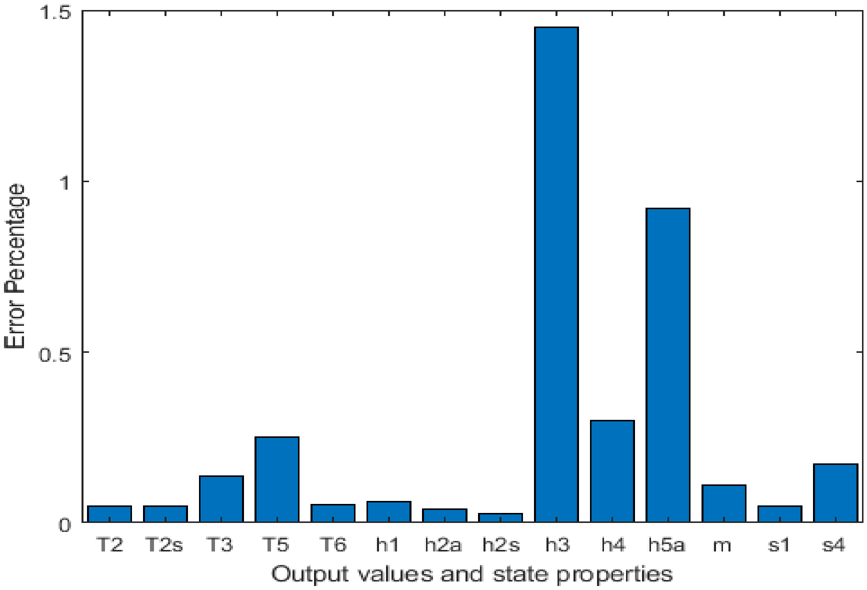

Figure 3. Estimated Error Percentage from the 1-D Simulation.

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13. Feasibility analysis of a battery system for a passenger ferry

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[b)] Protacon Technologies Ltd

13.1 Introduction

According to an extensive literature review of CO2 reducing methods applicable to ships in [1], the hybridization of a ship's electric auxiliary power and propulsion is a strong candidate among the methods with a potential reduction of 2-45% in CO2 emissions. This paper work is specifically focused on studying the benefits of integrating a battery system into a ship's auxiliary power network. The realized fuel consumption reductions are expected to result from operating the combustion engine driven generators closer to their optimal loads, as the battery can be used for power-peak shaving. In addition, benefits are expected to emerge from supplying the thruster generated power peaks from the battery, rather than the generators.

The proposed battery system brings flexibility to the energy system, as the total output power of the engines no longer needs to equal the power demanded at each moment. Instead, either the power output of the engines that exceeds demand can charge the battery or engine power may be reduced and the difference discharged from the battery. Furthermore, in the multi-engine configuration of the auxiliary system, the engines are installed in pairs of two that have different rated powers. The power demand can therefore be supplied by different combinations of engines and their loads.

To the authors' knowledge, none of the current literature describes the feasibility of including a battery system aboard a conventional direct driven ship with onboard electricity demand supplied by combustion engine driven generators. This work seeks to contribute in battery system capacity and power rating selection process, optimal power distribution management and economic feasibility evaluation of the battery system for the studied vessel topology.

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13.2 Methods

The analysed ship is a conventional direct drive passenger ferry that operates in the Baltic Sea. The propulsion system consists of four internal combustion engines that drive two main propellers through two gearboxes. The system is decoupled from the auxiliary power generating sets. Auxiliary power is generated by four internal combustion engines that drive generators. Two of the engines have 2400 kW maximum continuous rating and the other two 3200 kW.

A set of auxiliary power consumption measurements with 2-minute sampling rate were analysed. The hotel load of the ship ranges between 2000 kW – 3000 kW. The use of thrusters when manoeuvring at harbour causes power peaks, which magnitude depends on the load of the thrusters and how many are operated simultaneously. Auxiliary engine loads in the studied ship are concentrated in two clusters, as shown in Figure 6. The group on the left is centred at the 35% loading point, where the engines' specific fuel oil consumption is approximately 8% higher than in the design point at 85% load. This illustrates a potential for improving the ship's energy system efficiency by shifting the loads closer to the engine design points at 85% load.

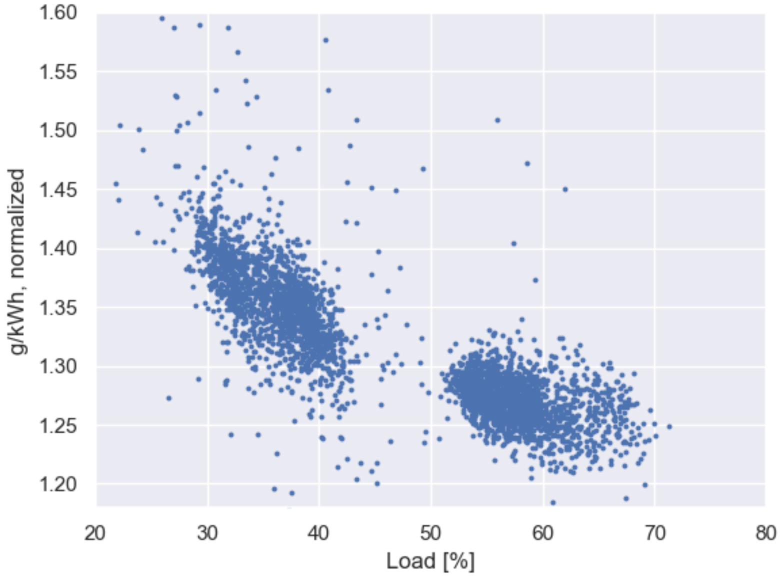

Figure 1. Auxiliary engine operating points.

The battery may be specified according to the required power and energy for thrusters under all manoeuvring scenarios represented by the data. This essentially means that the usable capacity should be derived from manoeuvring events that demanded the most energy. Usable capacity was determined to be a state of charge (SOC) range of 95% – 20% to achieve high cycle life for the battery.

Figure 2 shows a bar diagram of the energy consumption of the thrusters in all the analysed manoeuvring events. As can be seen, the highest energy consumed is approximately 850 kWh, with 3 out of 27 events consuming this amount of energy. The lowest energy consumed in the analysed events is approximately 300 kWh, with the rest of the values quite evenly distributed between the maximum and minimum values. Based on the analysed data, the 95% – 20% SOC range should correspond to a battery capacity of 850 kWh, so the total capacity of the battery should be around 1130 kWh.

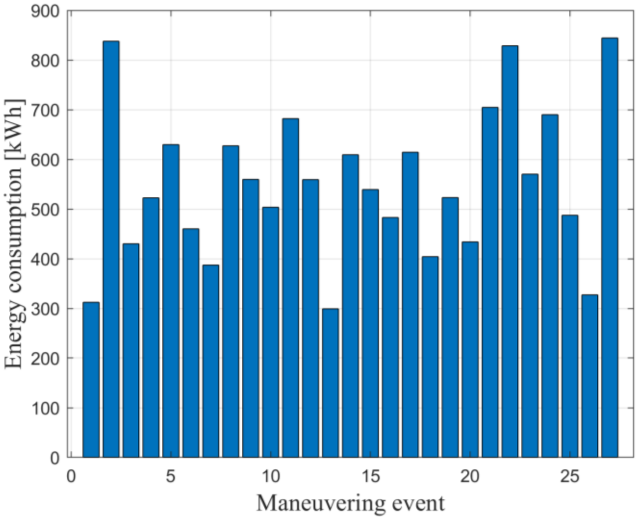

Figure 2. Total energy consumed by thrusters in each of the manoeuvring events.

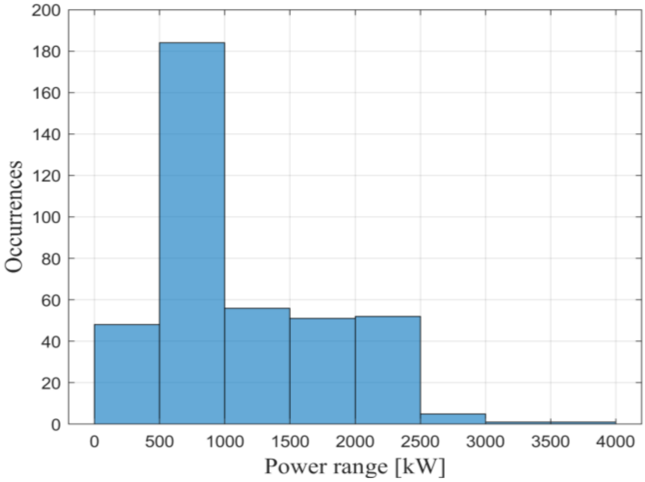

Figure 3. Thruster power demand histogram.

In addition to choosing a suitable capacity for the battery system, the maximum power demand must also be satisfied. A histogram of thruster power demand is shown in Figure 3. As can be seen, the majority of thruster power demand is in the range of 500 – 1000 kW, with a small number of occurrences where demand exceeds 2500 kW. The maximum thruster power demand was 3830 kW. With an 1130 kWh capacity battery, this would mean a discharge rate of 0.5-1 C during most of the operation, with a peak of approximately 3.5 C. These values are well in the acceptable range of current NMC chemistry battery systems [2]. In the following analysis and discussion, the battery topologies are abbreviated to LC for the low capacity battery, which is sufficient for the reserve power requirement, and HC for the high-capacity battery, sized to supply the largest port manoeuvre energy demand.

A fuel consumption minimizing power management strategy for the engines and the battery is found by formulating and solving an appropriate optimization problem as explained extensively in [3]. The load-sharing problem under investigation involves a dynamic system, which requires a multi period model. This limits the model selection to linear, quadratic, and mixed integer linear programs (MILP), which can be solved relatively fast and robustly for many thousands of decision variables [4]. Therefore, the generator set and the battery load-sharing problem is formulated as a MILP model. This approach is similar to the one presented in [5]. The model is limited to controlling the component operation. System topology is fixed and component sizes are manipulated separately for each model run.

The overall goal is to minimize the total fuel consumption for the operation cycle. The objective function to be minimized includes fuel flow rate for running the engines and additional fuel consumption equivalent costs for starting the engines. Total fuel consumption is computed by the addition of the fuel consumptions of each time step and engine. The fuel flow rate equation coefficients are computed to approximate MAN 8L27/38 specifications for an auxiliary engine configuration [6]. The engine model also includes mechanical efficiency variation as a function of load. When the vessel is disconnected from an external electric grid, the engine power exceeding the vessel demand is utilized for charging the battery and vice versa.

Maritime safety regulation [7] determined reserve power requirement constraint demands that, at each time period, the total available power of running engines must be equal to or greater than a specified threshold value. Different values are applied based on the energy system topology, such that the threshold is relaxed for the hybrid topologies. Engine operation is further constrained by a droop control load sharing constraint that is active when two or more generators supply the same alternating current electricity bus. The engines are required to operate at equal loads, specified as a percentage of maximum continuous rating [8].

The battery model includes maximum charge and discharge rate dependent on the state of charge. 18% decrease in maximum power output between 100% and 0% SOC is assumed based on measured data of a NMC cell [9]. Battery aging was taken into account by over-dimensioning the capacity by a factor of 1.25, which accounts for a 20% decrease in capacity over the lifetime of the battery [10].

13.3 Results

Figure 4 shows the optimal dispatch of the auxiliary engines and the battery for the HB case. Two out of the six thruster demand peaks are entirely supplied from the battery, while the other four peaks are primarily supplied by starting up an additional engine. However, in three of six cases, the battery still supplies a small share of the total demand. In one manoeuvring event, engines supply excess energy that is then charged to the battery. During the sea cruising periods, the battery functions mostly as a reserve power unit without active use. Although the battery brings flexibility to the energy system, allowing the engines to operate continuously at the design point loading, this functionality is not taken advantage of in the HC case during sea cruising.

Compared to the default ship topology that does not have a battery, the largest absolute fuel saving of 0.494 tons per journey is achieved with the HC battery option, as expected. The difference in savings between LB and HB cases is very small, although HB capacity is almost twice the size of LB. The reported fuel savings can be entirely attributed to the battery, as shore charging is excluded from the figure.

Investment profitability is presented for the LC battery in Figure 5, considering a range of battery system costs and fuel costs. A positive NPV is obtained independent of the fuel cost when battery cost is less than 350 €/kWh. On the other hand, the investment is profitable when fuel cost is higher than 490 €/t regardless of battery cost. Furthermore, the difference in NPV between extreme ends of the cost ranges is approximately 70% higher for fuel cost than for battery cost.

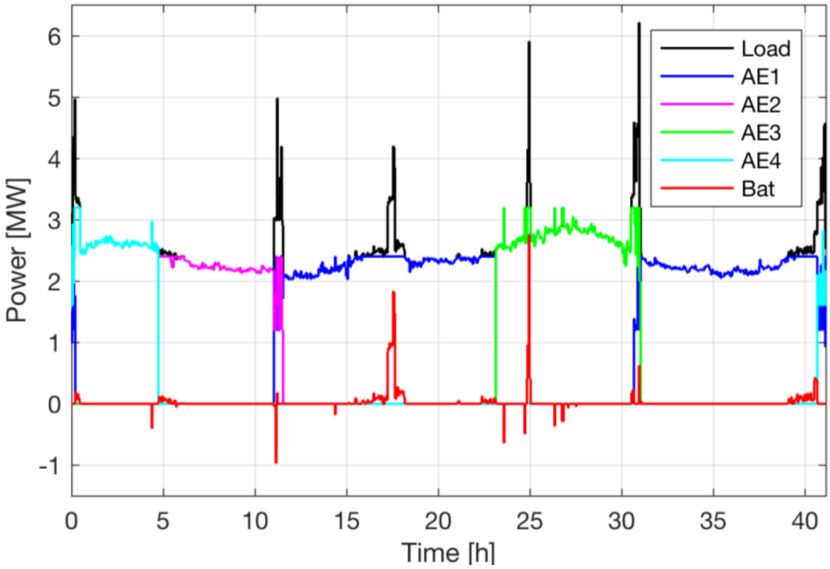

Figure 4. Optimal dispatch of the HC battery and the generators.

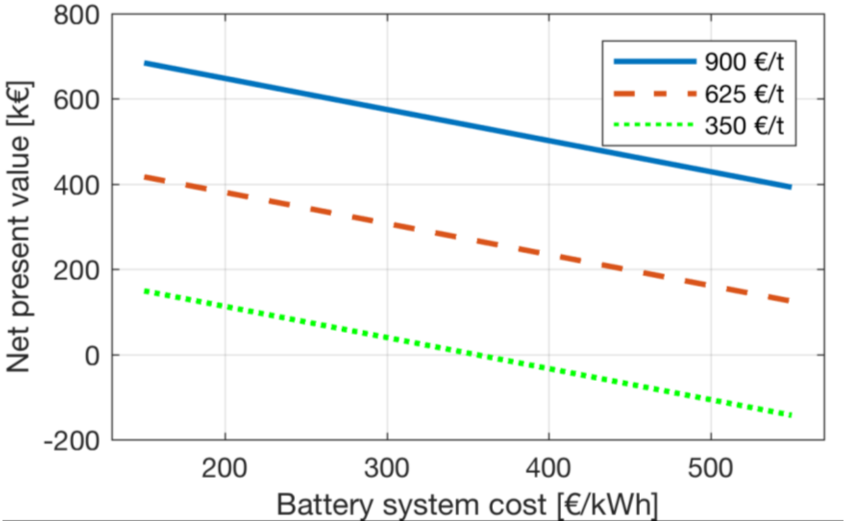

Figure 5. Net present value of the LC investment for a continuous range of battery costs and three fuel costs.

13.4 Discussion

Feasibility of a battery system was evaluated for a conventional direct driven passenger ferry. The optimized power production for the ship's generators and the battery system showed that fuel consumption could be reduced by 88.74 tons, or 2.7%, annually for the studied vessel.

The results suggest that the benefits of the battery are derived mostly from the relaxation of the marine safety regulation imposed reserve power requirements and not from active battery usage for improving engine operating points. In other words, the installation would be economically feasible even if the battery was not used at all, but only acting as a reserve power source allowing the power demand supply from a single engine at high efficiency instead of two or more operating at a low-efficiency point. This is illustrated by the fact that the most economically attractive investment is the low capacity battery option.

Previously, for instance Pyrhönen et al. [11] have studied cruise ferry battery installation feasibility with similar operational profile as the case vessel in the present analysis. The battery was controlled with a rule-based strategy and enabled relaxed reserve power requirements for the generator sets. Results in the paper point to the same direction as the present work in a sense that a small capacity battery was found to be the most economically compelling. This supports a conclusion that the most attractive battery use case is for reserve power, at least for vessels operating fairly short distances in archipelagos.

Battery benefits may be underestimated, because the utilized power demand data does not have a sufficient sampling rate to accurately model power demand fluctuations in port operations and to capture the benefits of battery's faster response to changes in electricity demand compared to a generator set. For instance, brief power peaks that do not show up in the data would be profitable to supply from the battery instead of starting a generator or having a generator idle as a power source. Secondly, the true cost of starting a generator might be much higher than in the present study. Requirements for idling the engine before shutdown and increased preheating, wear and maintenance cost caused by starting events were ignored. The battery also almost halved total auxiliary engine running hours, which would translate directly to reduced maintenance costs. However, these costs were not evaluated or included in the economic feasibility analysis.

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14. Power availability calculation and optimization of hybrid vessel powertrain in planning robust automation

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14.1 Introduction

As the current trends of development in all fields of mobility focus on energy efficiency and emissions reduction, the marine industry is rapidly developing new hybrid and full electric systems to comply with the stricter regulations and to preserve our environment. [1] Currently autonomous systems are being developed. Networking and cloud services may vastly improve the overall efficiency of modern marine systems. [2] [3]

The technology is rapidly developing, and marine vessel scale units are becoming more available and accessible for the shipyards. It is also a chance for new system providers that may bring more economical or more flexible solutions to the market. Not only hardware is required, but more increasingly complex software solutions to control the onboard technology in an efficient way.

This opens new perspectives to a robust automation, more specifically the robust control of the vessel powertrain, which has been studied as a part of the INTENS project. This paper discusses the principles of such a robust control, which is used to define control references for the available equipment. The travel plan must always comply with the safety requirements and environmental operational limits, and simultaneously provide an efficient plan for economical use of the vessel.

14.2 The cost optimization method

A method relying on cost optimization was used to simplify the problem and optimize the control of a vessel powertrain and energy balance before and after equipment

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failure. The method proposes that the cost function should divide the travel plan in distance steps and let the optimization algorithm determine the best way to produce power, optimize the use of energy storage systems and propulsion. Using additional inputs to the functions it is possible to assess the weather conditions and their effect on the travel plan, and thus always produce the most optimal solution to reach the destination or whatever closes harbour is possible to reach.

14.2.1 Allocation

A method of allocating the power production and consumption is used here to describe a system which effectively ensures that there is always enough power available and that the operation comprises to the rules of the class or other safety requirements. The principle of the optimization pipeline is shown in Figure 1.

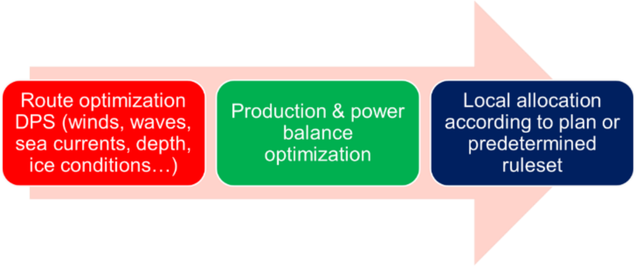

Figure 1. Optimization pipeline.

The allocation process is illustrated in Figure 2. The route optimization and power plan optimization units of Figure 1 produce the inputs of the allocation unit. If there is a difference in equipment availability between the route plan and actual situation, a new route optimization will be carried out to match the current situation.

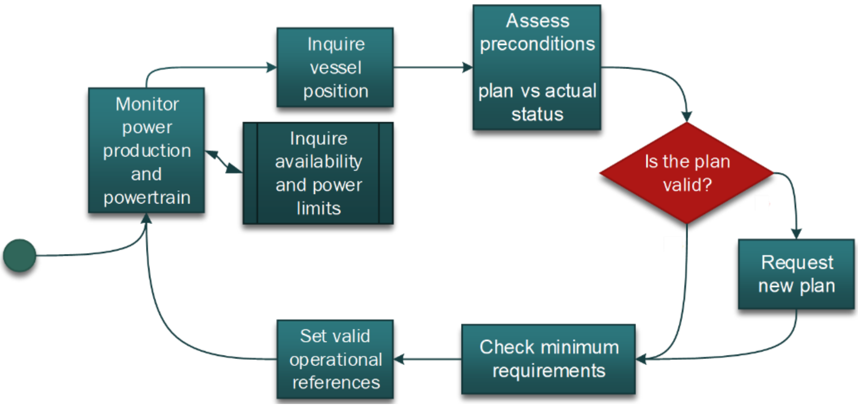

Figure 2. Illustration of the allocation process.

14.2.2 Optimization

The method of optimization used is in principle a cost optimization problem. A cost function is defined to cover all the operational aspects and an optimal solution is solved according to the selected constraints.

Typically, a vessel operates on a planned route that has certain boundary conditions, for example speed limits. As the route is already determined, the operation logic may be chosen within the set boundaries and constraints. The vessel hydrodynamics define the requirements for propulsion power, and external conditions may apply additional resisting forces on the vessel. Thus, the power production plan may effectively be used to control the propulsion power, and to control the vessel speed.

Each combustion engine has a starting cost and operational cost. The model may include a warmup time and cooling period. The costs should include also service costs. Additionally, the engines must also have a binary condition that will determine if the use of the engine is allowed or not. Similarly, there may be a binary condition to account for running an engine on idle, even if no power production is currently requested from the engine. These conditions ensure the use of full electric modes, when applicable, as well as class requirements for power production margin.

The energy storage costs should account for the lifetime costs, e.g. estimate the decrease of lifetime of the battery. As the use of power from the energy storage is more inexpensive than using the combustion engines, the optimization algorithm tends to drain the battery towards the end of the trip. If a certain level of state of charge is preferred at the end of the trip, the cost function must include a reward or penalty as a cost factor. [4]

14.2.3 Use of constraints

Several constraints must be used to direct the optimization to find satisfactory results. Naturally, the route might include speed limits, but there are also power limits for each device. The energy storages have their operational limits, consisting of minimum and maximum state of charge and sometimes-asymmetric power limits. It is also possible, that classification requires that a certain number of power producers are online.

The use of a battery is the most problematic aspect of optimizing the travel plan using distance steps. The distance of the step and chosen power production results in the required travel time to cover the step length, and simultaneously the over or undercharge of the battery must be prevented. To avoid the problem caused by averaging the power estimates, shorter fixed steps should be used, or to allow the optimizer to determine the proper step lengths on its own.

The constraints must be adjusted in some cases. For example, after the power production is decreased, the vessel maximum speed may be lower than the minimum speed limit, if such limit used. Similarly, it is useful to change the rewarding of the battery charge levels, as the optimizer might determine it economically sensible to drive slowly to charge the battery.

14.3 Results

The case example consists of two gensets, one propulsion motor and a battery energy storage that were used to model a simple hybrid powertrain. However, in the example no local allocation unit is used. The travel plan is re-optimized from the occurrence of fault.

Figure 3 and 4, show how the system is able to react to the situation where one of the two gensets is declared as unavailable in the middle of the travel. The rest of the travel is re-optimized using the available resources. In this example, the constraints are not modified after the occurrence of the fault.

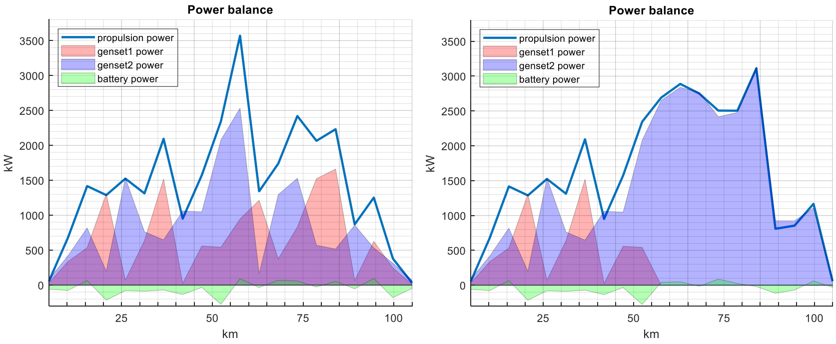

Figure 3. The power balance illustration of the initial travel plan (left) and the optimized travel plan (right) where the second-half of the travel was re-optimized according to the practical operating situations.

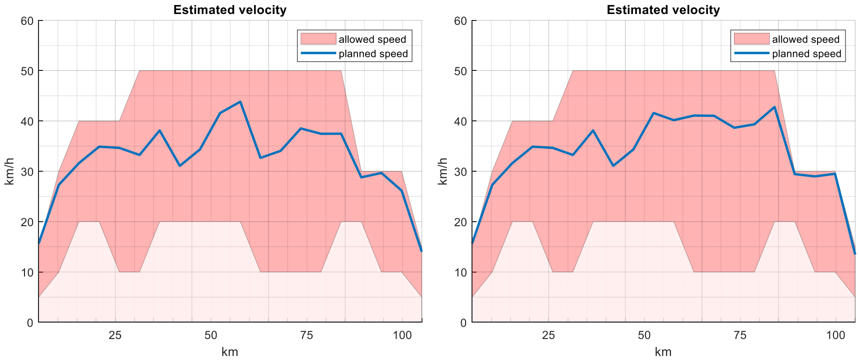

Figure 4. The velocity comparison of the initial travel plan (left) and the optimized travel plan (right) where the second-half of the travel was re-optimized according to the practical operating situations, given that the vessel is able to reach the target in time.

As it can be seen from the plot, the use of power in the plan is modified to accommodate the new situation and the algorithm provides a feasible solution to the problem. Thus, it was defined that the principle of this method is applicable to such a problem.

14.4 Summary

The use of a minimum cost optimization method was found efficient and applicable. It provides an approach which may be effectively used for vessel topologies. The more precision is required, the more complex the cost function will become. In addition, careful attention to how the constraints, penalties and rewarding is adapted to different situations.

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15. Comparison of AC and DC power systems in hybrid ferries

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15.1 Introduction

Energy efficiency is one of main key parameter indicator of the vessel electric system. This is because it directly affects to engines' fuel consumption. Nowadays, the vessel electric system is typically based on alternating current (AC) technology. However, in hybrid vessels power electronic converters are used to connect many of the subsystems, such as propulsion systems, and energy storage systems to the electric system. Power electronic converter could also be used in direct current (DC) based electric systems. In DC-based power distribution systems less conversion stages are needed, making the DC-based approach attractive. Less power conversion stages lead to minor power losses compared with the AC one. Concept of DC-based PDS configuration enables to drive engines with variable speed. This may also be beneficial.

AC- and DC-based hybrid vessel power distribution systems are analysed and compared through energy efficiency and performance. Based on the analysis, power generators, that is, diesel generators integrated with energy storage systems are chosen as the base for the PDS configuration. As and outcome of the analysis, both AC and DC network-based PDS configurations, are considered, compared and analysed.

15.2 Case vessels

Hybrid PDS analyses are carried out for the case vessels under study, with methodology described in [1]. Comparison between AC- and DC-based power distribution networks are carried out in the study, following the Figure 1.

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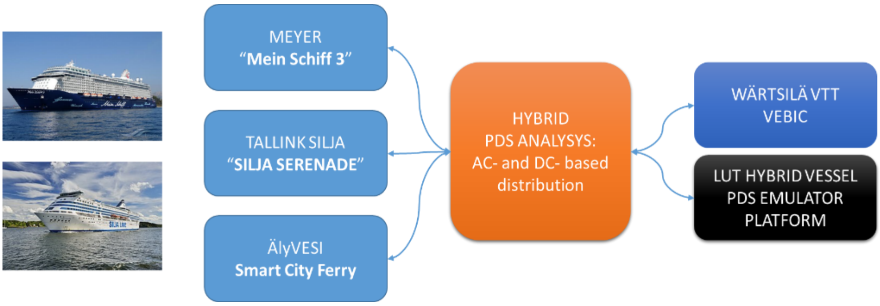


Figure 1. Hybrid PDS analysis.

15.2.1 Smart city ferry

Case one vessel is a city ferry. Synthetic load profile of the ferry based on its actual ferry route, schedule and maximum speed of 20 km/h are used as an input data. The ferry route is TST-TET-TST-TET (Turku-Saaronniemi-Turku on TST ja Turku-Ekvalla-Turku TET), ferry PDS configuration is:

1) Main propulsion 2x 120 kW, Volvo Penta D5A TA,
2) 20 kW aux. gen, Solé Diesel G-25T-3,
3) Bow thruster 33 kW (hydraulic).

The simplified hybrid AC and LVDC PDS for vessel with electric propulsion are illustrated in Figure 2 a) and b).

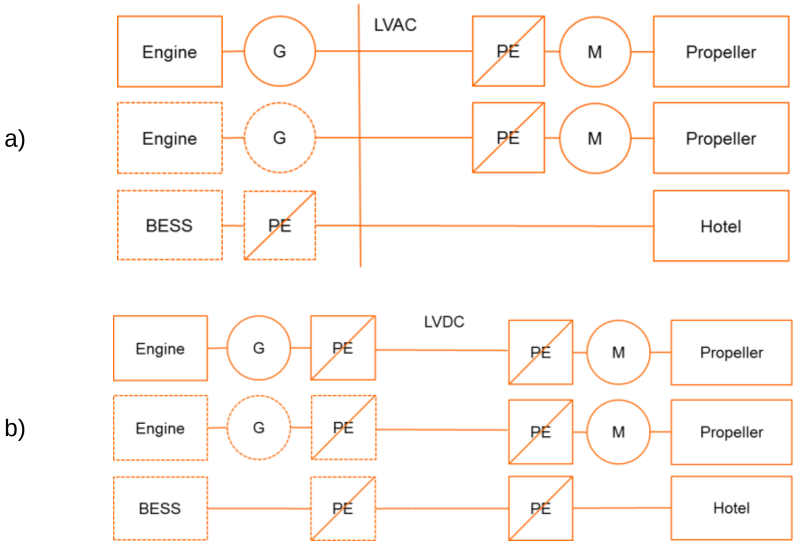


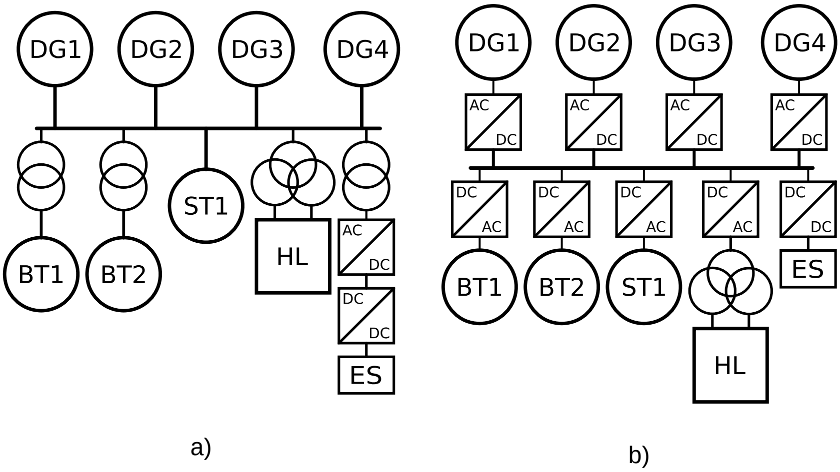
Figure 2. Simplified PDS of smart city ferry, a) LVAC b) LVDC.

15.2.2 Cruiseferry: Silja serenade

Case 2 vessel is a cruise ferry; Silja Serenade, having the following input data:

1. Load profile of auxiliary power distribution system, daily route Helsinki-Stockholm.
2. 2 x Wärtsilä Wasa 6R32 and 2x Wärtsilä Wasa 8R32
3. High power loads: Stern thruster: ST1, Bow thrusters: BT1, BT2; Air conditioning: AC1, AC2.

Simplified single line diagrams of auxiliary power distribution system presented in Figure 3.



a)

b)

Figure 3. Simplified auxiliary PDS of cruise ferry, a) LVAC b) LVDC.

15.3 Energy efficient operations of hybrid PDS

The aim of the study is to determine energy efficiency of the PDS configurations of the case vessels (Fig. 4). AC- and DC-based power distribution system with LV- and MV- configurations are analysed and compared. Vessel operation profiles used in studies were synthetized and measured. Energy storage operation profiles and dimensioning was made case by case for both vessels. From energy storage technologies, application of ESS based li-ion batteries was carried out in the analysis. As an outcome, operations for vessel one and two are illustrated in Figure 5 and 6, respectively. Accordingly, distribution of energy losses of the LVAC and LVDC PDSs for the Smart city ferry are shown in Figure 7 and 8.

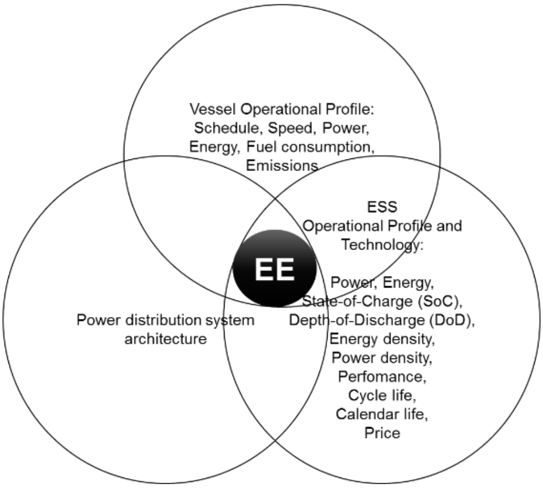


Figure 4. Energy efficiency.

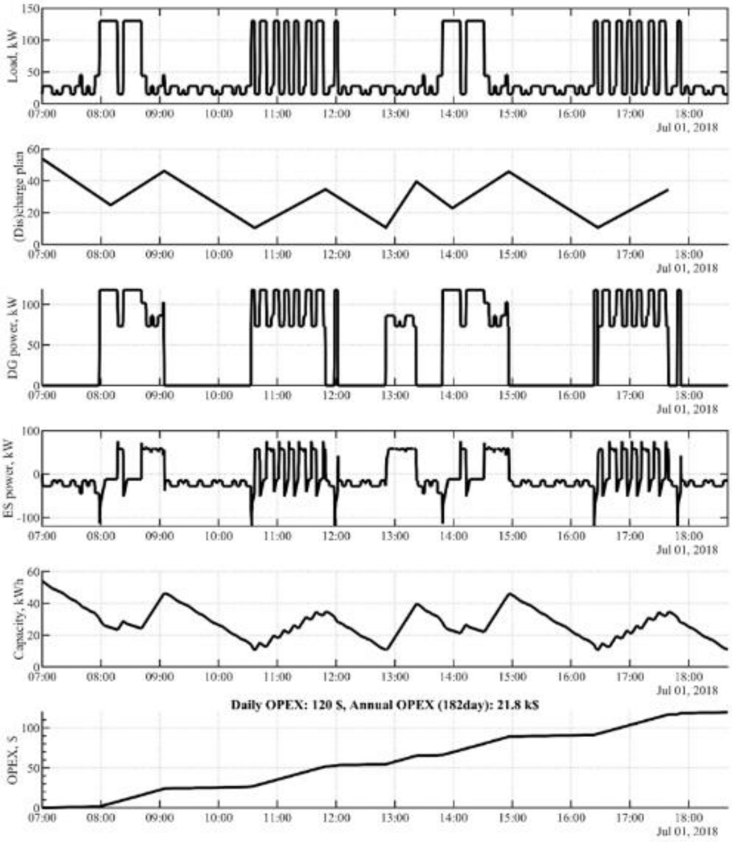


Figure 5. Operation of vessel hybrid PDS - smart city ferry.

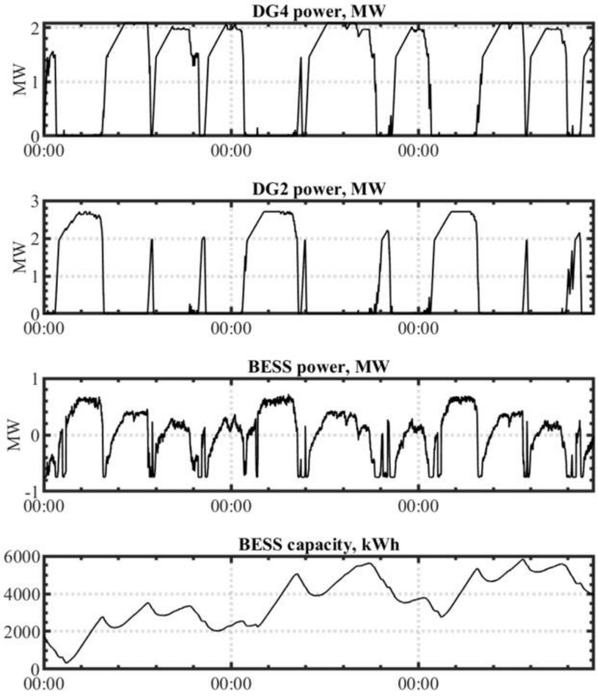


Figure 6. Operation of vessel hybrid PDS - auxiliary power plant of cruise ferry.

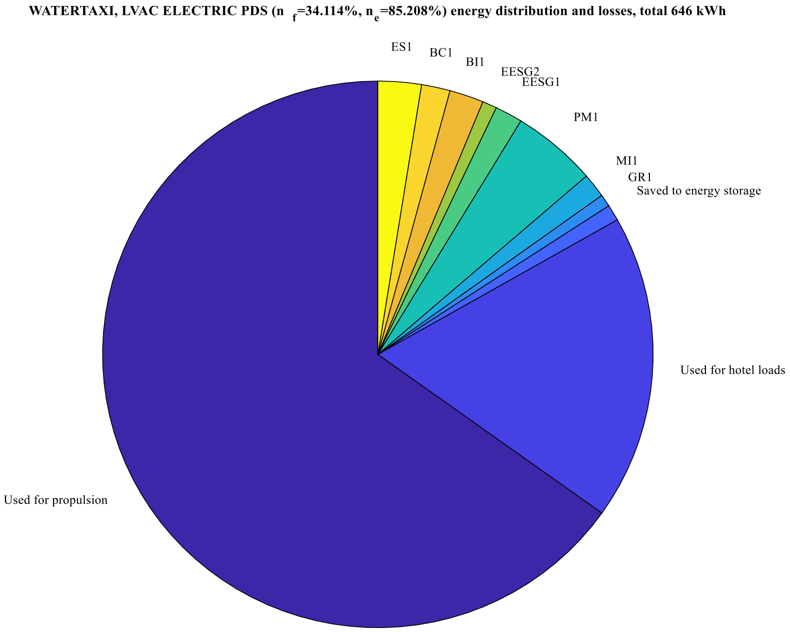


Figure 7. Energy distribution in smart city ferry - LVAC PDS

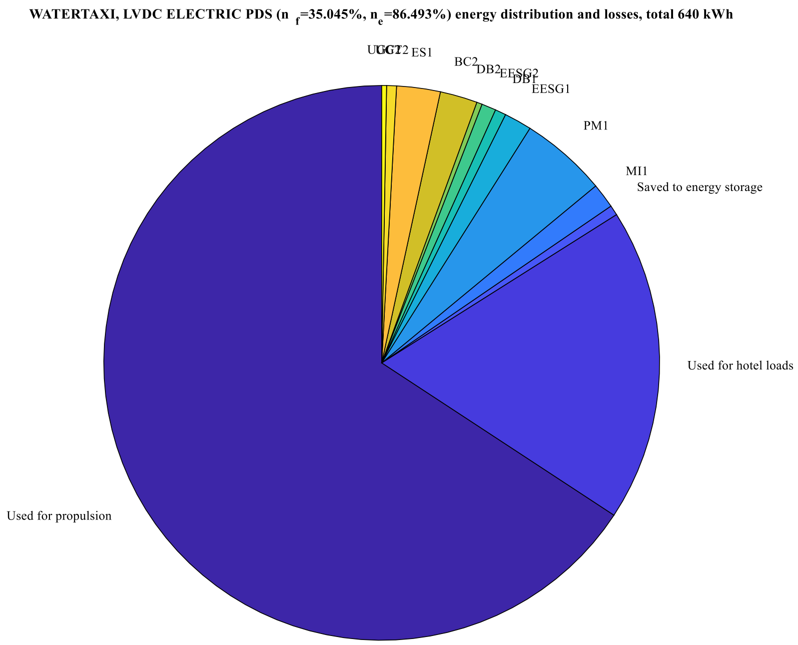


Figure 8. Energy distribution in smart city ferry - LVDC PDS.

15.4 Conclusion and further steps

The configurations of hybrid PDS were studied for the case vessels. Power loss distribution on system components and energy efficiency is analysed. Results give estimations on component dimensioning, life span and requirements. Results allow evaluation of control and energy management functionalities.

As a result of the study carried out, next steps could be planned

1) Improvements of power system component models
2) Optimisation of energy storage operation and dimensioning
3) Energy storage life span modelling
4) Emulation of PDS and hybrid operations in laboratory

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16. Ship emissions review

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16.1 Introduction

The emissions from ships can be a significant source of air pollution in coastal areas and port cities and can have negative impact on human health and climate. Therefore, the International Maritime Organisation (IMO) has implemented regulations to reduce emissions from ships. So far, these regulations cover emissions of sulphur oxides and nitrogen oxides. However, several other emission components in the ship exhaust are harmful, and new regulations are anticipated in the near future.

As a part of Business Finland funded INTENS project, Task 3.3.1 "Ship emissions in the future" reviewed the ship emissions including introduction to current emission legislation and results of various emission species from marine engines [1]. Consideration was given to the ship exhaust emissions already regulated, and the emissions anticipated to be regulated in the near future, namely particulate matter, particle number and black carbon emissions. Other emission components, such as methane emission, were also presented as well as some possible technology pathways to decrease emissions. Development of these technologies can be considered when preparing for the future ship emission regulations. Aim is to produce valuable information for the work where the minimized emissions are one basic criteria.

16.2 Results

The IMO regulates NO_x and SO_x emissions globally, and regional emission regulations are set also e.g. by EU, USA and China.

Emission measurements from a liquefied natural gas (LNG) powered ship have shown reduction of SO_x and PM emissions of almost 100% and NO_x emissions

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about 90% compared to marine fuel oils. This indicates that LNG is a possible way to handle the regulation of both SOx and NO_x emissions. Methanol as marine fuel has slightly lower emission reduction potential (99% for SOx, 60% for NO_x and 95% for PM) than LNG.

Exhaust treatment with SO_x scrubber removes SO_x emissions almost completely. Selective catalytic reduction (SCR) is efficient for reduction of NO_x. SO_x scrubber, SCR and diesel oxidation catalyst (DOC) may also remove PM to some extent, and possibly some other emission components. Combination of distillate fuel, SCR and diesel particulate filter (DPF) would reduce almost 100% of SO_x and PM emissions, and more than 90% of NO_x emissions. However, particulate filters are not yet in commercial use for marine diesel engines using marine fuels, or proven for long-term durability.

When approaching climate-neutral shipping, renewable fuels (methane, methanol and distillate-type fuels), hydrogen and batteries are potential options. Albeit being fossil fuel, LNG has shown lower CO_2 emissions than marine fuel oils, and thus also GHG mitigation potential, although compensated to some extent by methane emissions from LNG use.

Summary of the evaluation of the exhaust emissions using different marine fuels and exhaust treatment technologies compared with residual fuel use in marine diesel engine is presented in Table 1. There are several technologies capable to meet the present and future emission regulations for ships, although some of these technologies are still developing, and some have other limitations (e.g. regarding retrofitting). However, low-emission performance of ships could be achieved by different choices of technologies depending on edge-conditions for specific ships, regions and routes, amongst others.

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Table 1. Evaluation of impacts of different technologies on the exhaust gas emissions from marine engines compared with residual fuel use in marine diesel engine. - = base (residual fuel), + = better than base, ? = further research needed.

	SO$_x$ emission	**NO$_x$ emission**	**PM emission**	**PN emission**	**BC emission**	**Other emissions**	**Score**
Fuel							
Residual fuel	-	-	-	-	-	PAH, metals	**- - - - - -**
Distillate fuel	+		+	?		*	**++**
Biodiesel	+		+	?	+	*	**+++**
LNG	+	+	+	?	+	Methane*	**++++**
Methanol	+	+	+	?	+	*	**++++**
Treatment							
SCR		+		?		Ammonia	**+**
SOx scrubber	+		+	?		*	**++**
DOC			+	?		*	**+**
Combined							
Dist+SCR+DPF	+	+	+	+	+	*	**+++++**
Other							
Hydrogen/FC or batteries	+	+	+	+	+	+	**++++++**

*Other emission species to be considered, e.g. formaldehyde.

17. Catalytic aftertreatment systems for marine applications

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17.1 Introduction

Marine transport has been increasing continuously worldwide and the total and local engine exhaust gas sources form a crucial part of harmful emissions emitted to air and water. The emission legislation for marine applications have been relatively behind the mobile vehicles' and stationary power plant emission control. However, the emissions are increasing the total emissions, which are spread in atmosphere all around earth causing e.g. the global acid rain deposits (sulphuric and nitric acid) on ground and seas. The emission legislation and fuel reserves in earth have been the driving forces to alternative (gaseous) fuels for energy and transportation. The tightening CO2, SOx and particulate emission limits for marine applications favour the use of natural or other gases in combustions. Emission legislation has been concentrated on NOx and SOx, where SOx is mainly aimed to be controlled by fuel-S content and NOx by selective catalytic reduction (SCR) using ammonia or urea as a reductant. On-ship SOx removal as developed by Wärtsilä is also a potential method and makes possible to use cheaper high sulphur fuels in all sea areas.

Natural gas (NG) is an alternative fuel to replace partly conventional liquid fuels to improve fuel economy (less CO2) and decrease pollutants (particulates). Stoichiometric NG engines with Three-way Catalysts (TWCs) are a main solution with mobile heavy-duty engines in transient on-road drive. However, lean NG combustion results in a lower fuel consumption and thus NG and dual-fuel lean combustion is a main stream in large marine engines.

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17.2 Catalytic aftertreatment methods for diesel engines and NOx

Conventional systems like SCR are used for exhaust gas purifications with diesel (LFO, HFO) fuels. If the fuel-S is high, the vanadium-SCR catalyst possibly with an Ammonia Slip Catalyst (ASC) downstream is the NOx removal system. These SCR catalysts are based on titania (TiO2) support with tungsten oxide (WOx) as a promoter and vanadium oxide (VOx) as an active compound. Ammonia or urea are used as selective reductants for NOx. Vanadia-SCR catalysts are chemically more durable and cheaper than copper and iron SCR catalysts applied in latest mobile applications. SCR catalysts are coated on ceramic/metallic substrates or they are extruded ones, which are popular with low cell densities in “dirty” exhaust gases. In addition to ammonia, ASC will oxidize a part of HC and CO, which is formed also from urea. ASC is small and Pt loading very low keeping sulphate formation low. This is a natural solution for marine applications, where the use of efficient DOC with platinum is limited due to its high sulphate formation. SO2 is oxidized to SO3 reacting fast to sulphates, which are absorbed on soot particles and increased the particulate (PM) emissions. Particular DOCs with a low sulphate formation is a development target in this project. Diesel Particulate Filters (DPF) are also under examinations for marine applications. Due to higher PM emissions, the cell density (channel size) of catalyst converters need to be low (< 100 cells per in2) to prevent blocking of catalysts. Vanadium SCR catalysts have been prepared on round and metallic but in ceramic substrates in Dinex (Figure 1).

Figure 1. SCR products prepared by Dinex Finland.

17.3 Catalytic aftertreatment methods for natural gas engines

Natural gas (mainly methane) has almost no sulphur (<1 ppm) and harmful SOx emissions are negligible. Natural gas is a good alternative but requires the development due to regulations for methane emissions. Methane (CH4) has also a much stronger greenhouse effect than CO2 (25x higher). Methane combustion results in less CO2 than diesel (~ CH1.8) combustion. Methane is the most difficult hydrocarbon to be oxidized in any conditions, which is very challenging for the catalyst. If using more NG, PM, SOx and CO2 emissions will decrease but the GHG of methane will increase drastically without control.

Particular Methane Oxidation Catalysts (MOC) have been developed for methane removal in lean exhaust gases. They are usually metal oxide based with thermal promoters with a high loading (> 5 g/L) of active noble metals (e.g. Pt, Pd), which makes that large MOC very expensive. MOCs are weak for sulphur accumulation and a sulphur tolerance is the key property in catalyst and system development. Pd-rich catalysts are slowly sulphated in use conditions, even if sulphur is originating solely from lubrication oil. Therefore, regeneration method and strategy is a part to keep MOC functionality. MOC is regenerated at higher temperatures (>500°C) in lean or stoichiometric conditions. When stoichiometric conditions are practically limited with larger engines, it is also possible to use a higher concentration of methane, other HCs or hydrogen in sulphate decomposition in lean (Figure 2).

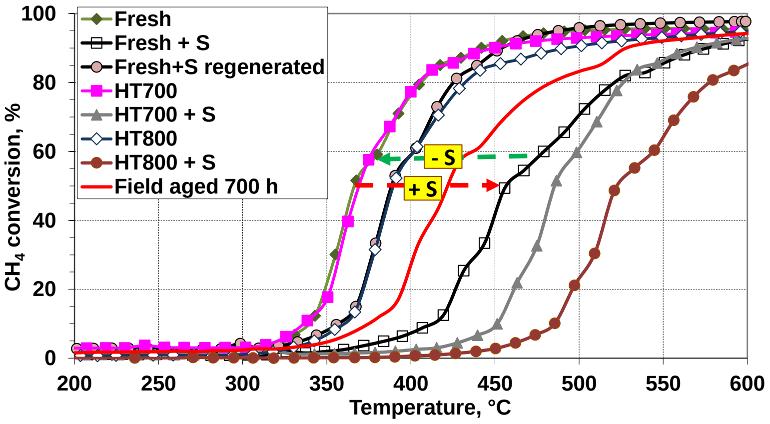

Figure 2. Methane conversion as a function of ageing conditions on a MOC in simulated lean NG exhaust gas (1500 ppm CH_4, 300 ppm C_2H_6, 100 ppm C_3H_8, 150 ppm aldehydes, 1200 ppm CO, 500 ppm NO, 7.5% CO_2, 8% water, bal. N_2; λ 1.78, SV 50.000 h^{-1}, Sulphating with 25 ppm SO_2 for 20 h with water and air).

Regenerated at 650°C with 1% methane in lean test gas mixture (Maunula et al. 2016).

17.4 Summary

ATSs are gradually applied also for marine applications, focusing first on NOx and SOx emissions. The improved diesel fuel quality decreases naturally harmful emissions (SOx, PM) and enables the use of other methods like DOC and DPF in marine applications. Natural gas, hybrids and dual-fuel engines together with tailored systems give challenges for catalytic ATS development and optimization. A pre-turbo catalyst assembly has been also under development with marine engines to optimize the heat management for methane oxidation or SCR reactions.

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18. Emission reduction by biogas use in short sea shipping

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18.1 Introduction

Climate change recently has received increased attention in the shipping sector. This is mainly due to growing awareness of the need to cut global emissions and the fact that shipping is one of the fastest-growing sectors in terms of greenhouse gas (GHG) emissions [1]. In April 2018, IMO Marine Environment Protection committee (MEPC) finalized and adopted the Initial IMO Strategy on Reduction of GHG Emissions from Ships, designed to minimise air pollution in line with the central climate goal defined in the Paris Agreement, limiting global warming to well below 2°C. More specifically, MEPC outlined a target to reduce the total annual GHG emissions by at least 50 % by 2050 compared to 2008, while also pursuing efforts to phase them out completely [2].

The shipping industry is now striving to find strategies to meet forthcoming emission regulations. Fuel is an important factor in emissions, so a transition to alternative fuels is one of the options being examined. However, a fuel's environmental impact relates not only to combustion in the engine but also to its whole life cycle, starting at the well [3]. Fuels invariably incur release of emissions at various stages of their life cycle, such as during refining and transport [4]. This means that use of a fuel that appears favourable in the combustion phase may have large environmental impacts in the upstream processes or vice versa [3]. Considering the environmental life-cycle impacts of fuels is therefore essential to ensure any alternative fuel delivers meaningful emissions savings. [4]

There is increasing focus on gas as an alternative to conventional fuels. Switching to LNG instead of heavy fuel oil would significantly improve the overall environmental performance because gas produces less NOx and particulates in the exhaust, and SOx emissions are almost eliminated. However, the impact on climate

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change is less clear. In contrast, liquefied biomethane (LBG) exhibits, in principle, a neutral recirculation loop for CO2, which is one of the main causes of global warming.

Reducing the impact on climate change is important for all shipping segments, but for short sea vessels in regional operations near coasts and populated areas, local pollutants must also be addressed [5]. In this study, the emission performance of LBG in short sea shipping was investigated and compared to LNG and conventional marine diesel oil (MDO). The emissions quantified are three greenhouse gases (CO2, CH4, and N2O) and four local pollutants (SOx, NOx, NH3, and particulate matter). Life Cycle Assessment (LCA) was used to assess the complete global warming potential of each fuel. The local and regional environmental impacts of their combustion were also assessed. The study used a Ro-Ro/passenger ship vessel scheduled service in the Baltic Sea ECA as its basis.

18.2 Materials and methods

Table 1. Modelling choices of the study.

Functional unit	1 year of RoPax ferry service to and from Vaasa and Umeå
Fuel chains	Marine Diesel Oil (MDO) 0.1 % S Liquefied natural gas (LNG) Liquefied biomethane (LBG)
Geographical boundaries	The sulphur emission control area (SECA) in the Baltic Sea The NO_x emission control area (NECA) in the Baltic Sea (1.1.2021)
System boundary	For GHG-emissions, the whole fuel life cycle is included from raw material extraction to combustion in marine engines. Local and regional environmental impacts are assessed from the tank-to-propeller perspective.
Included primary pollutants	GHG (LCA) • carbon dioxide (CO_2), • methane (CH_4), • nitrous oxide (N_2O) Other pollutants (local and regional impacts) • nitrogen oxides (NO_x), • sulphur dioxide (SO_2), • particulate matter (PM_{10}) and • ammonia (NH_3)
Impact categories	Global warming potential (GWP_{100}) Local and regional environmental impacts • Acidification potential • Eutrophication potential • Human health damage (DALY)

18.3 Results and discussion

All three investigated alternatives, LNG, LBG, and MDO combined with SCR, comply with the strictest ECA regulations currently in force or effective from 2021. However, the two gaseous fuels, LNG and LBG, showed better local and regional environmental performance compared to MDO+SCR in terms of their acidification and eutrophication potentials. Gaseous fuels also can deliver significant cuts to emissions of PM, yielding benefits in terms of impact on human health (Fig. 1).

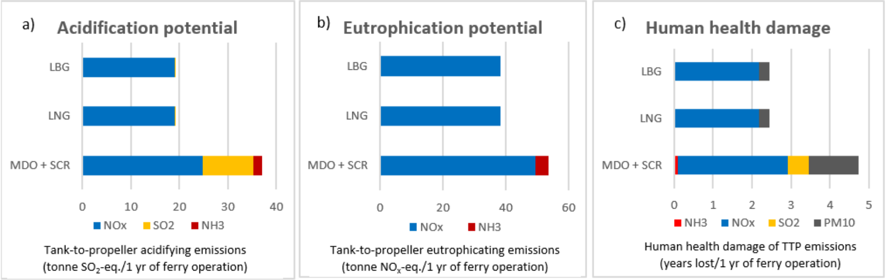

Figure 1. Environmental impacts with MDO, LNG and LBG for impact categories a) acidification potential, b) eutrophication potential, and d) human health damage.

This study identifies substantial life cycle GHG emission benefits associated with shifting from fossil fuels to LBG (Fig. 2). The CO_2-eq. reduction compared to LNG is evaluated at 58 %, and at 60 % compared to MDO. This difference stems from the fact that CO_2 emissions released when biomethane produced from organic waste materials is combusted are biogenic, not contributing to climate change and so reported as zero. LBG's tank-to-propeller phase GHG emissions are mainly caused by methane slip from the dual-fuel engine and to a minor extent from the MDO pilot fuel used for ignition.

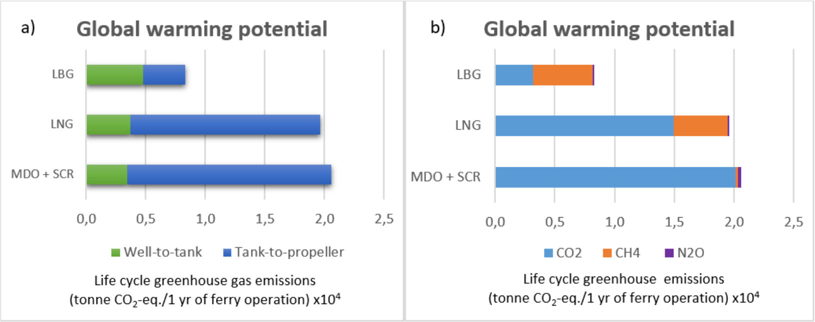

Figure 2. a) GWP_{100} for LBG, LNG and MDO+SCR divided into well-to-tank and tank-to-propeller phases. b) Life cycle GHGs divided into the different contributing emissions.

The overall GHG impacts of LNG are highly dependent on methane leakage rates in LNG production and distribution, and especially on methane slip rates from fuel combustion (Fig. 3). Approximately 2.5 % methane slip from fuel combustion cancels out the decreased emissions of CO_2, leading to GWP_{100} equal to diesel fuel's. Therefore, it seems LNG currently does not offer the significant CO_2-equivalent reduction needed to sustain the IMO's vision of decarbonising shipping. This conclusion is in line with many other studies [3, 4, 6, 7, 8].

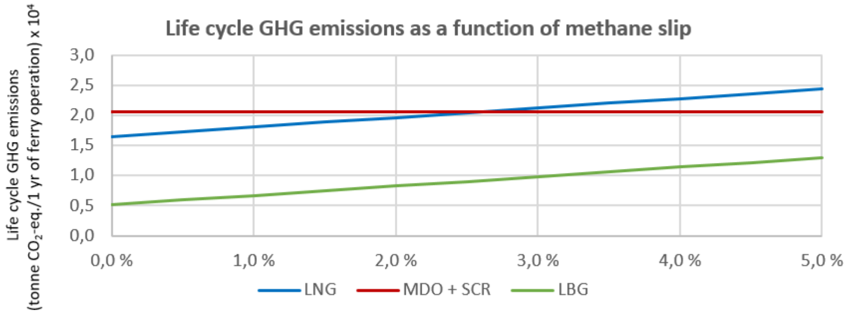

Figure 3. Life cycle GHG emissions as a function of methane slip from engine.

This study indicates the short sea shipping fuel with the best overall environmental impact is LBG, followed by LNG. LBG's lower life cycle emissions of greenhouse gases put it ahead of LNG. The major challenge for LBG is fuel availability in the quantities needed for shipping. Today, a switch to LNG could be part of a long-term solution for short sea shipping, providing a bridge technology to be followed by the use of LBG. Introduction of biofuels on the market is also possible through blending with fossil fuels [1].

18.4 Conclusion

The purpose of this study was to evaluate the emissions performance of biogas in short sea shipping. Other investigated fuels were LNG, and MDO combined with SCR. Based on the life cycle GHG emission analysis and the emissions matrix for local air pollutants, the following conclusions could be made:

- LNG is a promising option for meeting existing regulation, but is not a low-GHG fuel.
- A shift to LNG in the shipping sector would have significant benefits in terms of reducing local air pollutants, but LNG's impact on climate change is of the same magnitude as that of traditional marine fuel.
- Reducing total annual emissions from shipping in line with the initial IMO strategy objective of at least 50 % GHG reduction by 2050 from 2008 levels seems possible only with fuel produced from renewable sources.

- The use of LBG produced from municipal organic waste has potential to reduce life cycle GHG emissions from short sea shipping by 60–75 % compared to marine diesel, and would significantly reduce the impact of ship emissions on local air quality.
- The major challenge for LBG is fuel availability in the quantities needed for shipping.
- LNG can provide a bridge technology for a low-carbon shipping sector.
- Lowering methane emissions is an important development focus for the coming decade.

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19. Optimal control maps for fuel efficiency and emissions reduction in maritime diesel engines

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19.1 Introduction

Oceangoing ships are the largest single cause of nitrogen oxides (NOx) emissions globally, and NOx is generally a major air pollutant in the atmosphere. Most of these emissions are released near the land, which causes a major pollution problem and health risk to the people. It has been reported that outdoor air pollution caused about three million premature deaths globally in 2010. Since ship transportation is constantly increasing, it is easy to understand that the International Maritime Organization (IMO) is setting more and more stringent restrictions to ship emissions. Large tankers are major pollutants driven by diesel engines. Even if the number of diesel engines in automobile industry is foreseen to decrease fast in the future, such a trend cannot be foreseen for maritime engines, because replacement of large diesel engines as power source in maritime applications seems to be a hopeless task for several decennia to come.

The engine manufacturers are interested in developing more and more efficient engines with increasing efficiency, reduced fuel consumption and reduced emissions. Unfortunately, considerable efficiency increase is already hard to establish, and reducing fuel consumption generally implies higher NOx emissions and vice versa. Because of this, IMO has set regulations (Tier II and Tier III) that set limits to NOx emissions in some operation points (speed and load) of the ship. However, only a few operation points have been set, which means that it is unclear

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how the ship emissions should be controlled over the whole operation range. Even worse, the current regulations give a possibility to “cheat” by setting the emissions low at the given operation points (high fuel consumption) but use all effort to save fuel in other operation points (high NOx emissions).

In Figures 1 and 2, the emission standards by the International Maritime Organization (IMO) have been given. The maximum allowed emission is in one operation point or then by several under the given weights shown in Figure 2. There the speed is considered constant but the load is varying, which leads to the use of weights applied in each specific load.

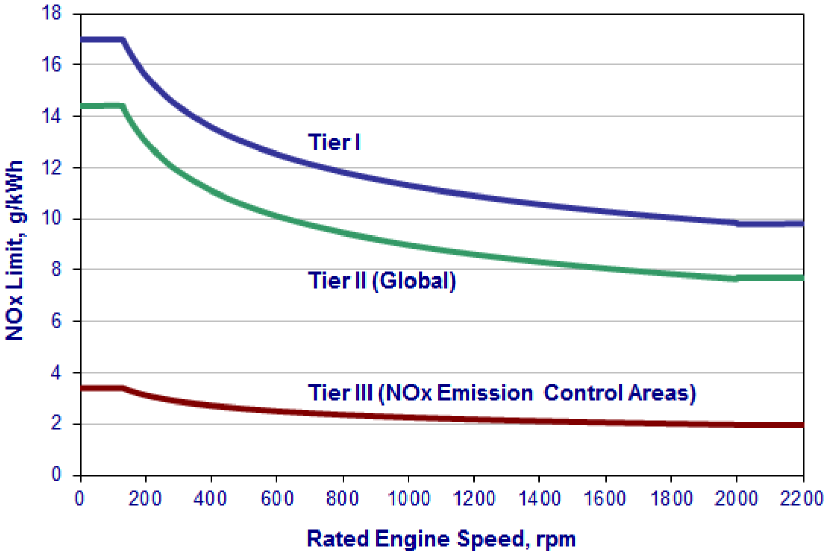
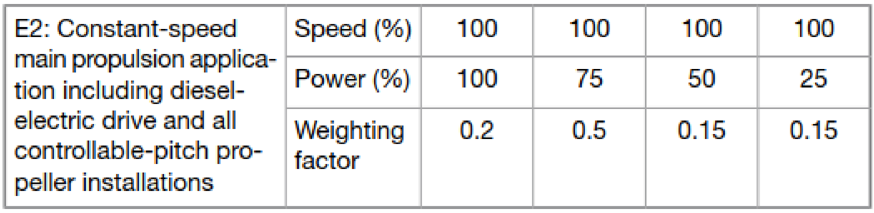


Figure 1. NOx emissions under Tier I, II and III



E2: Constant-speed main propulsion application including diesel-electric drive and all controllable-pitch propeller installations	Speed (%)	100	100	100	100
	Power (%)	100	75	50	25
	Weighting factor	0.2	0.5	0.15	0.15

Figure 2. Setpoints with different weights

Figure 3 shows cruise statistics of a real ship, and the idea is to minimize the BSFC under the constraint of the Tier II NOx limitations.

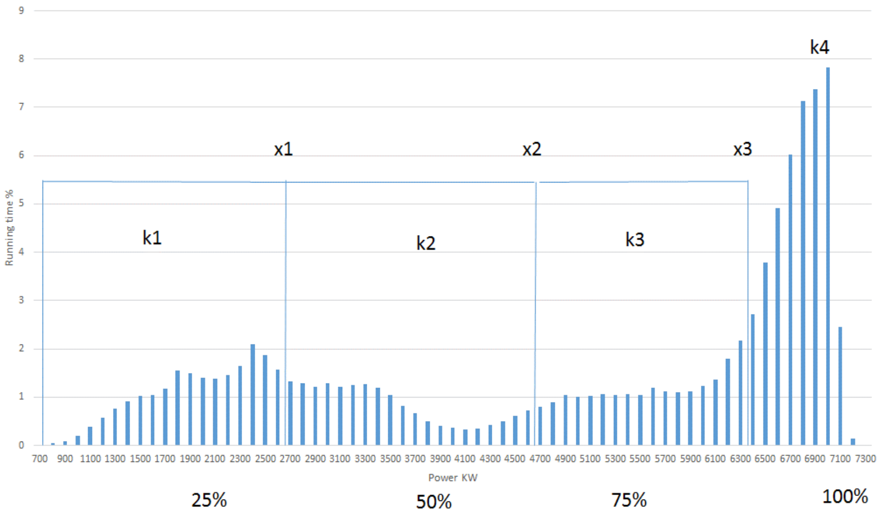


Figure 3. Cruise characteristics of a ship.

19.2 Methods

In this research a method has been presented, where the Design of Experiments (DOE) method is used to model the fuel consumption and NOx emission at any given operation point. It then becomes possible to construct smooth functions to cover all operation points of the ship engine. At any operation point, an optimization problem can be set and solved, where the fuel consumption is minimized under a given constraint of maximum NOx emission. The solution gives certain control parameters of the ship (common rail pressure, charge air pressure, start of ignition timing), which are to be used in the operation point in question for optimal performance. It now becomes possible to compare the fuel consumption and emission level under standard routes travelled by the ship. In addition to that, it becomes possible to construct optimal operation parameters and allows NOx levels under a large number of operation points, thus giving advice to IMO how the future regulations could be stated, in order to cover all operational areas and to avoid all possibility to cheat.

The results of the research have been obtained and confirmed using real diesel engine data, in co-operation with Wärtsilä, received from the experiments at the VEBIC laboratory in University of Vaasa.

During the on-going research, experimental data was first obtained by two separate test periods in Vaasa. The Design of Experiments (DOE) method was used to construct regression models for Break Specific Fuel Consumption (BSFC) and Nitrogen Oxide Emissions (NOx) at several operation points (engine speed and load). Data from eight different operation points were obtained.

19.3 Results

As a result of optimization, the control parameters of the ship engine (Common rail pressure, crankshaft angle at 50% fuel burnt and charged air pressure) were obtained for each load during the cruise. The optimization problem was set under the hard constraint that the Tier II requirements were satisfied. Some results are shown Figure 4.

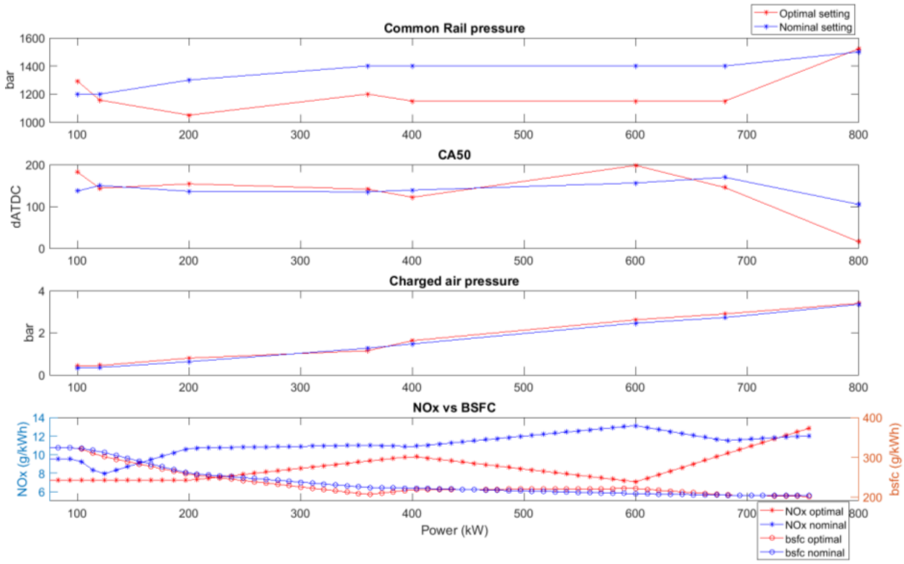


Figure 4. Results following the optimization procedure

It is evident that the savings obtained were not large, but the NOx emissions were considerably reduced when compared to nominal data. The result was obtained mostly because of a reduced setpoint value in the common rail pressure. However, it must be taken into account that soot formation, NOx emissions and particulate matter emissions were not considered. In addition, it is to be understood that the available data is limited, and therefore some interpolation has been used. The research is on-going and the results shown are preliminary.

The relevance of the method being developed is in constructing a systematic method for solving optimal control parameters for a cruise ship, which minimize the fuel consumption and emissions such that the IMO regulations are fulfilled. There is no doubt that the method can be used for general emissions also (not only NOx). In addition, the design gives valuable information on the Tier regulations as such, specifically on how they should be considered over a whole cruise of a ship.

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Title	**Integrated Energy Solutions to Smart And Green Shipping** 2019 Edition
Author(s)	Zou Guangrong (Editor)
Abstract	The global marine cluster is in major transition to smart and green shipping. The pressure and need for the decarbonization, digitalization and automation in shipping are high from regulatory, environmental, economic and technological perspectives, which poses challenges and opportunities to the cluster. It is imperative for Finland since the hi-tech and marine industries are two of the mainstay industries for the country. This book is one of the activities to disseminate and showcase the Finnish expertise, practices and on-going efforts towards smart and green shipping, It also acts as the proceedings of the first public seminar of the INTENS project, which is a national collaborative research and innovation action striving to advance and promote the digital transformation and collaboration in the Finnish marine industries and beyond. It features a collection of extended abstracts, concerning simulations, algorithms, technologies and practical applications of major digital transformation methods, including Artificial Intelligence (AI), Big Data, Digital Twins, Industrial Internet of Things (IIoT) and Cloud Computing, specifically to the energy efficiency improvement and emissions reduction of ship energy systems. It highlights the prominent roles of both innovations and collaborations in the digital transformation and decarbonization of global shipping.
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