



# IAMU 2014 Research Project (No. 20140301)

# Improving Energy Efficiency of Ships through Optimisation of Ship Operations

By Istanbul Technical University (ITU)

August 2015

IAMU International Association of Maritime Universities This report is published as part of the 2014 Research Project in the 2014 Capacity Building Project of International Association of Maritime Universities, which is fully supported by The Nippon Foundation.

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Published by the International Association of Maritime Universities (IAMU) Secretariat Toranomon 35 Mori Building 7F, 3-4-10 Toranomon, Minato-ku, Tokyo 105-0001, JAPAN TEL : 81-3-5408-9012 E-mail : info@iamu-edu.org URL : http://www.iamu-edu.org Copyright ©IAMU 2015 All rights reserved ISBN978-4-907408-11-4





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Contractor: Oğuz Salim SÖĞÜT, Dean, ITU Research Coordinator: Ozcan ARSLAN, ITU Research Partner: Elif BAL BESIKCI, ITU Aykut I. OLCER, WMU

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# Improving Energy Efficiency of Ships through Optimisation of

# **Ship Operations**

# Theme: Sustainable modern shipping technologies

Istanbul Technical University (ITU)

### And

World Maritime University (WMU)

#### Ozcan ARSLAN,

Associate Professor, Istanbul Technical University, arslano@itu.edu.tr

#### Elif BAL BESIKCI,

Research Assistant, Istanbul Technical University, <u>bale@itu.edu.tr</u> And

#### Aykut I. OLCER,

Professor, World Maritime University, aio@wmu.se

*Abstract* Increased environmental concerns, resulted in new legislation, and high and volatile fuel prices are today's driving forces to reduce operational costs and become greener. Reduction of fuel consumption acts as the main contributor towards this. In the context of the given economic pressure and from international law point of view, the amount of energy-savings by vessel fuel should be increased and energy consumption should be reduced as much as possible. From the shipping industry perspective, there exists good practices and technological solutions for energy efficient ship operations. However, opting for the right practice and monitoring it on a timely basis during a voyage are complex challenges that the shipping industry is faced with today. Even if the right mean was selected for a ship's voyage, fuel savings might not be satisfactory as predicted due to the real-time environmental conditions such as weather and sea state etc.

The purpose of this project is to create a mechanism and develop a Decision Support System (DSS), which is to monitor the energy consumption on a real-time basis and to optimise it through a real-time decision support system that will help improve the energy efficiency of ship operations within SEEMP. Therefore, a decision support system will be developed for real-time energy monitoring and making optimal decisions during ship operations. Energy simulation software from the literature will be selected and combined with an optimisation algorithm to form a decision support system to be used on-board vessels as well as onshore for energy efficient ship operations.



DSSs for the optimization of energy efficiency on ship operations help decrease the complexity of the situation and in this way the managers' (the captain of the ship and /or enterprises operating units) awareness can be simultaneously strengthened. The developed DSS is illustrated and exemplified in two scenarios, which helps draw the conclusion of its promising potential in providing a strategic approach when ship operators provide decisions at the operational level considering both the economic and environmental aspects.

Finally, a decision support system will be developed, which is intended to be used by the Captain of the ship and on-board personnel and ship management operators onshore. Thus, companies will be able to obtain broad long-term gains by the optimization and measurement of the ship's operational efficiency.

Keyword: Ship Energy Efficiency, Operational Measures, Fuel Savings, Decision Support System



# 1. Introduction

## 1.1 Recall of the Project's Overall Subject

The research project 'Improving Energy Efficiency of Ships through Optimization of Ship Operations' brought together two recognized IAMU institutions by merging and combining their research competencies on specific subject areas related to energy efficient shipping. Under the leadership of Istanbul Technical University (ITU) and cooperation with World Maritime University (WMU), the partners commonly developed their ideas for the project dedicated to investigate the potential for fuel savings for existing ships through operational measures by providing a strategic approach to identify energy efficient solutions.

This project report deals with the investigations to describe the potentials for energy-efficient operations and focuses on the application of the research outcomes into the development of Decision Support System (DSS) to monitor the energy consumption on a real-time basis and to optimize it through a real-time decision support system that can improve the energy efficiency of ship operations within SEEMP.

In this respect, this project deals with the enhancement of the amount of energy-savings by ships' fuel and reduction of energy consumption as much as possible for the economic pressure and international legislation.

The research project is specifically dedicated to apply a Decision Support System (DSS) intended to be used by the captain of the ship and on-board personnel and ship management operators onshore. In addition, energy simulation software from the literature will be selected and combined with an optimization algorithm to form a decision support system to be used on-board vessels as well as onshore for energy efficient ship operations. A web page related to ship energy efficiency will be created to that extent and finally, a training 3-D video will be developed that will be integrated into the web page.

#### 1.2 Project Aims and Objectives and Methodological Approach

Carbon emissions from maritime industry accounts for a significant part of total global greenhouse gas (GHG) emissions. The International Maritime Organization (IMO) has indicated that the contribution from ships was estimated to be 1016 million tonnes for the period 2007-2012, which make up approximately 3.1% of global carbon emissions [1]. With the tripling of world trade, if no action is taken, these emissions are forecasted to increase by 50% - 250% until 2050 [1]. OECD also stated a similar level of prediction in the increase in  $CO_2$  emissions from the shipping industry [2].

On the other hand, shipping companies encounter high risks as a result of increased fuel prices to maintain their competitive power in the market. The fuel cost represents a large amount of the total operating cost of a shipping company, which is estimated to be 50% [3] or even more than 60% [4]. Consequently, shipping companies focus on energy-efficient procedures and operations for decreasing energy consumption in order to lower their management costs and thus maintain their competitive position in the market.

In this respect, the amount of energy-savings by ships' fuel should be increased and energy consumption should be reduced as much as possible to deal with the economic pressure and cope with international standards in respective legislation. Ship energy efficiency measures propose various alternatives to ship owners and operators to lower fuel consumption and carbon emissions. The potential for fuel savings in shipping by 25% to 75% is achievable through more efficient operations of existing ships and increased energy efficiency in the design of new builds [5]. IMO's Marine Environment Protection Committee (MEPC) adopted the addition of new regulations related to energy efficiency of ships to MARPOL (International Convention for the Prevention of Pollution from Ships) Annex VI, as a new chapter (Chapter 4). In this context, as of 1st of January 2013, all new ships have



to comply with an Energy Efficiency Design Index (EEDI) and all ships have to carry a Ship Energy Efficiency Management Plan (SEEMP) [6]. Moreover, Energy Efficiency Operational Indicator (EEOI) was recommended as a form of guidance to monitor the progress of the SEEMP [7]. While EEDI suggests technology and design based measures at a minimum level with a long-term impact for new ships, the aim of SEEMP is to enhance the energy efficiency through energy efficient ship operations using available technologies on board a ship. Although there are many technological and design based approaches, limitations of these measures due to the long payback duration have led to discussions on the potential of implementing operational changes. Due to the given reasons, the fuel saving of ships has become paramount for ship energy efficiency.

Decision support systems (DSS) is a computer-based approach that helps decision makers use data, models and other knowledge on the computer to solve semi structural and some non-structural problems, which cannot be measured or modelled. These problems require human intervention, and therefore, solutions to semi-structured problems are often obtained by allowing a decision-maker to select and evaluate practical solutions the set of feasible alternatives. The goal of DSS is improving decision-making effectiveness and efficiency by integration of information sources and analysis tools [8].

Providing a strategic approach to identify energy efficient solutions becomes more complicated for ship operators due to its complexity and difficulty. There is a need for decision support to provide quickly and directly solution for predicting fuel consumption at an operational level through implementing the most appropriate operational measures to increase energy efficiency against high oil prices and greenhouse emissions. DSSs for the optimization of energy efficiency on ship-voyage management help to decrease the complexity of the situation, and by this way, the operator will be strengthened for the awareness of the situation.

The overall purpose of this project is to create a mechanism and develop a decision support system based on Artificial Neural Network (ANN) method for ship operators (the captain of the ship and /or enterprises operating units) which is to monitor the energy consumption on a real-time basis and to optimize it through a real-time decision support system that can improve the energy efficiency of ship operations within SEEMP. Therefore a decision support system has been developed for real-time energy monitoring and making optimal decisions during ship operations. Energy simulation software from the literature will be selected and combined with an optimization algorithm to form a decision support system to be used on-board vessels as well as onshore for energy efficient ship operations.

The main aim of this project is twofold: (i) predict ship fuel consumption for various operational conditions through an inexact method, Artificial Neural Network ANN; (ii) develop a decision support system (DSS) employing ANN based fuel prediction model to be used on-board ships on a real time basis for energy efficient ship operations.

The work in the project was organized and structured in the following work packages:

WP1:

#### - Interim Report

WP2:

- Literature survey about ship energy efficiency.
- Determining of best measures for energy consumption areas on-board.
- WP3:
  - Classification of ship energy consumption areas that could be controllable and determination of ship voyage energy efficiency parameters.

WP4:

Collecting of ship voyage performance data (noon reports) from shipping companies.



- Analysis of ship voyage energy efficiency data and creating decision support system for captain or management officers.

#### WP5:

- Creation of database, interface and web page.
- Creation of short training video with 3D. (Although, this video did not include in the application form, it has been generated to be embed to the website for training purposes).
  In order to realize the aims and objectives, the partners have been performed several working activities. The following activities and tasks were performed and accomplished:
- The progress of project and all the management items has been monitored continuously to assess the status of project implementation in relation to the approved work packages and budget.
- Literature survey for ship energy efficiency has been carried in detail and operational ship energy efficiency measures has been identified and examined within the scope of SEEMP.
- The information and data of ship fuel consumption are acquired mainly from noon reports and also supported by daily reports of the tanker ship. Tanker ship data are collected from shipping companies.
- This project is conducted using 3646 ship noon reports, which have covered the sailing of the ship over since it was built.
- In this research, a neural network model has been implemented to create a mechanism and develop a decision support system based on Artificial Neural Network (ANN) for ship operators (the captain of the ship and /or enterprises operating units).
- The important impact parameters have been determined statistically and are to be used as input in the network training for fuel consumption forecasting model.
- The results using the ANN developed above are compared with multiple regression analysis (MR), other well-established method of surface fitting.
- Analyzing of data; energy simulation software combined with optimization algorithm has been created to form a decision support system for a captain of a ship and on-board personnel as well as onshore operators.
- The web page has been created, which is composed of information and important documents related ship energy efficiency that can be seen on the link below.
  'www.ship-energy.com'.
- Short training video with 3D has been created to assist users with teaching the importance of ship energy efficiency measures and improving the energy efficiency of ship operations within SEEMP.

The most important deliverable from the project is the final report document. Several preliminary results and outcomes were produced during the research phase of the project. On the basis of interim project results, a manuscript has been submitted to the international journal and accepted for publication.

In addition, an interim report was prepared and a paper has been presented during 15th IAMU Annual General Assembly in Launceston, Tasmania in 27 - 30 October 2014. The slides are attached to this final report as a separate appendix.

# 1.3 Research Activities and Distribution of Results

The principle work of this project phase followed the above mentioned work packages.

For the coordination of the partners' activities virtual (Skype conference) meetings and e-mail correspondence have been handled to monitor the progress of the project.



The project leader Istanbul Technical University has coordinated the project partners and their common activities. In addition, within the scope of this project, there were also some travel activities.

- First, partner-meetings was organized in Turkey to discuss and monitor the progress of the project.
- Second, partners attended the IAMU AGA 15 conference held in Tasmania and presented the progress report of the project.
- Finally, partner-meetings was organized in Turkey in the date of 11.May.2015 to discuss the results and draw the conclusion of the project.

During the course of the project, the following papers referring to work done and results gained in this project have been delivered:

- Arslan, O.; Bal Besikci, E., Olcer, I.A., Improving Energy Efficiency of Ships Through Optimisation of Ship Operations. Paper presented at the 15th IAMU Annual General Assembly in Launceston, Tasmania in 27 30 October 2014.
- Bal Besikci, E., Arslan, O., Turan, O., Olcer, I.A., An artificial neural network based decision support system for energy efficient ship operations, Computers and Operations Research, Article accepted for publication: 9-APR-2015. DOI information: 10.1016/j.cor.2015.04.004

The presentation and the accepted manuscript were partly based on the outcomes of work performed in the frame of this project. The chapters reflect the content of these studies.

## 1.4 Research Results and Structure of the Report

In terms of ship energy efficiency, fuel consumption has become a primary concern. The lowering of fuel consumption is considered to be the ultimate goal, which is the result of economic pressure and environmental regulations.

The potential for fuel savings is possible for existing ships through operational measures. The ideal situation for the ship operators would be to have an efficient support system in making decisions concerning the implementation of operational measures to improve ship energy efficiency.

In this research, an Artificial Neural Network (ANN) based decision support system that supports the ship operators in making decisions concerning the implementation of operational measures to improve ship energy efficiency, is presented.

The proposed method can be considered as a successful decision support tool for ship operators in forecasting fuel consumption based on different daily operational conditions.

The remainder of this paper is organized as follows. Section 2 discusses the international regulations related ship energy efficiency. Section 3 examines operational ship energy efficiency measures in details. In Section 4, the methods and data conducted in this study are presented. Section 5 describes the design, development and performance of the ship operational energy efficiency ANN system that predicts ship fuel consumption under various operational conditions, based on the noon data. Section 6 discusses the design of the (DSS) for improving ship energy. The last section draws the conclusion and narrows down the recommendations for further research.



# 2. International Regulations for Energy Efficiency

This chapter describes the international regulations for energy efficiency. United Nations Framework Convention on Climate Change, Kyoto Protocol, the intergovernmental panel on Climate Change, The Copenhagen Accord and finally The IMO's Environmental Regulation including EEDI, SEEMP and EEOI are explained in detail to emphasize the importance of energy efficiency.

# 2.1 United Nations Framework Convention on Climate Change

Scientists began to rise concern about climate change in the early 1980s and this generated an international response to climate change starting with The United Nations Framework Convention on Climate Change treaty, UNFCCC. There are some important actions taken at an international level towards the mitigation of climate change.

The United Nations Framework Convention on Climate Change (UNFCCC) is an international environmental treaty generated at the United Nations Conference on Environment and Development (UNCED), informally known as the Earth Summit, held in Rio de Janeiro from 3 to 14 June 1992. The treaty entered into force on 21 March 1994. The Parties meet annually in the Conference of Parties (COP) to evaluate progress regarding climate change. Presently, there are 195 Parties (194 States and 1 regional economic integration organization) to the United Nations Framework Convention on Climate Change [9].

At the COP, the Parties share state-of-the art information about GHG emissions, national policies, and best practices to mitigate Climate Change and adapt to its' impacts. They also review current conventions (i.e. past decisions about actions to take) as well as new scientific advice and support from expert groups: such as

- The Subsidiary Body for Scientific and Technological Advise (SBSTA)
- The Subsidiary Body for Implementation (SBI)
- The Intergovernmental Panel on Climate Change (IPCC)

The objective of the UNFCCC treaty is for the COP to consider what they could do to limit average global temperature increases and the resulting climate change, and to deal with whatever impacts were, by then, inevitable [9].

The aim of the treaty is the stabilization of greenhouse gas concentrations in the atmosphere at a level that would avoid dangerous anthropogenic interference with the climate system. Such a level should be attained within a time-frame sufficient [10].

#### 2.2 Kyoto Protocol

The Kyoto Protocol was adopted by 186 members at COP3 held in Kyoto, Japan in December 1997.. It then entered into force on 16 February 2005. This Protocol brings about enforcement for emission reductions defined under the UNFCCC treaty. The major feature of the Kyoto Protocol is that it sets binding targets for 37 industrialized countries and the European community for reducing greenhouse gas (GHG) emissions [9].

The Kyoto Protocol also identifies the need to monitor and record emissions by each country and for trade, and thus meet required targets. This is in addition to the Montreal Protocol on Substances that Deplete the Ozone Layer. Under the Kyoto Protocol the IMO and ICAO (the international governing bodies for shipping and aviation retrospectively) are recognized as individual industries due to the complexity and internationality of the industries.



On the 8th of December 2012, amendments to the Kyoto Protocol were made in Doha, Qatar. The significance of these amendments primarily related to the revised lists of GHG, to be reported by Parties and amendments to articles for updated and new commitments for Annex I countries.

### 2.3 The Intergovernmental panel on Climate Change

The Intergovernmental Panel on Climate Change was brought together by the United Nations Energy Program (UNEP) and the World Meteorological Organization (WMO) in 1988, which is to provide the governments of the world with a clear scientific view of what is happening to the world's climate [11]. The IPCC reviews and assesses the most recent scientific, technical and socio-economic information produced worldwide relevant to the understanding of climate change [11].

The IPCC presents this review in: Scientific reports, Assessment reports, Methodology reports, Special Reports and Technical papers.

In some instances the UNFCCC, international organizations and governments have identified specific topics for the IPCC to address. The following provides brief details about the comprehensive assessment reports that have been used to shape the international response to climate change.

# 2.4 The Copenhagen Accord

The Copenhagen Accord was adopted at COP5, which was held in Copenhagen, Denmark in December 2009. This accord recognized the goal of limiting a global temperature rise to 2 degrees, with the following long term goal,

"We agree that deep cuts in global emissions are required according to science, and as documented by the IPCC Fourth Assessment Report with a view to reduce global emissions so as to hold the increase in global temperature below 2 degrees Celsius, and take action to meet this objective consistent with science and on the basis of equity." [12]

# 2.5 The IMO's Environmental Regulation

The IMO, to date, has successfully proposed and implemented many international legislation (including safety, security, and efficiency of navigation and 23 that address the prevention and control of pollution). The IMO, is therefore, recognized as an expert organization in implementing regulations within the specific, international and dynamic shipping industry. It is for this reason the COP recognizes the IMO (under the Kyoto Protocol) as the correct organization to introduce carbon emission reductions in the shipping industry.

The IMO first adopted the International Convention for the Prevention of Pollution from Ships (MARPOL) in 1973 and. In 1997 a protocol was adopted to add an additional annex i.e. Annex VI (Prevention of Air Pollution from Ships). This entered into force on the 19th of May in 2005.

At MEPC 63 (2nd March 2012) it was agreed that further amendments were to be made to Annex VI of MARPOL. These amendments included the addition of the following energy efficiency regulations to Annex VI and these amendments became mandatory on the 1st of January in 2013.

The Second IMO GHG Study 2009 presented the key ideas and the strategy that the IMO proposed and are implementing for improving energy efficiency and hence, reducing carbon emissions emitted by the shipping industry. The principal of the strategy is to approach reductions primarily in two ways; improved ship design and improved ship operation.

Technical and design improvements can arguably offer some of the largest step changes in reducing carbon emissions emitted as a result of increased shipping. However, the drawback with the design options proposed that they will not be as effective in the short term due to;



- Retrofitting being expensive and generally requiring increased dry-docking time (loss of revenue).
- Many new technologies will only be applicable or cost effective to implement on new build ships.
- There is a lot of uncertainty associated with new technologies regarding their reliability, their potential savings per voyage or per year, and their total savings when installed in conjunction with other new technologies and devices.

Therefore, the full potential of the technical/design methods for reducing emission may not be realized until the next generation of the world fleet.

On the other hand, the operational methods can be carried out by all ships (new builds and existing ships). However the savings observed from implementation of these methods will be proportional to the existing energy efficient of the ship and its operation.

Considering operational improvements, reduction in voyage speed is the most effective method as the amount of carbon emitted is proportional to fuel consumed, which increases proportionally (approximately to the third) with speed. This solution suits well with the current economy where there is an oversupply of ships in comparison to demand and therefore, it is more economical to save on fuel costs by proceeding at lower speeds. However, it cannot be expected that this scenario will persist, and therefore, when the shipping demand increases operating a lower speeds will become less economical and a 'less useful' measure. After all, the business of shipping is to transport the cargo from one place to another to match the charterers' requirements.

Achieving energy efficiency and reducing fuel consumption ultimately reduces operational (fuel) costs. In addition to this an added advantage is that 'greenness', 'environmentally friendliness' and/or 'social responsibility' is becoming a much more important factor to many customers along the supply chain. Therefore, becoming energy efficient has the potential to offer a commercially competitive advantage, attracting increased charters.

However, despite the advantages associated with becoming energy efficient, it is still expected that effective carbon emission reductions from shipping on a global scale are not likely to be made without incentive. Therefore, the IMO has introduced regulations (with the intention to make them more stringent over time) and market based measures (financial incentives).

#### 2.5.1 The Energy Efficiency Design Index, EEDI

The EEDI is one of two energy efficiency regulations that was included into ANNEX VI of MARPOL, which became mandatory on the 1st January 2013 [13].

The EEDI is a tool that can be used to calculate an estimated amount of carbon emissions that will be emitted by a ship. It is based on the ships design and technologies installed and hence, it is a technological measure taken to reduce carbon emissions emitted by ships. The EEDI is a calculation that must be carried out during the design stage of a new ship and any existing ship that undergoes a major conversion as of the 1st of January 2013 and onwards. The calculated EEDI is then compared to a required EEDI value (i.e. the maximum allowable value for the calculated EEDI) based on a reference curve for each ship type and selecting the value corresponding to the same deadweight. The central objective is that the required EEDI is made more stringent over time.

The aim of the EEDI is to ensure that the design and technical measures to increase energy efficient are implemented during the design of each new ship. An advantage of the EEDI is that it is non – prescriptive and performance-based so the choice of design and technologies to achieve the required EEDI remains flexible. It is expected that the EEDI will catalyze the development and then installation of new low carbon technologies on board for new ships.



#### 2.5.2 The Ship Energy Efficiency Management Plan, SEEMP

The SEEMP is the second energy efficiency regulation that was included into ANNEX VI of MARPOL that became mandatory on the 1st of January in 2013 [14]. Compared to the EEDI, the SEEMP is concerned with increasing the operational energy efficiency of the ship. The SEEMP is a management plan that should be integrated with existing company policy and management plans and a SEEMP should be developed for each individual existing ship as well as new ships. The guidelines provided by the IMO for the development of the SEEMP provides information on the steps that should be followed to plan, implement and monitor operational energy efficiency improvements. The guidelines go on to describe the type of operational improvements that should be considered as an example layout for the SEEMP.

The operational practices described within the SEEMP require the involvement, contribution and commitment of different stakeholders and for many operations several stakeholders are involved. Therefore, communication and co-operation between these stakeholders is a key element.

The development and utilization of the SEEMP consists of four phases. These are planning, implementation, monitoring and self-evaluation and improvement. These phases, and how they relate to each other, are illustrated in Fig. 1. When the targets defined in the SEEMP are reached, the project should be closed and the process of identifying new initiatives repeated. The SEEMP then enters the planning phase again and in this way the SEEMP leads to continuous improvement towards the ultimate goal of reduced fuel oil costs and carbon dioxide emissions.



Fig. 1 Illustration of the continuous process of SEEMP



#### 2.5.3 Energy Efficiency Operation Indicator, EEOI

Within the SEEMP, the EEOI is listed as a recommended method for measuring energy efficiency improvement and the IMO has also provided guidelines for its use [7]. However, the EEOI is not a mandatory measure and it does not need to be calculated and results do not need to be publica information. However, the EEOI results may offer companies a method of demonstrating their energy efficiency performance to the public and thus it may be beneficial to share the results.

The EEOI is similar to the EEDI in that it is a calculation that quantifies the amount of carbon emission emitted dependent on the useful work done by the ship. However, rather than being based on fuel consumption for the designed ship, actual fuel consumption record for each voyage is used. By averaging the EEOI for many voyages (the rolling average) then operational performance over different useful time periods can be considered along with the performance of sister ships and fleets.

The EEOI value can be improved by reducing fuel consumption for the same voyages, or by increasing the amount of cargo carried and/or utilization of the ship (i.e. reduced time in ballast and in port). There are many uncertainties that remain with the EEOI, particularly with its benchmarking, and for this reason it has not been made mandatory and improved methods for quantifying operational performance are still being considered.



# 3. Operational Ship Energy Efficiency Measures

This chapter defines the operational measures related ship energy efficiency. The measures are handled into six main section which are voyage performance, hull and propeller, engine, fuel management, system energy management and finally the importance of increasing awareness of energy.

# 3.1 Voyage Performance Management

#### 3.1.1 Speed Optimization

Speed is an important element in maritime transportation. High-speed ships are required with the growth of the world trade volume. The high ship speed provides economic benefits such as the receipt of the cargo in time, lower inventory costs and increasing trade volume per unit time. However, the increase in fuel prices and the environmental problems have brought a new perspective to ship speed. Therefore, optimizing the ship speed has become an important research topic.

The optimum ship speed is not the lowest speed, but the speed determined by considering all the parameters affecting the voyage plan. Although the speed reducing is profitable in terms of fuel consumption, it must be balanced in line with other commercial and operational needs.

The optimum speed for voyage should be determined taking into consideration all costs to create an appropriate balance between low speed sailing, fuel economy and market demands. Because market demands show a continuous alteration, the optimum speed is not constant during the voyage; the optimum speed of the ship should be updated in accordance with the information obtained from related parties (maritime companies, ship agents, ship charterer, etc.).

Reducing the speed of the ship is the most efficient method in terms of fuel economy. There is a nonlinear relationship between ship speed and fuel consumption. The ship speed has a major impact on fuel consumption due to its third-order function with the power output required for propulsion [15, 16, 17, 18, and 19]. This means that, if the ship speed is increased by two times, the power output required for propulsion will increase six times. In other words; if the ship speed is reduced by 10%, the amount of fuel consumed by ship will reduce by about 27% [20]. For example, a typical voyage from the Persian Gulf Asian continent with the tanker-type ship of the company of Maersk takes 42 days (if the ship is loaded, its speed is 15 knots. If it is ballasted, its speed is 16 knots.). When the ship reduces its speed to 8.5 knots in ballasted condition, the voyage takes 55 days and the obtained fuel economy from the voyage reaches \$ 400.000 [21]. However, due to the delivery time of the cargo and the agreements between the parties (charter parties), the market demand makes the low speed voyage of the ship impossible or needs more ships for the transportation of the cargo.

Ship speed reduction is the field about which most researches are conducted among the operational measures because it has great importance in ensuring fuel efficiency. Notteboom and Vernimmen (2009) determined the economic and environmental benefits provided by low speed by examining the relationship between fuel consumption and speed [22]. Corbett and the etc. (2009) have calculated the cost-effectiveness of the container ships at the low speed. Unlike those who defence the reduction in ship speed [23]. Psaraftis and Kontovas (2013) stated that the reduction in ship speed will cause economic and environmental damage [24]. They also emphasized that the low speed will cause the need for operating more ships at the same time and that there will be several disadvantages such as penalties caused by the late delivery of cargo.

The ships, by taking into account the voyage plans, present fuel economy significantly when they sail under the design speed. The relationship between ship speed and engine load under normal conditions



is given in Fig. 2. According to this, it is observed that when the ship speed decreases, the engine load is significantly reduced. When the power required by the engine is reduced, the consumed amount of fuel is reduced.



Fig. 2 The relationship between ship speed and engine load [25]

Chang and Chang (2013) applied three different scenarios by reducing rates of 10%, 20% and 30% of bulk carriers in the study [25]. Table 1 shows the daily and voyage reduction in the amount of fuel caused by the speed reduction of bulk carriers. According to the results of the study, it is indicated that although the low speeds of the ships provide fuel economy, it increases the operational costs due to the low-speed charter contract.

Table 1 Daily and Voyage Fuel Savings [25]											
Scenario	Scenario1 (%)	Scenario2 (%)	Scenario3 (%)								
Speed Reduction	10	20	30								
Fuel consumption reduction-daily	27,1	48,8	60,3								
Fuel consumption reduction-trip	19	36	51								

In fig. 3, the fuel consumption of the VLCC ship in loaded and ballasted situation is given. The amount of fuel consumed by the auxiliary enginery of the ship is also included in the study. According to this, it is seen that the fuel amount of the loaded ship is higher than its ballasted situation and the speed increasing of the ship increases the fuel consumption non-linearly.





Fig. 3 Speed dependent fuel consumption for VLCC ships [26]

In fig. 4, the fuel consumption of 4 different container ship at 9 different speeds is seen. The fig. 4 indicates that doubling the ship speed will cause high amount of fuel consumption. For example, when the speed is increased from 23 knots to 26 knots for an 8000-TEU (twenty-foot equivalent unit) ship, the fuel consumption of container ship increases up to 80 tons per day.



Fig. 4 Fuel consumption of four different ships at different speeds [22]



For the low speed voyage of the ship, a well communication is required between the parties in freight logistics network including port authorities and cargo relevant people. For example, voyage planning of liner service ships (container and ferries) are firmly depended on total service planning and load management. The high penalties resulting from being late have restrained the low speed voyage of the liner ships and therefore fuel economy. For the tramp service ships (tankers and bulk carriers), the ship speed shall be determined in accordance with the estimated time of arrival (ETA) usually during the contract. The ship should be ready for loading at the given time by voyaging to this determined speed. In these types of contracts, the flexibility can occur due to delays that may arise from the port rules. If the ship sails at a low speed instead of waiting to enter to the port (due to congestion at the port), it gains up to 10% of fuel economy during the voyage [27].

Waiting / delay ratios of ships at the ports are given in a study [28]. According to this study, the waiting rates are determined as following;

- 65.5% due to the port / terminal density (the unforeseen waiting times before berthing or before loading/discharging),
- 20.6% due to the lower rate of ports / terminals (loading/discharging) productivity than expected,
- 4.7% for pilotage and towage in the channel inlet before the port [28].

Norlund and Gribkovskaia (2013) have exemplified the waiting times between voyages in order to reduce the speed and thus the consumed fuel during the sailing of the ship [29]. According to the results of the study, approximately 10% economy has gained in fuel by reducing the sailing speed of the ship and the waiting times during the voyage.

Shortening of the waiting time allows the low speed voyage of the ship. Low speed sailing of the ship may occur as a result of the rapid mooring of ships and the quick occurrence of the load transfer at the port. The waiting duration of the ships at the port will shorten if the investments are made on these issues such as increasing the number and speed of the cargo handling equipment, additional stevedores, improving the ship and port mooring equipment and procedures and the improvement of the terminal management. Thus, the ship will save time and this situation allows low-speed voyage of the ship during the voyage. In addition, the prolongation of port durations increases the contamination and sediments which occur in ship hull. The contamination in the ship hull are generally seen in stagnant waters.

If the speed of the ship is too low, this situation results that the main engine and its auxiliary systems work at low power and sometimes under their manufacturer standard. This situation accelerates the wear of main engine and the auxiliary systems. In addition, if the ship enginery is operated under minimum power standard, the fuel consumption increases as 10% [30].

#### 3.1.2 Trim Optimization

Trim optimization is important to improve fuel economy and reduce emissions. The optimum trim is specific to the ship and depends on the ship's speed and draft.

The trim of the ship leads to hull resistance. Hull forms usually have been designed by taking into consideration the specific drafts. If the trim of the ship is set according to these drafts, the ship resistance will decrease. In some cases, if the trim is not suitable despite the low ship draft, much ship resistance will consist depending on the appropriate trimming situation whose ship draft is much [30]. The fluid pressure resistance which is formed by area of the ship under the water and the resistance which is caused by the waves during movement of the ship vary while the trim changes. In fig. 5, the resistance impact of the trim in different draft of changes is seen.





Fig. 5 Trim effects on ship resistance [31]

Optimizing the ship trim improves fuel efficiency for the specified draft and speed. Trim changes are performed with load stacking, fuel distribution and the ballast changes. In addition to the ship, ballasting increases the fuel consumption because of increasing the ship's displacement. It is possible to provide economy up to 5% in fuel with trim optimization [32].

There are some operational risks and challenges caused by the oversights of bending moments and shear forces of the trim optimization. In addition, the trim changes due to the consumed fuel and water during the sailing, the ballast exchange requirements, designing trim of the ship (such as the location of drains and scuppers) and the control of the vessel in bad weather conditions are some of the practical difficulties throughout the voyage [33].

Hull forms usually have been designed by taking into consideration the specific drafts. If the trim of the ship is set according to these drafts, the ship resistance will decrease. The required engine power for ships varies by over 10% in the best and the worst trim implemented [34]. The optimum draft and trim can be provided through the proper distribution of cargo, ballast and consumables by ship's captains and cargo planners. Achieving optimum draft and trim for the given voyage leg usually requires monitoring tools [27]. Although trim-power tables based on model-tests in the ships, the seafarers are mostly reluctant to use these tables. Therefore, the use of information system based on the various numerical experiments, where ship-specific comprehensive hydro-dynamic information exists, are very useful for seafarers. Fig. 6 shows exemplary software that can be mounted to the ships [35].





Fig. 6 An exemplary software for trim [35]

Monitoring systems provide the most efficient trim for a given draft and allow adjusting ballast and other consumables to gain some improvement. It is possible to provide fuel economy up to 5% with implementation of software [36]. (Fig. 7)



Fig. 7 Trim effects on engine power [36]

#### 3.1.3 Weather Routing

In recent years, the routes, whose safe and energy-efficient are high, are emphasized instead of fast routing. The aim on weather routing is to achieve optimum speed in order to provide the voyage plan energy efficiency and to reduce fuel consumption by providing the safety of ship, crew and cargo. Being the ship at the port on time and effective ship planning of the port constitute a part of the weather routing. The potential of performing weather routing reduces fuel consumption by up to 3% apart from time savings [33].



Ship weather routing is defined as determining the optimum route by taking into account the weather forecasts, specific characteristics of the ship and sea conditions along the designated voyage [37, 38].

The optimum route designated for the voyage is considered as the route with safety and comfort [39, 40], greatest energy efficiency [41, 42, 43], or the combinations of these factors under various weather conditions [44, 45]. Weather routing optimization aims to provide the expected time of arrival (ETA) with the minimum fuel consumption and sailing time based on the safety margins of the ship [46].

Examining the actions of the ship in various weather conditions provides benefit both economically and environmentally. In order to achieve the fast and safe voyage of the ship at a low cost, its actions in various weather conditions have importance in terms of ship owners and ship's crew. While the serious rate decreases due to weather conditions, the power consumed by the ship and therefore the fuel consumption increase.

There are usually two parameters that affect the weather routing optimization: Voluntary and involuntary speed loss. Voluntary speed loss performance depends on the preferences of captain and navigator of the ship. The involuntary speed loss of the ship occurs due to the effect of sea and weather resistance on the ship. The ship resistance varies according to the weather conditions. The ship is exposed to strong environmental forces in heavy weather. Consequently, various dynamic factors lead to a decrease in ship speed. Increasing the ship resistance will increase the engine power required by the ship and hence, fuel consumption.

There are weather routing services provided by a number of companies to collect meteorological data, examine wind and sea conditions, evaluate ship responses in the predicted conditions and notify the route information should be followed based on weather conditions. The ship may get the weather routing information via e-mail or computer applications Furthermore, visual information sharing in a wide range including ship / ships and fleet management can take place with computer applications.

The shortest distance between two points (ports) is not always the fastest due to the currents, wave height and winds. When the modern systems are integrated with the bridge computers, the fuel-efficient routing is possible according to real-time weather routing services. (Fig. 8). In this way, it is possible to provide fuel economy up to 10% [47].





Fig. 8 An exemplary software for weather routing [30]

## 3.1.4 Optimum Use of Autopilot

The movements of the rudder create additional drag to the hull and increase ship resistance. Reducing the frequency of rudder usage and the amount of rudder angle for course keeping leads fuel savings. Autopilot is auxiliary equipment for the supporting bridge team, reducing the sailing distance as a result of decreasing rudder movements and thus lowering the ship resistance as well as the required power to maintain course.

Conventional autopilots are based on simple relationships between rudder angle and rate of change of heading. These are practicable for directionally stable hull forms and small angles. If the ship is exposed large vessel dynamics due to wind, waves and current, large rudder angles can be required. Furthermore, changes in draft, speed and water depth can alter relationships between rudder angle and ship's turning rate. Adapted autopilot systems have various features such as a high accuracy of desired route, the rudder actions in a short time with a smaller angles, the reduction of deviation in ship's bow even in strong waves and wind.

Although it is less important for the adaptive system of the autopilot due to the its own ability to autotune to the weather and load conditions, in general, the efficient use of autopilot by adjusting of steering features to compensate for wind, waves, current, speed, trim, draft and water depth have an impact on fuel savings. According to Buhaug et al. [5], autopilot adjustment creates by 0.5-3% reduction in fuel consumption.

# 3.2 Hull and Propeller Management

#### 3.2.1 Roughness and Its Effect on Ship Resistance

The roughness is seen the surface of the ship which is in contact with water, especially sharp sections of the propeller. Over time, this formation leads to much more fuel consumption of the ship. The roughness formation affects the operating costs, speed, power change and performance values of the ship.



The hull roughness caused by both the physical and biological (environmental) factors. The physical roughness arises from damage, failure of applied coating (peeling, blistering and cracking) or misapplication of coating. Fouling (Biological roughness) is the attachment and growth of marine organisms on immersed surfaces. (Fig. 9).



Fig. 9 Surface roughness [48]

According to the properties of seawater, bacteria that cause this formation vary widely. The researches have stated that the type of coating is important in order to reduce the formation of roughness [49]. Casse and Swain (2006) studied the surface model coated with four different coatings which are exposed to the same bacterial culture and released under the same environmental factors [48]. They demonstrated that the coating type is important in the formation of the roughness.

Hull resistance of the ship consists of the frictional resistance and the wave resistance. The friction resistance on the wet surface and attachments of the hull constitutes 85% of the total resistance of the ship [50]. When the ship speed increases, the wave resistance increases, but still the frictional resistance constitutes a large part of the total resistance.

The amount of frictional resistance depends on the roughness of the ship underwater surface. Each 10 microns and 20 microns increase of roughness increases the total hull resistance about 1%. In fig. 10, it is given that the increase in roughness in container ship increase the fuel consumption [30].



Fig. 10 Effect of roughness on fuel consumption [30]



#### 3.2.2 Hull Management

The amount of roughness varies according to the operational profile of the ship such as ship's age, spending time at ports, sailing areas and etc. Fouling generally occurs in stagnant water especially in the port area. In Fig. 11, it is observed that ships' waiting in port for a long time affects the ship resistance. Accordingly, at the end of its 4-week stay in port, it is reported that ship's resistance increased by 20%, resulting in speed reduction by about 0.9 knots for the same power or its daily fuel usage increased by 8 tons for the same speed [51].



Fig. 11 Waiting durations effects on ship resistance [51]

Both physical and environmental (biological) hull roughness have effect on a ship's frictional resistance. For a smooth hull surface, maintenance should be provided at appropriate intervals. Maintenance includes addressing both mechanical damages and failures as well as fouling.

The aim of hull cleaning is to remove biological roughness or fouling. The cleaning process may require partial or general maintenance based on the degree and type of biological roughness. The proper maintenance interval should be determined taking into consideration all operational and maintenance costs.

#### 3.2.3 Propeller Roughness Management

Roughness is observed on the surface of the propeller particularly on the sharp sections. Propeller surface roughness increases fuel consumption by about 6% [30].

The physical surface roughness occurs on the propeller due to many reasons such as fouling, corrosion, cavitation and impingement attack. Improper propeller maintenance can also increase surface roughness; this could be overspray of the coating or hard implementation of the polishing.

Propeller maintenance strategy causes great potential rates of return on the relatively low investment. Propeller polishing reduces roughness and the accumulation of organic materials and thus the frictional resistance of the ship [51]. (Fig. 12)





## 3.3 Engine Management

#### 3.3.1 Ship Resistance

The components of resistance should be explained in order to have a general opinion regarding the required of ship power. The ship resistance is generally divided like below;



Fig. 13 Resistance decomposition [52]



Residual resistance; the difference between the total resistances to hull friction resistance.

- Friction resistance; the resistance is on the surface of the ship and the direction of motion is the sum of tangential stresses.
- Pressure resistance; the resistance is on the surface of the ship and it is the sum of total normal stresses (perpendicular to the surface).
- Wave resistance; the resistance component is caused by energy which creates gravity during movement of the ship in the water.
- Viscous pressure resistance; It is the sum of the normal stress components which are caused by the turbulence and the viscosity. This value cannot be measured directly from the ship unless it is completely submerged in the water. If it is fully submerged in the water the viscous pressure resistance is equal to pressure resistance.
- Wave breaking resistance; the resistance component is caused by the waves which occurs bow of the ship.
- Viscous resistance; the resistance component is caused by energy which viscous resistance effects consume.
- Added wave resistance; the ship has to consume more energy based on the wave resistance. The effects of the added wave resistance are changeable in different environmental condition.
- Added wind resistance; the added wind forces cause extra energy losses
- Fouling resistance; the loss of the energy due to moss, rust coating etc. on the surface of the ship that cause flow distortion.
- Yaw resistance; the resistance occurs in the situation of requiring continuous steering correction to go through the correct route.
- Shallow water resistance; the resistance increases due to flow of water between ship bottom and seasurface.
- Appendage resistance; the resistance is caused by rudder, shaft, bracket, strut, etc.

#### 3.3.2 Main Engine and Propeller

Fig.14 shows the propeller curves and engine operating points for ship sailing at various ship resistance and loading conditions. The Propeller curve no. 6 corresponds to ship full load condition and sailing at clean hull and calm water conditions. In such conditions and assuming that the engine operates at 90% of its MCR power (point M in fig. 14), the engine operating point will be S0, as shown in fig. 14. For unchanged the ship loading condition and engine power but in case of increased ship resistance, the ship propulsion engine operating point moves to S2, which lies on the propeller curve 6.2.

For the case of ship sailing at full load condition but the hull is fouled and encounters adverse weather conditions, the ship propeller will operate at heavy running and the engine operating point (SP) will move to the propeller curve 2, which denoted the propeller curve passing through the engine MCR operating point.

Sailing of the ship in even more adverse weather conditions will result the operation of the propeller at even heavier running (propeller curve 6.3 and engine operating point S3).

On the other hand, the engine sailing at ballast conditions with the ship hull clean and calm water will result in lighter propeller running according to the propeller curve 6.1 (engine operating point S1).





Fig. 14 Propeller curves and engine operating points for ship sailing at various [53]

The followings cause that the propeller works in heavy load [53]:

• Severe weather and sea conditions: when the ship sails against severe weather and sea conditions, the propeller works on a heavier load by 7-8% in calm conditions. In fig. 15, the propeller shaft power of the container ship in three different weather conditions is seen.



Fig. 15 Shaft power in different weather condition [53]



- Fouling of hull and propeller: Fouling and roughness of the hull and propeller increase the ship resistance and propeller torque.
- Ship acceleration: Ship acceleration will increase the propeller torque, and thus give a temporarily heavy running propeller.
- Shallow Waters: Shallow water increases the hull resistance and reduces the ship's directional stability.
- Displacement Effect: When is ship fully loaded, the required propeller power will increase with the ship resistance impact.

#### 3.3.3 Efficient Use of Engine

In order to reduce fuel consumption, MCR should be at optimum values for the ship. The ship MCR consumes the 70% low fuel for electronically controlled engines and 80% for mechanically controlled engine [53].

When the ship sails with constant RPM instead of continuous changing the engine power for adjusting the ship speed, the fuel consumption will decrease and energy efficiency will increase. Using the system automated engine management to regulate speed adjustment would be much useful than human intervention.

In fig. 16 and 17, a product whose deadweight is about 3800 serves actions in the different uses of the carrier type ship enginery. The ship uses two-stroke diesel engines and hard-bastard propellers. The MCR of the ship engine is 7860 kW in the worth of 129 RPM.

Engine break power (EBP): the reduced friction losses form from the power produced by the engine and revolutions per minute (RPM) are shown in fig. 16. In fig. 16, EBP (revolution per minute (RPM) of the speed and its cubic-function relationship are observed. In addition, as a result of the increase of the resistance on the ship, the power consumed by the engine and fuel consumption also increase in order to keep the speed constant [54].



Fig. 16 The relationships between speed and EBP-RPM [54]



The engine fuel mass flow rate and fuel consumption at different ship speeds are presented in fig. 17 [54]. Accordingly, increasing of the resistance on the ship increases the fuel mass flow rate and the amount of fuel consumed by the engine because of the need of more power. The MCR range, in which the fuel consumption is the lowest, is between 75% and 90%. The case, in which the ship speed is 13.3, is the most efficient case of ship enginery. (Fuel consumption; 179 g/kWh).



Fig. 17 The relationship between speed and mass flow rate-fuel consumption [54]

# 3.3.4 Engine Performance and Maintenance

The effective use of the main engine can be improved by using automated electronic engine control and monitoring systems. Regular performance testing standards of the engine manufacturers and maintenance are essential for efficient engine operation [55].

Real time monitoring tools provide ships to detect engine performance with key main engine performance parameters. These systems can also be used to identify and solve the problems caused by the maintenance and performance issues (Fig.18) [33].



# **Overall Engine Condition**

	Previous Report								Current Report									
Summary	Eng.	Cylinders T						TCs	m	ញ្ញ Cylinders							TCs	
		1	2	3	4	5	6	7	1	ıg.	1	2	3	4	5	6	7	1
Overall																		
Performance	0		0				0			0		0		0			0	
Fuel Oil	0									0								
Scavenge Air									0									0
Combustion						٠	٠				0			٠	0	٠	0	
Wear																		
Water		0		0	0	0	0	0										
System Oil																		
CLO Feed																		

Green - Normal Yellow - Caution Red - Action Required

Fig.18 Snapshot from Flame diagnostic report [33]

The optimum setting of tuning of main engine for operation at the most commonly used load ranges reduce the fuel consumption by up to 1% even in extreme cases. [5]. The optimum setting of tuning of main engine for operation at the most commonly used load ranges reduce the fuel consumption by up to 1% even in extreme cases. In addition, a one bar increase in maximum cylinder pressure causes about 0.1-0.2 g / kWh reduction in fuel consumption [33].

# 3.4 Fuel Management

The rising energy prices and fuel costs constitute a major problem for ship operations. Since the fuel costs forms 60% of ship operation costs, the rise in oil prices constitutes a potential barrier to trade [56]. UNCTAD (2010) has showed that the rise in oil prices increases the transportation costs for all cargo types including bulk cargo and container [57].

Another study has indicated that the rise in fuel costs causes the change in trade shapes as a result of the competition between the manufacturers in different regions is affected from the increase in transportation costs in the long term [58]. Therefore, the cost control and fuel consumption management are the elements including a number of strategies with operational and technical measures (for example, speed management through low-speed, selecting the most economical route and technology-based solutions) [59]. Fuel costs is an important factor that determines the ship operation competition because of forming a large part of the ship operation costs. \$500 of fuel prices per ton for tanker ship constitutes the rate between 67% and 87% of the total time costs [5].

The fuel price is an important variable determining the net cost effectiveness of the fuel consumption reduction measures. Its worldwide use leads to the additional fuel costs in the emission control areas of the low sulphur fuels instructions. In view of the increasing of the ship operating and relatively the famine that will occur in naturally occurring low sulphur fuels, the fig. 19 shows that the increase of the fuel prices (crude oil and sulphur fuels) with respect to time.





Fig. 19 Increase of the fuel prices with respect to time [60]

While the freight activities have role in fuel usage according to the ship category (in terms of  $CO_2$  emissions), the passenger ships constitute only 11% of total fuel consumption (except for the fisheries, services and offshore supply ships). While the container ships have a maximum value of 25%, the tanker ships represent 28% of the total (Fig. 20). This case arises from more powerful engine features and high operating speed due to the characteristics of the container ship [5].



Fig 20 Fuel consumption according to ship types [5]

Ship operations have implemented the fuel management to struggle against the difficulties brought by the rise in fuel prices. The high rise of the fuel prices leads the shipping companies to cheaper alternatives. The fuels with low cost and higher viscosity, such as IFO, are preferred for economic benefits despite the use challenges [22].

Because the ship design affects the fuel consumption, Veenstra and Ludema (2006), in their study, have modelled the variables which need to be considered in terms of fuel consumption in the purchase of ship for owners [61]. The fuel consumption depends on ship design such as to be more efficiently used engine in ships, to develop the hull forms (for example weather lubrication systems and coating



applications) and special structures (such as Bulb), to increase the efficiency of the auxiliary engines, and to regenerate other consumers (heating, lighting, etc.).

# 3.5 Ship Systems Management (Other Consumers)

Ships should also pay due consideration to optimize the use and operation of mechanical and electrical systems on board. Options for reducing on board power demand offer improvements in fuel consumption.

The electrical power is needed with various auxiliary systems such as cooling-water pumps, ventilation fans, control and navigation systems except for the main propulsion power requirement. For example, a considerable power is needed for bow thruster which is used by many ships to manoeuvre at low speeds. In addition, cargo equipments on board usually require high power during loading and discharging. While cooling is needed for frozen cargo, on the contrary, heating is required for some cargo such as crude oil, heavy fuel oil, bitumen, etc. The investment is required to motivate and train the crews and to follow the energy consumption on the ship. In addition, the automation and process control improvements such as automatic temperature control, flow control (automatic speed control for pumps and fans), automatic lights, etc. are several applications that can help energy savings. With system energy management, 1-2% reduction in total fuel consumption can be achieved [5].

#### 3.6 Energy Awareness

Energy awareness makes individuals and parties to draw on their knowledge and skills for ship energy efficiency. It also causes promoting motivation and focus or emphasis on daily operational activities. However, energy efficiency measures will require the cooperation of many parties. The departments and the individuals in the organisation should reveal the necessary expertise in energy efficiency in order to overcome difficulties in implementing of measures.



Fig. 21 Stakeholders [62]



- The parties having a role in ship energy efficiency are described below:
  - Ship owner: Ship owner should make the optimum decision by keeping all the factors such as the investment decisions, investment and operating costs related to the new technologies and techniques that can be implemented in terms of energy efficiency measures. However, the implementation of these technologies to the existing ships is often very difficult and may be costly. In addition, the potential savings of new applications are less when compared to the investment risk. The implementation of appropriate technologies is more suitable for new ships due to the low risk investment. In this case, the ship owner should save energy by increasing the operational efficiency of ships for existing ships.
- Ship operation: The ship operation may be conducted by either the ship owner or the charterer that manage the ship for commercial use. If the ship is operated with a charter agreement, the charterer usually meets the fuel and port costs of the ship. Therefore, the voyage information (load information, estimated time of arrival (ETA) and voyage planning, etc.) are transferred to the charterer. The ship operator should evaluate issues such as performance of the ship, the maintenance activities of the ship, spare parts, shipyard time and personnel management by organizing all these activities in timely and cost effective manner. It also provides technical support to the ship in the ship's operational procedures.
- Ship: The ship is a party implementing operational measures within the scope of SEEMP. According to the distribution of shipboard duties, each seafarer will contribute within his expertise in respect of energy efficiency. In order to increase energy awareness of the ship staff, training should be conducted by the company and by the ship's captain.

The ship's personnel are responsible for optimum operation of the ship in many subjects such as the voyage planning, optimal weather routing, trim, autopilot use, cargo and ballast operations. However, the ship operators and other parties have also responsibilities to increase the awareness of the ship's personnel in all these areas.

Other parties: The cargo owners, ship agency, port authority, brokers, weather routing other companies are the other related parties.

One disruption caused by one of the parties affects all other units. Therefore, awareness of this condition constitutes the importance for all parties. However, mutual support between the parties, cooperation and information sharing is extremely important and necessary to minimize these disruptions.


## 4. Methodology

This chapter describes the methodology used for this project. These are Artificial Neural Networks and Multiple Regression Analysis.

### 4.1 Artificial Neural Networks

One of the methods, which is alternative for traditional estimation methods found in recent years is artificial neural networks. Artificial neural networks are computer systems, which were developed in order to conduct automatic skills such as generating new knowledge through learning, forming and discovering new knowledge which are characteristics of human brain without getting any help. Artificial neural network is a field of science, which is developed for problems that are too difficult or even impossible to conduct through traditional methods and it is based on processing adaptive data.

In prospective estimation studies, one of the methods which is used as alternative for traditional estimation methods is artificial neural networks [63]. ANN is a system, which was designed to model the brain's performance method of any function and they are computer systems which were developed for the solution of complex problems.

The concept of ANN, which was suggested for the first time by Tuning in 1948, is a programming approach which was formed by simulation of operation of a simple biological neural system (Chua and Yang, 1988a, 1988b). Artificial neural networks models aims to solve complex problems and solves most of them [64].

#### 4.1.1 Biological Neural Networks

The human brain consists of about 10 billion biological nerve cells, which are the basic elements of biological neural networks. The biological neural networks called neurons are distinguished as three basic elements [65];

- the cell body,
- the dendrites,
- the axon.

The cell body, or soma, provides the support functions of the cell; it collects and processes information received from other neurons. The axon stretches away from the cell body and provides information travel to other neurons. The dendrites are tube like extensions that branch repeatedly and form a bushy tree around the cell body; they provide the main path on which the neuron receives the coming information. A nerve impulse is stimulated, at the origin of the axon, by the cell body in response to the received information; the impulse sweeps along the axon until it reaches the end. The joint point of an axon with a dendrite of another neuron is called a synapse, which consists of two parts: the knob like axon terminal and the receptor region. There, information is transmitted from neuron to neuron by means of chemical transmitters, which are released by arriving nerve impulses. Fig. 22 shows the components of biological neural network [65].





Fig. 22 Biological neuron model

### 4.1.2 Neuron Model

Artificial neural networks are formed from combination of neurons. Neurons are processors with very simple function, which form neural networks. Artificial neuron mainly consists of weight, bias and activation functions as presented in fig.23.



Fig. 23 Basic elements of an artificial neuron

Each neuron receives inputs x1, x2,..., xn, attached with a weight xi which indicates the connection strength for a particular input for each connection. Then it multiplies every input by the corresponding weight of the neuron connection. A bias bi can be defined as a type of connection weight with a constant nonzero value added to the summation of inputs and corresponding weights u, given as follows:

$$u_{i} = \sum_{j=1}^{n} W_{ij} X_{j} + b_{i}$$
(1)



where ui is the net inside activity level of ith neuron, wij is the jth weight value of the ith layer, xj is the output value of the jth layer, and n is the number of the neurons.

The activation function yi will create an actual output. The summation ui is transferred using a scalarto-scalar function called an "activation or transfer function", f(ui), to yield a value called the unit's "activation", given as

$$y_i = f(u_i) \tag{2}$$

#### 4.1.3 Neuron Model

The way in which the neurons of a neural network are interconnected determines its structure. The most used structures are single-layer feed forward networks, multilayer feed forward networks, radial basis networks, dynamic (differential) or recurrent neural networks.

#### 4.1.3.1 Single-layer feed forward networks

It is the simplest form of feed forward networks. It has just one layer of neurons as shown in fig. 24. The best known is the so called perceptron. Basically it consists of a single neuron with adjustable synaptic weights and threshold.



Fig. 24 Single-layer feed-forward network [65]

### 4.1.3.2 Multilayer feed-forward neural networks

Even if some problems can be solved with the use of a single artificial neuron cell, generally, in many situations, the solution of the problem requires a high number of artificial neuron cells. A feed-forward MLP (multi-layered perception) paradigm consisting of one or more inputs, hidden layers and an output layer has been used in the majority of studies. They distinguish themselves by the presence of one or more hidden layers (Fig. 25) whose computation nodes are called hidden neurons. Typically the neurons in each layer have the output signals of the preceding layer as their inputs. If each neuron in each layer is connected to every neuron in the adjacent forward layer, then the neural network is named as fully connected, on the opposite case, it is called partly connected.





Fig. 25 Multilayer feed-forward network [65]

The most commonly used training algorithm for the multi-layer perception is a back propagation algorithm (BPA) [66]. MLP trained with BP are chosen due to their documented ability to model any function [67].

The back propagation algorithm has become the most popular one for training of the multilayer perceptron. It is compositionally very efficient and it is able to classify information non-linearly separable.

### 4.1.3.3 Radial basis function neural networks

Radial basis function (RBF) neural networks have three entirely different (Fig. 26).

- 1. The input layer made up of input nodes.
- 2. The hidden layer, with a high enough number of nodes (neurons). Each of these nodes performs a nonlinear transformation of the input, by means of radial basis functions.
- 3. The output layer, which is a linear combination of the hidden inputs neurons. Radial basis functions were first introduced for the solution of multivariate interpolation problems [68]. The first application of radial basis functions to neural networks design is reported in Broomhead and Lowe (1988) [69].



Fig. 26 Radial basis function network [65]



#### 4.1.4 Neuron Model

A common approach for encoding temporal information using static neural networks is to include delaying inputs and outputs.

However, this representation is limited, since it can only encode a finite number of the previous measured outputs and imposed inputs; moreover, it tends to require prohibitively large amounts of memory, thereby hindering its use for all but relatively low order dynamical systems. As a very efficient and promising alternative, the international research community has been exploring the use of recurrent or dynamic neural networks (Fig. 27).

Recurrent or dynamic neural networks distinguish themselves from static neural networks in which they have at least one feedback loop. One of the first surveys of structures is learning algorithms and applications of this kind of neural networks [70]. There, it is signalled that neural networks, whose structures include feedback, are present from the very earliest development of artificial neural networks; in fact, [71], McCulloch and Pitts developed models for feed-forward networks, which have time dependence and time delays; however, these networks were implemented with threshold logic neurons. Then, they extended their network to those with dynamic memory; these networks had feedback. Later, these networks were modelled as finite automata, which is usually referenced as the first work on this kind of automata [72].



Fig. 27 Discrete time recurrent neural network [65]

#### 4.2 Multiple Regression Analysis (MR)

One of the most commonly used methods for determining the relationship between the variant factors in studies, is the regression analysis technique. Multiple regression analysis (MR) is a linear statistical technique which is utilized in, through the least square method, revealing the best relationship between a variable (dependent, predicant) and several other variables (independent, predictor). Multiple regression analysis model is then developed for predicting the fuel consumption as:

$$Y = a_0 + a_1 V_1 + a_2 V_2 + \dots + a_n V_n + \varepsilon$$
(3)



where  $a_0$ - $a_n$  are the regression coefficients,  $V_1$ - $V_n$  are the independent variables, and  $\varepsilon$  is model error. The model has a linear form in order to represent linear relationships between the dependent variable and the independent variables and interaction between independent variables,

It is important to consider the goodness-of-fit and the statistical significance of the estimated parameters of the developed regression models. A model with the highest  $R^2$  can be designed through a combination of forward, backward and stepwise regression adjustments. The variables significant at P=0.05 are always maintained for the final model [73].



# 5. Modelling of Ship Fuel Consumption

This chapter describes the development and modeling of ship fuel consumption using ANN method. In addition, the performance of the developed Artificial Neural Network (ANN) is compared with multiple regression analysis (MR), another well-known surface fitting method.

### 5.1 Data Gathering

In the data acquisition, the information and data of ship fuel consumption are acquired mainly from daily reports of the tanker. These reports are mostly 'noon reports', i.e. recorded each day at noon whilst full away sailing at sea. There are also 'port reports' and other reports that are recorded on approach to port, on arrival, daily in port, on departure. This Daily Data is based on real data which is recorded daily by crew and collected by head office of the company. The daily data of the ships includes the information below;

- Date and Time
- Voyage Number
- Position (Lat., Long.), Port name
- Engine Rpm
- Average Speed
- Beaufort number
- Wind direction
- Loading condition
- Operation Type (Sailing, Port Stays (Loading or Discharging Operations), Waiting (Anchorage or Drifting)
- Drafts (forward, mean, aft)
- Next Port, Miles to port and ETA next port
- Main Engine Fuel Consumption
- Auxiliary engines consumption
- Boilers fuel oil consumption

In addition to daily reports, ship particular information and sea trial conditions are used to compare to the performance of ships with its actual performance and the other ships.

In order to observe and evaluate the changes in the operation systems of ships, which sail in various conditions, acquiring daily data is very important. Daily reports are a major indicator of the amount of fuel that ships consume in varied weather conditions and at varied sailing speeds. They provide valuable information on the fuel consumption of ships under various loading, speed and weather conditions that can be utilized for fuel consumption prediction and forecasting.

This study is conducted noon report data for 7 tanker ships for the period 2012–2014. These tanker ships analyzed in this study are considered as a one ship as they are sisterships and shows the same basic characteristics, equipped with a one fuel propulsion engine with internal combustion. (Table 2) Fuel consumption, expressed as metric tons per hour (mtons/h), is a measurement of fuel consumption in this study.



Туре	Oil Tanker
Length (m)	274.5
Breadth (m)	48
Moulded Depth (m)	23.7
Design Draft (m)	16
Displacement (t)	184349
Shaft Power (kw)	18660
RPM	91

### Table 2 The Baseline Characteristics Of The Analysed Ships

Five important impact factors for ship fuel consumption which include revolutions per minute (RPM), mean draft, trim, beaufort number (BN) and relative wind direction are examined in this system, which are used as independendant variables for MR and inputs in the network training for fuel consumption forecasting model.

### 5.2 Statistical Analysis Results

This section aims to explore the effects of operational factors related voyage performance management on fuel consumption. The information and data of a ships' fuel consumption are obtained from ship noon reports. Pearson's correlation coefficient and scatter plot graphs are used to test the correlation between fuel consumption and operational parameters, which are used as measures of ship energy efficiency.

In this project, drawing the graphs and statistical analysis have been performed under SPSS software. The data set used to architecture Pearson's correlation coefficient analysis is 3646 noon reports.

The average fuel consumption in this study is 1.71 metric tons per hour as show in table 3. Fuel consumption ranged from 0.45 to 3.12 mtons/h and the average fuel consumption of ships ranged between 1.70 and 1.72 at the 95% confidence interval.

Table 3 Statistics of Fuel Consumption (Mtons/H)							
	Min.	MAX.	MEAN	SD	95%		
					CONfil	DENCE	
					İNTEF	RVAL	
					LOWER	UPPER	
MTONS/H	0.45	3.12	1.71	0.39	1.70	1.72	

Table 4 shows the correlation between the fuel consumption and impact factors for fuel consumption based on operational measures including RPM, draft, trim, (beaufort number) BN and relative wind direction related voyage performance management. Ship operators manage the operational measures depending on the speed optimization (RPM), draft optimization (trim and draft) and weather routing (BN and relative wind direction). There are significant positive correlations between the fuel consumption and both the variables of RPM, draft and BN, with r=0.953, r=0.498 and r=0.17, respectively. Additionally, there is a negative significant correlation between the fuel consumption and both the variables of trim and relative wind direction with r=-0.472 and r=-0.088, respectively.



					Relative Wind		
				Beaufort	Direction		Fuel Consumption
		Draft (meter)	Trim (meter)	Number (BN)	(angle)	RPM	(mtons/hour)
Draft (meter)	Pearson Correlation	1					
	Sig. (2-tailed)						
	Ν	3646					
Trim (meter)	Pearson Correlation	-,908(**)	1				
	Sig. (2-tailed)	,000					
	N	3646	3646				
Beaufort Number (BN)	Pearson Correlation	,116(**)	-,094(**)	1			
	Sig. (2-tailed)	,000	,000				
	N	3646	3646	36467			
Relative Wind Direction (angle)	Pearson Correlation	-,074(**)	,063(**)	-,142(**)	1		
	Sig. (2-tailed)	,000	,000	,000			
	N	3646	3646	3646	3646		
RPM	Pearson Correlation	,503(**)	-,477(**)	,069(**)	-,061(**)	1	
	Sig. (2-tailed)	,000	,000	,000	,000,		
	Ν	3646	3646	3646	3646	3646	
Fuel Consumption (mtons/hour)	Pearson Correlation	,498(**)	-,472(**)	,127(**)	-,088(**)	,953(**)	1
	Sig. (2-tailed)	,000	,000	,000	,000	,000	
	Ν	3646	3646	3646	3646	3646	3646

### Table 4 Statistics of Fuel Consumption (Mtons/H)

\*\* correlation is significant at the 0.01 level (2-tailed).

bold marked values indicate the correlated variables with fuel consumption.

Fig. 28 showed that there are strong significant correlations between the variable RPM and ship's fuel consumption with r=0.915. This means, the variable of RPM has greatest impact on fuel consumption when comparing the other variables, as can be seen in both table 5 and fig. 28.



Fig.28 Correlation between RPM and ship's fuel consumption



Fig. 29 shows that ship's draft has a positive correlation with fuel consumption (R=0.248). When examining the relationship between draft and fuel consumption, it can be seen that the data for ship's draft are gathered almost two sections. The reason for this is that ships are sailing generally on ballast or loaded condition. Middle parts indicate the partly loaded section.

The reason for this is that ships are sailing generally on ballast or loaded condition. Middle parts indicate the partly loaded section.



Fig.29 Correlation between draft and ship's fuel consumption

Fig. 30 presents the correlation between trim and fuel consumption of ships with r=0.223.



Fig.30 Correlation between trim and ship's fuel consumption



Fuel consumption is positively correlated with BN (r=0.016) and negatively correlated with relative wind direction (r=0.008) with smaller correlation coefficient. (Fig. 31 and 32)



Fig.31 Correlation between beaufort number (BN) and ship's fuel consumption



Fig.32 Correlation between relative wind direction and ship's fuel consumption

The results of this research show that fuel consumption depended heavily on RPM, followed by draft and trim variables. Therefore, reducing fuel consumption can lead to reduced RPM which is related to speed optimization. Secondarily, trim optimization is an effective measure to improve energy efficiency. However, this study shows a small but statistically significant correlation between fuel consumption and both BN and relative wind direction.



### 5.3 Design of ANN Model

In this study, a neural network model has been implemented with Neural Network toolbox presented in MATLAB 2010a.

The data set derived from 3646 noon reports are used to design and construct the ANN. Initially, a sample of 70% of noon reports was randomly selected for training, and the remaining sample of 30% of the data was used for validation. There are five input variables; revolutions per minute (RPM), mean draft, trim, beaufort number (BN) and relative wind direction. The output parameter of the ANN model is ship fuel consumption (mtons/h).

MLP trained with BP is chosen for this predictive forecasting model because of its documented ability to model any function. A simple model with the highest  $R^2$  can be designed in this study through stepwise regression. The modelling method for ANN was based on the back-propagation learning algorithm used in feed forward with one hidden layer. A primary task in ANN studies is to identify the ideal network architecture which is related to the number of hidden layers and neurons in it. Considering the ANN performance, the number of hidden layer(s), the neurons in the hidden layer(s) and the value of the training parameters for every training algorithm were determined through a trial and error method. The optimal architecture of the ANN was constructed as, 5–10–1 NN architecture for fuel prediction representing the number of inputs, neurons in hidden layers, and outputs, respectively. The proposed ANN model is given in fig. 33. The learning algorithm used in the study is Levenberg–Marquardt (LM), activation function is logistic sigmoid (logsig) transfer functions (inputs and outputs are normalized between 0.1 and 0.9 for the neural network model) and number of epochs is 1000.



Fig.33 The schematic of ANN structure [74]

Determination coefficient  $(R^2)$  and error variance criteria (MSE and RMSE) have been used for comparing prediction models. The most widely used error indicator, the MSE, of the prediction over all the training patterns for a one output neuron network can be formulized as:

$$MSE = \frac{1}{2N} \sum_{i}^{N} (t_{i} - z_{i})^{2}$$
(4)

N is the total number of training patterns where ti and zi are the predicted output for the ith training pattern and the target [75]. Another error estimation criterion is the RMSE (root mean square error) and through it, the error is shown in the units of target and predicted data. According to these criteria, high  $R^2$  and low MSE and RMSE values are indicating a well-fitting model.



### 5.4 Performance of ANN Model

In this section, the results and system efficiency used in forecasting the fuel consumption of a ship will be described. For an estimation model, artificial neural network (ANN) methods were developed. Fig.34 and 35 illustrate the training and validation of the ANN model for observed and predicted values for fuel consumption. The  $R^2$  was 0.922 and 0.923 for training and validation of the ANN model, respectively.



Fig. 34 Relationships between actual and predicted fuel consumption (Training) using the ANN model





Fig. 35 Relationships between actual and predicted fuel consumption (Validation) using the ANN model

Capability is achieved for both training and testing data sets of fuel consumption. Therefore, the ANN appears to have a high generalization capability. The statistical values for fuel consumption in training and test sets are given in Table 5. As seen in Table 5, a low mean square error (MSE) and a low root mean square error (RMSE) are obtained for the training and testing data sets for fuel consumption.

	Training	Test	
MSE	0,003	0,003	
RMSE	0,055	0,055	

 Table 5 MSE and RMSE for training and validation of the MR and ANN models.

### 5.5 Validation and Benchmarking

In this section, the results using the ANN developed above are compared with multiple regression analysis (MR).

MR has been performed under IBM SPSS Statistics 21.0 software. Multiple regression with the highest  $R^2$  can be designed in this study through enter method.

The performance was assessed using the same data sets for examining the performance of the ANN.

The linear relationships of the dependent variable with the independent variables are represented by a multiple regression analysis model. Same data sets was used for the training of the ANN in order to compare more comprehensively with the ANN model and predictions on validation data were estimated after running the model. A multiple regression analysis model could be fitted to fuel consumption data and accounted for around 75% of the variance in validation data. Fig. 36 and 37 compare the predicted and actual ship's fuel consumption for training and validation data, respectively.





Fig. 36 Relationships between actual and predicted fuel consumption (Training) using MR model



Fig. 37 Relationships between actual and predicted fuel consumption (Validation) using MR model

For both training and validation data, the correlation between the actual and predicted energy consumption for the ANN model was shown to be much higher than the correlation for the linear regression model by the comparison done between ANN model and multiple linear regression models.



# 6. Design of the Decision Support System (DSS) for improving ship energy efficiency

Ship operators, making decisions concerning the implementation of operational measures to improve ship energy efficiency, could use with advantage the results obtained from the developed ANN. Table 6 shows the seven parameters and their controllability by ship operators for decision support.

	A	
Variables	Control	Description
RPM	$\checkmark$	RPM can be increased or decreased considering voyage plan
Draft	-	Draft is adjusted depending on the ship's displacement
Trim	$\checkmark$	Trim can be adjusted according to draft.
BN	-	BN can be obtained from the weather reports.
Relative Direction	Wind 🗸	Relative wind direction can be arranged with course alteration

Table 6 The parameters can be controlled by ship operators

### Accordingly;

Ship operator can adjust speed and RPM with consideration of voyage plan (time constraint may occur due to the trading environment). Cargo quantity determines the displacement of ship, so cargo quantity and draft parameters are uncontrollable, only used for prediction. Trim can be optimized according to draft. Wind and sea effects can be used in support of fuel savings by weather routing.

The design of this DSS (from the effects of ship operational energy efficiency measures on fuel consumption forecasted by the use of ANN) is shown in fig. 38.



Fig. 38 Design of ship operational energy efficiency ANN DSS



The database of DSS contains data from the developed ANN. This ANN was run having as input the seven important impact factors(ship speed, revolutions per minute (RPM), mean draft, trim, cargo quantity on board, wind and sea effects) and the result of the ANN for all these 2337 different input samples were recorded and stored in the database of DSS. It should be noted that; instead of having the results of the ANN for the 2337 different cases stored in the database, the ANN itself could be inserted in the DSS. In this way, based on the user's input, the ANN would produce dynamically its output on a real time basis.

The ANN based DSS functionality follows these steps:

Step 1: The ship operator enters all the necessary variables including input parameters for ANN and other essential parameters for the voyage of ship such as distance between ports, required date for cargo delivery and the course of ship following prompts from the system.

Step 2: Depending on the input of the ship operator, the system makes the necessary queries to the database.

Step 3: The results of the queries are returned and are presented to the ship operator, who can evaluate them. The user, at this point, can either finish the interaction or continue by returning to Step 1.

To illustrate the functionality of the developed DSS, hypothetical case with two scenarios are presented below, corresponding to ship speed optimization decision-making situations due to their great significant impacts on fuel savings.

Step 1: The ship operator enters parameters for draft, trim, beaufort number, relative wind direction and RPM used for ANN and additional information such as the distance between ports in nautical mile (d) and required date for cargo delivery. In order to evaluate two scenarios for speed optimization, ship operator enters two different RPM values to receive the outputs of ANN based DSS.

The ship is ballasted condition with 17 m draft and 0 m trim. Beaufort number is 4 and the wind adversely affects the ship. The distance between ports is 1000 nautical mile. Ship speed is 10.4 knots and RPM is 62 for Scenario 1 while ship speed is 12.4 knots and RPM is 73.5 for Scenario 2.

Step 2: ANN calculation is performed when operational information is input to the interface. Then, the outputs (fuel consumptions) are 1.24 mtons/hour for Scenario 1 and 1.86 mtons/hour for Scenario 2.

Table 7 gives the results of decision support information. The emission factor of  $CO_2$  is 3.17 [76, 77, 47]. The fuel price is \$100 per metric ton used for calculating the total amount of fuel cost for voyage [46].

			11 9			
Scenario	d (NM)	t (hours)	Output FC (mtons/h)	Q (mtons)	P (\$)	CO <sub>2</sub> (tons)
Scenario 1	1000	96	1.24	120	1200	380
Scenario 2	1000	80.7	1.86	150	1500	476

Table 7 Decision support information

where, t is the sailing duration based upon cargo delivery date, Q and P are the total amount of fuel consumption in metric tons and fuel cost in dollars for the voyage, respectively.

Step 3: According to the obtained information, decision maker can manage the operational parameters for decision support. The input information will change according to operational information and requirements considering voyage plan of ship and decision support information will change according to changes in the input information. Ship operator is concerned with the optimum speed that a ship can reach the port on time. (Extra waiting durations for cargo at anchorage or port as a result of high



speed ships or delay for cargo due to the slow steaming are not intended) Thus, ship speed can be optimized through adjusting sailing duration (t) considering required date for cargo delivery. In this hypothetical case, the difference between two scenarios are approximately 30 metric tons of fuel consumption, 3030 dollars of fuel cost and 96 tons of  $CO_2$  for present voyage with 1000 nautical mile (NM) distance. The user, after receiving the information shown in table 7, can either continue with an additional investigation concerning a new operational values for different RPM or exit from the system.



## 7. Conclusion

Lowering fuel consumption against high fuel prices and greenhouse emissions is a primary concern for shipping industry. As the energy efficiency of a ship depends upon the amount of consumption of bunker fuel oil, the estimation of fuel consumption has a significant role in a significant reduction in fuel and improving the energy efficiency of ship operations. Predicting fuel consumption assists in identifying over-consumption of operating situations and suggests enhanced operation strategies; thus, it can potentially reduce GHG emissions, conserve fuel and reduce fuel costs.

The potential for fuel savings is possible for existing ships through operational measures. The ideal situation for the ship operators would be to have an efficient support system in making decisions concerning the implementation of operational measures to improve ship energy efficiency.

The main objective of this project is to develop an Artificial Neural Network (ANN) based decision support system that supports the ship operators in making decisions concerning the implementation of operational measures to improve ship energy efficiency. The proposed decision support system provides a strategic approach when ship operators have to make their decisions at an operational level considering both the economic and environmental aspects. The obtained results make it clear that the neural network can learn very accurately the relationships between the input variables and a ship's fuel consumption. Furthermore, ANN provides relatively better prediction results for ship fuel consumption when compared to the results derived using the MR model. The proposed method can be considered as a successful decision support tool for ship operators in forecasting fuel consumption based on different daily operational conditions.

This research has demonstrated two novelties; the first one is predicting ship fuel consumption by employing an inexact approach i.e. ANN. The second one is to develop a decision support tool to help ship personnel making optimal decisions on a real time basis for energy efficient ship operations.

The developed DSS including the prediction model can also be used during ship design to assess fuel consumption and environmental aspects for design alternatives.

Increasing the number of samples and testing more variables for larger number of ships can help design a model to predict the trend of ship fuel consumption under different operating conditions. The results in this study may be considered as a first step in developing methods suitable for predicting fuel consumption for multiple ships by using technical and operational factors together. For further study and research, the method can be applied to other types of ships with various characteristics such as bulk carriers, containers etc.



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# Appendix

# **PPT-Presentation: Interim Project Presentation at IAMU Conference**







# Improving Energy Efficiency of Ships Through Optimisation of Ship Operations

Project coordinator

Assoc. Prof. Dr. Capt. Ozcan ARSLAN
Istanbul Technical University, Maritime Faculty
<u>Project partners</u>

Rs. Ast. Elif BAL, Ph.D. Candidate
Oceangoing Chief Officer

Istanbul Technical University, Maritime Faculty
Assoc. Prof. Dr. Aykut I. Ölcer

World Maritime University

#### GANT CHART

	May[14	Jun14	July14	Aug14	Sep14	Oct14	Nov14	Dec14	Jan15	Feb15	Mar15	Apr15
WP1 - MANAGEMENT							_		_	_	_	-
WP1-1: Monitoring the progress of the project			_		_		_		_		_	_
WP1-2: The overall legal, financial management of the project			_	_				_	_		_	
WP1-3: Reporting to the IAMU	l	_	_		_	_	_		-		-	Ι
WP2 - LITERATURE SURVEY			•									
WP2-1: Literature survey for ship energy efficiency												
WP2-2: Identification best measures		-	Þ									
WP3 - CLASSIFICATION AND QUANTIFICATION			ļ	_	•							
WP3-1: Classification of ship energy comsupton areas			ļ									
WP3-2: Quantification of priorities among controllable factors				ļ								
WP4: COLLECTING and ANALYZING of DATA					-	_		_	•			
WP4-1: Data acquisition					-	_	•					
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WP5: CREATION of SOFTWARE and FINAUZATION								•				
WP5-1: Creation of database, interface and web page											_	
WP5-2: Tests of system												Ī



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- 2. Operational Ship Energy Efficiency Measures
- 3. Methods and Data
- 4. Model Design
- 5. Performance Evalution
- 6. Conclusion



# 1. Introduction







CO<sub>2</sub> emissions generated by maritime transport represent a significant part of total global greenhouse gas (GHG) emissions.

Ships emitted 1046 million tonnes of  $CO_2$  in the year 2007 which make up approximately 3.3% of global emissions.







# 1. Introduction

- The fuel cost constitutes a large proportion of the total operating cost of a shipping company which is estimated to be 50% [4] or even more than 60% [5].
- For example, when fuel price is around 500 USD per ton, the fuel cost accounts for about three quarters of the operating cost of a large containership [6].









 The potential for fuel savings in shipping ranged from 25% to 75% is possible through more efficient operations of existing ships and increased energy efficiency in the design of new ship [2].





# 1. Introduction

 IMO's Marine Environment Protection Committee (MEPC) adopted the addition of new regulations related energy efficiency of ships to MARPOL (International Convention for the Prevention of Pollution from Ships) Annex VI, as a new chapter (Chapter 4). Through this, since 1st of January 2013;

EEDI (all new ships) [7]







 While EEDI offers technical measurements (for technology and design) at a minimum level with a long term impact for new ships, SEEMP aims to increase the energy efficiency through the operational implementations using existing technologies in ships.



# 1. Introduction

- Decision support systems (DSS) are kinds of computer-based information system that can help decision makers utilize data, models and other knowledge on the computer to solve semi structural problems.
- The aim of DSS is to help decision makers improve decision-making effectiveness and efficiency by combining information resources and analysis tools [11].





- The overall purpose of this project is to create a mechanism and develop a decision support system based on Artificial Neural Network (ANN) for ship operators (the captain of the ship and /or enterprises operating units) in making decisions concerning the implementation of operational measures to improve ship energy efficiency.
- DSSs for the optimization of energy efficiency on shipvoyage management help to decrease the complexity of the situation, and by this way, the operator will be strengthened for the awareness of the situation.



# 2. Operational Ship Energy Efficiency Measures

- 2.1 Voyage Performance Management
- 2.1.1 Speed Optimization
- Lowering ship speed creates by shortening of emissions and also substantial gains in revenues [13].
- A main reason is that the power output required for propulsion is a function of the speed to the power of three [14]. Therefore, the speed of ship has a major impact on reducing fuel consumption and if the ship reduces its speed by 10%, its fuel consumption will reduce by about 27% [15].







• 2.1.2 Optimum Use of Autopilots



 The efficient use of autopilot by adjusting of steering features to compensate for wind, waves, current, speed, trim, draft and water depth have an impact on fuel savings. Autopilot adjustment creates by 0.5-3% shortening of fuel consumption [2].





• 2.1.3 Weather Routing





[16].





- 2.1.4 Trim and Draft Optimization
  - e power for ships varies
- The required engine power for ships varies by over 10% in the best and the worst trim implemented [17].
- The optimum draft and trim can be provided through the proper distribution of cargo, ballast and consumables by ship's captains and cargo planners.



- 2.2 Hull and Propeller Condition Management
- For a smooth surface, maintenance should be provided at appropriate intervals.
- Hull cleaning and propeller polishing reduces roughness and the accumulation of organic materials.
- On the other hand, coating systems can prevent both fouling occurrence, galvanic corrosion of ship hull and cavitation erosion.







- 2.3 Engine Management
- Ships should operate at optimum ranges of maximum continuous rating (MCR) which is generally obtained at 75-90% [18] and with constant revolutions per minute (RPM) rather than changing in order to reduce fuel consumption.
- Regular performance testing required standards of the engine manufacturers and maintenance are essential for efficient engine operation [19].



- 2.4 Fuel Management
- Determining the correct fuel type for ships and ordering the optimum quantities of fuel are important for energy efficiency.





• 2.5 System Energy Management (Other Consumers)



 With system energy management, 1-2% reduction in total fuel consumption occurs by a saving of 10% [2].





- 2.6 Increasing Energy Awareness
- Energy awareness makes individuals and parties to draw on their knowledge and skills for ship energy efficiency.
- Energy efficiency measures will require the cooperation of many parties.





- 3. Methods and Data
- · 3.1 Modelling of ship fuel consumption
- The information and data of ship fuel consumption are acquired mainly from noon reports and also supported by daily reports of the tanker ship.
- Noon reports, which ship crew fill every 24 hours at sailing, contain the daily fuel consumption of the ship as well as the daily average of operational details such as draft, speed, duration, distance covered, location, port arrivals, departure, weather, fuel consumption of main engine and auxiliaries as well as the type of fuel used.



### 3.1 Modelling of ship fuel consumption

 The oil tanker used as a case study in this project spends 51% of her time sailing, 25% at anchor, 11% at port, 9% manoeuvring and 4% drifting. This project is conducted using 233 ship noon reports which have covered the sailing of the ship over the 17 months of operation since it was built.

Туре	Oil Tanker	
Built	21.6.2012	
Length (m)	265.07	
Breadth (m)	48	
Moulded Depth (m)	23.7	
Summer Draft (m)	17	
Deadweight (t)	156597	
Shaft Power (kw)	18660	•
Break Horse Power (kw)	25023	
	<pre>//</pre>	international association of neurose universities


### 3.2Artificial Neural Network (ANN)

- The concept of ANN, first suggested by Tuning in 1984, is the programming approach which simulates the organisation of a simple biological neural system [22,23].
- Artificial neural network is a computer system which is developed to create the ability to produce and discover data without the aid of outside sources, by utilizing the learning function of the human brain.



### 3.2Artificial Neural Network (ANN)

 Artificial neural networks are formed from combination of neurons. Neurons are processors with very simple function which form neural networks. Artificial neuron mainly consists of weight, bias and activation functions.





### 3.2 Artificial Neural Network (ANN)

 A bias b<sub>i</sub> can be defined as a type of connection weight with a constant nonzero value added to the summation of inputs and corresponding weights u, given as follows:

$$u_i = \sum_{j=1}^n W_{ij} X_j + b_i$$



#### 3.2Artificial Neural Network (ANN)

 The activation function yi will create an actual output. The summation ui is transferred using a scalar-to-scalar function called an "activation or transfer function", f(ui), to yield a value called the unit's "activation", given as:

$$y_i = f(u_i)$$



### 3.2Artificial Neural Network (ANN)

- A feed-forward MLP (multi-layered perception) paradigm consisting of one or more inputs, hidden layers and an output layer has been used in the majority of studies.
- The most commonly used training algorithm for the multi-layer perception is a back propagation algorithm (BPA) [24]. MLP trained with BP is chosen for predictive forecasting models because of its documented ability to model any function [25].



#### 3.3 Model Design Using Neural Network

- In this research, a neural network model has been implemented with MATLAB Neural Network toolbox.
- The data set derived from 233 noon reports are used to design and construct the ANN. Initially, a sample of 164 (70%) of noon reports was randomly selected for training, and the remaining sample of 69 (30%) of the data was used for validation.





3.3 Model Design Using Neural Network

- There are seven input variables;
- □ship speed,
- revolutions per minute (RPM),
- mean draft,
- □trim,
- Cargo quantity on board,
- wind and sea effects.
- · The output parameter of the ANN model is;
- □ship fuel consumption (mtons/h).



#### 3.3 Model Design Using Neural Network

- The optimal architecture of the ANN was constructed as, 7–12–1 NN architecture for fuel prediction representing the number of inputs, neurons in hidden layers, and outputs, respectively.
- The learning algorithm used in the study is Levenberg–Marquardt (LM), activation function is hyperbolic tangent sigmoid transfer functions (inputs and outputs were scaled between -1 and +1 for the neural network model) and number of epochs is set to 10,000.





#### 3.3 Model Design Using Neural Network

 Determination coefficient (R<sup>2</sup>) and error variance criteria (MSE) have been used for comparing prediction models.

$$\mathsf{MSE} = \frac{1}{2N} \sum_{i}^{N} (t_i - z_i)^2$$

- Another error estimation criterion is the RMSE (root mean square error) and through it, the error is shown in the units of target and predicted data.
- According to these criteria, high R<sup>2</sup> and low MSE and RMSE values are indicating a well-fitting model.



- 4. Performance evaluation of prediction
- In this section, the results and system efficiency used in forecasting the fuel consumption of a ship will be described. Artificial neural network (ANN) was developed for an estimation model.







Relationships between actual and predicted fuel consumption (Training) using the ANN model



Relationships between actual and predicted fuel consumption (Validation) using the ANN model



# 5.Validation

 Multiple regression analysis (MR) is a linear statistical technique which is used for establishing the best relationship between a variable (dependent, predicant) and several other variables (independent, predictor) using the least square method. A multiple regression analysis model is then developed for predicting the fuel consumption as:

$$Y = a_0 + a_1V_1 + a_2V_2 + \dots + a_nV_n + \varepsilon$$



# 5.Validation

- MR has been performed under SPSS software. A simple model with the highest R<sup>2</sup> can be designed in this study through stepwise regression.
- The performance of was examined using the same data sets, as was used for examining the performance of the ANN.







Relationships between actual and predicted fuel consumption (Training) using MR model



Relationships between actual and predicted fuel consumption (Validation) using MR model



	MR		ANN	
	Training	Validation	Training	Validation
MSE	0,034	0,041	0,02	0,037
RMSE	0,185	0,204	0,141	0,193



# Conclusion

- In terms of ship energy efficiency, fuel consumption has become a primary concern. The lowering of fuel consumption is considered to be the paramount goal as a result of economic pressure and environmental regulations.
- The potential for fuel savings is possible for existing ships through operational measures. The ideal situation for the ship operators would be to have an efficient support system in making decisions concerning the implementation of operational measures to improve ship energy efficiency.





# Conclusion

 In this research, an Artificial Neural Network (ANN) based decision support system that supports the ship operators in making decisions concerning the implementation of operational measures to improve ship energy efficiency, is presented. The proposed method can be considered as a successful decision support tool for ship operators in forecasting fuel consumption based on different daily operational conditions.



- Web site : http://www.ship-energy.com/
- Training Video
- Software (under construction)





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Thank You...





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Toranomon 35 Mori Building 7F, 3-4-10 Toranomon, Minato-ku, Tokyo 105-0001, Japan Tel : 81-3-5408-9012 E-mail : info@iamu-edu.org URL : http://www.iamu-edu.org ISBN No. 978-4-907408-11-4