ENERGY-EFFICIENT HYDRODYNAMIC DESIGN OF SHIPS FOR INLAND WATERWAYS OF BANGLADESH BASED ON FUEL CONSUMPTION AND EMISSION CONTROL

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Certificate of Approval

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ABSTRACT

The adoption of the Energy Efficiency Design Index (EEDI) by the International Maritime Organization (IMO) for seagoing ships has improved the situation, however, controlling emissions from inland shipping was included in the national target. As a result, though the reduction possibility of CO_2 emission from inland shipping found a significant prospect, the world lacks real-time emission data for inland waterways. In addition to that, the other carriers that compete with inland navigation are making advances in reducing their greenhouse gas emissions. To retain the competitive advantage of inland navigation as being 'low cost' and 'environmentally friendly, the inland shipping industry also needs to further reduce its greenhouse gas emissions. The focus of this study is to reduce CO_2 emissions from inland ships of Bangladesh by developing an energy-efficient ship design method based on fuel consumption and emission control.

It has been observed that direct use of the EEDI by IMO formulation for the inland ships will not provide the correct result. The prime reason is the effect of shallow water on the ship resistance. In addition to that, cargo availability and fuel quality issues for the inland vessels of Bangladesh forbid the use of IMO guidelines. Furthermore, a generalized formulation is not possible for inland ships either, mainly because of the variations in the geographic condition, economic size, and inland maritime law. Therefore, the EEDI formulation needs to be modified to be useful for an individual country.

To find out the necessary modification of EEDI by IMO to be useful for inland ships of Bangladesh, several field visits, investigations, and laboratory tests have been conducted. The results of these visits, investigations and tests have been used to quantify the hydrodynamic effect of shallow water on ship resistance, actual average operational condition, cargo availability and actual carbon content in fuel. These corrections have been integrated with EEDI by IMO which has been used for the inland ships of Bangladesh.

To quantify and set up the CO_2 emission level of the Inland Maritime sector of Bangladesh, verified ship data and operational profiles are necessary. A good number of inland ship data

were collected which have undergone several data verification processes. Using the verified ship data, EEDI baselines for Bangladeshi inland cargo, oil tanker and passenger ships were established. These baselines are one of the first steps in the world for inland ships using verified ship data and are termed as $EEDI_{BD}$.

To a ship design method that will ensure the reduction of CO_2 emission, sensitivity analysis has been carried out. Three existing ships (cargo, oil tanker and passenger) of Bangladesh have been analysed in

EEDI by IMO aimed at the reduction of CO_2 emission from the atmosphere, stepwise. To do that IMO provides several guidelines, which are most appropriate for seagoing ships. This research assessed the possibility to reduce CO_2 emission from the current stage. To do that, a sensitivity analysis was carried out on the inland ship design parameters of Bangladesh.

The outcome of the sensitivity analysis is a set of inland ship design suggestions that will lower the $EEDI_{BD}$ value from the current stage. These ship design suggestions have been implemented on three existing inland ships (cargo, oil tanker and passenger) of Bangladesh. These existing ships resistance have been examined in commercial Computational Fluid Dynamics (CFD) software, named 'Shipflow.' Those ships' designs have been improved based on the ship design suggestions and reanalysed in the same CFD software. For fare comparison, the capacity and speed of both parent and the redesigned ship kept the same. It has been found that remodelled ship designs have 10-15% less resistance in comparison with the parent hull.

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Symbols and Abbreviations

Symbol	Description
C_F	Carbon emissions factor
P_{AE}	Auxiliary engine power
P_{ME}	Main engine power
P_{PTO}	Shaft Generator power
P_{PTI}	Shaft Motor power
f_i	Capacity factor
V_{ref}	Reference speed
f_w	Weather factor
GT	Gross tonnage
f_c	Cubic capacity correction factor
R_T	Total Resistance
R_F	Frictional resistance
R_W	Wave making resistance
R_{APP}	Resistance of appendages
R_{TR}	Additional pressure resistance of immersed transom stern
L_{WL}	Water line length of the ship
A_x	Maximum cross-sectional area of the hull
F_N	Froude Number
F_{Nh}	Depth Froude Number
R_e	Reynold's Number
A_M	Midship Sectional Area under water
C_h	Hourly fuel consumption from main engine
C_T	Total resistance coefficient
ρ	Water density
V	Volume Displacement of ship
P_E	Effective Power
h_R	Relative Rotative Efficiency
h_o	Open Water Efficiency

h_s	Shafting Efficiency
h_H	Hull Efficiency
P_B	Break power of main engine

Symbol	**Abbreviation**
DWT	Deadweight
SFC	Specific fuel consumption
IMO	International Maritime Organization
EEDI	Energy Efficiency Design Index
$EEDI_{BD}$	Energy Efficiency Design Index for inland ship of Bangladesh
EEOI	Energy Efficiency Operational Index
SEEMP	Ship Energy
GHG	Green House Gas
MEPC	Marine Environment Protection Committee
MARPOL	Marine Pollution
IWT	Inland Waterborne Transport
UNESCO	United Nations Educational Scientific Cultural Organization
MDG	Millennium Development Goal
EU	European Union
BIWTA	Bangladesh Inland Water Transport Authority
BIWTC	Bangladesh Inland Water Transport Corporation
ITTC	International Towing Tank Conference
DOS	Department of Shipping
MMD	Mercantile Marine Department
DOE	Department of Environment
CFD	Computational Fluid Dynamics
RPM	Revolution per minute
IWW	Inland water way
RANS	Reynolds-Averaged Navier-Stokes

CHAPTER 1

INTRODUCTION

1.1 Background study

Seaborne trade has become the foundation of the present economy, as 90% of global trade depends upon the shipping industry. (Baldi, 2016). Our daily life and all basic needs are made cheaper and more reliable because of the seaborne transportation around the globe. However, in recent years, the shipping sector has been challenged by factors such as rising fuel prices and stringent environmental laws. Though the share of shipping to the global anthropogenic emissions (2.89% as estimated in 2018) (IMO GHG study, 2020) it has been under scrutiny to achieve more energy efficiency and participate in the sustainable economy. Therefore, the necessity of the reduction of greenhouse gases from shipping has become a global agenda.

1.2 Development of EEDI: Historical Background

IMO started working to have an emission control measure to hold the CO_2 increment from the shipping industry as a mandate under Kyoto Protocol. Since that, IMO formed several working Groups to identify the total volume of CO_2 emission, the growth rate of the shipping industry. These investigations were significant around then to comprehend the current effect on the climate and expectation on future effects if IMO does not have any emanation control measure.

IMO has been working on emission control from shipping as a mandate to the Kyoto Protocol (MEPC 62/24, 2011). During the 40th Marine Environment Protection Committee (MEPC) meeting, the mandatory measures to reduce emissions of greenhouse gases (GHGs) from international shipping were adopted at the 62nd MEPC by IMO and added to MARPOL Annex VI.

The parties under the Kyoto Protocol decided that (Naoki, 2009), Annex I shall ensure limiting emissions of greenhouse gases not controlled by the Montreal Protocol from

Aviation and Marine Bunker Fuels. In addition, it was decided that Annex I shall ensure that their aggregate anthropogenic carbon dioxide equivalent emissions of the greenhouse gases do not exceed their assigned amounts. Figure 1.1 shows the historical background and decision made by IMO at different MEPC meetings to introduce several emission-control indexes.

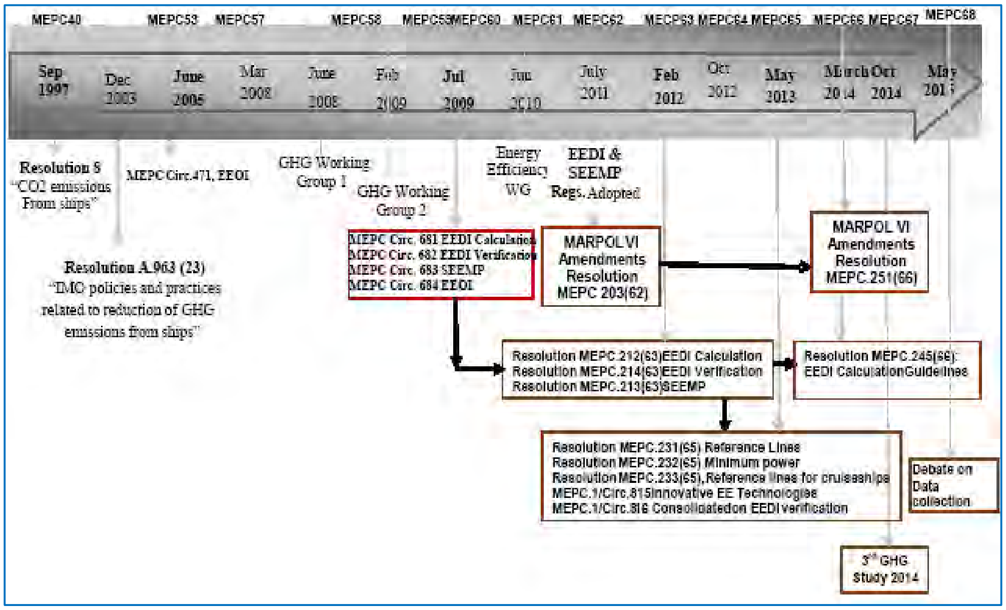

Figure 1.1: IMO Energy Efficiency Regulatory Developments (Bazari, 2016)

The adopted decisions by IMO at the 62nd MEPC are as follows:

a) New ships (building contract as from 1st of January 2013 and the delivery of which is on or after 1 July 2015.) will have to meet a required Energy Efficiency Design Index (EEDI).
b) All ships (new and existing) are required to keep on board a ship-specific Ship Energy Efficiency Management Plan (SEEMP) which may form part of the ship's Safety Management System.

1.3 The need for energy efficiency in shipping

Reduction of fuel consumption by increasing the energy efficiency of the ship will decrease CO_2 emissions. Over the last decade, there has been a surge in research and development activities aimed at improving ship energy efficiency. New solutions have emerged as a result of enhancements to existing components. For this reason, the ship's energy system has become more complicated. The optimization of complicated system design and operation is likewise a difficult task.

1.3.1 Reduction of GHG emissions: Environmental point of view

The issue of lowering shipping fuel usage is linked to the issues of global warming. CO_2 emissions are widely acknowledged as the primary contributor to anthropogenic global warming. Shipping-related emissions now account for 2.5 per cent of overall anthropogenic emissions (Smith et al., 2015), but they are anticipated to rise by up to 250 per cent in the future due to rising trade volumes, as illustrated in Figure 1.2. (Anderson and Bows, 2012). Other industries' emissions are expected to decrease over the same period (Smith et al., 2015). However, according to the most optimistic scenario provided in IMO assessments, shipping emissions will be substantially greater than what is necessary to avoid global temperatures from rising beyond tolerable levels (Figure 1.2).

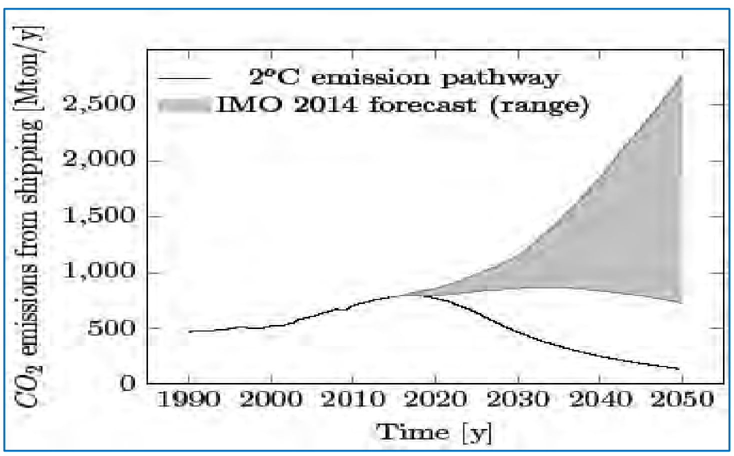

Figure 1.2: GHG emissions from shipping are compared to potential paths for meeting the 2-degree climate goal (Anderson and Bows, 2012)

1.3.2 Economic point of view

Shipping is mainly a business, and its primary goal, regardless of environmental considerations, is to make a profit. Gasoline prices are believed to be the greatest immediate economic incentive to reduce fuel usage. Many techniques have been shown to enhance energy efficiency at a negative cost, according to research (Eide et al., 2011).

However, the majority of these factors are based on the cost of gasoline. Bunker prices are considerably lower than they were at their high in 2012. (Figure 1.3). Heavy Fuel Oil (HFO) prices tend to fluctuate between 71 per cent and 76 per cent of the crude oil price, according to historical observations (Ship and Bunker, 2015). Crude oil prices are expected to fluctuate between $30 to $100 per barrel, according to current forecasts. As a result, bunker fuel costs are expected to range between 226 to 753 USD per metric ton (Ship and Bunker, 2015). In 2010, however, the estimates for bunker fuel costs were different. As a result, the accuracy of these projections might be questioned (Baldi, 2016). The present trend cannot be used to anticipate the price of gasoline.

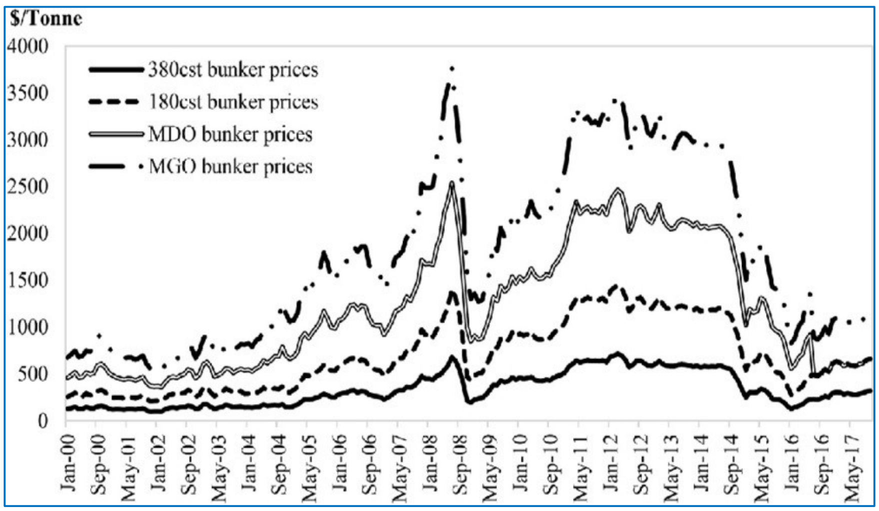

Figure 1.3: Bunker prices evolution since 2000 (Yin and Fan, 2018).

1.4 Importance of Inland Shipping

Inland waterways are widely acknowledged as playing a critical part in any country's marine development. Smaller vessels have been the basis of interior waterways for millennia, connecting towns all over the world. This has progressed to large-scale commercial shipping in some situations, particularly around ports and coastal locations. A well-coordinated inland waterways network may significantly alter the country's coordinating situation. It is a pre-built infrastructure network that may be used without a significant financial commitment. The burden on roads and highways may be substantially alleviated by maximizing the use of waterways. Waterways, in general, do not have land acquisition issues, which have long been a touchy subject.

Among the numerous modes of transportation, waterways are the least expensive. It lowers the cost of goods transportation from point A to point B considerably. Even though inland water transport is not as fuel-efficient as seagoing ships, it is nevertheless seen as a cost-effective and environmentally benign method of transportation when compared to other inland modes.

1.4.1 The need for energy efficiency in inland shipping

More than 9 years have passed after IMO adopted EEDI as a mandatory index for the sea-going ship. The regulations by IMO in 2011 (and have been updated since then) has forced the sea-going ship design and technology to achieve more energy-efficient ship. The study by Alexandar Simic (Simic, 2014) found that these regulations imposed enormous application of already existing technologies, which were forsaken without proper incentives before. However, despite there are thousands of inland ships plying within the national boundary, any regulations related to the energy efficiency for inland waterway ships still does not exist. Moreover, like seagoing ships, there is no benchmark standard of CO_2 emission or energy efficiency for inland ships, which fails to force Naval Architects to have a design with minimum energy efficiency.

Over many decades, inland waterborne transportation (IWT) has influenced the sustainable development of new nations and established economies. It also aided in the formation of international bridges (UNESCO, 2009). It can assist poor nations in achieving many Millenniums Development Goals (MDGs), particularly MDG 7 (Ensure Environmental Sustainability) and MDG 8 (Achieve Economic Growth and Poverty Reduction) (Develop a Global Partnership for Development). Energy Efficiency Design Index (EEDI) was created by the International Maritime Organization (IMO) under the auspices of the United Nations (UN) to minimize CO_2 emissions from seagoing ships at the design stage (IMO, 2011). However, studies on environmental sustainability and reduction of Green House Gas (GHG) from inland shipping were somewhat limited, although many studies were found on sea-going ships (Ebert, 2005).

So far, the IMO's EEDI formula for increasing the energy efficiency of seagoing ships has been effective (Bazari and Longva, 2011). The IMO, on the other hand, has yet to issue standards for inland ships to improve their energy efficiency. CO_2 emissions account for 93-95 per cent of total GHG emissions from transportation activities (Tatar and Ozer, 2018). Even though inland shipping emits about 9% of total CO2 from global shipping (Naya et al., 2017), the lack of acceptable energy and emissions standards for inland waterway self-propelled ships is a major roadblock to improving their performance (Simic, 2014).

The 4th Green House Gas report by IMO (GHG, 2020) shows that inland ships of the world have emitted 76 million tonnes of CO_2 in 2012 which has increased to 97 million in 2018 (28% rise). At the same time, the rise in international shipping from 2012 t0 2018 is only 8%. Figure 1.4 shows the amount of CO_2 emitted from 2012 to 2018 by international shipping and domestic navigation.

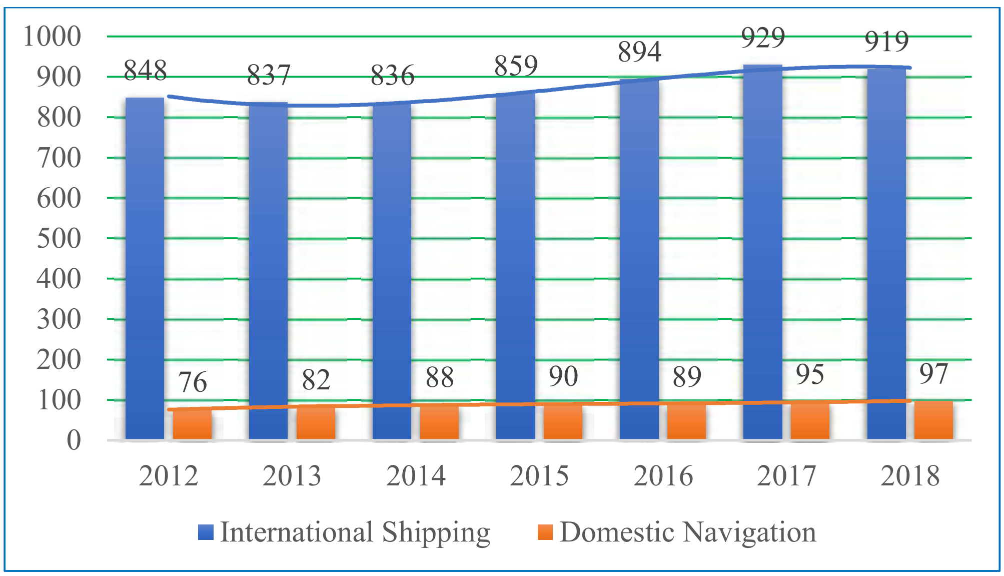

Figure 1.4: CO_2 emission from the shipping sector from 2012 to 2018

Inland ships often demand more power than equivalent open water/sea-going ships (Karim and Hasan, 2017), as seen in Figure 1.5 (EU, 2020). CO_2 emissions per tonne-km for inland and short sea shipping were 38 and 15, respectively (Otten et al., 2017), according to CE Delft (An independent research and consultancy organization based in The Netherlands, Otten et al., 2017). On the other hand, the Logistics Research Centre (Heriot-Watt University, United Kingdom) reported 20 and 8.4 CO_2 emissions per tonne-km, respectively (Mckinnon and Piecyk, 2010). In all situations, it is demonstrated that inland shipping emits more than twice as much CO_2 per tonne-kilometre than sea-going ships.

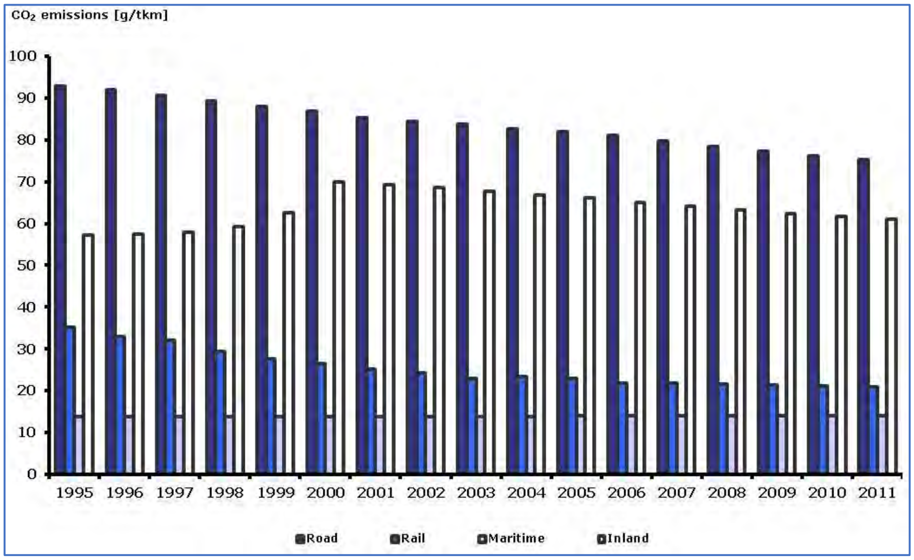

Figure 1.5: Specific CO_2 emissions per tonne-km of a different mode of transport in Europe (EU, 2020) (Permission granted for reusing, shown in Appendix-A)

Although inland shipping contributes to just 9% of world shipping's total CO_2 emissions (Naya, et al., 2017), efforts to lower CO_2 from its current level will be highly beneficial to any country from both an economic and environmental standpoint.

1.4.2 Major Challenges

The EEDI quantifies the transport work for estimating the amount of CO_2 emissions by sea-going ships (Hasan and Karim, 2019). However, inland waterways are composed of a complex network with diversified sectors that involve wide varieties of vessels with different purposes (Walker et al., 2011). In general, inland ships require more power at the same speed in comparison to open water/sea-going ships of similar type, mostly because of the speed drop due to shallow water effect and design constraint for the restricted river/channel depth and width.

Because of the above-mentioned unfavourable conditions, CO_2 emissions per tonne mile are in general higher than sea-going ships. Inland ship design faces some unique design challenges that increase power. The main reasons for that are:

a. The shallow-water effect drops the speed;
b. Ship design is mostly governed by the river width and depth;
c. Choice of Length, Breadth, Draft and Propeller diameter of the ship are not free as open sea ship design.
d. Freshwater density is lower than seawater. For this reason, the deadweight capacity becomes lower at the same draft in comparison to a seagoing ship. Deadweight has a very high impact on EEDI calculation.

It becomes worse for the designed ships. Restrictions on inland navigation will not be the same for all countries since the geographical conditions are not the same. For these reasons, like EEDI by IMO, a generalized EEDI is not possible for inland ships. Zakaria and Rahman (2017) have calculated EEDI baselines for different types of inland ships of Bangladesh to establish a baseline. However, the procedure followed for this establishment is for sea-going ships as directed by IMO (IMO, 2011) and did not consider the shallow water effect and other restrictions for inland vessels. In addition to that, the geometrical, hydrodynamic and propulsion data of the inland vessels used for the calculation of EEDI were not verified and the consistency of those data is not checked yet. Especially for Bangladesh, fuel quality is an important issue, because, it was found that, mixing impurities (burnt oil, burnt lube oil etc.) is a common practice here. As a result, standard Carbon content cannot be used like it was easily used for calculating EEDI for sea-going ships by IMO.

1.5 Motivation

The operation of inland shipping is growing, like sea-going ships. At the same time, customers preference for constructing cost-effective ships and new regulations on the environment challenge the conventional inland ship design methods. Is standard ship design practice enough to meet future emission regulations or the increasing demand for a cost-effective ship? Conventional ship design (especially commercial ship) primarily focuses on meeting the staff requirement of the shipowner, such as the payload, speed, and fuel consumption per hour. In doing so, designers ensure all the stability and pollution regulations (and other associated rules). A better ship is the one, which has a higher payload at the same speed and has lower operational and the first cost. As stated, before regarding the absence of appropriate energy and emissions benchmarks for inland ships, an attempt to have energy and emissions benchmarks for Inland Waterways is a good start from the research point of view.

The inland ships of Bangladesh have been chosen for this study. Thousands of various types of ships sail the rivers in this South Asian riverine country. This country's economy is heavily reliant on the network of these rivers. Unfortunately, any sort of ship's energy usage in Bangladesh is unknown. Bangladesh Inland Water Transport Authority (BIWTA), Department of Shipping (DOS), Mercantile Marine Department (MMD) and Department of Environment (DOE) are some departments/authorities of Bangladesh that are involved with the shipping and the environment. However, these organizations do not store any kind of energy consumption or CO_2 emission data from inland shipping of Bangladesh. As mentioned, the reason a generalized benchmark is not possible for inland shipping, individual efforts on the establishment of a CO_2 emission benchmark in the inland shipping sector, will lead Bangladesh to achieve MDG 7 (Ensure Environmental Sustainability) goal.

One of the important tasks of this research would be the sensitivity analysis of primary ship design particulars. Based on this analysis, suggestions for initial design for inland ships can be made. Karim and Hasan (2016) have shown that few initial design improvements considering EEDI, may lead to 20-40% energy efficiency improvements. The result of the research by Karim and Hasan (2017) has also motivated to have a sensitivity analyses-based suggestion and the cost-effectiveness of design modification.

1.6 Objectives of the Study

The prime objective of this research is to develop the energy-efficient hydrodynamic design of ships by reducing fuel consumption and CO_2 emission for inland ships of Bangladesh. The prime objective can be subdivided into the following sub-objectives:

a. To revise the EEDI formulation applicable for inland ships of Bangladesh.
b. To establish a standard $EEDI_{BD}$ baseline for Passenger, General Cargo and Oil Tankers, based on the revised $EEDI_{BD}$ formulation using a verified ship database.

c. To carry out sensitivity analysis of different ship design parameters and develop an energy-efficient ship design method incorporating $EEDI_{BD}$ with the existing design method.
d. To recommend the ranges of ship design parameters that will ensure low fuel consumption and low CO_2 emission.

1.7 Outline of Methodology/Experimental Design

As mentioned in the previous Sections, CO_2 emission benchmarks are required for inland ships. This benchmark will vary for each country. It would be much easier to follow the direct procedure by IMO. However, inland ship design needs some additional design factors to be considered. One of the prime factors is the shallow water effect which drops the speed in comparison to the open water speed. In addition to that, faulty ship data, cargo availability and inconsistency of fuel quality have made the procedure of establishment of a benchmark for Bangladesh harder.

Consideration of the above issues forced this research to start with revising the EEDI formulation by IMO. To establish $EEDI_{BD}$ baselines for Bangladesh, the differences of EEDI by IMO is addressed and quantified first by the following adjustment:

a. Adjustment of reference ship speed because of shallow water effect.
b. Adjustment of the required main engine power considering shallow water effect and speed loss.
c. Adjustment of the Maximum Continuous Rating (MCR) of the main engine at the service condition.
d. Adjustment of the value of deadweight capacity considering the average cargo availability.
e. The carbon content of the fuel, as investigations have found the tendency of mixing impurities (Burnt Lube Oil, Burnt Diesel Oil, etc).

After the above adjustment, EEDI formulation by IMO has been revised and made use for the inland ships of Bangladesh. Using the revised EEDI formulation (termed as

$EEDI_{BD}$), baselines/benchmarks for inland cargo ships, oil tankers and passenger ships have been established for Bangladesh.

Since EEDI is simply the ratio of 'Environmental Cost' and 'Benefit to the Society,' the 'Environmental Cost' involves the total input and output for a ship, including ship design parameters (Larkin et al., 2011). Therefore, a sensitivity analysis of ship design parameters for the inland ships of Bangladesh will identify the influence of those parameters on EEDI. This sensitivity analysis has been conducted after the EEDI benchmarks are established for Bangladesh.

Sensitivity analysis is started by the discretization of $EEDI_{BD}$ results into three different Groups, based on the ship length. Each Group has been again subdivided into the ship design principal particulars, such as length/Beam, Beam/Draft, Deadweight (DWT)/Displacement, ship speed, Froude number, block coefficient and finally the calculated value of $EEDI_{BD}$. These subdivisions allow us to identify the ranges of efficient and poor ship design parameters ranges for inland ships of Bangladesh. This analysis provides a clear picture of the ship design particulars that a have higher influence on $EEDI_{BD}$. A set of design suggestions is proposed aiming at achieving efficient ship design parameters.

To verify these suggestions, an existing ship design from each type of ship has been selected for CFD analysis. The same vessel is remodelled based on the provided suggestions. The parent and remodelled design are analysed by the commercial CFD software 'Shipflow') (Flowtech, 2010). The CFD results have been presented for comparison to validate the suggestions from the sensitivity analysis. Since the reduction of the $EEDI_{BD}$ value implies the reduction of CO_2 emissions per tonne-nautical mile, the environmental benefit has been achieved. The basic flowchart of the above-discussed methodology is presented in Figure 1.6.

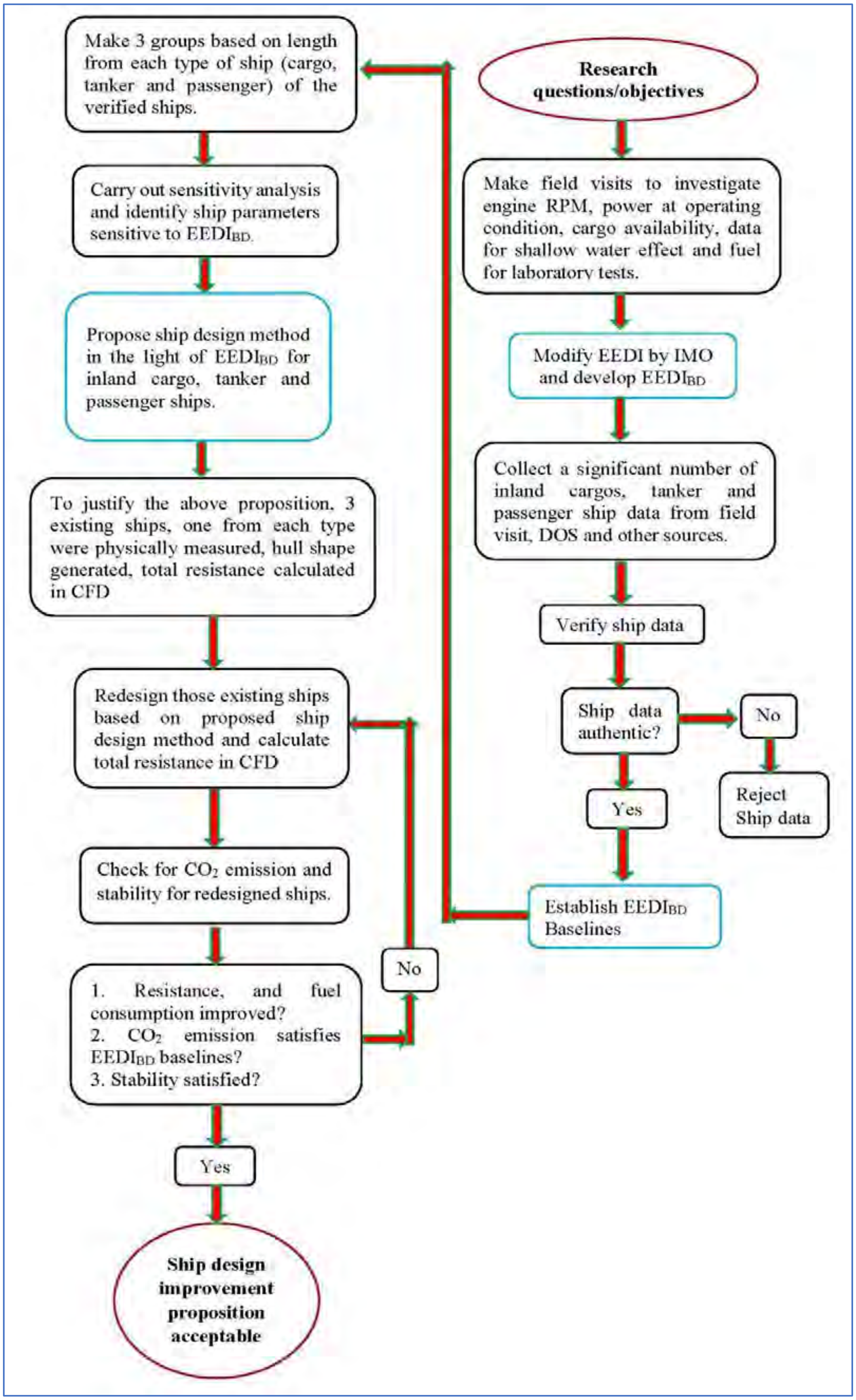

Figure 1.6: Methodology flowchart

1.7.1 Revising EEDI formulation- methodology to incorporate the shallow water effect.

To revise the EEDI of IMO to be useful for the inland ships of Bangladesh, the prime adjustment was the incorporation of the shallow water effect. The shallow water effect causes speed loss. EEDI formulation by IMO for sea-going ships considers the ship speed at the 75% Maximum Continuous Rating (MCR) of the main engine. Fixing an MCR for inland shipping is not possible mainly because of the shallow water effect.

The shallow water effect on inland ships is one of the classical problems in the field of Naval Architecture. Several empirical formulas have been developed by many researchers to incorporate the shallow water effect into the design. The gap between the keel and river bed governs this effect. The low the gap is, the higher the effect is.

Bangladesh is a land of rivers and canals. Only 11.39% (683 Kilometre by length) of the rivers of Bangladesh has a minimum depth of 3.66 meters (BIWTA, 2020). It signifies that most of the inland ships of Bangladesh encounter shallow water effects.

By the analysis of different inland routes, using the year-round water depth data from the 'Flood Forecasting and Warning Centre' under Bangladesh Water Development Board (BWDB), field measurement and utilization of the empirical formula of the shallow water effect, necessary corrections on the shipping speed and main engine's MCR were made.

1.7.2 Revising EEDI formulation- fixing Maximum Continuous Rating (MCR)

The speed at 75% MCR is the reference speed in the EEDI formulation by IMO. The prime reason behind fixing 75% by IMO is that, on average, sea-going ships MCR is 75%. However, this may not be correct to use for inland ships without investigation. The following procedure was used to fix the MCR to be used for the inland ships of Bangladesh:

a. Measuring Engine RPM physically at different service conditions
b. Power against the RPM from Engine Power Vs RPM curve.

1.7.3 Revising EEDI formulation- fixing capacity

IMO has used the total deadweight capacity for sea-going ships. However, for inland ships, cargo availability is an important issue. In many cases, freight earning inland ships of Bangladesh, ply partially loaded primarily because of cargo availability and grabbing the next best opportunity.

It has also been found that plenty of ships is not constructed according to the original design or design was originally faulty. As a result, those vessels become trimmed by the bow when fully loaded. These vessels never can carry her design deadweight.

Another reason is the river and canal draft. The rivers of Bangladesh are generally full from the month of June to October. On the other months, bigger vessels are not fully loaded to avoid grounding. Because of the above reasons, the average cargo carried by the general cargo and oil tankers were considered and incorporated into the revised EEDI formulation.

1.7.4 Revising EEDI formulation- fixing carbon content

Mixing impurities into the ship's fuel is a common practice in Bangladesh. Naturally, the carbon content will vary from the standard, in general, carbon content goes up. Therefore, like IMO, direct use of standard carbon content cannot be used in the EEDI formulation. To find the carbon content of the diesel used, a sample from the ship's service tank has been tested chemically. The average carbon content of that collected sample is considered as the carbon content of the diesel fuel used in the inland marine sector and has been used in the revised EEDI formulation of Bangladesh.

1.7.5 Methodology of Sensitivity Analysis

Sensitivity Analysis is the impact of the independent variables of a system or mathematical model under a given set of constraints and assumptions. Sensitivity analysis is mostly used when there are too many designs or test variables. This analysis helps to understand, which variables have the most influence on the final output or result. An independent variable has an independent impact under a given constraint. As a result, before optimization of any design where too many variables are available, sensitivity analysis is a very good option to sort the variables with the highest impact. This analysis is also used to ensure that any suggested formulation is valid and reliable (Mizythras et al., 2016).

Qinxian (2014) has mentioned several types of sensitivity analysis, which can be summarized as

a. Factor Screening determines the variables that have the greatest impact on a given system.
b. Global Sensitivity Analysis removes uncertainty from the model output across all response ranges.
c. Distributional Sensitivity Analysis extends the Global Sensitivity Analysis approach to scenarios where just a part of the variation of a component is decreased.
d. A partial response area is the subject of Regional Sensitivity Analysis.

This study might benefit from a sensitivity analysis based on factor screening. This technique has sorted out the impact of specific ship design factors on EEDI.

1.7.6 Methodology for design modification based on EEDI

A simple methodology is followed for the moderation of the inland ship design of Bangladesh. 'Sensitivity Analysis' has led the research to identify factors with the highest influence on ship design (focusing on $EEDI_{BD}$). This analysis determines the variables that have the highest influence over the output. Thus, a set of suggestions would be possible from the sensitivity analysis, which has been used to redesign existing inland ships of Bangladesh. The total resistance of the parent and redesigned ship based on the suggestion from the sensitivity analysis has been analysed by commercial CFD software called 'Shipflow,' a specialized CFD software for ship design applications.

1.8 Literature Review

1.8.1 The energy efficiency of inland waterway self-propelled cargo ships

Simic and Radojcic (2013) proposed that one EEDI baseline be calculated for each speed of the same kind of inland vessel in research on the energy efficiency of inland waterway self-propelled cargo boats. The idea was made to protect the vessels from external disruptions and to maintain the same fairway conditions. (For example, two sister vessels at different inland waterways; one waterway is free from shallow water effect and another affects. These two vessels will have different speeds at the same operational profile. If there are different EEDI baselines for different speeds, those two vessels will be able to use different EEDI baselines. Thus, the external disturbances can be compensated.). Figure 1.7 shows the proposed EEDI baselines from that study (Permission granted to reuse this Figure is, shown in Appendix A).

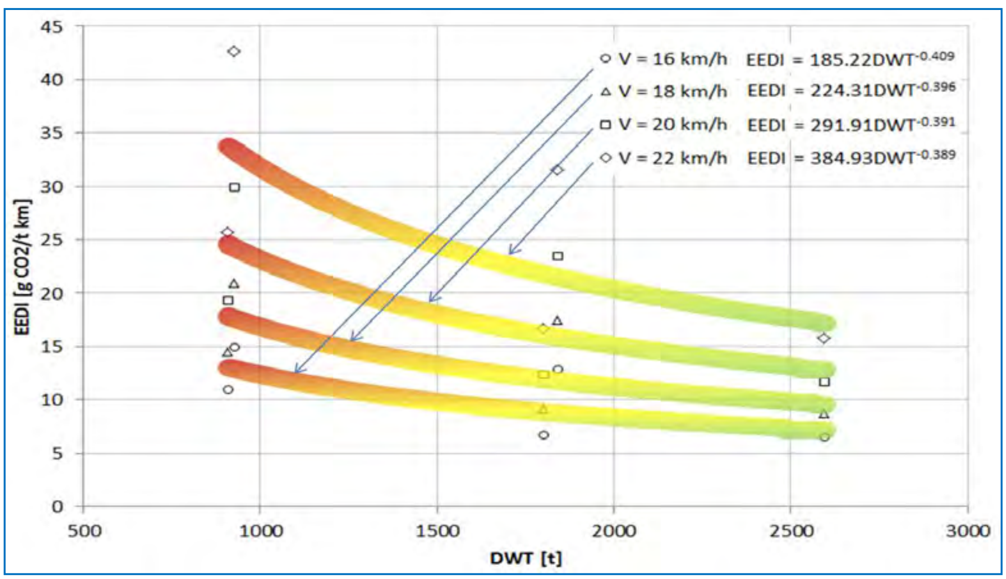

Figure 1.7: Proposed EEDI baseline for inland cargo ships (Simic and Radojcic, 2013)

However, though the proposed baselines consider the drop in speed because of shallow water effects, it is against the spirit of IMO regarding EEDI. The IMO's EEDI initiative aims to encourage innovation and technological progress throughout the design phase. Since the study by Simic and Radojcic (2013) allows the higher value of EEDI at higher speeds, urge for innovative technology to have efficient hull designs (L, B, T, C_B, etc.)

for a practical design speed in shallow water (and other restrictions) may be discouraged. A single baseline for each type of ship (as IMO has done for seagoing ships) will restrict ships to emit CO_2 irrespective of speed. This will enhance the technological advancement to have a more energy-efficient ship. In this paper, the effort was given in line with IMO guidelines and established a single baseline for each type of vessel.

1.8.2 Use of alternative fuel: inland water transport in Bangladesh

Alternative marine fuels have the potential to significantly cut CO_2 emissions globally. The MDG's climate change target is largely reliant on the decarbonization of the atmosphere. In comparison to fossil fuel, the shipping sector has already joined, albeit on a modest basis. Shipbuilders, engine manufacturers, and classification societies have all begun to produce greener ships and engines in recent years. With excellent market supply infrastructure in place, LNG and methanol appear to be the most attractive options right now.

Ecorys Netherlands BV (2011) evaluated vessels of Bangladesh Inland Water Transport Corporation (BIWTC) in a study on inland water transport in Bangladesh to improve energy efficiency. Because of the usage of outdated engines and poor vessel design, the energy efficiency performance of inland boats in developing nations is worse than that of industrialized countries, according to the research. It is suggested in the paper to use Converted Natural Gas (CNG) as fuel. The cost-effectiveness has also been calculated which states a break-even period of approximately 1.1 years. However, the fact for Bangladesh is very different regarding CNG or other alternative fuels at present. The pilot project seemed very promising, but the expansion of the pilot project will not be feasible because low-cost CNG is not guaranteed in Bangladesh. In addition, around 95% of the natural gas of Bangladesh is used in different industrial sectors and domestic uses, (Yusuf et. al., 2012) which are the economic backbone of Bangladesh. Due to these facts CNG as alternative fuels was not considered in this paper, rather better hull shape and fuel economic design and operation of ships were preferred. Based on the work in Bangladesh, Ecorys BV (Ecorys, 2011) has suggested some fuel efficiency improvement means, which is shown in Table 1.1. None of the options presented in the Table has a large impact on the environment. The environmental impact is only low to moderate when investment costs are low, low to moderate, high, and extremely high.

Table 1.1: Assessment of fuel efficiency improvement means (Ecorys, 2011)

Means	**Investment Costs**	**Cost Savings**	**Environmental effect**	**Safety**
		Conventional means		
Optimization Operations	Low	Low	Low	None
Minimizing Resistance	Low to Moderate	Low/Moderate	Low	Low
Propulsion system and steering gear	Moderate to high	Moderate to high	Moderate	Low
Adapting fairways	Very high	Moderate to high	Moderate	Low
Adapting fairways	Very high	Potentially very high	Emissions moderate,	Moderate
		Advanced means		
Alternative fuels	Moderate	Moderate to high	Moderate	Low
Advanced low resistance design	High	High	Moderate	Low
Advanced high-efficiency propulsion systems	Moderate to high	High	High	Low
New logistical concepts	Low to high	Low to high	Low to Moderate	None

1.8.3 The CO_2 reduction potential of EEDI from the world shipping industry.

This research was co-authored by Lloyd's Register of Shipping (LRS) in the United Kingdom and Det Norske Veritas (DNV) in Norway. The study's findings suggest that using EEDI in the maritime sector from 2013 onwards has the potential to cut CO_2 emissions. According to Bazari and Longva (2011), the IMO EEDI mandates a minimum energy efficiency level (CO_2 emissions) per capacity mile for different ship types and size segments (Bazari and Longva 2011). EEDI will enforce ongoing technical research to design more energy-efficient solutions for ships as the level is tightened over time. SEEMP and EEDI's overall yearly CO_2 reduction potential in 2020 is depicted in Figure 1.8.

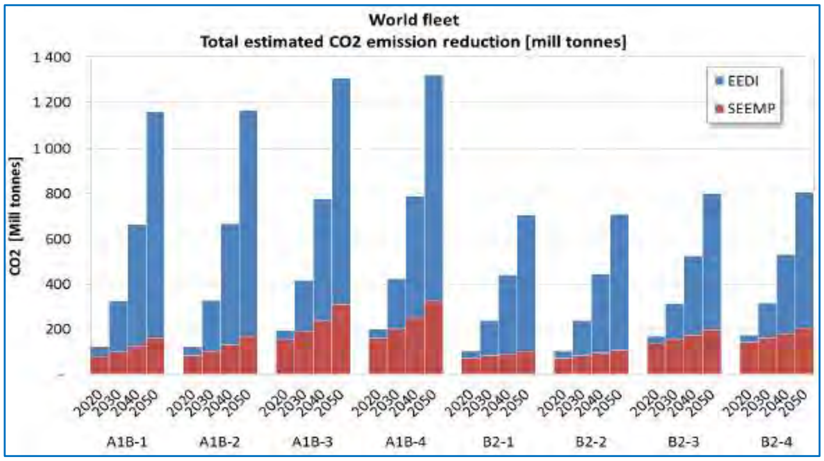

Figure 1.8: CO_2 reduction potential by SEEMP and EEDI (Bazari and Longva, 2011).

1.8.4 Comparison of inland shipping emission to other modes of transport

In terms of emissions, Ebert (2005) showed that rail and inland shipping had obvious benefits over road and air travel. Academic journal papers, official government publications, and even research financed by the shipping industry were used to compile the data for the study. It also says that the rates of fuel consumption and emissions from ships vary depending on the kind of general cargo and container ship. Wet and dry bulk carriers, which are bigger and slower than general cargo and container ships, perform better. The findings of the technical study are consistent with current studies since slow steaming vessels with big capacities perform better in terms of EEDI.

Figure 1.9 shows that from 1990 to 2000 in the European Union countries, Inland Navigation emissions have been slightly above rail emission, and well below road emissions.

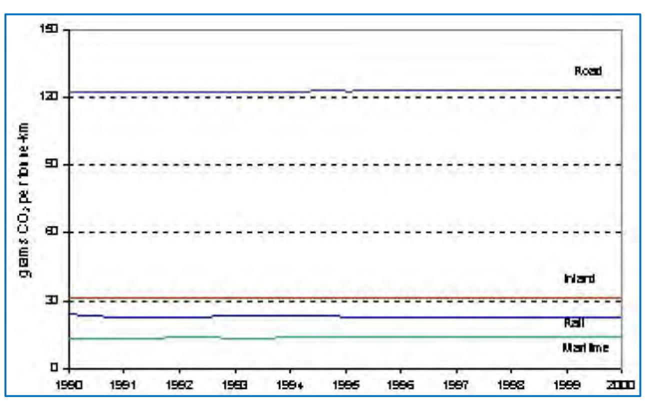

Figure 1.9: Specific emissions of CO_2 per tonne-km and per mode of transport in EU-15

1.8.5 Use of marginal abatement cost to assess CO_2 emission

A Marginal Abatement Cost Curve (MACC) is commonly used to estimate the CO_2 emission reduction potential of markets, according to Alvik et al. (2010). This might not be the ideal tool for comparing CO_2 Reduction Measures (CRMs) on a ship-by-ship or fleet-by-fleet basis. This curve might also be deceiving because:

a. CRMs are assumed to be implemented in a certain order. As a consequence, depending on the location where the ship is operated, contractual requirements, and the ship itself, certain CRMs may be more favourable than others.
b. For a fair comparison, more than one MACC is required.
c. As mentioned by Kesicki et al., measures are often analysed individually to arrive at a specific cost and abatement alternatives (2011).

1.8.6 Problems with the available fuel-saving options for ships

Usually, CO_2 Reduction Technologies (CRT) is produced by a manufacturer and as a result, most of the available data on CRTs reflects the wishes of the manufacturer operators. Available fuel-saving options for ships have shown large scatter in saving potential. In addition, the saving potential as declared by the manufacturer is unreliable.

Hochkirch and Volker (2010) have shown the major problems, which include

a. A failure to take uncertainty into account (normally a single value is quoted with no error bar).
b. A lack of assumptions about how the CRT will be used, as well as a consideration of ship design and type, may affect the CRT's performance (in terms of cost as well as CO_2 emissions).
c. A scarcity of onboard measurements and trial data, especially publicly available data.)
d. A lack of citations (publishing of information on data sources).
e. There aren't only technical barriers to getting a CRT on the market (as described above).

1.8.7 Improving the energy efficiency

Considering EEDI, ship design can be optimized. Gerhardt (2014) has shown several methods to optimize EEDI at the design stage. The research result by Frederik Gerhardt can be summarized in the following manner:

a. Lowering the hull's power requirement by optimizing key characteristics like length or beam while maintaining deadweight and speed.
b. Using hull form optimization, or traditional hydrodynamic enhancements, to reduce the power consumption of a hull with given primary parameters.
c. Using major parameter optimization, increasing the product of engine output (due to speed) and deadweight capacity without increasing needed power.
d. Tailoring the engine's sea margin component to a ship's demands under predicted operating circumstances.

1.8.8 Ship design for sea versus ship design for EEDI

Hagesteijn (2014), senior project manager at MARIN in the Netherlands, rebuilt an existing ship to accommodate a variety of loading situations, based on the vessel's real operational profile. The other design is designed for a wide range of speeds and drafts based on the vessel's operational characteristics. The EEDI and energy consumption for a type and a typical operational profile were determined for these designs. It is feasible to experiment with all of the major details and coefficients during the design stage to minimize the power demand at the same time. Hagesteijn (2014) did not explore holistic optimization, which gave the author superior results.

1.8.9 Impact of power reduction on sustained speed and reliability

Dallinga et al. (2014) at MARIN (Maritime Research Institute of the Netherlands), is working on the speed and reliability impact due to the reduction of engine power. It is true that if the ship's energy efficiency level is not increased day by from the current stage, there is no other way but to reduce the size of the engine to meet EEDI criteria at the stringent phases. However, one of the major goals of implementing EEDI was to encourage innovation and technological improvement of all aspects that improve a ship's energy efficiency throughout the design phase.

1.8.10 Establishment of link among population growth, technology, resources, and CO_2 emission

CO_2 emission growth is directly related to the growth of the population. It is not the amount of CO_2 emitted from a population of the world, but it is the increasing needs of the population. Hundred years ago, and before that, the needs of human beings are fulfilled mostly from nature and useful hands. However, the huge population growth after the 18th century, useful hands were not enough. Industrialization took place the useful hands, free trade economy system, transportation of goods, huge advancement of science and technology has increased the CO_2 emission exponentially. Ehrlich and Holdren (1971) have described the relationship between population, resources, and the environment. As explained by Ehrlich and Holdren (1971), Amount of CO_2 = f(Number of Population) x f(Cost/Number of People) x f(Amount of CO_2/Cost)

1.8.11 Environmentally friendly inland waterway ship design- Danube-Carpathian program

Radojcic (2009) at World Wide Fund for Nature International Danube-Carpathian program (WWF-DCP) has given importance to the shallow water effect and shown some ways to overcome the effect. One of the concluding remarks was: ‘Inland (shallow water) vessels should be designed (matched) according to waterway characteristics, i.e., the vessel’s main parameters (Draft, length, propeller size etc.) should be adjusted to the specific waterway.’

1.8.12 Third IMO Green House Gas (GHG) study

The global shipping sector released 796 million tonnes of CO_2 in 2012, according to the third GHG analysis (Smith et al. 2015). This amounted to around 2.2 per cent of total CO_2 emissions worldwide. According to the same report, emissions may increase by 50% to 250 per cent by 2050, depending on economic growth and energy advancements.

1.8.13 Fourth IMO Green House Gas Study

The 74th Marine Environment Pollution Committee meeting decided on the terms of reference for the Fourth IMO GHG Study, which follows the Initial IMO Strategy on reducing GHG emissions from ships and its schedule of follow-up measures through 2023. (IMO GHG study, 2020). According to the fourth research, overall CO_2 emissions from shipping (international, domestic, and fisheries) rose from 962 million tonnes to 1056 million tonnes over six years beginning in 2012.

1.8.14 A green and economic future of inland waterway shipping

Inland waterway transportation has a green and profitable future, according to Wilfried et al. (2015). According to his research, the adjustable LNG-gas-electric propulsion system would enhance resource efficiency by up to 30%. Furthermore, improved design can cut fuel usage by 10%. The study's main goals are to cut greenhouse gas emissions and other contaminants. This novel breakthrough will be included in a ready-to-use inland waterway transportation model to meet the European Commission's aims for competitive and resource-efficient transportation (EC, 2008).

1.8.15 Improving the efficiency of small inland vessels

Stefan et al. (2010) looked at the smaller inland boats (250–1350 tons) that ply the Belgian canals. In this carrying capacity range, three types of inland ships have been recognized. The average annual fuel consumption and emissions for these three classes of ships are determined based on the operational profile of each of the Belgian waterway classes. The research includes a literature review, an examination of current inland boats, and a review of available data on resistance and propulsion. According to the study, the following measures should be examined to determine the ways that can lead to an optimization of the inland vessel design.

a. Lowering hull resistance.
b. Improving the design and selection of an ideal propeller to improve the propeller's hydrodynamic efficiency.
c. Improving the engine's efficiency.

d. Any further measures (for example, control devices).

1.8.16 Ship emissions study

This research by Psaraftis and Kontovas (2008) may have an edge over others that attempt to estimate world emissions since, in addition to modelling, it incorporates real data obtained from industry. The study's primary weakness is the lack of data availability, quality, and dependability. Additional data, such as ship movements on a global scale and precise bunker consumption numbers for the global fleet, is required to conduct a more in-depth and comprehensive study.

1.8.17 Estimation of emissions from shipping in the Netherlands

In the Netherlands' BOP study, Hugo and Hulskotte (2010) defined inland shipping as vessel transit through inland waterways (canals, rivers) between inland ports, quays, and wharves. Klein et al. explain the approach for estimating emissions from inland shipping in the Netherlands (2015). However, they merely provide technique; particular emission variables and activity statistics may be obtained in separate Dutch reports. Statistics Netherlands can provide statistics from the previous year. As a result, based on the data, this report gives an overview of the methodology as well as significant Figures. Klein et al. (2015) made a distinction between actual emissions, NEC emissions and IPCC emissions.

1.8.18 Environmental performance of inland shipping

The goal of this study by Schilperoord (2004) is to assess the environmental performance of propulsion engines in inland shipping in Europe. The environmental performance of inland shipping is assessed to understand whether the change towards inland shipping contributes to the improvement of the environmental performance or not. The general environmental performance of a transport modality constitutes many environmental parameters. The most significant parameters in inland shipping are the Nitrogen Oxides (NOx), Carbon Dioxide (CO_2), Particle Matter (PM10) and Sulphur Dioxide (SO_2) emissions from propulsion engines.

1.8.19 European Union activities in controlling CO_2 emission from shipping

As part of the Kyoto Protocol, the European Union (EU) is actively collaborating with other industrialized nations to reduce emissions from international marine transportation. Despite its dissatisfaction with the IMO's progress, the European Commission (EC) backed the plan to reduce GHG emissions. The EC plan seeks to dramatically decrease premature mortality due to air pollution while also addressing environmental effects like acidification and eutrophication, as well as concomitant biodiversity losses.

1.8.20 Life cycle assessment

Tincelin, et al. (2010) present a comprehensive strategy to assess and reduce a vessel's or maritime equipment's environmental effect. To choose the environmental options that are dependent on the ship energy efficiency index, a simple and conclusive design criterion has been established. EVEA (environmental consultant) created the ‘SSD' program in collaboration with shipbuilders and subcontractors who provided a wealth of data on their technologies. This comprehensive approach does not provide quantitative technology selection guidelines to the designer's shipyards and suppliers; rather, these SSD tools allow the designer to assess the environmental benefits of a technical solution on a specific ship design without conducting a detailed life cycle analysis of the entire ship.

1.8.21 Environmental ship index (ESI)

The Environmental Ship Index (ESI) was created by Laar (2009) as part of the World Ports Climate Initiative (WPCI). The world's top 55 ports have pledged to reduce GHG emissions while maintaining the port's primary function. This index will detect seagoing ships that do not comply with current emission control rules. This index has been described as a self-managed system. This method was created to aid marine shipping's environmental performance. The ESI system index assigns points to ships based on their performance and compares them to current international regulations (mainly IMO). This index applies to all sorts of ships. ESI scores range from 0 to 100 for a ship that fulfils environmental requirements and produces no SOx or NOx while reporting or monitoring its energy efficiency. The ESI points can be determined by comparing the ship's real performance.

CHAPTER 2

REVISING EEDI FORMULATION APPLICABLE FOR INLAND SHIPS OF BANGLADESH

2.1 Brief description of EEDI by IMO

EEDI by IMO is the most recent and one of the most important technical metrics aimed at forcing naval architects, researchers, and ship owners to adopt more innovative energy-efficient measures for new seagoing ships. The EEDI concept is that it promotes efforts by all stakeholders to decrease CO_2 emissions by representing a ship's energy efficiency in real usage and that its computation is simple and capable of wide use. One of the primary goals of enacting obligatory measures is to encourage and assist naval architects and researchers in furthering the technological development of all components that influence the fuel efficiency of a ship. According to the accepted MEPC decision (MEPC, 203(62), 2011), new ship designs must reach the reference level for their ship type starting January 1, 2013, after a two-year phase zero period.

The following are the goals of the IMO's EEDI (Hasan, 2011):

a. Achieve a minimum energy efficiency level for new ships;

b. Investigate the continued effort on the technical development of all components that influence fuel efficiency;

c. Distinguish technical and design-based measures from operational and commercial measures; and

d. Compare the energy efficiency of individual ships to similar ships of similar size that have undergone similar operations.

The formulations, which were recommended at different stages, are given below.

$$EEDI = \frac{CO_2\ Emission}{Transport\ Work}$$

$$\frac{Power \times Specific\ Fuel\ Consumption \times CO_2\ Conversion\ factor}{Factors \times Capacity \times Speed}$$

$$= \frac{Emission\ from\ Main\ Engine + Emission\ from\ Auxiliary\ Engine + Emission\ for\ running\ shaft\ motor\ -Efficient\ Tech.\ Reduction}{Different\ factors \times Capacity \times Reference\ Speed}$$

$$= \frac{\left(\prod_{j=1}^{n} f_j\right)\left(\sum P_{ME(i)} \underset{i=1}{\overset{nME}{\times}} C_{FME(i)} \times SFC_{ME(i)}\right) + (P_{AE} \times C_{FAE} \times SFC_{AE}) + \left(\prod_{j=1}^{n} f_j \sum_{i=1}^{nPTI} P_{PTI(i)} \times C_{FAE} \times SFC_{AE}\right) - \left(\sum_{i=1}^{neff} f_{eff(i)} \times P_{AEeff(i)} \times C_{FAE} \times SFC_{AE}\right) - \left(\sum_{i=1}^{neff} f_{eff(i)} \times P_{eff(i)} \times C_{FME} \times SFC_{ME}\right)}{f_i\ X\ f_c\ X\ f_l\ X\ f_W\ X\ Capacity\ X\ V_{REF}} \quad (2.1)$$

$$= \frac{kW \times \frac{g_{fuel}}{kWh} \times \frac{g_{CO_2}}{g_{fuel}}}{Tonne \times \frac{nautical\ mile}{hour}}$$

$$= \frac{g_{CO_2}}{Tonne \times nautical\ mile}$$

Equation 2.1 of EEDI contains different constants and coefficients. The definition and meaning of those are described in IMO MEPC resolution (MEPC 308 (73), 2018), which is presented in the following Table 2.1.

Table 2.1. Description of different parameters of EEDI by IMO

Parameter	Description	Unit
P_{ME}	75% of the rated installed power for each main engine (MCR)	Kilowatt
C_{FME}	The non-dimensional conversion factor for the main engine between fuel consumption and CO_2 emission	Non-dimensional
SFC_{ME}	Certified Specific Fuel Consumption of the main engine	g/kWh
P_{AE}	Auxiliary Engine Power	Kilowatt
C_{FAE}	The non-dimensional conversion factor for auxiliary engine between fuel consumption and CO_2 emission	Non-dimensional
SFC_{AE}	Certified Specific Fuel Consumption of auxiliary engine in g/kWh	g/kWh
$P_{PT(i)}$	75% of rated power consumption of shaft motor	Kilowatt
$f_{eff(i)}$	Availability factor of innovative energy efficiency technology	Non-dimensional
$P_{AEeff(i)}$	Auxiliary power reduction due to innovative electrical energy-efficient technology	Kilowatt
$P_{eff(i)}$	The output of innovative mechanical energy-efficient technology for propulsion at 75% main engine power	Kilowatt
f_i	Correction factor to account for ship specific design elements. (For example, ice-classed ships, shuttle tankers)	Non-dimensional
f_C	Cubic capacity correction factor (for chemical tankers and gas carriers)	Non-dimensional
f_J	The factor for general cargo ships equipped with cranes and other cargo related gear to compensate in a loss of deadweight of the ship	Non-dimensional
Capacity	1. For Passenger Vessel: Gross Tonnage (GT). 2. For Cargo and Oil Tanker: Computed as a function of Deadweight as indicated in 2.3 and 2.4 of MEPC 245(66) “2014 Guidelines on the calculation of the Attained EEDI for new ships”	Tonne
f_W	Non-dimensional coefficient indicating the decrease of speed in representative sea condition of wave height, wave frequency and wind speed	Non-dimensional
V_{REF}	Ship speed in nautical miles per hour at P_{ME}	Knot

2.1.1 Attained EEDI

The ship designer must know what would be the value of EEDI for a new ship. If the new ship's EEDI value is above the current baseline, all the efforts by the designer will be in vain. For this reason, based on the preliminary ship design data, the EEDI value is calculated by Equation 2.1. This value is called the Attained EEDI which is the actual value of EEDI at the design stage. It must be guaranteed that the EEDI criteria, as well as the minimum required power for the ship's manoeuvrability in bad weather conditions, are met throughout the design stage.

According to MARPOL Annex VI, Chapter 4 (IMO, 2016) regulation:

a. The obtained EEDI must be computed for each new ship. Furthermore, any new ship that undergoes a substantial conversion, as well as older ships that undergo several alterations, must have its EEDI computed.
b. The Attained EEDI is only applicable to a limited number of ship types.
c. The Attained EEDI must be computed in accordance with all applicable IMO rules.
d. Along with the completed EEDI computation, an "EEDI Technical File" must be produced. The process for obtaining EEDI computation and data collecting must be detailed in this technical documentation.
e. The EEDI technical file must be verified by the administrative authority or any other authorized agency.

2.1.2 EEDI Baseline/Reference line

The calculated attained EEDI for each existing ship plotted against the deadweight capacity. A regression-based curve along the scattered plot of attained EEDI value for a specific type of defined Group of ships is called the EEDI 'Baseline/Reference line'. For any new ship to be designed, the attained EEDI value must be below the value of this baseline. A sample baseline/reference line developed by IMO is shown in Figure 2.1 (MEPC 231(65), 2013). IMO had developed one baseline of each type of seagoing ship.

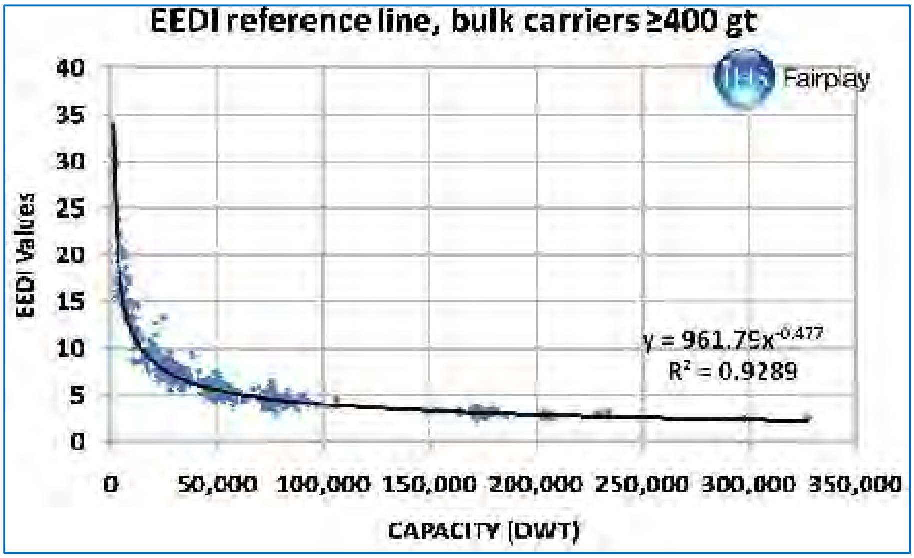

Figure 2.1: IMO proposed baseline for bulk

The Baseline values shall be calculated as follows:

Baseline value, $y = a \times b^{-c}$ (2.2)

where the parameters a, b, and c are shown in Table 2.2. (IRS, 2015). The current EEDI standards will be increasingly strict, with the EEDI baseline value being reduced by 10% every five years based on the original value (Phase 0) and vessel size. There is no decrease below a particular size. When a ship reaches a particular size, the reduction is generally 10% for each reduction phase.

Table 2.2. Parameters for determination of reference values

Ship type defined in regulation	**a**	**b**	**c**
Bulk carrier	961.79	DWT	0.48
Gas tanker	1120	DWT	0.46
Tanker	1218.8	DWT	0.49
Container ship	174.22	DWT	0.2
General cargo ship	107.48	DWT	0.22
Refrigerated cargo carrier	227.01	DWT	0.24
Combination carrier	1219	DWT	0.49
Ro-Ro cargo ship (vehicle carrier)	(DWT/GT)-0.7* 780.36, where DWT/GT<0.3 and	DWT	0.47

	1812.63, where DWT/GT≥0.3		
Ro-Ro cargo ship	1405.15	DWT	0.5
Ro-Ro passenger ship	752.16	DWT	0.38
LNG carrier	2253.7	DWT	0.47
Cruise Passenger Ship having non-conventional propulsion	170.84	GRT	0.21

2.2 Reasons for revised EEDI for inland ships

In 2011, the International Maritime Organization (IMO) created EEDI for seagoing ships (MEPC 62, 2011). Later, in 2018, it was updated with some significant changes (MEPC 308(73), 2018). For new rules, this sort of modification is fairly common. This type of amendment is quite normal for new regulations. New proposals are still coming from different sides of researchers to update/modify existing baseline formulation for sea-going ships (Vladimir et al., 2018).

There is a distinct difference in ship design between sea-going and inland/domestic ships. The EEDI as adopted by IMO for seagoing ships cannot be used for inland ships for the following reasons:

a) Apart from capacity and speed, there are major design differences between seagoing and inland ships. Without any exception, the draft restriction is not a design obstacle for seagoing ships. However, inland ship design is mostly governed by this effect, which leads to a speed drop. For this reason, the choice of main engine power is different from sea-going ships. Speed and power are the two input values for EEDI that influences EEDI the most.

b) Capacity is another input value of EEDI that influences EEDI value to a great scale. Availability of cargo for inland ships is a prime concern for Bangladesh. Most of the voyages are not guaranteed full load capacity.

c) When the type of fuel is known, a standard carbon content value can be used. Standard carbon content, on the other hand, cannot be utilized in Bangladesh. The investigation has shown that combining contaminants (Burnt Lube oil/diesel, etc.) with gasoline is a common practice in Bangladesh.

Because of the above-mentioned reasons, the following changes of EEDI by IMO are required to have EEDI formulations for inland ships of Bangladesh:

a) Inclusion of speed loss because of shallow water effect.

b) Fixing the Maximum Continuous Rating (MCR) to define P_{ME} considering shallow water effect.

c) Defining the reference speed (V_{REF}).

d) Fixing the deadweight capacity value considering the average cargo availability.

e) Carbon content of the fuel, as investigations have found the tendency of mixing impurities (Burnt Lube Oil, Burnt Diesel Oil, etc).

2.2.1 Inclusion of speed drop due to shallow water effect in $EEDI_{BD}$

One of the most well-known difficulties in the field of ship resistance is shallow water effects. When a ship enters shallow water squat effect comes into force because of the limited draft. The water velocity surrounding the ship hull rises, which causes more drag and eventually lowers the ship hull efficiency. The shallow water effect mostly depends upon the bottom clearance and the speed of the ship. This speed varies with the underwater clearance. These hydrodynamic effects affect any ship (regardless of size) that enters restricted waters.

2.2.2 Hydrodynamic effects of confined waters on ship resistance

In confined or restricted water, both the water depth and breadth are limited. When a ship enters into restricted waters, its hydrodynamics alter. The hydrodynamic shift causes changes in surge waves, return flow, squat, draw-down, sediment resuspension, and bank scouring. The pressure distribution is altered in limited waterways for inland ships. The water in front of its bow is pushed, causing a pressure rise in front of the bow and a pressure reduction behind the stern. As a result, water flows from all directions to fill the void/gap. Furthermore, the propeller draws in water from behind the ship and expels it in the opposite direction of the ship's forward motion. The flow around the ship is also accelerated as the portion where water may flow is reduced, resulting in an increase and decrease in kinetic and potential energy, respectively. The decrease in potential energy and pressure generates drawdown, which is the decrease of the water level. As the water speed under the ship increases, the pressure decreases, causing a vertical force to be exerted to the ship, causing it to descend vertically into the water. The uneven pressure distribution along the ship’s hull creates a moment along the transverse axis which lead the ship to trim by the bow or the stern. Ship squat refers to the combination of vertical sinkage and trim. In extreme circumstances, when the keel clearance is insufficient, the ship may potentially touch the channel's bottom. The channel shape, shipment speed, and blockage factor all influence return/backflow speed. Ship squat and return flow in a limited canal are depicted in Figure 2.2.

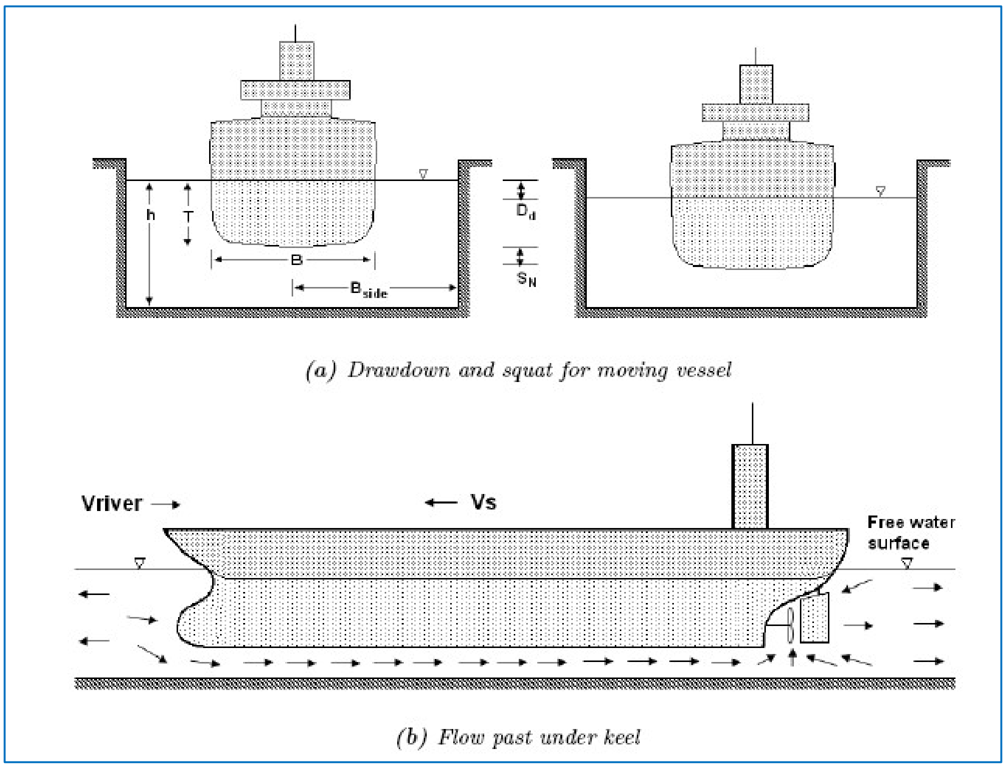

Figure 2.2: Schematic diagram of ship squat and return flow. a) Drawdown and squat for moving vessel b) Flow past under keel (Florian, 2019).

Because of the above discussed hydrodynamic effects of restricted water on ship hull, the followings are the impact of resistance:

a. The viscous resistance on the hull increases as the speed of the flow around the hull increases.
b. As the ship squats, the wetted surface area of the ship increases, creating frictional resistance.
c. At the same speed, waves created in shallow water tend to be bigger than waves produced in the deep sea.

2.2.3 Characterization of channel restriction

The following characteristics are often used to determine the type and amount of limitation of a waterway: water depth to draft ratio (H/T), canal width to ship breadth ratio (W/B), and canal Section (AC) to midship Section (AS) ratio AC/AS (blockage ratio). The geometric characteristics of the canal are shown schematically in Figure 2.3.

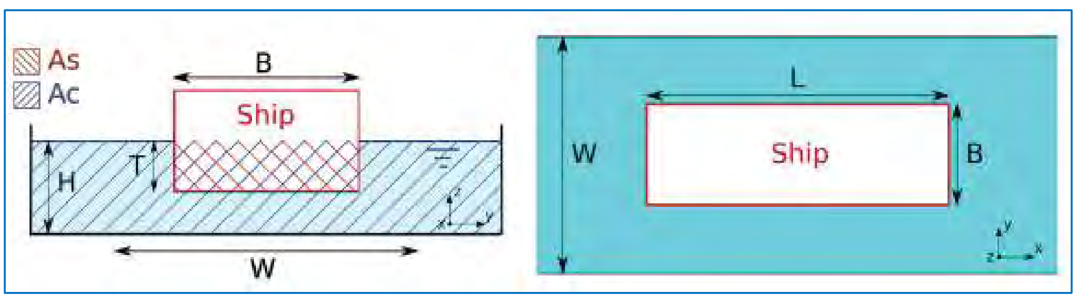

Figure 2.3: Schematic representation of the waterway geometric parameter.

As per ITTC 87 (ITTC, 1987), an influence of the bottom or the banks occurs when H/T < 4 or W/B < 4; and a general restriction of the waterway starts when AC/AS < 15.

2.2.4 Ship speed loss prediction (Schlichting's method)

Schlichting (1934) proposed a comprehensive investigation of ship speed loss in shallow water. The study by Schlichting (1934) covered the rise of total ship resistance in shallow water at subcritical speed (PNA, 1988). The research was based on theoretical considerations as well as model tests in the Hamburg and Vienna tanks (Prakash and Chandra, 2013).

The following derivations for the prediction of ship speed loss in shallow water are presented from the book named 'The Principles of Naval Architecture, volume 2 (PNA, 1988). Figure 2.4 depicts typical frictional and total resistance curves for deep water at a given speed by the Schlichting method. At this speed, the ship's produced wave pattern will have a wavelength L_W equal to

$$V_{\infty}^2 = \frac{gL_W}{2\pi}$$

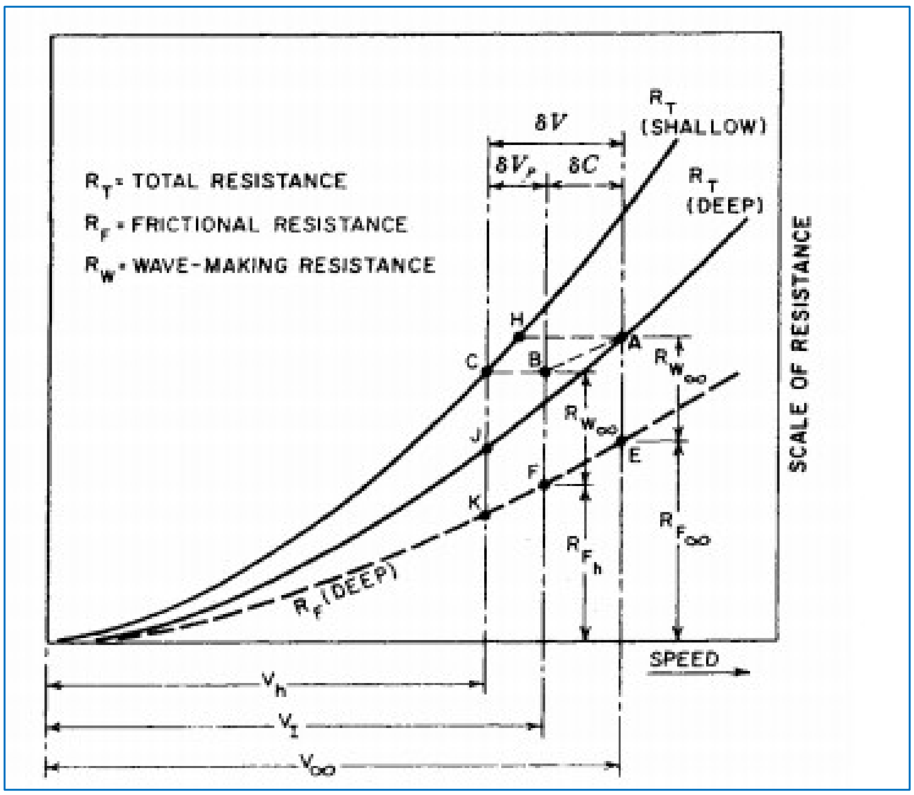

Figure 2.4: Ship Resistance for deep and shallow water (PNA, 1988)

In the water of depth 'h', the same wavelength 'L_W' would be generated at some lower or intermediate speed 'V_I', where,

$$V_I^2 = \left(\frac{gL_W}{2\pi}\right) * \frac{\tanh 2\pi h}{L_W}$$

And the ratio of the two speeds is

$$\frac{V_I}{V_\infty} = (\frac{\tanh 2\pi h}{L_W})^{1/2}$$

$$\frac{V_I}{V_\infty} = (\frac{\tanh gh}{V_\infty^2})^{1/2}$$

A curve of $\frac{V_I}{V_\infty}$ to the base of $\frac{V_\infty}{\sqrt{gh}}$ shown in Figure 2.5. The reduction in speed on this account is given by

$$V_\infty - V_I = \delta C$$

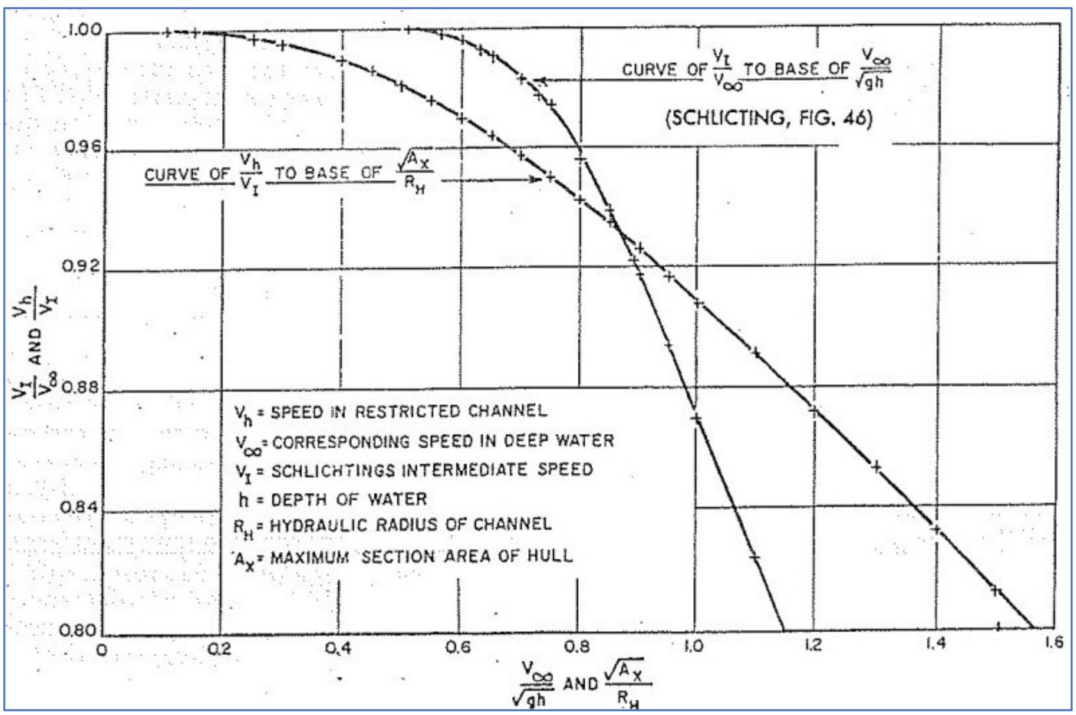

Figure 2.5: Different velocity ratio curves for calculating resistance in shallow water (PNA, 1988).

Schlichting assumed that the wave-making resistance would be the same at speed V_I in shallow water and speed V_∞ in deep water. The total resistance at speed V_I can be found at point B by adding the wave-making resistance $R_{W\infty}$ to the appropriate frictional resistance at this speed R_{Fh} (Figure 2.4).

A further speed loss, δV_P will occur because of the rise in potential flow around the hull due to the limitation of the region by the proximity of the bottom, providing the final speed as:

$$V_h = V_I - \delta V_P$$

Schlichting investigated this reduction in speed by model tests in deep and shallow water, using geosim models to detect any laminar flow on the one hand and tank wall interference on the other hand. He found that the principal factor controlling δVp was the ratio

$$\frac{\sqrt{A_x}}{h}$$

Where,

Ax = Maximum Cross-Sectional area of the hull

h = Depth of water

Figure 2.5 shows the curve of $\frac{V_H}{V_I}$ against $\frac{\sqrt{A_x}}{h}$ derived by Schlichting from his model tests and the relation between V_I and V_∞ for different depths of water h. The total speed loss is given by:

$\delta V = \delta C + \delta Vp$, which can be expressed in per centage terms as

$$\delta V/V_\infty \; X\ 100 = \frac{V_\infty - V_A}{V_\infty} X100$$

Figure 2.6, these percentages are shown in contour form. Although Schlichting's approach is not theoretically rigorous, it provides a good solution to difficult problems. This method works well for calculating shallow water resistance at speeds below critical.

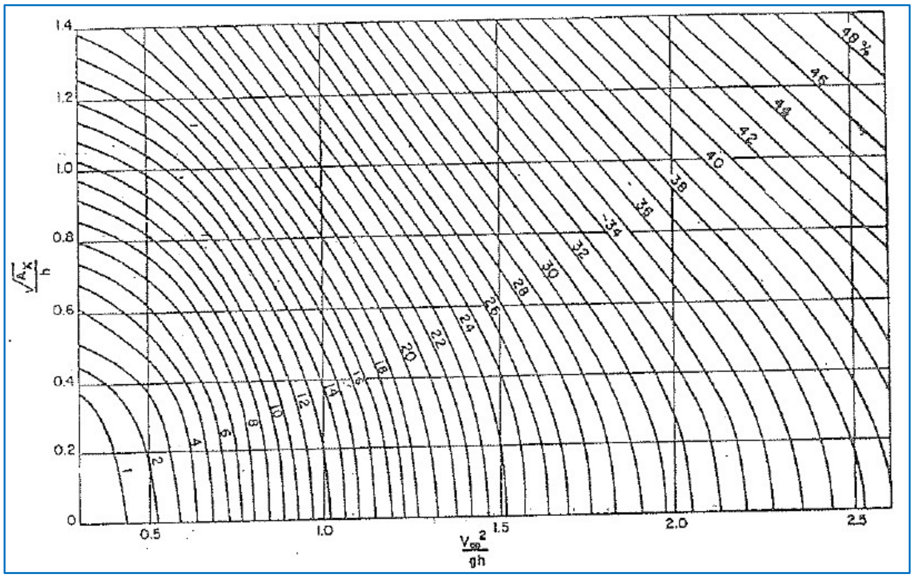

Figure 2.6: Chart for calculating the reduction in speed in shallow water (PNA, 1988)

A technical report by 'Hydrocomp' (Hydrocomp, 2003) used the same method to estimate the effect of shallow water. The 'Depth Froude Number (F_{rh})' was described by 'Hydrocomp' to characterize the characteristics of shallow water as

$$F_{rh} = \frac{V}{\sqrt{g * h}}$$

Where,

V = Speed of the ship

g = Gravitational constant

h = Water depth.

According to Schlichting (Schlichting, 1934), there is typically no measurable speed loss if F_{NH} is less than about 0.4. As the depth Froude number increases, the speed loss begins to take effect according to the following Table 2.3.

Table 2.3. Speed loss in shallow water

F_{NH}	0.00-0.4	0.6	0.8	1.0
Speed Loss	No loss	1% loss	4% loss	14% loss

Figure 2.7 (Hasan, 2013) is a representation of the data shown in Table 2.3, where speed loss is shown as a percentage against the deep-water speed for different water depths.

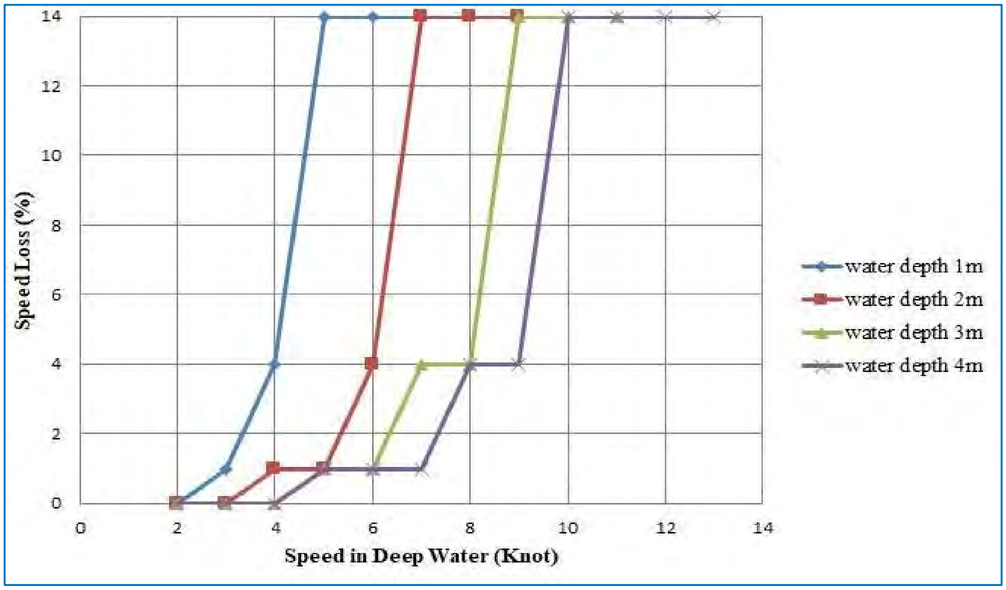

Figure 2.7: Speed loss in shallow water

2.2.5 Ship speed loss prediction (Barras method)

The speed losses are estimated in percentage at different Water depth (h)/Ship's draft (T) ratios using the approach given by C. B. Barrass (Barras, 2004). Barras suggested two Equations, one for a range of h/T values from 1.10 to 1.50 and the other for a range of h/T values from 1.50 to 3.00. The first range was chosen because it contains the riskiest circumstances, which might result in groundings. The second range leads to high-speed grounding, which is less likely. Barrass proposed the following Equations of speed loss in shallow water:

% loss in speed = 60 – (25 X h/T), for H/T of 1.1-1.50

% loss in speed = 36 – (9 X h/T), for H/T of 1.5-3.00, where,

h = Water depth in meter

T = Draft of the ship in meter

Figure 2.8 shows the speed loss in shallow water as described by Barras.

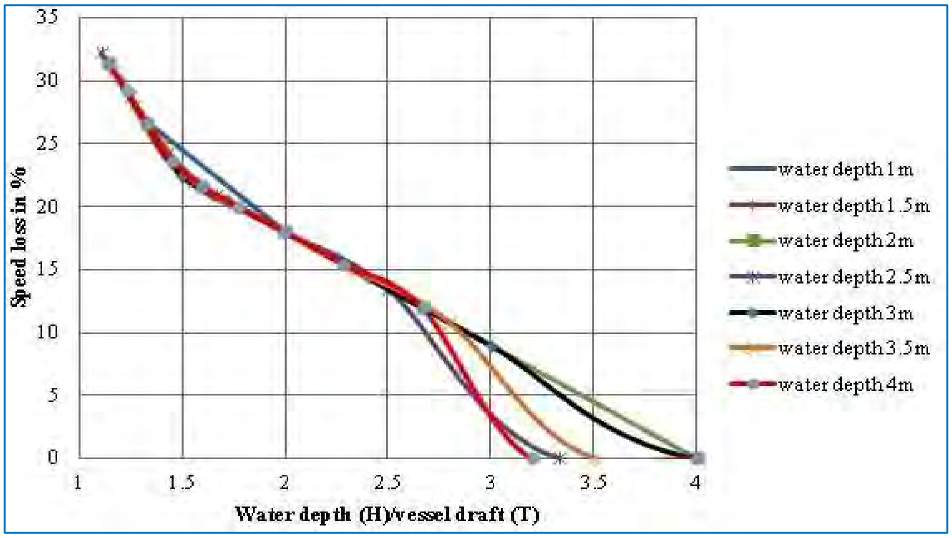

Figure 2.8: Speed losses in the shallow water of Bangladesh (Barras's method)

2.2.6 Speed correction due to lateral restriction of the channel in shallow water

When the shallow water is restricted laterally, the speed drop will further increase. Schlicting's method does not cover this effect on speed. Landwever (1939) had taken into consideration this effect and published the results of experiments on the resistance of a merchant ship model in several different sized rectangular channels, all at speeds below the critical speed.

Landweber presented his result in the form of a curve of $\frac{V_h}{V_I}$ to the base of $\frac{\sqrt{A_x}}{R_h}$, where R_h is the 'Hydraulic Radius' of the channel defined as

$$R_h = \frac{Area\ of\ Cross\ seciton\ of\ chann}{Wetter\ Perimeter}$$

For a rectangular channel of width B and depth h

$R_h = Bh/(B+2h)$

When B becomes very large, R_h = h, this corresponds to the case of shallow water of unlimited width.

When a ship or model is in a rectangular channel, the hydraulic radius is

$R_h = (Bh-A_X)/(B+2h+P)$

Where A_X = Maximum Cross-Sectional area of the hull
P = Wetted Girth of the hull at this Section

From the model results, Landweber was able to deduce a single curve giving the ratio V_h/V_I in terms of $\frac{\sqrt{A_x}}{R_h}$ for use in restricted, shallow channels.

2.2.7 International Towing Tank Conference (ITTC) guideline

Shallow water effect adjustments should be made if the water depth is less than the greater of the values determined by the following formulae, according to the ITTC (ITTC, 2017).

$h = 3\sqrt{B.T_M}$ and
$h = 2.75\frac{V_S^2}{g}$

Where,
h = Water depth in meter
B = Ship's breadth in meter
T_M = Draught at midship in meter
V_S = Ship's speed in m/s
g = Acceleration of gravity in m/s^2

If the above conditions are satisfied and the effect of shallow water on a ship's speed needs to be predicted, ITTC recommended the Lackenby method (Lackenby, 1963) or the Raven Shallow Water Correction Method (Raven, 2016).

2.2.7.1 Ship speed loss prediction (Lackenby's method)

The shallow-water correction method most often used is that of Lackenby (1963). It modifies the speed-power curve by correcting the measured speed, assuming unchanged power. Lackenby extended Schlichting's (1934) diagrams towards smaller effects and has cast it into a simpler form.

This speed correction follows from:

$$\frac{\partial V}{V} = 0.1242\left(\frac{A_M}{h^2} - 0.05\right) + 1 - \sqrt{\tanh\left(\frac{gh}{V^2}\right)}$$

Where,

V = Ship speed (m/s)

∂V = Reduced speed due to shallow water effect (m/s)

A_M = Midship Sectional Area under water (m^2)

h = Water depth (m)

g = Gravitational Force (m/s)

2.2.7.2 Ship speed loss prediction (Raven's method)

The ship speed prediction method as proposed by Raven (Raven, 2016) is based on CFD analysis and has been validated with sea trials for four commercial boats at various water depths and speeds (600-ton, 3000-ton, 10000 ton and 80000 m^3 LPGC). The adjustments for power on shallow water can be calculated from propulsion model testing for the specific vessel on deep and shallow water corresponding to the water depth during the speed/power trials provided the builder, owner, and verifier agree. These model experiments must be carried out in a towing tank with enough breadth, and the findings must be confirmed via full-scale testing in shallow water. The following is the acceptable basin width:

a. Blockage (midship Sectional area/tank cross-Section < 2.0%)
b. 2.0 model lengths for $F_{Rh} <= 0.5$
c. 2.7 model lengths for $0.5<F_{Rh}<0.7$

The ITTC recommended procedure, including the form factor, must be used to extrapolate the model test findings to full size, with the form factor established for the water depth considered. To extrapolate the model scale values to full scale in deep and shallow water, the same methodologies, processes, and empirical coefficients must be utilized (Raven, 2012).

2.2.8 Chosen method to incorporate shallow water effect

The evaluation and presentation of Schlichting's (1934) results, did not cover all range of ship parameters. The assumption of equal wave resistance in deep and shallow water when the lengths of the ship-generated waves are the same is questionable (PNA, 1988). For the frictional resistance, Schlichting derived an empirical correction in terms of an assumed Overspeed along the hull dependent on the ratio of Hull Midship Area and Depth of the water. However, its value was derived from his model-test data, to cover the remaining gap in total resistance after the wave correction had been made, and with some support from velocity measurements in the model basin. Now this wave resistance correction is a severe simplification. It assumes that ship waves propagate with the same speed as the ship, which is only true for transverse waves. Also, the wave resistance depends not just on wavelength but also on wave amplitude. An effect of additional sinkage in shallow water is disregarded. Therefore, the wave resistance correction cannot be expected to be accurate; and its deviations are implicitly incorporated in the frictional-resistance correction, found by correlating with the model-test data. Moreover, Schlichting's model tests were just for 3 cruisers of that era, with extreme slenderness and rather high speeds. Tentative application by Schlichting's (1934) to some trial data again was for such ships, at high F_{Nh} values; and yield-ed mixed results. In his paper, Schlichting never claims this is a final solution, but just hopes it is a step forward.

ITTC (2017) approved two procedures for power trials in shallow water, namely Lackenby (1963) and Reven (2016) method. The Raven (2016) does not provide any formulation, rather it is a procedure for a series of tests, which starts with CFD analysis. Later, this analysis is validated with model test and trial data. In practice, this is a very accurate process, but not a generalized process. In addition to that, the builder, owner, and verifier must agree upon this process, as stated in the ITTC (2017) guideline.

Lackenby (1963), extended the well-known Schlichting's method towards smaller effects and has cast it into a simpler form. This method is approved internationally and by ITTC and is much easier to be used for research purposes where many ships are under consideration. However, Maimun et al., (2014) compared the experimental data to evaluate the Lackenby method. When CFD and experimental findings are compared, Lackenby's shallow water resistance yields a higher total resistance value. Raven (2012) also mentions this result, stating that the Lackenby approach yielded greater total resistance estimates. Figure 2.9 presents total resistance for various water depths plotted against the Froude number.

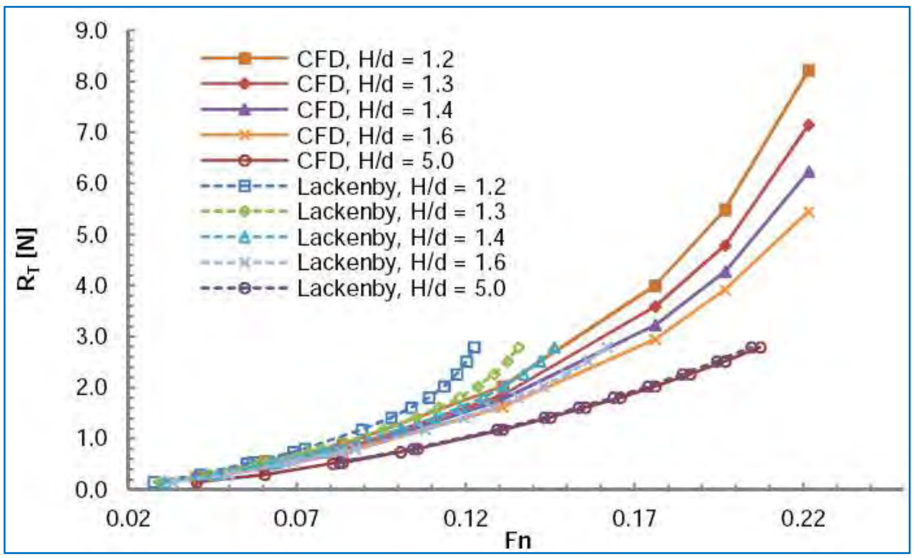

Figure 2.9: Shallow water resistance by CFD and Lackenby (Maimun et al., 2014)

Barrass (2004) on the other hand has produced a very simple formula and is easy to use to all channel configurations. However, his formula overestimates ship squat due to its simplicity. Moreover, using bigger squat values than real ones can be considered a precautionary measure in terms of navigation safety in shallow waters.

Though both Lackenby (1963) and Barrass (2004) methods have limitations, this research selected Lackenby (1963) method for theoretical calculation which has been approved by ITTC (2017). In addition to that, the procedure as proposed by Barras (2004) has also been calculated to compare both theoretical results. Finally, both results have been evaluated with the physical measurement for Bangladeshi inland ships.

2.2.9 Assumptions on the considerations of the effects of confined waters on ship resistance

In this research, the effect of widths of the riverbanks on the resistance has not been considered and assumed to have a negligible effect. According to the ITTC report (ITTC, 1987), if water-width to the ship-length ratio (W/L) is less than 0.35, there is an influence of bow wave reflection from the lateral boundary on the stern flow and when water-width to the ship-beam ratio (W/B) is less than 4 or W/L is less than 1, the flow around the hull changes. Without any exception, the maximum breadth of the inland ship of Bangladesh is 14 meters. Only very few passenger ships have breadth larger than that. A vessel with a 14-meter breadth when moves through a channel of width less than 56 meters, only then the river bank effect will increase the resistance. However, it is very unlikely in Bangladesh that, a vessel having a breadth of 14 meters, plys through a narrow channel of width less than 56 meters. Again, the maximum length of inland vessels of Bangladesh does not exceed a water line length of 80 meters. The commercial inland routes for an 80-meter-long vessel are greater than 80 meters. Therefore, this assumption can be considered a valid assumption.

The water depth of a certain route is not uniform. For this reason, the effect of shallow water will not be uniform as well. This research relies on the river water depth data at certain points only, which are measured daily by different government organizations of Bangladesh. Therefore, in this research, the average speed as measured in a certain route has been considered as the gained speed after overcoming the average effect of shallow water. In addition to that, the measured highest speed in each case has been considered as the achieved speed without any effect of shallow water, because in these routes there may be certain regions where the depth of water may be quite high than the measured depth at different locations.

2.2.10 Investigated results on shallow water effect for the inland ships of Bangladesh

To find the actual shallow water effect on ship speed, the actual speed of 15 vessels (5 from general cargo ships, 5 from oil tankers and 5 from passenger ships) have been measured. Android-based app (Speedometer GPS) was used to measure ship speed using satellite. The travelled routes were different and water depths were varied. For this reason, measured speed also varied for the same RPM of the engine. The average speed has been considered as the gained speed after the shallow water effect. Following Table 2.4 to 2.9 presents the investigated results. The travelled route details have been shown in Appendix B. Appendix C has presented the calculation of shallow water effect as per the method explained by Lackenby (1963) and Barras (2004) methods for each examined ship.

The mean water level of the selected river route is also presented in Tables 2.4, 2.6, and 2.8, based on tide charts provided by the Bangladesh Inland Water Transport Authority (BIWTA, 2017, 2018) and Tide chart, data from the Bangladesh Water Development Board's (BWDB, 2017-2019), and data from the Chittagong Port Authority.

Tables 2.5, 2.7 and 2.9 present the speed measured for investigated ships at different locations. Measured top speed in each case has been considered as the achieved speed without any effect of shallow water. These top speeds have also been tested by Holtrop-Mennen (1978, 1982 and 1984) method for deep water cases. The decrease in speed because of the shallow water is not uniform. For this reason, the speed drops have been presented in a range. The speed drop has also been calculated theoretically by the approved method of ITTC (1987) and Barras (2004) method. All results have been presented side by side.

Table 2.4 presents the information on the routes of the investigated general cargo ships. More details of these routes have been presented in Appendix B. The water depth of different points of a specific route was found from several organizations of the Bangladesh Government. The average depth of the water for each channel has been considered for the theoretical calculation of the Shallow water effect.

Table 2.5 presents the investigated results of 5 numbers of general cargo ships. Other than the vessel GC-4, the actual shallow water effect varied from 15%- 29% with an average effect of 19.90% at actual. For the same cases, the average shallow water effect as calculated by Lackenby (1963) is 21.91% and for Barras (2004) is 23%.

Table 2.4: Investigated cargo ship's particulars, route, and water depth during the investigation

Ship's Dimension (m)	Travelled date	Travelled Route	Distance (km)	Water depth (m)	Average water depth (m)
G.C-1: LXBXT= 47.24X07.95X2.55	3 August, 2017	Dhaka to Chandpur	68.22	1. Milbarak, Dhaka, Buriganga River: 4.10 m 2. Mirkadim, Munshiganj, Dhaleshwari River: 3.50 m 3. Char Ramdaspur, Chandpur, Meghna River: 4.05 m	3.88
G.C-2: LXBXT= 63.00X11.60X3.00	14 July, 2018	Meghnaghat, Naryanganj to Chittagong	273.89	1. Gazaria, Munshiganj, Meghna River: 4.90 m 2. Char Ramdaspur, Chandpur, Meghna River: 4.50 m 3. Sadarghat, Chittagong, Karnaphuly River: 5.03 m	4.81
G.C-3: LXBXT= 66.00X10.98X3.00	15 September 2018.	Rupshi, Narayanganj to Chittagong	275.75	1. Narayanganj, Shitalakhya River: 4.6 m 2. Mirkadim, Munshiganj, Dhaleshwari River: 3.60 m 3. Char Ramdaspur, Chandpur, Meghna River: 3.77 m 4. Sadarghat, Chittagong, Karnaphuly River: 4.39 m	4.09
G.C-4: LXBXT= 43.76X7.77X2.29	17 June 2017	Fatullah, Narayanganj to Baghabari	189.86	1. Fatullah, Narayanganj, Buriganga River: 4.10 m 2. Mirkadim, Munshiganj, Dhaleshwari River: 5.10 m 3. Char Ramdaspur, Chandpur, Meghna River: 4.050 m 4. Bhagyakul, Munshiganj, Padma River: 4.30m 5. Aricha, Manikganj, Jamuna river: 7.25m 6. Baghabari, Sirajganj, Jamuna River: 3.90m	4.78
G.C-5: LXBXT= 71.94X13X4.00	11 August 2018	Meghnaghat, Nataryanganj to Chittagong	273.89	1. Gazaria, Munshiganj, Meghna River: 5.45 m 2. Chandpur, Meghna River: 4.43 m 3. Sadarghat, Chittagong, Karnaphuly River: 4.98 m	4.97

Table 2.5: Investigated cargo ship's particulars and measured speed

Ship's Dimension (m)	Measured maximum speed (Knot)	Speed measured in shallow water (Knot)	Actual shallow water effect (Range and average)	Lackenby (1963) method	Barras (2004) method
G.C-1: LXBXT = 47.24X07.95X2.55	9.5	7.50-8.00	16%-21% (18.50%)	19.93%	22.31%
G.C-2: LXBXT = 63.00X11.60X3.00	10	7.50-8.50	15%-25% (20%)	20.61%	21.57%
G.C-3: LXBXT = 66.00X10.98X3.00	10.5	7.50-8.00	24%-29% (26.50%)	29.47%	25.92%
G.C-4: LXBXT = 43.76X7.77X2.29	9.5	8.00-9.00	5%-16% (10.50%)	10.83%	17.21%
G.C-5: LXBXT = 71.94X13X4.00	10.5	7.50-8.50	19%-29% (24%)	28.73%	28.94%

Table 2.6 presents the information on the routes of the investigated oil tankers. More details of these routes have been presented in Appendix B. The water depth of different points of a specific route was found from several organizations of the Bangladesh Government. The average depth of the water for each channel has been considered for the theoretical calculation of the Shallow water effect.

Table 2.6: Investigated oil tanker's particulars, route and water depth during the investigation

Ship's Dimension (m)	Travelled date	Travelled Route	Distance (km)	Water depth (m)	Average water depth (m)
O.T-1, LXBXT= 50.67X10.68X1.80	10 June 2017	Fatullah, Narayanganj to Baghabari	189.86	1. Fatullah, Narayanganj, Buriganga River: 3.85 m 2. Mirkadim, Munshiganj, Dhaleshwari River: 5.10 m 3. Char Ramdaspur, Chandpur, Meghna River: 3.35 m 4. Bhagyakul, Munshiganj, Padma River: 3.90 m 5. Aricha, Manikganj, Jamuna river: 5.00 m 6. Baghabari, Sirajganj, Jamuna River: 2.90m	4.02
O.T-2, LXBXT= 57.24 X10.00X1.80	10 August, 2017	Dhaka to Chandpur	68.22	1. Milbarak, Dhaka, Buriganga River: 3.90 m 2. Mirkadim, Munshiganj, Dhaleshwari River: 3.50 m 3. Char Ramdaspur, Chandpur, Meghna River: 3.84m	3.75

O.T-3, LXBXT= 70.80X12.50X4.00	22 September, 2018	Meghnaghat, Naryanganj to Chittagong	273.89	1. Gazaria, Munshiganj, Meghna River: 5.00 m 2. Chandpur, Meghna River: 4.80 m 3. Sadarghat, Chittagong, Karnaphuly River: 5.00 m	4.93
OT-4, LXBXT = 53.00X11X1.8	23 June 2018	Godnail, Narayanganj to Barishal	134.56	1. Godnail, Narayanganj, Shitalkhya River: 3.79 m 2. Munshiganj, Dhaleshwari River: 3.50 m 3. Char Ramdaspur, Chandpur, Meghna River: 3.49m 4. Barishal, Kirtankhola River: 2.15 m	3.23
OT-5, 49.50X10.00X2.00	13 October 2018	Dhaka to Bhairab	110.81	1. Milbarak, Dhaka, Buriganga River: 4.00 m 2. Munshiganj, Dhaleshwari River: 3.80 m 3. Gazaria, Munshiganj, Meghna River: 2.60 m 4. Ashuganj, Brammanbaria, Meghna River: 3.60 m	3.50

Table 2.7 presents the investigated results of 5 numbers Oil Tankers. The actual shallow water effect varied from 12%- 29% with an average effect of 19.30% at actual. For the same cases, the average shallow water effect as calculated by Lackenby (1963) is 23% and for Barras (2004) is 20.49%.

Table 2.7: Investigated oil tanker's particulars and measured speed

Ship's Dimension (m)	**Measured maximum speed (Knot)**	**Speed measured in shallow water (Knot)**	**Actual shallow water effect (Range and average)**	**Lackenby (1963) method**	**Barras (2004) method**
O.T-1, LXBXT= 50.67X10.68X1.80	9.50	7.50-8.00	16%-21% (18.50%)	17.62%	15.90%
O.T-2, LXBXT= 57.24 X10.00X1.80	8.50	7.00-7.50	12%-18% (15%)	17.33%	17.25%
O.T-3, LXBXT= 70.80X12.50X4.00	10.50	7.50-8.50	19%-29% (24%)	28.30%	29.19%
OT-4, LXBXT = 53.00X11X1.8	9.00	7.00-7.50	17%-22% (19.50%)	29.55%	19.85%
OT-5, LXBXT= 49.50X10.00X2.00	8.50	6.50-7.00	18%-24% (21%)	22.20%	20.25%

Table 2.8 presents the information on the routes of the investigated Passenger Ships. More details of these routes have been presented in Appendix B. The water depth of different points of a specific route was found from several organizations of the Bangladesh Government. The average depth of the water for each channel has been considered for the theoretical calculation of the Shallow water effect.

Table 2.8: Investigated passenger vessel's particulars, route and water depth during the investigation

Ship's Dimension (m)	Travelled date	Travelled Route	Distance (km)	Water depth (m)	Average water depth (m)
P.V-1, LXBXT= 48.56X8.75X1.62	24 June 2017	Dhaka to Sureswar, Shariyatpur	85.82	1. Milbarak, Sadarghat, Dhaka, Buriganga River: 4.00 m 2. Munshiganj, Dhaleshwari River: 3.40 m 3. Sureswar, Shariyatpur, Padma River: 2.75 m	3.38
P.V-2, LXBXT= 45.95X09.15X1.40	25 August 2018	Dhaka to Tushkhali, Pirojpur	249.89	1. Milbarak, Sadarghat, Dhaka, Buriganga River: 4.00 m 2. Munshiganj, Dhaleshwari River: 3.40 m 3. Char Ramdaspur, Chandpur, Meghna River: 3.88m 4. Barishal, Kirtankhola River: 2.23 m	3.38
P.V-3, LXBXT= 67.47X10.98X1.70	07 July 2017	Dhaka to Chandpur	68.22	1. Milbarak, Sadarghat, Dhaka, Buriganga River: 4.0 m 2. Mirkadim, Munshiganj, Dhaleshwari River: 4.42 m 3. Char Ramdaspur, Chandpur, Meghna River: 4.0 m	4.14
P.V-4, LXBXT= 54.29X10.84X1.60	08 September 2017	Dhaka to Patuakhali	197.10	1. Milbarak, Sadarghat, Dhaka, Buriganga River: 4.00 m 2. Munshiganj, Dhaleshwari River: 3.20 m 3. Char Ramdaspur, Chandpur, Meghna River: 3.80 m 4. Patuakhali, Patuakhali River: 2.93m	3.48
P.V-5, LXBXT= 85.34X13.57X1.80	27 July 2017.	Dhaka to Barishal	147.61	1. Milbarak, Sadarghat, Dhaka, Buriganga River: 4.00 m 2. Munshiganj, Dhaleshwari River: 3.40 m 3. Char Ramdaspur, Chandpur, Meghna River: 4.0 m 4. Barishal, Kirtankhola River: 4.45 m	3.96

Table 2.9 presents the investigated results of 5 numbers of passenger ships. The actual shallow water effect varied from 14%- 25% with an average effect of 20.10% at actual. For the same cases, the average shallow water effect as calculated by Lackenby (1963) is 28.91% and for Barras (2004) is 15.64%.

Table 2.9: Investigated passenger ship's particulars and measured speed

Ship's Dimension (m)	**Measured maximum speed (Knot)**	**Speed measured in shallow water (Knot)**	**Actual shallow water effect range and average**	**Lackenby (1963) method**	**Barras (2004) method**
P.V-1, LXBXT= 48.56X8.75X1.62	11.5	8.50-9.50	17%-26% (21.50%)	28.56%	17.22%
P.V-2, LXBXT= 45.95X09.15X1.40	12	8.50-9.50	21%-29% (25%)	29.16%	14.27%
P.V-3, LXBXT= 67.47X10.98X1.70	13.5	10.50-11.00	18%-22% (20%)	29.83%	14.08%
P.V-4, LXBXT= 54.29X10.84X1.60	10	7.50-8.50	15%-25% (20%)	24.16%	16.43%
P.V-5, LXBXT= 85.34X13.57X1.80	12.5	10.50-11.00	12%-16% (14%)	32.85%	16.20%

2.2.11 Incorporation of shallow water effect to the $EEDI_{BD}$ formulation

Tables, 2.5, 2.7 and 2.9 has presented the practically found shallow water effect and the effect as calculated by Lackenby (1963) and Barras (2004) methods. The following Table presents the summary of the average on shallow water effects.

Table 2.10: Average shallow water effect

Type of inland ships of Bangladesh	**Average shallow water effect found**	**Average shallow water effect by Lackenby (1963)**	**Average shallow water effect by Barras (2004)**
Cargo Ships	19.90%	21.91%	23.19%
Oil Tankers	19.30%	23%	20.49%
Passenger Ships	20.10%	28.91%	15.64%

The average actual shallow water effect varied from 19.30% to 21.35% considering 15 measured ships of each type. Since this effect mainly depends upon the clearance under the keel, different ship drafts will produce different amounts of effect in the same channel. Practically it is not possible to fix a single factor of speed deduction while considering the shallow water effect. As shown in Table 2.10, the calculated value by Lakenby (1963) has provided a higher value in comparison with the actual measurement. On the other hand, the results of Barras (2004) method are higher for cargo and oil tankers, but lower in the case of passenger's vessels.

Based on the actual measurement, an average 20% shallow water effect has been considered to establish $EEDI_{BD}$ baselines for inland general cargo, oil tanker and passenger ships of Bangladesh.

2.3 Fixing the main engine MCR and P_{ME} considering shallow water effect.

The IMO defined PME as the main engine's power output at 75 % of the Maximum Continuous Rating (MCR), as specified in section 2.1. Seagoing boats, on average, move at a constant engine RPM for extended periods, which is 75 per cent of MCR (on an average as per IMO). Inland ships, on the other hand, find it extremely difficult to keep a constant engine RPM for extended periods. The main reason is the inland waterway traffic and to compensate for the effect of shallow water. In addition to that, it is a common practice in Bangladeshi inland ships to install overpowered engines mainly

a. to overcome the shallow water effect
b. to overcome the engine output shortage when an old engine is installed (Many ship owners of Bangladesh install older engines to minimize the first cost)

To fix the value of MCR and corresponding P_{ME} for the inland ships of Bangladesh, a physical investigation is necessary. 15 vessels as investigated to fix the shallow water effect (presented in Tables 2.4 to 2.9) had also been investigated to identify the MCR. During the physical investigation, the main engine RPM was measured when the ship started to move at continuous RPM for the maximum possible time. A digital tachometer was used for RPM measurement. The main engine load at the MCR was found from the Engine performance curve, which has been presented in Appendix-D. Tables 2.11, 2.12 and 2.13 present the onboard measured RPM data and corresponding main engine loads for Inland General Cargo Ships, Oil Tankers and Passenger Ships, chronologically.

Table 2.11: Measurement of main engine rpm at actual for 5 Inland Cargo Vessels of Bangladesh and corresponding main engine load from engine curve

Ship's ID	Main Engine Power (HP)	Engine RPM at a service speed	Main Engine Load
G.C-1	350X1	1395	78.00%
G.C-2	350X2	1402	80.00%
G.C-3	350X2	1275	61.00%
G.C-4	350X1	1380	76.00%
G.C-5	720X2	1044	64.50%

Table 2.12: Measurement of main engine rpm at actual for 5 Inland Oil tankers of Bangladesh and corresponding main engine load from engine curve

Ship's ID	Main Engine Power (HP)	Engine RPM at service speed	Main Engine Load
O.T-1	350X2	1320	67%
O.T-2	300X2	1320	65.00%
O.T-3	818X2	1256	77%
OT-4	300X2	1290	60%
OT-5	350X1	1395	76%

Table 2.13: Measurement of main engine rpm at actual for 5 Inland Passenger Ships of Bangladesh and corresponding main engine load from engine curve

Ship's ID	Main Engine Power (HP)	Engine RPM at service speed	Main Engine Load
P.V-1	350X2	1420	82%
P.V-2	300X2	1620	70%
P.V-3	750X2	1269	82%
P.V-4	350X2	1395	78%
P.V-5	1000X2	846	90%

The average main engine loads of investigated ships are

a. 71.90% for General cargo ships
b. 69% for Oil Tankers
c. 80.40% for Passenger Ships

Fixing 70% MCR for General Cargo and Oil Tanker seems reasonable. For passenger ships, MCR can be 80%, which is the average of the investigated ships MCR.

2.4 Fixing Deadweight capacity

When calculating EEDI, the ship's 100 % deadweight (DWT) must be taken into account, according to IMO guidelines (MEPC 62, 2011). A seagoing vessel, without exception, operates at full capacity. However, this may not always be the case with inland ships. It is contingent on cargo availability. In addition, inland ships of Bangladesh follow a roaster-based trip. For these reasons, ships fail to find full capacity cargo in many trips. In some cases, poorly designed ships do not allow the full capacity. Following are the reasons:

a. Ships can sometimes reach their load draft limit even if their holds aren't full or laden to their deadweight capacity. This implies that the lightweight has risen significantly higher than expected, indicating a significant design and construction problem.

b. Some vessels drafts do not achieve her loaded draft, though all holds are full. This condition again indicates a major design and construction flaw.

c. Sometimes, design faults restrict a ship to load into the forward holds to her full capacity as it makes her trim by bow.

d. Shallow water effects restrict loading a ship to its full capacity. In Bangladesh, from November to May, river water depth falls drastically. As a result, during these months, most of the cargo and tankers cannot carry her full load.

e. In Bangladesh, many companies maintain their vessels which are only used to transport their goods from mothership at the port to their industrial area. Sometimes, those vessels return to back to bring more cargo from port/mothership. This voyage is laden and during this voyage, the necessary draft is maintained by ballast water. IMO also had incorporated a similar issue for sea-going container ships, where 70% of the dead weight is being considered.

Because of the aforementioned difficulties, 100% design deadweight for inland ships in Bangladesh cannot be used when calculating EEDI. According to research on inland transportation in Europe (Konings 2015), the vessel's average load factor (in both directions) is 70%. Another study by Van Mol (Van M. B. 2001) finds that average loading factor is 83% and study from 'Promotie Binnenvaart Vlaanderen', Antwerpen, Belgium (Vito, 2003) finds the same as 87%. However, research and interviews under this research with ship owners, masters/drivers/operators indicated that Bangladeshi inland cargo and oil tankers have an average load factor of 85 per cent of the deadweight. For passenger ships, 100% gross tonnage is considered as per the directives of IMO (IRS, 2015). For this reason, in this research, 85% deadweight capacity for inland cargo and an oil tanker, and 100% gross tonnage have been assumed and considered for $EEDI_{BD}$ calculation.

2.5 Fixing Carbon content of fuel used in Bangladesh

Because ordinary fuel is utilized, fuel quality was not intended to be a major problem. It is, nevertheless, a major problem for Bangladesh. The IMO-defined EEDI calculation takes into account the carbon content of various fuel sources (MEPC 308(73), 2018). The grade of gasoline used in Bangladeshi inland ships varies depending on the user. Impurities are commonly mixed at the user end for Bangladeshi inland ships. When unburned methane emissions are taken into account, the Green House Gas (GHG) index value can climb by up to 11%, according to Attah and Bucknall (2015).

The standard C_F value (Nondimensional conversion factor for auxiliary engine between fuel consumption and CO_2 emission) based on the carbon content was used by IMO to compute EEDI. Table 3.2 displays the different types of fuel, carbon content, and CF value as certified by the International Maritime Organization (IMO) (MEPC 308(73), 2018). The four-stroke diesel engine used in Bangladesh's inland ships runs on High-Speed Diesel (HSD), which has varying carbon content as shown in Table 2.14.

Table 2.14: C_F values for different types of fuel.

Type of fuel	Reference	Carbon content	C_F (t-CO_2/t-Fuel)
Diesel/Gas Oil	ISO 8217 Grades DMX through DMC	0.8744	3.206
Light Fuel Oil	ISO 8217 Grades RMA through RMD	0.8594	3.151
Heavy Fuel Oil	ISO 8217 Grades RME through RMK	0.8493	3.114
Liquefied Petroleum Gas	Propane	0.8182	3
	Butane	0.8264	3.03
Liquefied Natural Gas		0.75	2.75
Methanol		0.375	1.375
Ethanol		0.5217	1.913

In addition to the above, investigations for the inland ships of Bangladesh have shown that, in many cases, burnt oil, burnt lube oil and other impurities are mixed in the fuel oil tank of inland ships of Bangladesh. By doing so, some ship owners try to decrease ship operational costs. As a result, standard fuel carbon for Bangladeshi inland ships should not be utilized and must be established precisely. All of these differences have been gradually integrated.

To find the carbon content of diesel used for the inland ships of Bangladesh, three samples of fuel have been collected from three different sources. The first sample was collected from Jamuna Oil Company Limited, a state-owned fuel oil supplier of Bangladesh (Jamuna, 2018). Jamuna Oil Company Limited is one of the state-owned fuel companies of Bangladesh

The other two samples were taken from two other ships' service tanks. At Telghat, Keraniganj, Dhaka, one sample was taken from a local diesel oil distributor for inland ships. Before docking at Dockyard and Engineering Works Limited, Narayanganj, the other sample was taken from the ship's fuel oil tank. These three HSD samples were evaluated at Dhaka University's Centre for Advanced Research in Science (CARS, 2018). The examination was carried out using a CHNS (Carbon, Hydrogen, Nitrogen, and Sulphur) elemental analyser from Vario Micro V1.6.1, GmbH, Germany (Elementar Analysensysteme GmbH, Germany, 2018). The liquid samples are put into tin capsules and analysed using a standard solid autosampler in this analyser. Table 2.15 displays the test results. Appendix-E has the CARS, Dhaka University, outcome datasheet.

Table 2.15: Test results for Carbon content for three different samples.

Sample collection	**Collection site**	**Carbon Content (%)**
Jamuna Oil Company	Authorized dealer	58%
Ship-1	Telghat, Keraniganj, Dhaka	72%
Ship-2	Sonakanda, Narayanganj	80%

The test results for carbon content from three distinct sources are shown in Table 2.15. In comparison to diesel samples from ships, fuel samples from the government distributor contain significantly less carbon. A comprehensive physical examination and interview were conducted to determine why there was a discrepancy in carbon content, and it was discovered that burned fuel and lubricating oil were being mixed with diesel in the ship's fuel tank. This pollutes gasoline and raises its carbon content. Because there are three distinct carbon content test results, the average of the greatest two-carbon content, which is 76%, is used.

2.6 Corrected EEDI parameters by IMO for inland ships of Bangladesh

Sections 2.3 to 2.6 have explained the required changes of EEDI parameters by IMO to be useful for Inland Ships of Bangladesh. Based on the physical investigation, measurement and test, the changed values of those parameters have also been proposed and presented in Table 2.16.

Table 2.16: A comparison of the values of several EEDI characteristics as established by the IMO with those for Bangladeshi inland ships.

EEDI Parameter	Defined by IMO resolution (MEPC 308 (73), 2018),	Revised value for the inland ship of Bangladesh
P_{ME}	75% of the main engine MCR in kW	70% MCR for Cargo and Oil Tankers and 80% for the Passenger Ships
V_{REF}	Ship speed in nautical miles per hour at P_{ME} (at 75% MCR)	Ship speed in nautical miles per hour at $P_{ME,}$ incorporating the average shallow water effect (at 70% MCR for cargo and oil tanker and at 80% MCR for passenger ships)
Capacity	100% dead weight and gross tonnage.	85% of the design deadweight for Cargo and oil tankers. For passenger ships, 100% gross tonnage is to be used.
Carbon Content of Diesel oil	0.87441	0.76
C_F (non-dimensional conversion factor between fuel consumption and CO_2 emission based on carbon content.)	C_F (IMO): Carbon Content in the fuel X (Molecular weight of CO_2/Molecular weight of Carbon) = 0.8744 X (44/12) = 3.206 gm CO_2/gm fuel	C_F (Inland ships of Bangladesh): Carbon Content in the fuel X (Molecular weight of CO_2/Molecular weight of Carbon) = 0.76 X (44/12) = 2.787 gm CO_2/gm fuel

As shown in Equation 2.1, the EEDI formula contains many different coefficients. Apart from the required modification of the EEDI formula by IMO, the following 2 factors are assumed 1.0 in the case of inland ships of Bangladesh (i.e, $EEDI_{BD}$). Those 2 factors along with the explanation are presented in the following Table 2.17. All the other parameters of Equation 2.1 will be the same as approved by IMO.

Table 2.17: Factors assumed in $EEDI_{BD}$ calculation

Factor	Coefficient description	Considered value for $EEDI_{BD}$
f_w	This is a non-dimensional coefficient reflecting the reduction in speed in representative sea conditions of wave height, wave frequency, and wind speed. For the attained EEDI calculated under regulations 20 and 21 of MARPOL Annex VI, f_w is 1.00. For other sea conditions, wave frequency and wind speed, the value should be determined from the guideline in MEPC resolution 308 (73) (IMO, 2018).	According to the 'Inland Shipping Ordinance' of Bangladesh (ISO, 1976), 'Except to proceed to the assistance of any vessel, craft or person in distress, no inland ship shall proceed on any voyage or be used for any service when there is hoisted or announced a danger signal of the storm or where there is a reasonable apprehension of a storm'. For this reason, the value of f_w is assumed 1.0 for inland ships of Bangladesh.
f_l	This is a consideration for general cargo ships that are outfitted with cranes and other cargo-related equipment to compensate for the ship's loss of deadweight. If no crane, side loader and ro-ro ramp are present, f_l = 1.0 (IMO, 2018).	It is assumed that there is no crane, side loader or ro-ro ramp present for inland cargo ships of Bangladesh. Hence the value of f_l is assumed to be 1.0.

2.7 Sample Calculation based on $EEDI_{BD}$ parameters

$EEDI_{BD}$ was calculated using the modified values and a good number of inland General Cargo, Oil Tanker, and Passenger Ships from Bangladesh. A sample calculation has been presented in Appendix-G (Table G-1), where the IMO defined EEDI and $EEDI_{BD}$ from revised EEDI parameters for Bangladesh are shown.

CHAPTER 3

ESTABLISHMENT OF $EEDI_{BD}$ BASELINES FOR INLAND SHIPS OF BANGLADESH

3.1. Establishment of $EEDI_{BD}$ Baselines

To establish baselines, verified ship data must be used. IMO used readymade verified ship data from the IHS Fair play database (MEPC 62/6/4, 2011) to develop EEDI baselines. Sea-going existing ship data of 400 Gross Tonnage and above, which were delivered in the period from 1 January 1999 to 1 January 2009 were used. Like IMO, readymade ship data is also available for Bangladesh. Several Government Authorities in Bangladesh such as the Department of Shipping (DOS), Bangladesh Inland Waterways Authority (BIWTA) store the ship design data. Unfortunately, in some cases, investigation shows that the actual measurement varies from the design data at DOS or BIWTA. Mostly, the deviation is found either in the principal particulars, main and auxiliary engine power, or speed. All those deviated particulars are the most important factors of EEDI. For this reason, unverified design data of DOS and BIWTA could not be used for this research.

In Section 2, the revised EEDI formulation that can be used for inland ships of Bangladesh has been established. However, baselines, represent the status of CO_2 emission per tonne mile. To quantify that amount, actual ship and operational data are required. The following Section will explain the required field data and how those data were verified before using it to establish $EEDI_{BD}$ baselines for Bangladesh. Section 3.2 elaborates the methodology as presented in Section 1.7.

3.2. Methodology to establish $EEDI_{BD}$ Baselines.

The IMO's EEDI simply calculates the amount of CO_2 emitted every tonne-mile. Many studies have attempted to estimate inland navigation's CO_2 intensity (Central Commission for the Navigation of the Rhine, 2012). The findings of this research, on the other hand, have a broad scope. As a result, these studies make it difficult to calculate the carbon footprint of inland transportation in a reliable manner for climate protection legislation. Furthermore, it is not possible to calculate the CO_2 emissions of coordination chains precisely. This brings up the problem of the output data needed to calculate an emission factor model's quality. The emission factors are available or are in the process of being produced, so they may be validated using data from inland navigation firms on fuel consumption and total transport performance of various vessel types, as well as transport statistics. On this foundation, accurate and acceptable data and statistics on CO_2 emissions from inland shipping should be easy to generate.

The results of the CCNR workshop on this issue, conducted in Strasbourg on April 12, 2011, highlight the obstacles to be overcome in estimating CO_2 emissions from inland navigation (Schepper 2011):

a. CO_2 emission factors vary greatly owing to various characteristics, values, and techniques.
b. Present methods still have a restricted scope due to knowledge gaps and constraints.

It is a complex field in development.CO_2 can be estimated in different methods. All the methods are not possible to use directly as each technique has its merit and demerits. All available methods of different CO_2 estimation methods and their effectiveness are described below in Sections.

3.2.1. Stoichiometric method (Energy-based approach)

Because almost all CO_2 emissions from cargo transportation are energy-related, the simplest and most precise approach of calculating these emissions is to track energy use and apply standard emission factors to convert energy values to CO_2 emissions (Mckinnon and Piecyk, 2010). Trucks, diesel-powered trains, barges, and ships will use litters of fuel as the unit of energy, whereas electrified rail and pipeline will use kilowatt-hours. The energy-based strategy is ideal for carriers and organizations with in-house transportation operations that have direct access to energy data. In any event, because most transportation operations in the European substance business are re-appropriated, carriers require direct access to this energy data. Some synthetic companies have sought this information and have received assessments of their carriers' overall eco-friendliness. When the carbon content of the utilized gasoline and the fuel consumption per hour is known, this approach may be employed. The stoichiometric oxidation Equation will be used to calculate the quantity of CO_2 (Dragalina, 2003 and Trifan, 2010). CO_2 emissions from burning one kilogram of fuel are calculated as follows:

$C + O_2 \rightarrow CO_2 + Qc$

Where, C = Carbon mass in the fuel (kg C/kg combustion)

O_2 = The Oxygen content in the supplied air (kg O_2/kg air)

Q_c = Heat energy from the chemical reaction (Mj/Kmol)

For a known fuel with carbon content ‘c’ (kg C/kg Combustion) the total mass of CO_2 (m_{CO2}) per hour can be found by the following Equation:

$$m_{CO2} = \frac{44}{12} * c * C_h \quad \text{(Kg } CO_2\text{/hr)} \qquad (3.1)$$

where, C_h = hourly fuel consumption (kg Combustion/hr).

3.2.2. Carbon Balance method

Direct use of gas analysers gives another way to quantify CO_2 emission. The Carbon Balancing method requires the following information:

a. Fuel consumption per hour
b. Air parameters (pressure and temperature)
c. Chemical components are used in the fuel in percentage.

The particular CO_2 emission is determined using the calculation procedure from the Technical Code for marine diesel engines (Cosofret, Bunea, Popa, 2016). The carbon balancing technique is used in this algorithm to estimate the mass flow rate of the exhaust gas (IMO Resolution MEPC 177 (58), 2008). This method takes into account the concentrations of components in the exhaust gases which is determined by experimental measurements.

Mckinnon and Piecyk (2010) offer two well-established methods for calculating CO_2 emissions from freight transportation operations: one based on energy consumption and the other on the amount of transport activity.

3.2.3. Activity-based approach

When fuel consumption data is not available, an engineering estimation is possible to measure the carbon footprint of a transport operation by applying a simple formula:

CO_2 = Cargo transported x Distance travelled x CO_2 emissions factor

Data on tonnages carried can be found in company records, ERP systems (Enterprise Resource Planning Systems), and delivery manifests. Estimates of average haul length can also be based on road movement data from other sources. To estimate road lengths, software programs such as MapPoint and Autoroute can be used to list consumer locations if necessary. Distance data for rail and water-borne transportation might be difficult to come by, but the Eco-Transit online environmental evaluation tool can help. In the case of multimodal transportation, shippers are frequently unaware of the route taken or the distance split between different means of transit. They normally rely on carriers for this information, but the Eco-Transit application may offer approximate route and distance statistics for intermodal flows that the speaker uses. The selection of carbon emission parameters for each mode is one of the most challenging challenges to answer when using the activity-based method. These are usually measured in grams of CO_2 per tonne-kilometre. The chemical sector benefits from this weight-based evaluation of emission parameters because its compounds have a relatively high density, causing cars to 'weigh out' before they 'cube out.' As a result, in the chemical sector, vehicle load factors are commonly expressed in weight terms. One of the chemical businesses consulted was able to create its own set of emission parameters by obtaining fuel usage data from some of its carriers. However, no generic emission factors for chemical transport have been computed to date. As a result, relying on the numerous studies done in Europe over the last decade to identify emission criteria for general freight movement via various modalities is critical.

3.2.4. The methodology used to estimate the status of CO_2 emission per Tonne mile for the inland ships of Bangladesh

Since the Stoichiometric method (Energy-based approach) is the simplest and the most accurate method to estimate CO_2 emission, it has been used to establish the CO_2 emission status for inland ships of Bangladesh. The approach requires only two basic pieces of information to estimate the CO_2 emission.

a. Amount of Energy used, that is, the fuel consumption.
b. The CO_2 conversion factor of fuel.

Equation 3.1 was modified to have the result as $\frac{g_{CO2}}{\text{Tonne}*\text{nautical mile}}$, as per the EEDI formulation, which is given below:

$m_{CO2} = \frac{44*c*C_h}{12}$ (Where c = carbon content of the fuel and C_h = Fuel Consumption per hour)

or, $m_{CO2} = C_F * C_h$ ($\frac{44}{12}*c = C_F = CO_2$ conversion factor)

$$\text{or, } \frac{m_{CO2}}{\text{Deadweight}} = \frac{C_F * C_h}{\text{Deadweight}}$$

Since m_{CO2} is the weight of CO_2 emission per hour, the above Equation becomes

$$\text{or, } \frac{CO_2 \text{ emission}}{\text{Hour} * \text{Deadweight}} = \frac{C_F * C_h}{\text{Deadweight}}$$

$$\text{or, } \frac{CO_2 \text{ emission}}{\text{Deadweight} * \text{Distance Travelled}} = \frac{C_F * C_h * \text{Hour}}{\text{Deadweight} * \text{Distance Travelled}}$$

$$\text{or, } \frac{CO_2 \text{ emission}}{\text{Deadweight} * \text{Distance Travelled}} = \frac{C_F * C_h}{\text{Deadweight} * \text{Ship Speed}}$$

$$\text{or}, EEDI_{BD} = \frac{C_F * C_h}{\text{Deadweight} * \text{Ship Speed}} \tag{3.2}$$

The right-hand side to Equation 3.2 is used for estimating the CO_2 emission from the inland ships of Bangladesh at actual per tonne mile, that is the value of $EEDI_{BD}$. Plotting this value against the deadweight will give us the $EEDI_{BD}$ baselines for inland ships of Bangladesh.

3.2.5. Assumptions to estimate the status of CO_2 emission per Tonne mile for the inland ships of Bangladesh

As presented by Equation 3.2, it is very much possible to quantify $EEDI_{BD}$ values for the existing inland ships of Bangladesh. The value of C_H (Fuel consumption per hour) has been considered from the engine SFC curve is supplied by the manufacturer. However, this SFC curve data may be true for new engines. For older engines, fuel consumption is practically higher than the SFC curve. Filthy fuel injectors, poor compression, incorrect oil viscosity, dirty air filter, clogged exhaust restriction converter, worn or fouled spark plugs, and other factors all contribute to higher fuel consumption in older engines.

The deviation of actual fuel consumption from the SFC curve can be easily found by actual measurement. However, it would be extremely difficult to investigate hundreds of ships. For this reason, fuel consumption per hour was also measured during the physical investigation of 15 ships presented under Section 2.3. The deviation between the actual fuel consumption from the engine SFC curve of these 15 vessels under investigation will provide us with a general idea about the increase in fuel consumption. This idea can be incorporated with another very important assumption is made while considering ship speed. Ship speed information that was not physically inspected during this research, have undergone a verification process. This verification process is based on the correlation between Reynold's Number and the lengths of the verified ship. The process has been explained in the following Sections. As presented in Section 2.6, speed has been generalized to 70% speed at MCR for cargo and tankers, and 80% for passenger ships. For this reason, it has been assumed that the regression lines produced as the result of correlation are also against the generalized speed as explained in Section 2.6.

A further assumption was made while verifying installed main engine power for those unverified ships. As we know, the main engine power is selected in such a way as to overcome the total resistance against a certain speed. In addition to that resistance, a certain amount of engine power is added for emergency use. Finally, the required brake horsepower of the engine is calculated. The cube of the shipment speed is believed to be proportional to the braking horsepower.

3.3. Required physical data and verification

Following ship data are required to estimate CO_2 emission per tonne mile at actual for inland ships of Bangladesh, according to Equation 3.2:

a. Fuel consumption per hour (C_h)
b. Deadweight capacity or Gross Tonnage for passenger ship.
c. Service speed of the ship

Sections 3.3.1, 3.3.2 and 3.3.3 explain the procedure of verification of physical ship data to establish $EEDI_{BD}$.

3.3.1. Fuel consumption per hour (C_h)

Fuel consumption per hour can be found from the Specific Fuel Consumption (SFC) curve using the following Equation:

$$\text{SFC x Main Engine output}$$

It is very difficult to physically measure all ships fuel consumption per hour data. For this reason, fuel consumption per hour has been measured for 5 ships of each type under investigation (As shown in Table 2.4 to 2.9). These results were compared with the main engine SFC curve to validate the assumptions made in Section 3.2.5.

Fuel consumption was quantified by measuring the gauge at the fuel oil tank of the ship. The initial and final levels of fuel oil as well the travelled time were recorded. Considering the size of the tank consumed fuel was calculated by the following Equation

Fuel Consumption = (L_{FT} X B_{FT} X H_{IFH} - L_{FT} X B_{FT} X H_{FFH}) X Density of the Fuel, where,

L_{FT} = Length of the fuel tank
B_{FT} = Breadth of the fuel tank
H_{IFH} = Initial height of fuel in the tank
H_{FFH}= Final height of the fuel in the tank

The data were recorded 3 times, the average of which is presented here. This real fuel consumption per hour for these investigated ships have been compared with the engine SFC curve and presented in Table 3.1, 3.2 and 3.3. The deviation in fuel consumption between actually measured and SFC curve has also been presented. The actual fuel consumptions were 5.91%, 6.93% and 6.76% higher on average for cargo, tanker and passenger ships, respectively than the fuel consumption of the SFC curve.

Table 3.1 (a): Measured engine RPM and corresponding engine load of cargo ships

Ship ID	Main Engine Power (HP)	Engine RPM at a service speed	Main Engine Load (Average)
G.C-1	350X1	1395	78.00%
G.C-2	350X2	1402	80.00%
G.C-3	350X2	1275	61.00%
G.C-4	350X1	1380	76.00%
G.C-5	720X2	1044	64.50%

Table 3.1 (b): Comparison of Specific Fuel Consumption (SFC) for cargo ships

Ship ID	Measured fuel consumption (Liter/hour)	SFC of measured ship (gm/kW.hr)	SFC from engine curve (gm/kW.hr)	Deviation in fuel consumption (%)
G.C-1	48.00X1	198	194	2.06%
G.C-2	50.00X2	201	194	3.61%%
G.C-3	41.50X2	219	195	12.31%
G.C-4	48.00X1	203	194	4.64%
G.C-5	90.00X2	218	204	6.86%

Table 3.2 (a): Measured engine RPM and corresponding engine load of oil tankers

Ship ID	Main Engine Power (HP)	Engine RPM at a service speed	Main Engine Load (Average)
O.T-1	350X2	1320	67%
O.T-2	300X2	1320	65.00%
O.T-3	818X2	1256	77%
OT-4	300X2	1290	60%
OT-5	350X1	1395	76%

Table 3.2 (b): Comparison of Specific Fuel Consumption (SFC) for oil tankers

Ship ID	Measured fuel consumption (Liter/hour)	SFC of measured ship (gm/kW.hr)	SFC from engine curve (gm/kW.hr)	Deviation in fuel consumption (%)
O.T-1	46.00X2	221	194	13.92%
O.T-2	38.00 X2	219	195	12.31%
O.T-3	123.00 X2	220	202	8.91%
OT-4	35.00X2	219	194	12.89%
OT-5	51.00X1	216	193	11.92%

Table 3.3 (a): Measured engine RPM and corresponding engine load of passenger ships

Ship ID	Main Engine Power (HP)	Engine RPM at a service speed	Main Engine Load (Average)
P.V-1	350X2	1420	82%
P.V-2	300X2	1620	70%
P.V-3	750X2	1269	82%
P.V-4	350X2	1395	78%
P.V-5	1000X2	846	90%

Table 3.3 (b): Comparison of Specific Fuel Consumption (SFC) for passenger ships

Ship ID	Measured fuel consumption (Liter/hour)	SFC of measured ship (gm/kW.hr)	SFC from engine curve (gm/kW.hr)	Deviation in fuel consumption (%)
P.V-1	54.00X2	212	194	9.28%
P.V-2	40.00X2	214	196	9.18%
P.V-3	130.00X2	238	202	17.82%
P.V-4	51.00X2	210	194	8.25%
P.V-5	162.00X2	202	193	4.66%

3.3.2. Deadweight/Gross Tonnage and ship data verification

Consideration of actual physical data of deadweight to establish an $EEDI_{BD}$ baseline may provide us with a wrong baseline. As explained in Section 2.4, 100% design deadweight capacity is not possible for all trips. For any given case, the ship may be fully loaded, which may be not true for every trip for the same ship. Therefore, while establishing the $EEDI_{BD}$ baseline, 85% design deadweight shall be used for cargo ships and oil tankers. 100% gross tonnage has been considered for passenger ships as explained in Section 2.4.

Deadweight capacity and gross tonnage depend upon the principal dimension of the ship. For this reason, the unverified ship data has undergone several verification processes. Department of Shipping (DOS) and Bangladesh Water Transport Authority (BIWTA) are the main source of ship data, all of which has not been verified physically under this research. The investigation has shown that the ship design particulars stored at DOS and BIWTA are faulty in many cases. For example, principal particulars do not match in some cases. Sometimes design deadweight is more or less than the actual capacity. Therefore, ambiguous ship data needs to be scrutinized first. The first scrutiny was done by comparing ship design with the ratios shown in Table 3.4. Table 3.4 shows the ranges of different ship parameter ratios and coefficients from numerous inland ships of Bangladesh which are based on my long field experience/shipyard visit/ship trial data and travel by ships since 2007 as well as literature review (Watson and Gilfillan, 1977, Roseman, 1974, Schneekluth and Bertram, 1998, Hossam and Ahmed, 2005). Ship data outside the ranges as presented in Table 3.4 were disregarded for further use. Used ship data has been presented in Appendix-F.

Table 3.4: Ranges of verified inland ship design parameters of Bangladesh

Ratio or Coefficient	**Range from verified ships**		
	Cargo Vessel	**Oil Tanker**	**Passenger Ship**
Length/Breadth	3.90-7.0	3.52-7.52	3.52-6.39
Breadth/Draft	2.12-5.46	1.7-6.11	2.58-8.47
Breadth/Depth	1.97-4.17	1.43-4.75	1.6-4.40
Deadweight/Displacement	0.6-0.81	0.62-0.83	Not considered
Block Coefficient	0.62-0.83	0.62-0.83	0.55-0.75

3.3.3. Service speed of the ship

The service speed at the Maximum Continuous Rating (MCR) of the main engine and main engine power is required for the vessels which have passed the first verification test. Since all vessels have not been investigated physically, the main engine power and service speed at MCR needs to verify as well.

In general, inland ships of similar type plys within a close speed range. It has been observed that the regression line along the scattered plots of Reynold's number against the waterline length has a very high correlation. Figures 3.1, 3.2 and 3.2 present the plots of Reynold's number against cargo, tanker, and passenger ship's waterline length, respectively. Regression lines have shown a very high correlation value. These regression line Equations have been used to find Reynold's number for the vessel which have passed the first scrutiny.

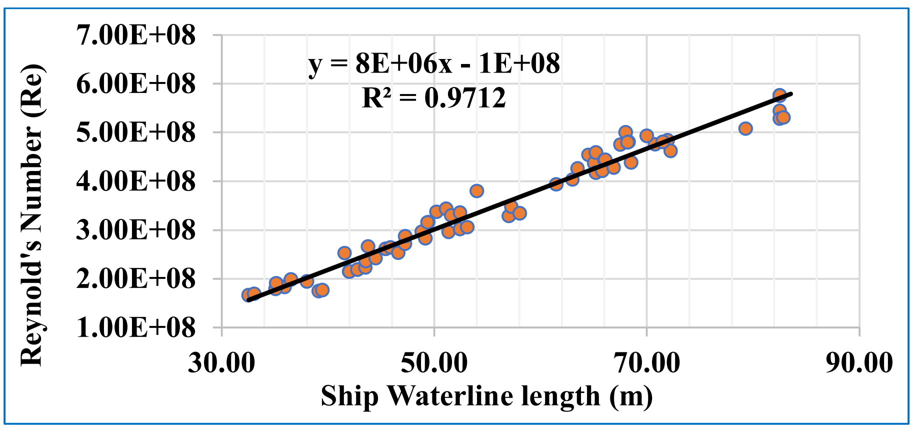

Figure 3.1: Reynold's number against verified inland Cargo Ships of Bangladesh

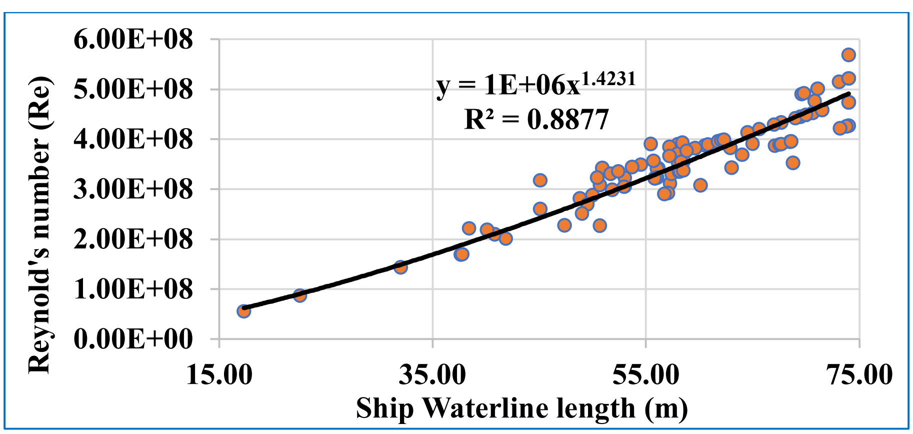

Figure 3.2: Reynold's number against verified inland Oil Tankers of Bangladesh

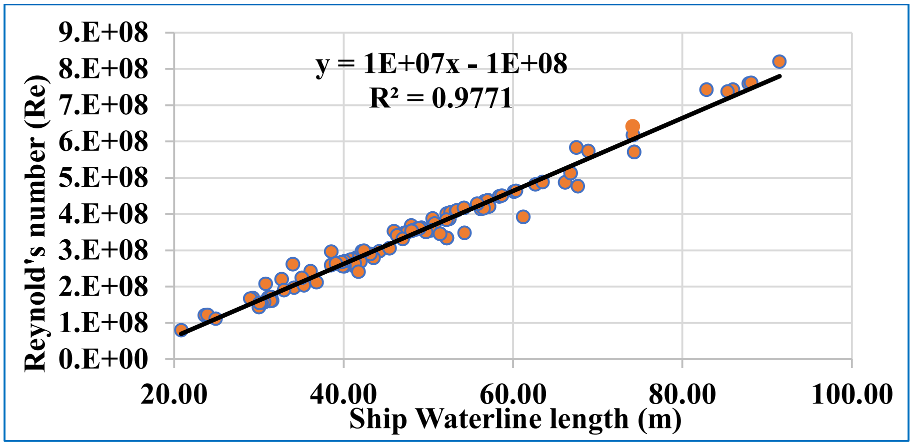

Figure 3.3: Reynold's number against verified inland Passenger Ships of Bangladesh

Since we have Reynold's number, using the following Equation, corresponding unknown speeds can be found,

Reynold's Number, $R_e = \frac{VxL}{\upsilon}$

or, $V = \frac{R_e x \upsilon}{L}$ (3.3)

Where,

V = Ship Speed

L = Ship's waterline length

ν= Kinematic viscosity

Using Equation 3.3, unknown service speeds can be found with reasonable accuracy. Reynold's number found from the regression lines and corresponding speeds are presented in Appendix-F. The speed found in this way is assumed to be the speed at 70% MCR for cargo and oil tankers. For passenger ships, the same was assumed at 80% MCR.

Now, the installed main engine powers for the unverified ship data needs to be verified. Theoretically, the selection of the main engine starts with the total ship resistance at a certain speed. Total ship resistance at a certain speed is,

$R_T = 0.5 \times C_T \times \boldsymbol{\rho} \times S \times V^2$ (3.4)

Where,

C_T = Total resistance coefficient

ρ = Water density

S = Ship's wetted surface area

V = Ship's speed

The wetted surface area of the ship is a function of the ship's waterline length, breadth, and draft which can be expressed by the following Equation (Hans and Marie, 2012),

$$S = 0.99 \times (\nabla/T + 1.9 \times L_{WL} \times T) \qquad (3.5)$$

Where,

∇ = Displacement of the ship in Tonne

T = Draft of the ship in meter

The effective power of ship P_E can be expressed as,

$$P_E = R_T \times V = 0.5 \times C_T \times \rho \times V^3 \times 0.99 \times (\nabla/T + 1.9 \times L_{WL} \times T)$$ (From Equation 3.4 and 3.5) (3.6)

Break Power of Main Engine, P_B can be expressed as

$$P_B = P_E/(\eta_R \times \eta_o \times \eta_s \times \eta_H) \qquad (3.7)$$

Where,

η_R = Relative Rotative Efficiency

η_o = Open Water Efficiency

η_s = Shafting Efficiency

η_H = Hull Efficiency

Therefore, from Equations 3.6 and 3.7, Main Engine Brake Power,

$P_B \quad = P_E/(\eta_R \times \eta_o \times \eta_s \times \eta_H)$

$= 0.5 \times C_T \times \boldsymbol{\rho} \times V^3 \times 0.99 \times (\nabla/T + 1.9 \times L_{WL} \times T) / (\eta_R \times \eta_o \times \eta_s \times \eta_H)$

$= \{(0.5 \times C_T \times \boldsymbol{\rho} \times 0.99)/(\eta_R \times \eta_o \times \eta_s \times \eta_H)\} \times V^3 \times (\nabla/T + 1.9 \times L_{WL} \times T)$

For a given ship and route, total resistance coefficient (C_T), water density ($\boldsymbol{\rho}$), relative rotative efficiency (η_R), open water efficiency (η_o), shafting efficiency (η_s), hull efficiency (η_H) can be assumed to be constant for a fixed speed. Therefore considering $\{(0.5 \times C_T \times \boldsymbol{\rho} \times 0.99)/(\eta_R \times \eta_o \times \eta_s \times \eta_H)\} = K$, the brake horsepower becomes

$P_B \quad = K \times V^3 \times (\nabla/T + 1.9 \times L_{WL} \times T)$

Or, $P_B \propto V^3 \times (\nabla/T + 1.9 \times L_{WL} \times T)$ (3.8)

The plot of the value 'K' for the verified ships against the installed main engine power is presented in Figures 3.4, 3.5 and 3.6 for cargo, oil tanker and passenger ships respectively. Each regression line has shown a very high correlation, having an R^2 value above 93% which is highly acceptable (Moore, et. al, 2013).

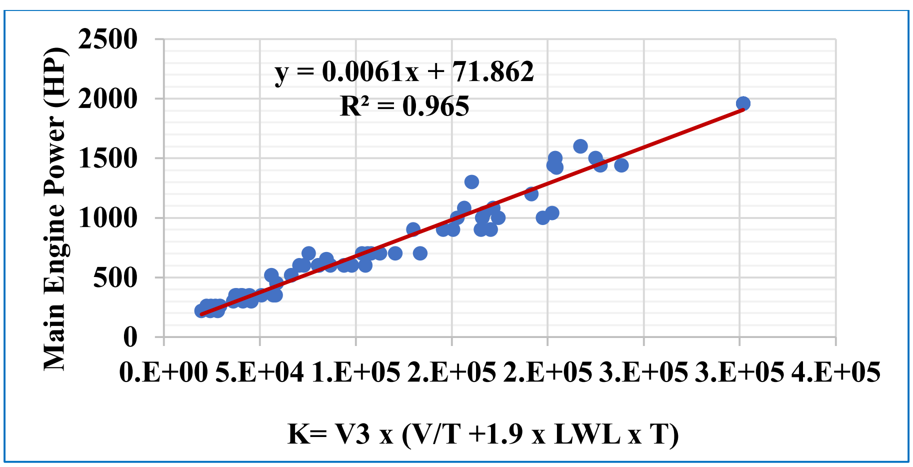

Figure 3.4: Main Engine power against K for verified cargo ships

Regression lines as shown in Figures 3.4, 3.5 and 3.6 are used to cross-check the unverified main engine information. Engine information that is not within the 10% limit of the regression line, have been rejected for further calculation.

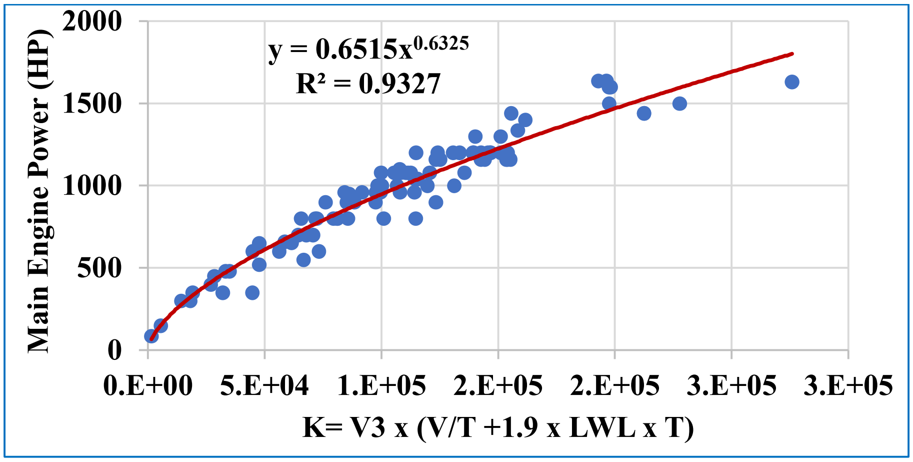

Figure 3.5: Main Engine power against K for verified oil tankers

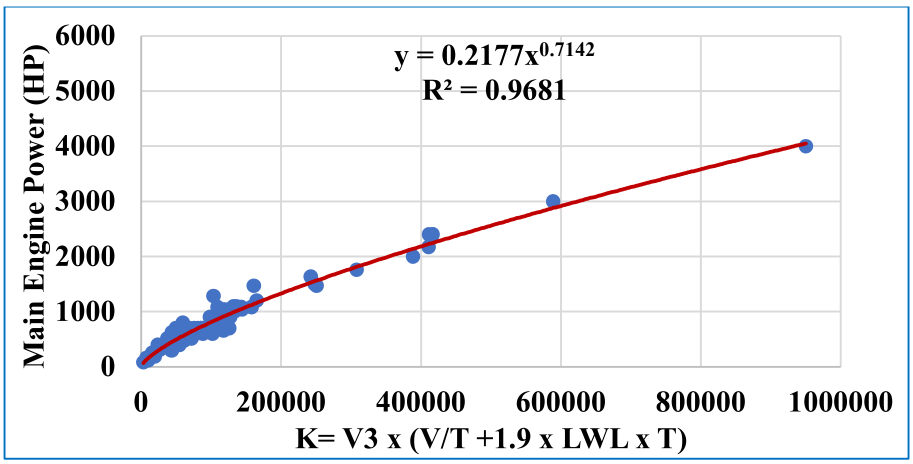

Figure 3.6: Main Engine power against K for verified passenger ships

3.3.4. Summary of the ship data verification

Table 3.5 presents the summary of the ship data verification result based on the ranges presented in Table 3.4 and the regression lines as presented in Figure 3.4, 3.5 and 3.6. The reasons for ship data rejection have been provided in Appendix-F.

Table 3.5: Summary of the ship data verification

Type of Ship	Total number ship data	The total number of ship data passed the first verification test	Reasons for selection/rejection of unverified ship data
General Cargo Ship	1634	281 (17.20% of the total)	a. L/B ratios of 47 cases (2.87%) were out of the verified vessels range.
			b. B/T ratios of 324 cases (19.83%) were out of the verified vessels range.
			c. DWT/Displacement ratios of 1263 (77.29%) cases were out of range of verified vessels.
			d. Inappropriate main engine data for 7 cases (0.43%)
Oil Tanker	134	124 (92.53%)	All but 12 ship data were verified by investigation, data provided by the state-owned oil company of Bangladesh namely Padma, Meghna and Jamuna oil company limited and oil tanker fleet information from Highspeed Group, Motijhil Dhaka. 12 numbers tanker failed the verification test because of inappropriate main engine data.
Passenger's vessels	479	199 (41.54% of the total)	a. L/B ratios of 28 cases (5.84%) were out of the range of verified vessels.
			b. B/T ratios of 07 cases (1.46%) were out of the range of verified vessels.
			c. Capacity information of 237 (49.47%) cases was inappropriate.
			d. Inappropriate main engine data for 8 cases (1.67%)

According to Equation 3.6, ship speed and required main engine power are proportional with the appropriate coefficient. Jan Holtrop and Frits Mennen proposed approximate formulations to predict the required propulsion power (Holtrop and Mennen 1982; Holtrop 1984, 1988). The formulas are based on a hydrodynamic theory with coefficients derived from regression analysis of 334 ship model tests conducted at Marin's model test basin. Holtrop and Mennen's (1982, 1984, and 1988) method is today considered one of the most accurate and efficient methods for predicting the resistance and propulsion power needs of typical monohull vessels during the design phase (Lampros and Evangelos, 2018). Holtrop-Mennen (1982, 1984 and 1988) method has been used to check the correctness of Figures 3.4, 3.5 and 3.6. To do that, randomly selected vessels from the accepted list of each category have been reanalysed. The summary of the result is presented in Tables 3.6, 3.7 and 3.8. Appendix-G presents one sample calculation.

Table 3.6: Comparison of speeds (General Cargo)

Name of the ship	Main Engine Power from Figure 3.4 (HP)	Speed from Figure 3.1 (Knot)	Speed calculated at 70% MCR by Holtrop-Mennen method (knot)	Deviation (%)
MV Tahsina	258	8.00	8.20	2.50%
MV Barsha-1	300	8.50	8.30	-2.35%
MV River Captain	1200	11.00	9.70	-11.82%
MV Felu Matubbar	700	10.00	9.10	-9.00%
MV Great Wall Logistics-2	900	10.50	9.80	-6.67%

Table 3.7: Comparison of speed (Oil Tanker)

Name of the ship	Main Engine Power from Figure 3.5 (HP)	Speed from Figure 3.2 (Knot)	Speed calculated at 70% MCR by Holtrop-Mennen method (knot)	Deviation (%)
OT Sadia Onik	350	7.50	8.00	6.67%
OT Shariah	700	9.00	9.30	3.33%
OT Choyon-3	350	7.00	8.40	20%
OT Nousher	700	9.50	9.30	-2.10%
M.T. Flamingo	400	7.50	8.70	16%

Table 3.8: Comparison of speed (Passenger Ship)

Name of the ship	Main Engine Power from Figure 3.6 (HP)	Speed from Figure 3.3 (Knot)	Speed calculated at 80% MCR by Holtrop-Mennen method (knot)	Deviation (%)
M.V. Manik-1	700	11.00	11.50	4.50%
M.V. New Sabbir	1080	12.00	12.30	2.50%
M.V. Shahrukh-1	900	12.00	12.00	0.0%
M.V. Takwa-1	700	12.00	11.50	-4.12%
M.V. Pubali-1	600	12.00	12.00	0.0%

Table 3.6, 3.7 and 3.8 presents the deviation of speed as calculated from Figures 3.1, 3.2 and 3.3 and by the Holtrop-Mennen (1982, 1984 and 1988) method. This shows a mixed result, where the deviation varies from

a. -9.0% to 2.50% for cargo ships
b. -2.10% to 20% for oil tankers and
c. -4.12% to 4.5% for passenger ships

The deviation of Holtrop-Mennen (1982, 1984 and 1988) results from the results of Figures 3.1, 3.2 and 3.3 is quite usual. Lampros Nikolopoulos and Evangelos Boulougouris of the University of Strathclyde (Lampros and Evangelos, 2018) have studied the deviation of the result of Holtrop-Mennen (1982, 1984 and 1988) calculation with the actual ship. They have studied 07 standard existing ships and analysed their resistance in Holtrop and Mennen (1982, 1984 and 1988) method at different Froude number ranges. The following Table presents their comparison result.

Table 3.9: Comparison of resistance between standard hull and Holtrop-Mennen (1982, 1984 and 1988) method

Standard Ship Hull	Approximate Deviation (%)
KVLCC2	-7.5% to 15%
VLCC	-2.8% to -7.8%
Newcastlemax	-2% to 6.5%
Capesize-1	-6% to -9%
Capesize-2	-9% to 1.8%
Ultramax-1	-17% to 2%
Ultramax-2	-22% to 7%

3.3.5. $EEDI_{BD}$ baselines for Inland General Cargo, Oil Tanker and Passenger Ships of Bangladesh

On the right-hand side of Equation 3.2, verified ship data was utilized, and the result was plotted versus deadweight (gross tonnage for passenger ship). Figures 3.7, 3.8, and 3.9 show the dispersed points from the computation for inland freight, an oil tanker, and passenger ships, respectively. For each ship type, a regression-based power curve line runs across the dispersed locations. These lines are the proposed $EEDI_{BD}$ baselines based on revised EEDI formulation and verified ship data. For comparison purposes, EEDI baselines as defined by IMO for cargo and oil tanker are presented in Figures 3.7 and 3.9. Since IMO has not introduced any EEDI baseline for a pure passenger ship, Figure 3.8 only presents the proposed $EEDI_{BD}$ baseline for passenger ships of Bangladesh.

Recalling Equation 2.2 which is the regression-based power curves Equation in the following form

$$y = a \times b^{-c}$$

Table 3.10 presents the value of a, b and c of the above Equation.

Table 3.10: $EEDI_{BD}$ reference values for the different types of inland ships of Bangladesh

Ship type	a	b	c	R^2
General Cargo Vessel	165.63	DWT	0.255	0.9114
Oil Tanker	680.72	DWT	0.419	0.8608
Passenger ship	1052.3	GRT	0.464	0.91

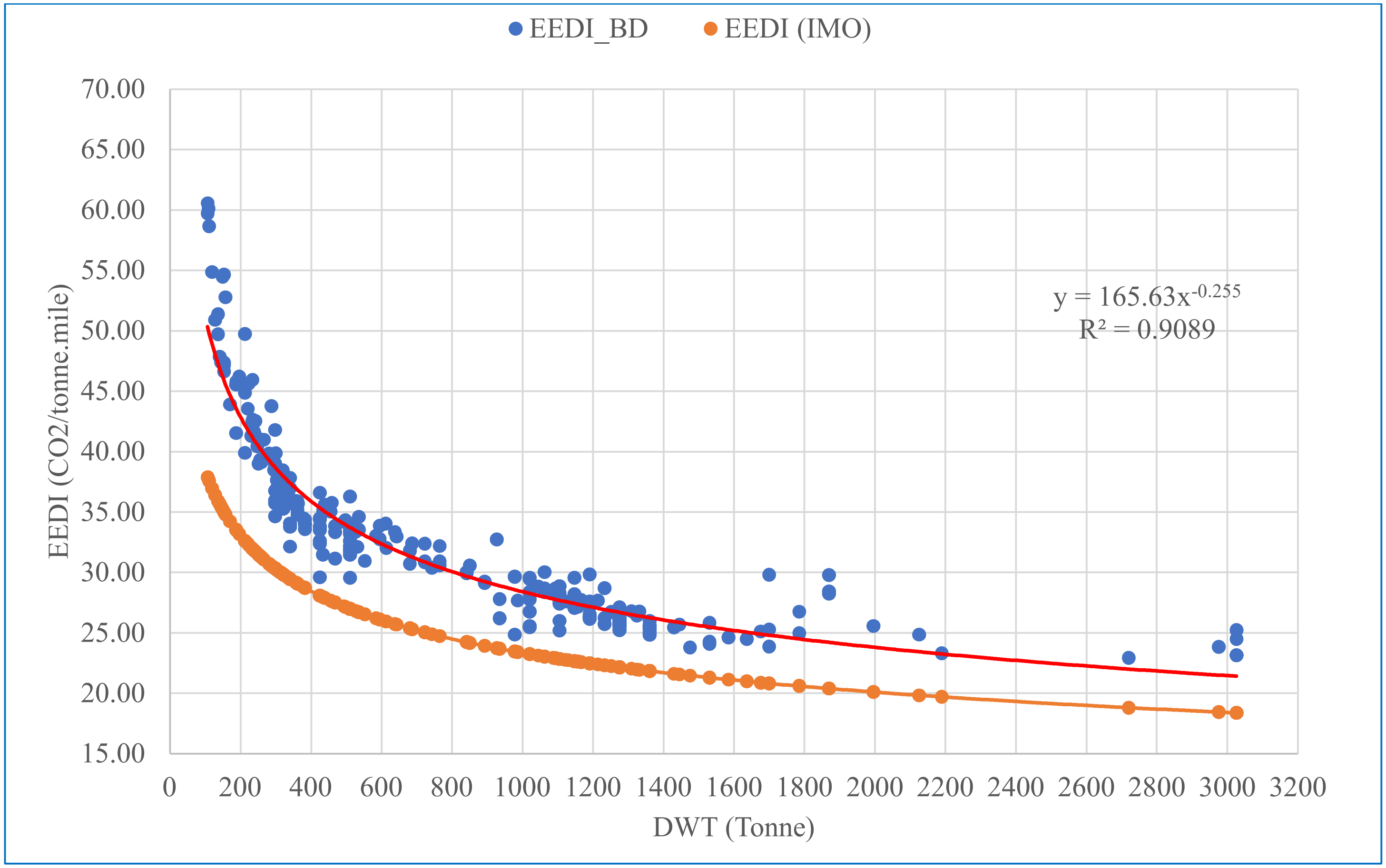

Figure 3.7: $EEDI_{BD}$ baseline for Inland General Cargo vessels of Bangladesh

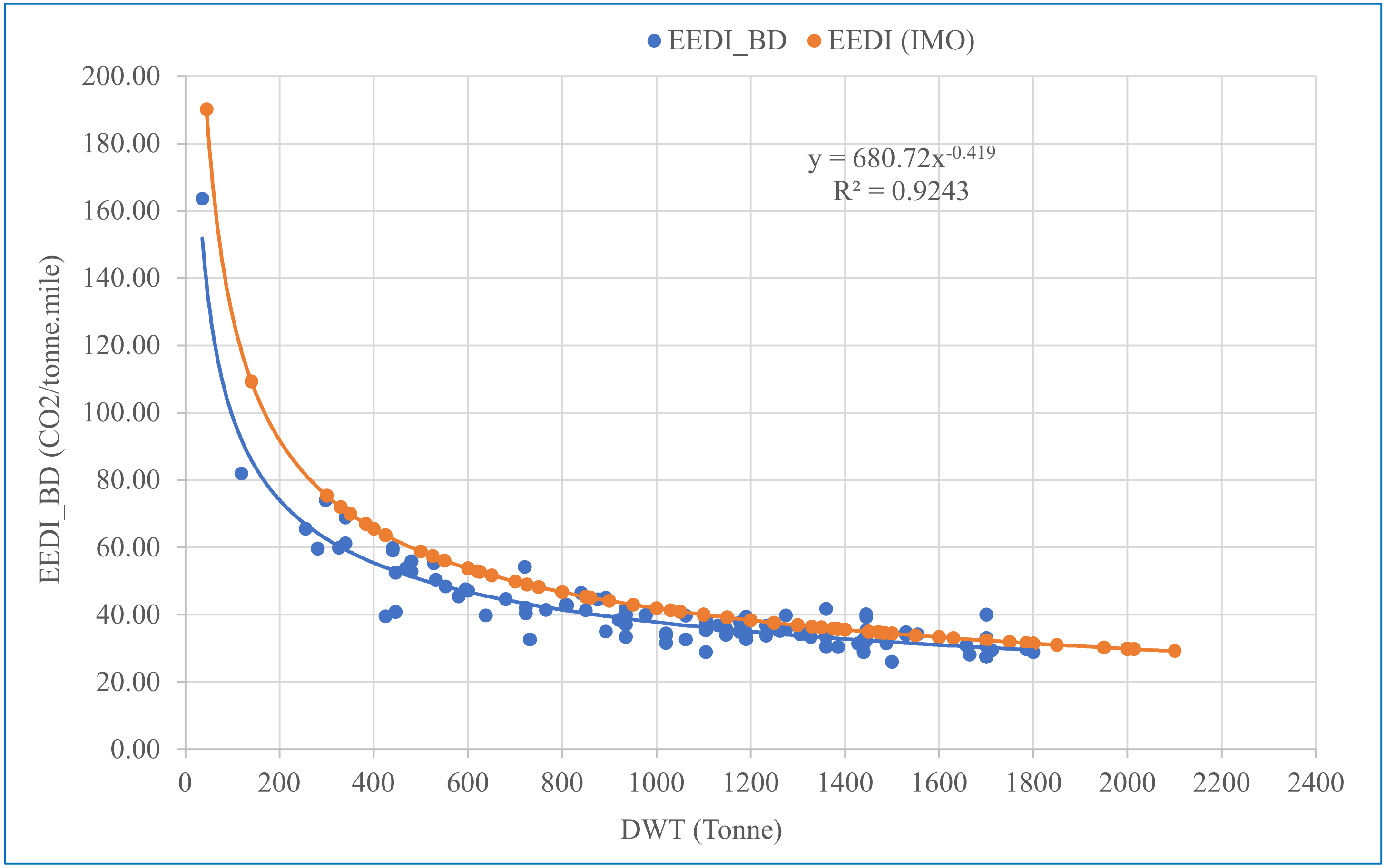

Figure 3.8: $EEDI_{BD}$ baseline for Oil Tankers of Bangladesh

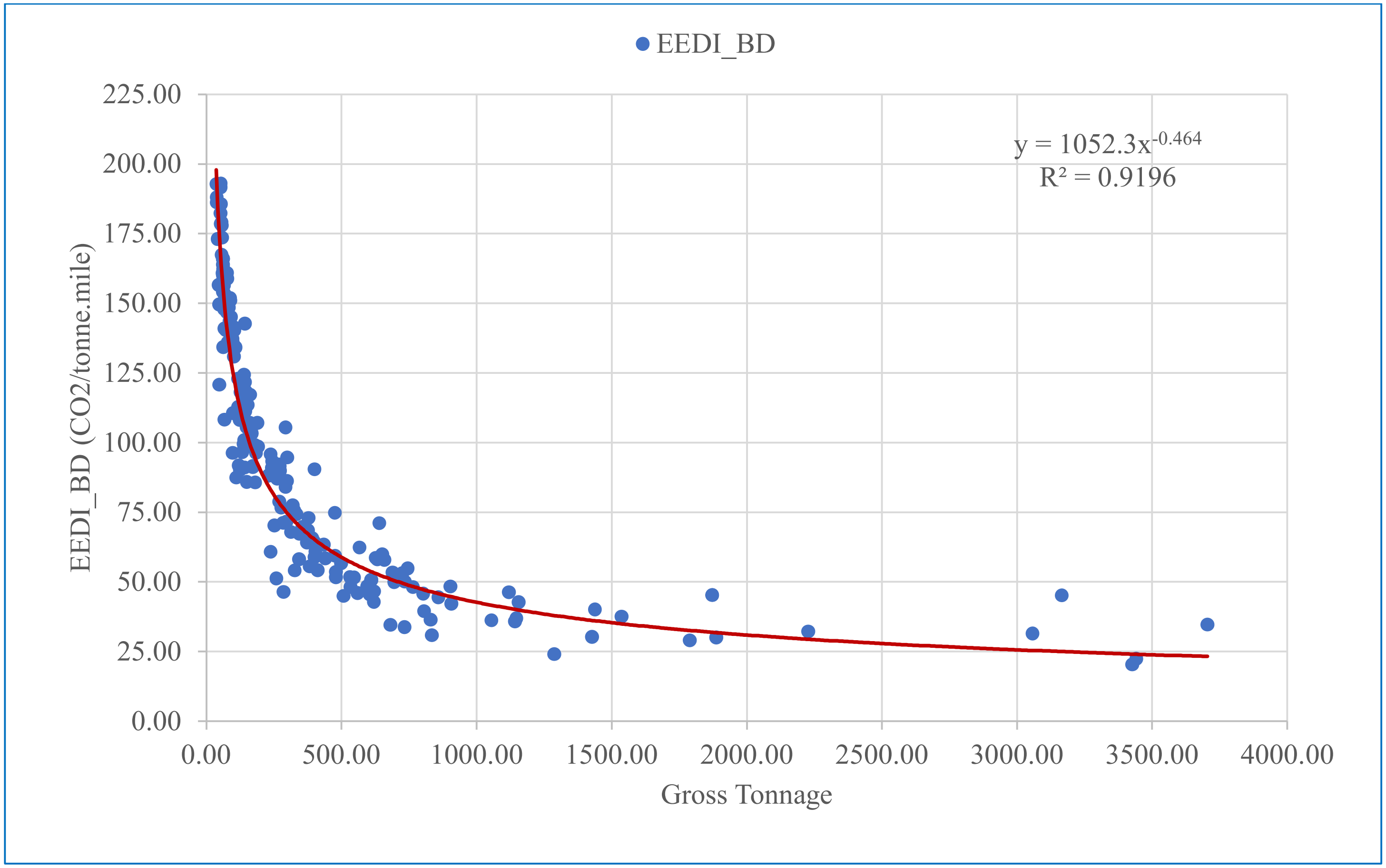

Figure 3.9: $EEDI_{BD}$ baseline for Passenger vessels of Bangladesh

3.3.6. General discussions on results

According to the IMO, the EEDI value represents the CO_2 emission per tonne mile of the vessel at the design stage. Vessels that are above the baseline, are identified as having insufficient energy efficiency, and vice versa. Calculated results for inland ships of Bangladesh show that the points are scattered and distributed around the baseline. Some vessels are under the line, which indicates efficient vessels from the current emission standard. From shown results in Figures 3.7, 3.8 and 3.9 two major remarks follow:

a. The database is scattered.
b. The R^2 value (Square of Correlation) between the baseline and EEDI values of analysed ships is above 0.9, which is reasonably high.

The following is an explanation for the random sequence of results:

a. Vessels under consideration are different in operational profile (Full load, Partial load, Ballast load, etc. operational profile).
b. Application of cargo handling gear.
c. Structural enhancements related to additional class notations.
d. Because of safety (excellent manoeuvrability) and other factors, installed engines in IWW self-propelled ships are often more powerful than is required for attaining real service speed.
e. Ships are fitted with different equipment's, especially for passenger ships.
f. Inland ships are often built based on experience-based on good existing ships. Nevertheless, some elements of ship structure sometimes deviate from structural elements of prototype, depending on the availability of shipyards stock. This could affect the lightweight of a ship, hence deadweight too.
g. Some of the considered ships are older than 20 years.

CHAPTER 4

ENERGY-EFFICIENT HYDRODYNAMIC DESIGN OF SHIP BASED ON FUEL CONSUMPTION AND EMISSION CONTROL

4.1 Hydrodynamics of Ship Design

Ship hydrodynamics deals with many aspects; one of the major aspects is the resistance of the ship while moving in the water. A design of a ship starts from the hydrodynamic analysis of the preliminary selected principal particulars of a ship. From the estimation of the propulsive power and fuel-saving to structural safety and manoeuvring, all are solved utilizing the hydrodynamic information. Proper hydrodynamic analysis and knowledge are required to have a hydrodynamically correct ship hull form. However, the hydrodynamic problems in ship design have always been a complex issue (Aksenov, et al., 2015).

A very important approximation was introduced by Prandtl (Prandtl, 1904). He suggested that the flow field around a body can be divided into two regions; an outer region where the viscosity can be neglected and an inner region where the flow is dominated by viscous forces. This means that an assumption about the fluid is introduced to solve the flow field in the outer region. Approximations are also needed to solve the flow field in the inner region. These approximations concern the type of flow field to be solved. The approximations for the inner region, where viscosity cannot be neglected, the differential Equations (Navier-Stokes's Equation) can be used. This Equation is solvable by the Finite Element (FE) or Finite Volume (FV) methods (Aksenov, et al., 2015), however, direct use of these methods require heavy resources for a real project. To solve this problem, a special numerical method based on Navier-Stokes's Equation has been developed which is known as the Reynolds-Averaged Navier-Stokes (RANS) Equations (Larsson and Raven, 2010).

For the inviscid region, a straightforward simplification of Navier-Stokes's Equations can be made when the viscous terms are neglected. This will then become the Euler Equations.

4.1.1 Shallow water effect on ship resistance and potential flow

Shallow water has a highly sensitive influence on a ship's resistance. First and foremost, there is a significant shift in potential flow around the ship's hull. When a ship is at rest in a moving stream with limited depth but unlimited breadth, the water underneath it must speed up more than in deep water, resulting in more pressure loss and increased sinkage, trim, and resistance. In very shallow water, sinkage and trim may limit the speed at which ships may go without colliding with the bottom.

Another impact may be seen in the wave pattern created while moving from deep to shallow water. For a point pressure impulse travelling across a free water surface, Havelock (1908) explained these modifications. The wave pattern in deep water is made up of transverse and diverging waves, as seen in Figure 4.1. The pattern is contained within the straight lines that form an angle of α = 19-degree 28 minutes on either side of the point's path of motion (PNA, 1988).

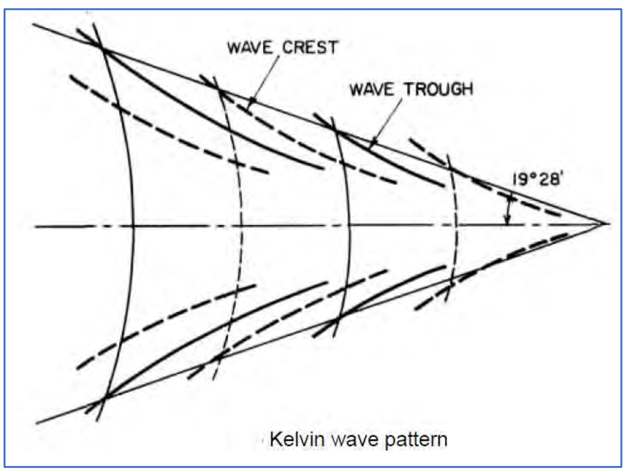

Figure 4.1: Kelvin wave pattern: transverse and diverging waves

As explained in the ‘Principles of Naval Architecture published by the ‘Society of Naval Architects and Marine Engineers’ second revision In a water of depth ‘h’, the velocity of surface waves is given by the expression

$$(V_e) = \left(\frac{gL_W}{2\pi}\right) * \frac{\tanh 2\pi h}{L_W}$$

Where L_w is the length of the wave from crest to crest.

As h/L_w increases, '$\frac{\tanh 2\pi h}{L_W}$' approaches a value of unity, and for deep water, this leads to the usual expression

$$V_e^2 = \frac{gL_W}{2\pi}$$

As the depth 'h' decreases, and the ratio h/L_w becomes small, $\frac{\tanh}{L_W}$ approaches the value $\frac{2\pi h}{L_W}$, and for shallow water, the wave velocity is approximately given by the Equation

$$V_e^2 = gh$$

The wave pattern for the pressure point goes through a critical change (Figure 4.2) when

$$(V_e) = \sqrt{gh}$$

When the speed is less than $\sqrt{gh}$, the system consists of a double set of waves, transverse and diverging as in deep water. When the ship speed is less than about $0.4\sqrt{gh}$, the pattern is enclosed between the straight lines having an angle α = 19-degree 28 minutes to the centreline, as for deep water. As the ship speed increases above this value, the angle increases and approaches 90 degrees as the speed approaches $\sqrt{gh}$ (Figure 4.2).

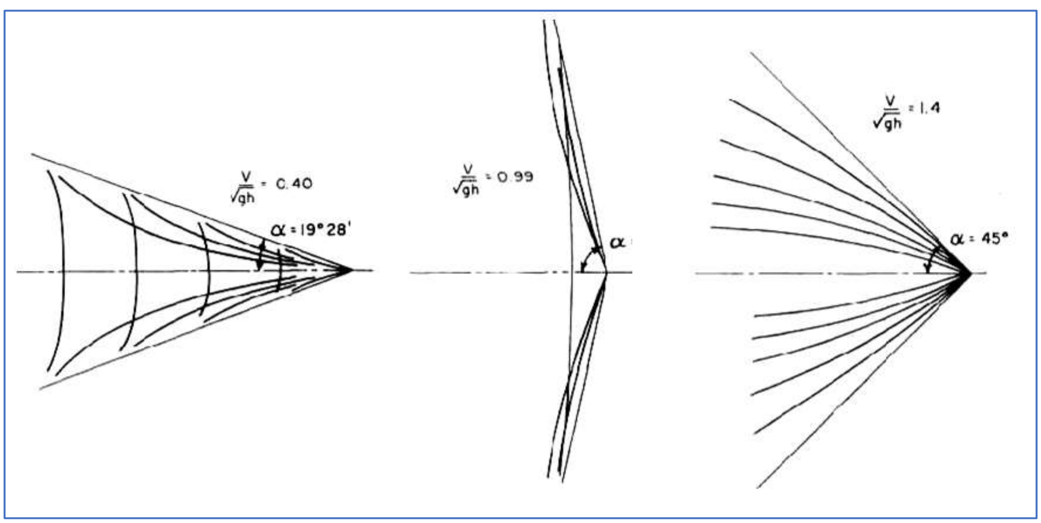

Figure 4.2: Shallow water effect on the wave pattern (PNA, 1988)

The pressure point is now generating a disturbance that is travelling at the same speed as itself, and all the wave-making effects are concentrated in a single crest through the point and at right angles to its direction of motion.

When the ship speed exceeds $\sqrt{gh}$, α begins to decrease again, the wave system is contained between the lines given by $Sin^2\alpha = gh/V^2$ (Figure 4.2). It now consists only of diverging waves, there being no transverse waves of cusps. The two straight lines themselves are the front crests of the diverging system, and the inner crests are concave to the line of advance instead of convex as in deep water.

Speeds below equal and above $V = \sqrt{gh}$ are referred to as subcritical and critical, respectively. Nearly all displacement ships operate in the subcritical zone. In the case of inland ships of Bangladesh, the value of $V = \sqrt{gh}$ usually ranges from 'Subcritical' to 'Critical'.

The effect upon resistance due to these changes in a wave pattern in shallow water has been investigated by Havelock (1908) for a pressure disturbance of linear dimension 'l', travelling over the water of depth 'h'. The resistance curves are reproduced in Figure 4.3.

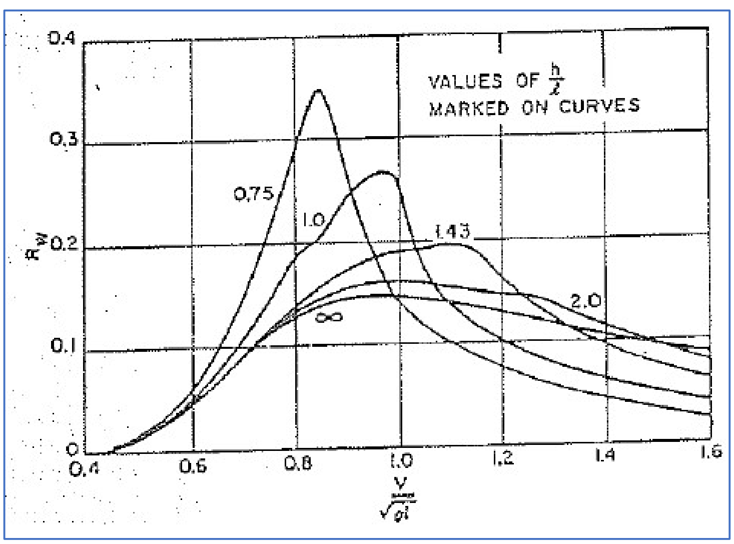

Figure: 4.3: Shallow water effect on wave resistance (PNA, 1988)

Each curve is marked with the value of the ratio of the depth of water 'h' to the characteristic length of the disturbance 'l', that marked '∞' being for deep water. When the ratio h/l is 0.75, there is a marked peak at a speed corresponding to a value of $\frac{V}{\sqrt{gh}} = 0.88$. Since $\sqrt{h/l} = 0.866$, this corresponds to a value of unity for $\frac{V}{\sqrt{gh}}$ so that the peak corresponds to the speed of the wave of translation for the particular depth of water, or the critical speed. At this speed, the resistance is very much greater than in deep water, but ultimately at a sufficiently high speed, it becomes less than in deep water.

Since most of the inland ships of Bangladesh operates from subcritical to critical zone, we can observe that the shallow water effect will increase the ship resistance or in other words ship speed will decrease for the same engine output. How much speed will be decreased for inland ships of Bangladesh has been discussed in Chapter 2 under Section 2.2.11. Also, different methods for calculating the shallow water effect have been discussed under Sections 2.2.4 to 2.2.7 and the reasons for using a particular method (Lackenby, 1963) to calculate the shallow water effect has been discussed. Other hydrodynamic effects on the ship, such as the waves, winds, motion, seakeeping were not directly taken into consideration in the calculation, rather incorporated by the factor 'f_w' as mentioned in Chapter 2 under Section 2.1. Moreover, the influence of hydrodynamics on ship resistance has been investigated using 'Shipflow' software as discussed below.

4.1.2 Viscous flow using RANS solver

Statistical turbulence studies have been used since the beginning, most notably in Reynolds' work (Reynolds,1894), but also implicitly in Boussinesq's earlier work (Boussinesq, 1877). Reynolds, Prandtl (Prandtl, 1904), Taylor, and others emphasized the perceived randomness of turbulent flows, implying that statistical approaches were the only way to analyse them, and this viewpoint was dominant during the early years of the development of turbulence modelling approaches dictated by averaging the nonlinear Navier–Stokes (N–S) Equations. The following are the N-S Equations:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + \nu(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2})$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial y}+v(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2})$$

$$\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial z}-g+v(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2})$$

It is feasible to convert Navier-Stokes' Equations into a form that can be solved numerically with today's computer capacity by dividing velocities and pressure into a time average and a fluctuating component. Reynold's Averaged Navier-Stokes is the name of this time-averaged technique (RANS). The time-averaged velocities are labelled as $u_i = \overline{u_1} + u'_i$, where $\overline{u_1}$ is the average and u'_i is the fluctuating component in the x, y and z-direction. When Navier-Stokes' Equations are time-averaged, all turbulent fluctuations are removed except for Reynolds stresses. The Reynold stresses add six more unknowns to the Equation system, which already has four Equations. This is handled by coupling the Reynold stresses with the average velocities using the turbulence model and RANS (Flowtech, 2010).

The RANS solver employs the finite volume technique, which divides the computational region into many cells. The governing Equations are integrated over each cell before the studied variable is approximated with a value at the cell's centroid. Because mistakes at the cell faces cancel with the faults of neighbouring cells, the finite volume approach assures that the number of variables such as mass, momentum, and energy is conserved.

The increase in the processing power of the present day's computer has opened several windows of solving numerical problems. Computational fluid dynamics (CFD), a branch of fluid mechanics, analyses and solves issues involving fluid flows using numerical analysis and data structures. It solves the viscous and inviscid fluid flow problems. Since CFD provides a low-cost initial design solution, it is replacing physical experiments, at least of a common type of hull shape.

CFD simulation begins with the creation of a body model of the ship hull (Larsson and Hoyte, 2010). A conceptual mathematical model is built when physical issues are discovered. Sets of differential or integral Equations make up this mathematical paradigm. To solve these Equations numerically, they must first be discretized, and then numerical methods must be used to solve them. Each step, however, introduces flaws into the solution (Nabila, 2014). Modelling mistakes are caused by assumptions used to build the conceptual model, as well as approximations in Equations like linearization and the use of empirical data.

'XCHAP' is a finite volume code developed by the 'FLOWTECH International AB', Sweden. This code solves the RANS Equations. It employs many turbulence models (EASM, k-w BSL, k-w SST). The solver may be applied in either a zonal or a global manner. The solver can be used in a zonal or a global approach. Several parametrised models of appendices are available in the system, e.g., rudder, shafts, brackets and vortex generators. Grids from external grid generators can also be loaded. A basic force model and a lifting line model are also accessible as actuator disk models. Commercial CFD software 'Shipflow' (which has been used in this research) uses this 'XCHAP' finite volume code which can compute the following quantities,

a. Velocity field
b. Pressure
c. Turbulent kinetic energy and specific turbulent kinetic energy.
d. The local skin friction coefficient
e. Friction and pressure resistance coefficients for the hull part covered by the grid
f. Total resistance and its components.

CFD analysis fulfils both Froude and Reynolds similarities, which is its major benefit. This implies that model-scale and full-scale results may be derived immediately while still providing a lot of information about the flow. In addition to that, since the Lackenby (1963) method as explained in Section 2.2.7.1 predicts the effect of shallow water, CFD analysis can be used to improve ship performance in shallow water.

4.1.3 Hydrodynamics and EEDI

The need for ecologically friendly transportation that consumes less fossil fuel is steadily growing. Since 1992, the United Nations Framework Convention on Climate Change

(UNFCCC) has encouraged corporate development and application of technologies that control, reduce, or prevent greenhouse gas emissions in all relevant sectors, including energy, transportation, industry, agriculture, forestry, and waste management. The EEDI as imposed by the IMO demands less emission of CO_2, economical and environmentally friendly technologies, and efficient ship design. EEDI's phase-by-phase rigorous requirements pushed ship designers and builders to develop innovative ways and techniques that help the UNFCCC achieve its goal of constructing greener ships. This can only be accomplished by lowering manufacturing and operating costs, optimizing ship hull forms, installing energy-efficient equipment, and using renewable energy sources.

In terms of resistance, propulsion, efficiency, stability or manoeuvring, the ship hull shape plays the most important role in the overall performance of a ship. For this reason, at the conceptual design stage, the optimal design of the ship hull should be as accurate as possible. Because of the increased demand for energy-efficient fuel-saving ships, the importance of the fuel-efficient hydrodynamic design of the ship is increased.

Hasan investigated the hydrodynamic impact of EEDI on ship design parameters (Hasan, 2011). The investigation was for the sea-going ships only, according to the adopted EEDI by IMO. Hasan's research work mainly focused on the hydrodynamic impact of individual ship design parameters on the EEDI of the sea-going ship. However, to understand the actual and total hydrodynamic influence of ship design parameters on EEDI, a comprehensive approach should be considered. EEDI is a value of a ship that calculates the benefit to society at the cost of the environment.

As presented in Section 2.1,

$$EEDI = \frac{CO_2\ Emission}{Transport\ Work}$$

$$= \frac{Power \times Specific\ Fuel\ Consumption \times CO_2\ Conversion\ factor}{Diffenent\ Factors \times Capacity \times Speed}$$

For specific fuel types, the CO_2 conversion factor is fixed. Depending upon engine life, specific fuel consumption (SFC) can be considered a fixed quantity at design RPM.

Different factors of the EEDI Equation are also have fixed values. Capacity is a fixed amount at the design draft for a specific ship. Therefore, with some appropriate proportional constant, EEDI can be expressed as,

$$EEDI \propto \frac{Power}{Capacity\ x\ Speed} \qquad 4.2$$

Equation 4.2 explains the primary dependency of EEDI for specific ship cases. If the required power can be lowered for the same speed and capacity, EEDI will be decreased.

The effective power of a ship,

P_E = Total Resistance (R_T) x Speed (V) = R_T x V

Section 4.2.1 has explained the hydrodynamics of ship resistance. Therefore, EEDI is highly dependent upon ship hydrodynamics.

4.2 Energy-efficient hydrodynamic design of Ship

According to Equation 4.2, a ship that requires less power emits a less amount of CO_2 in comparison to another ship of the same capacity and speed is more energy-efficient having a lower EEDI value. Equation 4.2 can be considered as the relationship between the hydrodynamics of ships and EEDI. To have a lower EEDI value at the design stage, the selection of principal particulars needs to be focused on EEDI value.

To establish $EEDI_{BD}$ baselines, 281 numbers general cargo ships, 124 numbers oil tankers and 199 numbers passenger ships' data have been used. According to the $EEDI_{BD}$ values and length, those vessels can be discretized into different Groups. It will help it identify the efficient and inefficient ranges of different ship design particulars considering $EEDI_{BD}$ values. Thus, a set of ship design suggestions can be produced based on this ship design particular sensitivity on $EEDI_{BD}$. Later, the hydrodynamic analysis will be performed on three existing ships. CFD software, 'Shipflow' will be used for this analysis. Those existing ship designs will be improved according to the ship design suggestion produced by the sensitivity analysis. Improved ships will undergo hydrodynamic analysis by ‘Shipflow.’

4.2.1 Sensitivity analysis of inland cargo ships of Bangladesh

The revised EEDI formulation was implemented on 281 general cargo vessels of Bangladesh. Based on length and EEDI values, the findings were further separated into the following categories.

a. ‘Group-1’ consists of ships having lengths below 41.00 m.
b. ‘Group-2’ consists of ships having a length ranging between 41.00 and 60.00 m.
c. ‘Group-3’ consists of ships having a length above 60.00 m.

The Groups were determined in such a way that a good number of vessels was available for analysis in each Group. For each Group, major ship design particulars have been presented in Tables 4.1 to 4.3.

A total number of 91 general cargo vessels were analysed under Group-1, and the results are presented in Table 4.1. The preliminary ship design ratios (Length over beam ratio, Beam overdraft, and Deadweight over displacement), Ship speed, Froude number, Block coefficient, and finally $EEDI_{BD}$ values, of those vessels are presented in the form range. To support the sensitivity analysis, those values of ship design parameters were further divided into well, average, and poor-performing vessels.

The same procedure was followed for Group-2 (a total of 89 general cargo vessels) and Group-3 (a total of 101 general cargo vessels). The results for Group-2 and Group-3 are presented in Table 4.2 and Table 4.3.

Table 4.1. Ship design particulars of a general cargo ship of Group-1, (Below 41.00 meter)

Ship Design particulars	Well Performing Vessels ($EEDI_{BD}$ < 38.00)			Average Performing Vessels ($EEDI_{BD}$ = 38-45)			Poor Performing Vessels ($EEDI_{BD}$>46)		
	Min.	**Max.**	**Avg.**	**Min.**	**Max.**	**Avg.**	**Min.**	**Max.**	**Avg.**
Length/Beam (L_{WL}/B)	3.96	5.59	4.72	3.90	6.68	4.81	3.91	5.60	4.69
Beam/Draft (B/T)	2.45	4.80	3.01	2.12	3.95	3.17	2.32	3.94	3.27
DWT/Disp.	0.60	0.85	0.70	0.59	0.79	0.70	0.69	0.78	0.73
Ship Speed (Knot)	7.00	9.00	8.22	7.00	8.50	8.01	6.25	8.50	6.93
Froude Number (F_N)	0.18	0.23	0.22	0.22	0.24	0.22	0.20	0.22	0.21
Block Coefficient (C_B)	0.68	0.75	0.72	0.65	0.78	0.71	0.65	0.71	0.69
$EEDI_{BD}$	29.55	38.99	35.66	38.46	45.95	41.58	46.21	60.55	52.23

Table 4.2. Ship design particulars of a general cargo ship of Group-2 (41.00-61.00 meter)

Ship Design particulars	Well Performing Vessels ($EEDI_{BD}$ < 31.00)			Average Performing Vessels ($EEDI_{BD}$ 31-35)			Poor Performing Vessels ($EEDI_{BD}$>36)		
	Min.	**Max.**	**Avg.**	**Min.**	**Max.**	**Avg.**	**Min.**	**Max.**	**Avg.**
Length/Beam (L_{WL}/B)	4.66	6.64	5.51	3.93	6.32	5.45	4.16	6.96	5.43
Beam/Draft (B/T)	2.36	3.61	2.69	2.20	3.37	2.67	2.13	5.46	2.87
DWT/Disp.	0.63	0.80	0.76	0.60	0.80	0.72	0.59	0.83	0.70
Ship Speed (Knot)	9.00	11.00	9.76	8.00	10.50	9.16	8.00	9.50	8.97
Froude Number (F_N)	0.19	0.25	0.21	0.20	0.24	0.22	0.20	0.24	0.22
Block Coefficient (C_B)	0.70	0.83	0.76	0.68	0.83	0.73	0.62	0.78	0.73
$EEDI_{BD}$	24.85	29.93	27.03	30.03	32.96	31.71	33.03	41.78	34.43

Table 4.3. Ship design particulars of a general cargo ship of Group-3 (Above 61.00 meters)

Ship Design particulars	**Well Performing Vessels ($EEDI_{BD}$ < 26.00)**			**Average Performing Vessels ($EEDI_{BD}$ 26-28)**			**Poor Performing Vessels ($EEDI_{BD}$>29)**		
	Min.	**Max.**	**Avg.**	**Min.**	**Max.**	**Avg.**	**Min.**	**Max.**	**Avg.**
Length/Beam (L_{WL}/B)	4.96	6.67	5.95	5.02	6.77	6.16	5.18	6.56	5.98
Beam/Draft (B/T)	2.20	3.90	2.80	2.28	4.37	2.84	2.90	4.02	3.35
DWT/Disp.	0.72	0.82	0.78	0.72	0.82	0.78	0.72	0.85	0.78
Ship Speed (Knot)	10.00	13.00	10.31	10.00	10.50	10.04	10.00	11.50	10.29
Froude Number (F_N)	0.18	0.23	0.20	0.20	0.21	0.21	0.20	0.23	0.21
Block Coefficient (C_B)	0.73	0.80	0.77	0.65	0.80	0.75	0.66	0.83	0.76
$EEDI_{BD}$	22.93	25.99	24.86	26.14	27.81	26.98	28.19	30.02	29.01

Following Table 4.4 presents the principal particulars of well-performed general cargo ships under Groups 1, 2 and 3 in comparison to the poorly performed ships.

Table 4.4. Comparison of Principal particulars of well-performed cargo ships

	Group-1	**Group-2**	**Group-3**
Length/Beam (L_{WL}/B)	Higher	Higher	Lower
Beam/Draft (B/T)	Lower	Lower	Lower
DWT/Disp.	Lower	Higher	Higher
Ship Speed (Knot)	Higher	Higher	Higher
Froude Number (F_N)	Higher	Lower	Lower
Block Coefficient (C_B)	Higher	Higher	Equal

4.2.2 Sensitivity analysis of inland oil tanker of Bangladesh

The revised EEDI formulation was implemented on 124 numbers inland oil tankers in Bangladesh. Based on length and EEDI values, the findings were further separated into the following categories.

a. 'Group-1' consists of ships having lengths below 51.00 meters.
b. 'Group-2' consists of ships having a length ranging between 51.00-60.00 meters.
c. 'Group-3' consists of ships having a length above 60.00 meters.

A total number of 23 oil tankers were analysed under Group-1, and the results are presented in Table 4.5. The preliminary ship design (Length over beam ratio, Beam overdraft, and Deadweight over displacement), Ship speed, Froude number, Block coefficient, and finally $EEDI_{BD}$ values, of those vessels are presented in the form range. To support the sensitivity analysis, those values of ship design parameters were further divided into well, average and poor-performing vessels.

The same procedure was followed for Group-2 (a total of 48 oil tankers) and Group-3 (a total of 53 oil tankers). The results for Group-2 and Group-3 are presented in Table 4.6 and Table 4.7.

Table 4.5. Ship design particulars of oil tankers of Group-1 (Below 51.00 meter)

Ship Design particulars	Well Performing Vessels ($EEDI_{BD}$ < 51.00)			Poor Performing Vessels ($EEDI_{BD}$>51)		
	Min.	Max.	Avg.	Min.	Max.	Avg.
Length/Beam (L_{WL}/B)	4.23	6.13	5.21	3.52	5.62	4.70
Beam/Draft (B/T)	1.90	5.00	3.15	2.22	5.93	3.86
DWT/Disp.	0.72	0.83	0.78	0.62	0.80	0.71
Ship Speed (Knot)	8.00	10.50	9.00	5.00	11.00	7.73
Froude Number (F_N)	0.19	0.24	0.21	0.16	0.27	0.20
Block Coefficient (C_B)	0.70	0.80	0.77	0.67	0.81	0.76
$EEDI_{BD}$	33.97	45.37	41.47	40.77	163.63	66.83

Table 4.6. Ship design particulars of oil tankers of Group-2 (51.00-60.00 meter)

Ship Design particulars	Well Performing Vessels ($EEDI_{BD}$ < 36.00)			Poor Performing Vessels ($EEDI_{BD}$>36)		
	Min.	**Max.**	**Avg.**	**Min.**	**Max.**	**Avg.**
Length/Beam (L_{WL}/B)	5.20	7.15	5.68	4.82	7.52	5.32
Beam/Draft (B/T)	1.86	3.24	2.72	1.70	6.11	3.90
DWT/Disp.	0.65	0.83	0.77	0.67	0.83	0.76
Ship Speed (Knot)	8.00	10.50	9.37	8.00	11.00	9.06
Froude Number (F_N)	0.17	0.23	0.20	0.17	0.24	0.20
Block Coefficient (C_B)	0.71	0.81	0.77	0.65	0.83	0.76
$EEDI_{BD}$	28.84	35.76	33.48	36.69	59.80	43.27

Table 4.7. Ship design particulars of oil tankers of Group-3 (Above 60.00 meters)

Ship Design particulars	Well Performing Vessels $EEDI_{BD}$ < 33.00)			Poor Performing Vessels ($EEDI_{BD}$>33)		
	Min.	**Max.**	**Avg.**	**Min.**	**Max.**	**Avg.**
Length/Beam (L_{WL}/B)	5.33	6.73	5.84	5.66	7.50	6.56
Beam/Draft (B/T)	2.38	3.28	2.91	2.15	3.30	2.64
DWT/Disp.	0.66	0.80	0.73	0.60	0.83	0.72
Ship Speed (Knot)	8.00	11.00	9.27	9.00	12.00	10.07
Froude Number (F_N)	0.16	0.21	0.18	0.18	0.23	0.20
Block Coefficient (C_B)	0.70	0.79	0.76	0.69	0.78	0.74
$EEDI_{BD}$	25.99	32.76	29.60	33.02	44.53	36.27

Table 4.8 presents the principal particulars of well-performed oil tankers under Groups 1, 2 and 3 in comparison to the poorly performed ships.

Table 4.8. Comparison of Principal particulars of well-performed oil tanker

	Group-1	**Group-2**	**Group-3**
Length/Beam (L_{WL}/B)	Higher	Higher	Lower
Beam/Draft (B/T)	Lower	Lower	Higher
DWT/Disp.	Higher	Higher	Higher

Ship Speed (Knot)	Higher	Higher	Lower
Froude Number (F_N)	Higher	Equal	Lower
Block Coefficient (C_B)	Higher	Higher	Higher

4.2.3 Sensitivity analysis of inland passenger ships of Bangladesh

The revised EEDI formulation was implemented on 198 numbers of inland passengers in Bangladesh. Based on length and EEDI values, the findings were further separated into the following categories.

a. ‘Group-1’ consists of ships having lengths below 32.00 meters.
b. ‘Group-2’ consists of ships having a length ranging between 32.00-45.00 meters.
c. ‘Group-3’ consists of ships having lengths above 46.00 meters.

A total number of 74 passenger ships were analysed under Group-1, and the results are presented in Table 4.9. The preliminary ship design ratios (Length over beam ratio and Beam over draft), Gross Tonnage, Ship speed, Froude number, Block coefficient, and finally $EEDI_{BD}$ values, of those vessels are presented in the form of range. To support the sensitivity analysis, those values of ship design parameters were further divided into well, average and poor-performing vessels.

The same procedure was followed for Group-2 (a total of 59 passenger ships) and Group-3 (a total of 65 passenger ships). The results for Group-2 and Group-3 are presented in Table 4.10 and Table 4.11.

Table 4.9. Ship design particulars of passenger ships of Group-1 (Below 32.00 meters)

Ship Design particulars	Well Performing Vessels ($EEDI_{BD}$ < 115)			Average Performing Vessels ($EEDI_{BD}$ 115-160)			Poor Performing Vessels ($EEDI_{BD}$ >161)		
	Min.	**Max.**	**Avg.**	**Min.**	**Max.**	**Avg.**	**Min.**	**Max.**	**Avg.**
Length/Beam (L_{WL}/B)	3.72	5.71	4.66	3.52	4.96	4.28	3.55	4.98	4.19
Beam/Draft (B/T)	2.58	7.87	4.58	4.36	7.41	5.44	3.46	6.28	5.08
GT	66.4	180.4	128.	45.13	142.0	84.67	36.66	62.20	52.45
Ship Speed (Knot)	7.50	11.00	8.94	6.00	11.00	9.46	8.00	9.00	8.74
Froude Number (F_N)	0.22	0.32	0.27	0.22	0.33	0.30	0.28	0.31	0.30
Block Coefficient (C_B)	0.58	0.68	0.60	0.60	0.70	0.62	0.61	0.62	0.61
$EEDI_{BD}$	85.	112.8	99.56	117.1	160.9	142.2	162.34	228.08	180.11

Table 4.10. Ship design particulars of passenger ships of Group-2 (32.00-45.00 meter)

Ship Design particulars	Well Performing Vessels ($EEDI_{BD}$ < 76)			Average Performing Vessels ($EEDI_{BD}$ 76-95)			Poor Performing Vessels ($EEDI_{BD}$ > 96)		
	Min.	**Max.**	**Avg.**	**Min.**	**Max.**	**Avg.**	**Min.**	**Max.**	**Avg.**
Length/Beam (L_{WL}/B)	3.74	6.21	5.13	4.10	6.04	5.29	4.04	5.48	4.81
Beam/Draft (B/T)	3.33	6.54	5.05	4.27	6.61	5.12	3.67	6.63	5.24
GT	237.4	640.0	349.2	172.1	319.2	256.7	137.4	293.1	167.1
Ship Speed (Knot)	9.00	12.00	10.80	9.00	12.00	10.90	9.00	11.00	10.61
Froude Number (F_N)	0.23	0.32	0.28	0.24	0.34	0.28	0.25	0.32	0.30
Block Coefficient (C_B)	0.55	0.73	0.65	0.55	0.68	0.64	0.58	0.71	0.63
$EEDI_{BD}$	44.9	75.53	63.45	76.63	95.80	88.30	96.28	142.7	108.9

Table 4.11. Ship design particulars of passenger ships of Group-3 (Above 46.00 meters)

Ship Design particulars	**Well Performing Vessels ($EEDI_{BD}$ < 41.00)**			**Average Performing Vessels ($EEDI_{BD}$ 41-50)**			**Poor Performing Vessel's ($EEDI_{BD}$ > 51.00)**		
	Min.	**Max.**	**Avg.**	**Min.**	**Max.**	**Avg.**	**Min.**	**Max.**	**Avg.**
Length/Beam (L_{WL}/B)	5.01	6.39	5.74	4.98	6.14	5.67	4.35	6.02	5.62
Beam/Draft (B/T)	3.39	8.47	6.82	5.70	7.32	6.28	3.94	6.48	5.47
GT	681.41	3704.64	1707.70	533.63	3165.81	967.83	375.03	744.29	513.38
Ship Speed (Knot)	10.00	14.00	12.32	10.00	14.00	11.81	11.00	12.00	11.64
Froude Number (F_N)	0.21	0.27	0.24	0.23	0.29	0.25	0.25	0.28	0.27
Block Coefficient (C_B)	0.65	0.75	0.67	0.65	0.71	0.67	0.60	0.70	0.65
$EEDI_{BD}$	20.41	40.11	32.43	42.14	50.73	46.82	51.53	90.48	60.57

Following Table 4.12 presents the principal particulars of well-performed passenger ships under Groups 1, 2 and 3 in comparison to the poorly performed ships.

Table 4.12. Comparison of Principal particulars of well-performed passenger ships

	Group-1	**Group-2**	**Group-3**
Length/Beam (L_{WL}/B)	Higher	Higher	Higher
Beam/Draft (B/T)	Lower	Lower	Higher
Gross Tonnage	Higher	Higher	Higher
Ship Speed (Knot)	Higher	Higher	Higher
Froude Number (F_N)	Lower	Lower	Lower
Block Coefficient (C_B)	Lower	Higher	Higher

4.2.4 Ship design suggestions for Inland Ships of Bangladesh based on sensitivity analysis

Tables 4.1 to 4.3 for general cargo ships, 4.5 to 4.7 for oil tankers, and 4.9 to 4.11 for passenger ships of Bangladesh show mixed results and inconsistency. For example, well-performed general cargo ships under Group-1 have a lower L_{WL}/B ratio, which contradicts the result of Group 2. Similar inconsistencies were also found for oil tankers and passenger ships. It would be much easier to conclude the design suggestion if the well-performing vessels of each Group showed a similar trend.

Froude numbers are low on most ships travelling in shallow water. At low Froude numbers, frictional resistance dominates the overall resistance (Hasan and Karim, 2020). As a result, reducing the wetted surface area is preferable to lower the ship's overall resistance. However, a ship's interior capacity will be reduced when the wetted surface area is reduced. This will drop the deadweight capacity from the original. For better $EEDI_{BD}$, higher carrying capacity is always desirable. Thus, to improve a vessel's design in light of $EEDI_{BD}$, the focus should be given to the reduction of wave resistance.

The slender ship generates lower wave resistance than the fuller one. L_{WL}/B should be increased to make a ship slender. This can be accomplished by lengthening it. Though in some cases the block coefficients of the well-performing vessels have higher values than the poor-performing vessels, lowering the block coefficient will decrease the wave resistance by making the ship slender.

Therefore, increasing the L_{WL}/B ratio and lowering the block coefficient will make the ship more efficient in waves. However, the stability criteria of the ship will not allow the L_{WL}/B ratio to be increased by lowering the breadth to a great extent. If any of the above processes decrease the ship's deadweight capacity, it should be compensated by increasing the draft of the ship. The higher draft will ensure the required displacement by lowering the Beam/Draft ratio. However, owing to the draft restrictions, this alternative must be carefully considered for inland ships.

It should be understood that in terms of EEDI, the efficient vessel is not that one that has comparatively lower resistance. The prime reason behind this fact is the value of the Energy Efficiency Design Index depends upon the hydrodynamic efficiency and 'Economic Benefit' to the society. This 'Economic Benefit' to the society depends on the carried cargo and delivery time (ship speed). Thus, a hydrodynamically well-performed vessel may show poor performance when she is judged by EEDI. Following Tables 4.13 and 4.14 will help to understand this paradox, where the sensitivities of individual ship design parameters were investigated for fixed and variable block coefficients.

An existing ship's parameter influence has been analysed in Tables 4.13 and 4.14. The 2nd row of Table 4.13 shows the original design parameters and in the 3rd row, the ship's waterline length has been increased by 5%. To compensate for the change in length at fixed block coefficient and displacement, breadth and draft were adjusted. The increase in length resulted in a 2.4% increase in surface area, which also increased the frictional resistance by 1.7%. However, wave resistance is reduced by 13.53% because of the increase in the L_{WL}/B ratio. Overall decreases in resistance and $EEDI_{BD}$ were 2.43% and 2.33%, respectively.

Table 4.13's fourth row indicates a similar shift; except this time the width rose by 5%. Displacement was maintained by reducing length and draft. Increasing the breadth and lowering the length and L_{WL}/B ratio lowered the frictional resistance by 0.27%; however, the wave resistance went up by 8.24%. Overall, total resistance and $EEDI_{BD}$ increased by 2.33% and 2.46%, respectively. A similar procedure was followed in the 5th row for the draft, where the draft increased by 5%. In all cases of Table 4.13, lowering the length has increased the $EEDI_{BD}$ value, because this change made the ship blunt and inefficient through waves.

Table 4.13. Sensitivity analysis for an example ship for fixed block coefficient (0.7), speed (10 knots) and displacement (945 tonnes).

	L_{WL} (m)	B (m)	L_{WL}/B	T (m)	B/T	Surface Area (m^2)	Frictional Resistance, (kN)	Wave Resistance, (kN)	Total Resistance, (kN)	$EEDI_{BD}$
Parent	50.00	9.00	5.56	3.00	3.00	581.01	14.71	6.43	32.56	30.28
5% L_{WL} increased	52.50	8.78	5.98 (+7.55%)	2.93	3.00 (0%)	594.93 (+2.40%)	14.96 (+1.70%)	5.56 (−13.53%)	31.77 (−2.43%)	29.57 (−2.33%)
5% B increased	48.80	9.45	5.16 (-7.19%)	2.93	3.23 (+7.67%)	577.71 (−0.57%)	14.67 (−0.27%)	6.96 (+8.24%)	33.32 (+2.33%)	31.02 (+2.46%)
5% T increased	48.80	8.78	5.56(0%)	3.15	2.79 (-7%)	571.42 (−1.65%)	14.51 (−1.36%)	6.83 (+6.22%)	32.70 (+0.43%)	30.35 (+0.22%)

Table 4.14. Sensitivity analysis example for fixed speed (10 knots) and displacement (945 tonnes) but variable block coefficient.

	L_{WL} (m)	B (m)	L_{WL}/B	T (m)	B/T	C_B	Surface Area (m^2)	Frictional Resistance, (kN)	Wave Resistance, (kN)	Total Resistance, (kN)	$EEDI_{BD}$
Parent	50	9	5.56	3	3	0.7	581.01	14.71	6.43	32.56	30.28
5% L_{WL} increased	52.5	9	5.83 (5.00%)	3	3 (0%)	0.67	592.01 (+1.89%)	14.89 (+1.22%)	4.55 (−29.24%)	30.45 (−6.48%)	28.74 (−5.07%)
5% B increased	50	9.45	5.29 (-4.76%)	3	3.15 (5.00%)	0.67	580.45 (−0.10%)	14.69 (−0.14%)	5.25 (−18.35%)	31.23 (−4.08%)	29.49 (−2.62%)
5% T increased	50	9	5.56 (0%)	3.15	2.857 (-4.76%)	0.67	576.30 (−0.81%)	14.59 (−0.82%)	5.20 (−19.13%)	30.86 (−5.22%)	29.07 (−3.98%)

Table 4.14 also presents a similar sensitivity analysis; however, this time it is for a variable block coefficient. The increase in individual particulars was offset by reducing the block coefficient in this example. For each case presented in Table 4.14, $EEDI_{BD}$ values decreased. However, the increase in L_{WL} reduced $EEDI_{BD}$ the most, as in this case, although there was a 1.22% increase in frictional resistance, the reduction in wave resistance was the highest (29.24%). Overall, there was a 6.48% reduction in resistance and a 5.07% reduction in $EEDI_{BD}$.

Every case presented in Tables 4.13 and 4.14 proves that to reduce CO_2 emissions by reducing $EEDI_{BD}$, slender ships give better results. The overall hydrodynamic performance of all a ship's design particulars determines its efficiency. EEDI incorporates the social benefit (transportation of cargo/passenger) to the ship's hydrodynamic performance. For this reason, when CO_2 emission reduction is required by increasing the ship's energy efficiency with a focus on $EEDI_{BD}$, the amount of cargo (GT for passenger ship) carried at a certain speed is a very important factor. If the procedure for any ship hull resistance improvement decreases the capacity of the ship, $EEDI_{BD}$ will increase. For example, Table 4.4 shows that the ranges of L_{WL}/B ratio are comparatively lower for vessels that lie in the efficient range. Further attempts to increase energy efficiency should start by lowering the L_{WL}/B ratio. This can be accomplished by either shortening the length or widening the width, or by doing both. Lowering the length will decrease the overall ship capacity, which will increase the $EEDI_{BD}$ value. This can be offset by raising either the block coefficient or the width, or by doing both. This correction, on the other hand, will make the ship fuller and bulkier, increasing the wave resistance at a given speed. This increase in wave resistance will increase the power requirement, and thus increase the value of $EEDI_{BD}$.

Based on the sensitivity analysis and above discussion, a set of ship design suggestions is presented in Table 4.15. A set of design suggestions have been produced focusing on the reduction of $EEDI_{BD}$ by improving the hydrodynamic performance of the ship.

Table 4.15. Ship design suggestions based on sensitivity analysis (Qualitative)

Ship Design Particulars	**Ship Design Improvement Suggestion**	**Hydrodynamic impact**	**Impact on $EEDI_{BD}$**
Water Line Length (L_{WL})	The length of the vessel should be the maximum possible that meets the required displacement and surface area.	a. Waterline length of a ship has a primary hydrodynamic influence on resistance, hull volume and sea keeping. b. Reynold's number and Frictional resistance coefficient increase with the increase of length. c. Wave resistance decreases.	When the length is increased in such a way that the decrease in wave resistance is higher than frictional resistance, the total resistance will decrease. Thus, the value of $EEDI_{BD}$ will decrease.
Length/Breadth (L_{WL}/B)	Increasing the L/B ratio is recommended. However, all types of stability criteria must be fulfilled.	A Higher L/B ratio ensures a slender and sharp hull, which provides better performance in waves by reducing wave resistance.	An increase in the L_{WL}/B ratio will lower the propulsion power requirement for the same speed and capacity. Thus, the value of $EEDI_{BD}$ will decrease.
B/T	Decreasing the B/T ratio is recommended.	a. The beam-draft ratio correlates strongly with residuary resistance, which increases for large B/T.	Lowering the B/T ratio by decreasing breadth (fulfilling all stability criteria) will decrease the capacity.

	This should be done by lowering breadth and/or increasing the draft. Since inland ships face draft restrictions, the maximum achievable draft should be used to achieve the required displacement.	b. Decrease of B/T ratio by decreasing breadth will also increase the L_{WL}/B ratio. As discussed before, having a higher L_{WL}/B ratio is desirable to reduce wave resistance. The increasing draft will lower the B/T ratio and also allow a larger propeller. c. For the cases with a high B/T ratio, the propeller slipstream area is small concerning the midship Section which reduces propulsion efficiency. The waterline entrance angles increase in comparison with other ships with the same fineness. This leads to relatively high resistance.	Decreasing capacity will increase $EEDI_{BD}$. This can be compensated by increasing length and draft. An increase in length is proven to reduce wave resistance. Therefore, the overall $EEDI_{BD}$ value will be decreased.
DWT/Displacement	High DWT/Displacement is desirable. This will decrease the numerator of the $EEDI_{BD}$ Equation, which will decrease $EEDI_{BD}$	This can be achieved by decreasing the lightship weight. A lighter ship will face lower hydrodynamic forces.	A higher DWT/Displacement ratio will ensure higher capacity, which is a very important factor for lowering $EEDI_{BD}$.
Block Coefficient (C_B)	Minimum C_B to achieve the desired displacement is recommended.	Reduction of C_B slightly increases in hull steel weight. However, lowering the C_B lowers the required propulsion power, engine plant weight, and fuel consumption.	Overall, the reduction of C_B will reduce $EEDI_{BD}$.

		Additionally, because of the increased resistance and less smashing, seakeeping performance will improve.	
Ship Speed (V) and Froude number (F_N)	Lowering Froude number and speed is recommended.	a. By reducing surface area for a given ship volume, viscous resistance can be achieved. For a given speed, increasing the length of a ship and lowering the beam reduces the surface area and viscous resistance coefficient. b. As a ship speed increases, the waves generated by the ship and the energy required to generate these waves rises with it. This wasted energy or wave-making resistance often becomes a limiting factor in a ship's speed. There are more wave crests on the side of the hull at low speeds and at high speeds, the wavelength lengthens. At some speeds, the stern has a crest, whereas, at others, it has a depression. These crests and troughs can either partially cancel or partially contribute to the stern wave system, resulting in greater resistance at particular speeds owing to interference. This results in "humps and hollows" in the overall resistance coefficient. For maximum fuel efficiency, the ship should be operated in a hollow. At a speed-to-length ratio of 1.34, or	Lowering the speed should increase $EEDI_{BD}$ as it will decrease the denominator of $EEDI_{BD}$ Equation. However, because of the hydrodynamic effect of speed on the resistance the required power increases roughly by the cube of the variation in speed (Molland et al., 2017). Thus, speed reduction will reduce the power requirement and $EEDI_{BD}$ to a great extent.

		Froude number (F_N) 0.4, there will be a significant increase in resistance. In terms of resistance, this is the last effective speed for a displacement ship. Wave-making resistance rises dramatically above F_N = 0.4.	

Based on the results of the sensitivity analysis presented in 4.1-4.12, the following Tables (4.16, 4.17 and 4.18) present the efficient ranges of different ship design parameters of inland cargo, oil tanker and passenger ships of Bangladesh. It should be noted that careful measures of Table 4.15 shall be considered while selecting ship design particulars from the following Tables.

Table 4.16. Proposed efficient ship design ranges for general cargo ships of Bangladesh

Waterline Length	**L/B ratio**	**B/T ratio**	**DWT/Displacement**	**Speed (knot)**	**Froude number**	**Block Coefficient**
Less than 41 meters	3.96-5.59	2.45-4.80	0.6-0.85	7.00-9.00	0.18-0.22	Lowest possible block coefficient that meets capacity and stability requirements
41-61 meters	4.66-6.64	2.36-3.61	0.63-0.80	9.00-11.00	0.19-0.25	
Above 61 meters	4.96-6.67	2.20-3.90	0.72-0.82	10.00-13.00	0.18-0.23	

Table 4.17. Proposed efficient ship design ranges for oil tanker of Bangladesh

Waterline Length	L/B ratio	B/T ratio	DWT/ Displacement	Froude number	Speed (knot)	Block Coefficient
Less than 51 meters	4.23-6.13	1.90-5.00	0.72-0.83	0.19-0.24	8.00-10.50	Lowest possible block coefficient that meets capacity and stability requirements
51-60 meters	5.20-7.15	1.86-3.24	0.65-0.83	0.17-0.23	8.00-10.50	
Above 60 meters	5.33-6.73	2.38-3.28	0.66-0.80	0.16-0.21	8.00-11.00	

Table 4.18. Proposed efficient ship design ranges for passenger ships of Bangladesh

Waterline Length	L/B ratio	B/T ratio	Gross Tonnage	Froude number	Speed (knot)	Block Coefficient
Less than 31 meters	3.72-5.71	2.58-7.87	66.64-180.40	0.22-0.32	7.50-11.00	Lowest possible block coefficient that meets capacity and stability requirements
32-45 meters	3.74-6.21	3.33-6.54	237.40-640.0	0.23-0.32	9.00-12.00	
Above 46 meters	5.01-6.39	3.39-8.47	681.41-3704.64	0.21-0.27	10.00-14.00	

4.3 Ship design suggestion validation

In order to validate the ship design suggestions as provided in Tables 4.15, 4.16, 4.17 and 4.18, the following procedure has been adopted:

a. Three existing ships, one from each category (general cargo, oil tanker and passenger ship) were measured physically and lines plans were developed according to physical measurements.
b. The developed lines plans were converted into 3-dimensional models using 'Maxsurf' software. These models were further used for CFD analysis by the software 'Shipflow' and the total resistance was calculated at the service speed.

c. In order to make an improvement, the parent hulls were redesigned by parametric variations based on the design suggestions given in Tables 4.15-4.18 keeping the same displacement, capacity and speed for both the parent and redesigned hulls.
d. Results of both the parent and redesigned hulls were compared and an improved ship hull was obtained.

The three ships which were taken for physical measurement has the following Principal Particulars:

Table 4.19: Investigated vessels for validation

Principal Particulars	**MV. Madina-5 (General Cargo Ship)**	**MT. Saima-1 (Oil Tanker)**	**MV. Takwa-1 (Passenger Ship)**
Overall Length	76.21 meter	62.50 meter	59.76 meter
Waterline length	72.024 meter	59.60 meter	57.05 meter
Breadth	11.58 meter	10.67 meter	9.76 meter
Depth	5.20 meter	3.66 meter	2.59 meter
Draft	4.88 meter	3.20 meter	1.60 meter
Maine Engine	550 BHP×2	480 BHP×2	350 BHP×2
Service speed	10 knots	10 knots	11.50 knots

4.3.1 CFD analysis assumptions

CFD software usually gives results for deep-sea cases. As the pattern of hydrodynamic performance, particularly resistance of the ship due to parametric variations will be the same for both shallow and deep-water cases, the effect of shallow water has not been considered separately.

4.3.2 Implementing design suggestion on MV Madina-5 (cargo vessel)

Based on the ship design suggestions, investigated cargo ship ‘MV Madina-5’ has been redesigned. The change made to improve the design of ‘MV Madina-5’ from the parent design, is presented in Table 4.20.

Table 4.20: Comparison between parent and improved design of MV Madina-5

Design Particulars	Parent Design	Improved Design	Change (%)	Efficient Ranges (From design suggestion)
Water line length, L_{WL} (meter)	72.024	75	4.13%	-
Moulded Breadth, B (meter)	11.58	11.54	-0.35%	-
L_{WL}/B	6.22	6.5	4.50%	4.96-6.67
Loaded Draft, T(meter)	4.88	4.88	0.00%	-
B/T	2.373	2.365	-0.34%	2.20-3.90
Block Coefficient, C_B	0.75	0.7225	-4.00%	Lowest possible block coefficient that meets capacity and stability requirements
Propeller Diameter, D (meter)	1.88	1.88	0%	-
Displacement (Tonne)	3052	3052	0.00%	-
Deadweight (Tonne)	2100	2100	0.00%	-
Speed (Knot)	10	10	0.00%	10.00-13.00
Froude Number, F_N	0.194	0.19	-2.06%	0.18-0.23

Figures 4.4 and 4.5 show the free surface wave, Figures 4.6 and 4.7 show the wave height along the hull and Figures 4.8 and 4.9 show the pressure coefficient distribution for parent and improved hull, respectively. Details of the CFD software output is presented in Appendix H.

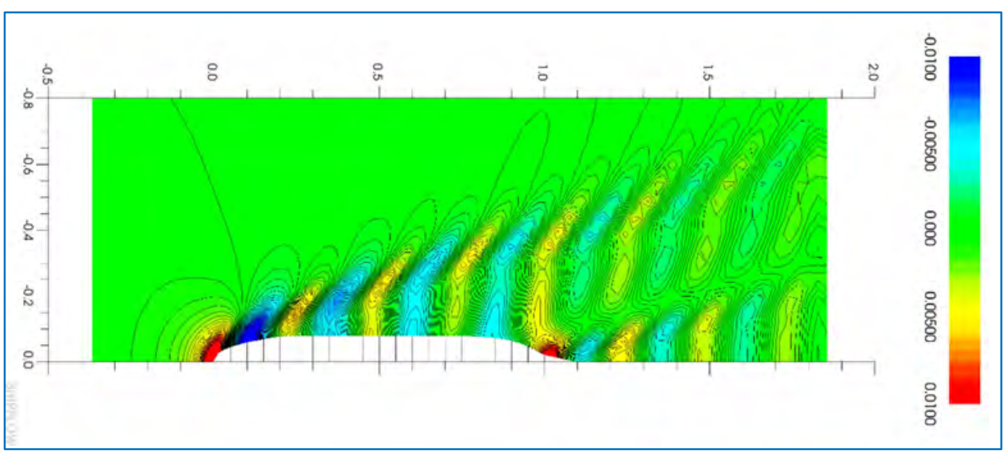

Figure 4.4: Free surface wave of MV Madina-5 (Parent Hull)

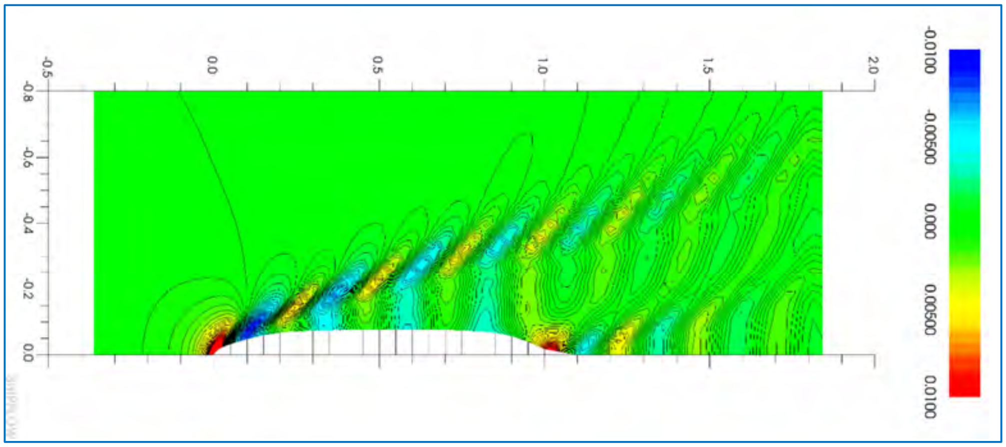

Figure 4.5: Free surface wave of MV Madina-5 (Improved Hull)

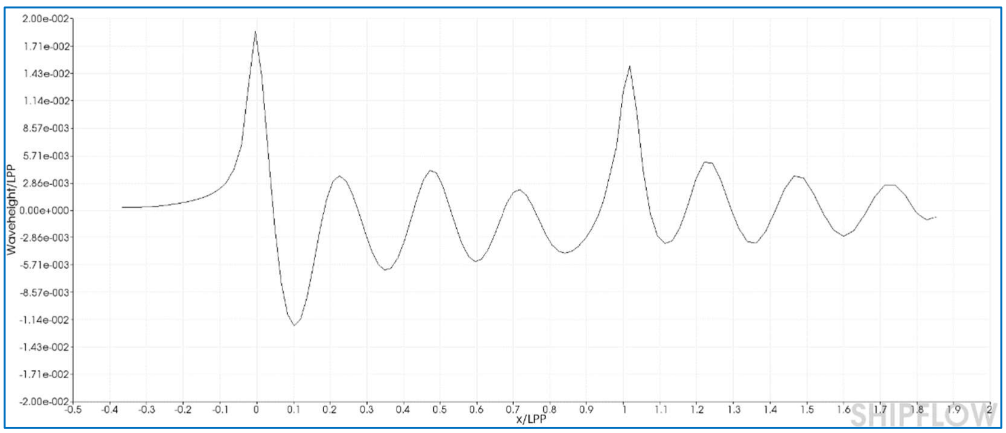

Figure. 4.6: Wave height along the hull of MV Madina-5 (Parent hull)

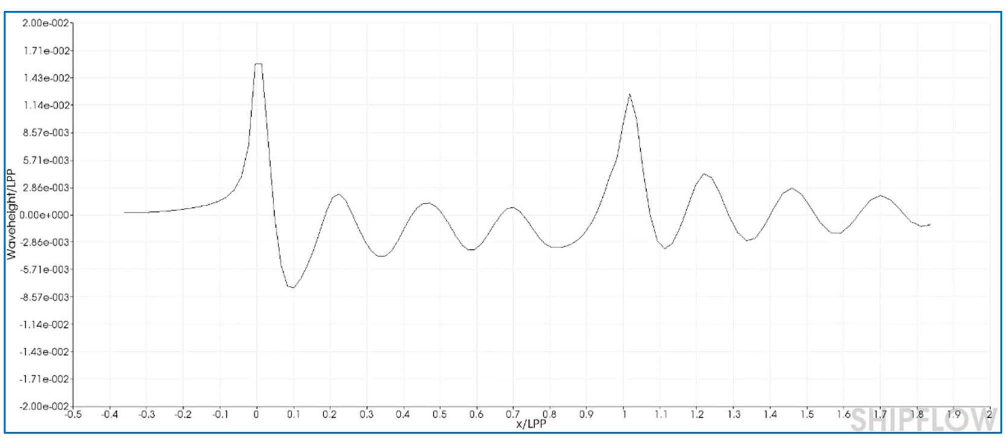

Figure. 4.7: Wave height along the hull of MV Madina-5 (Improved Hull)

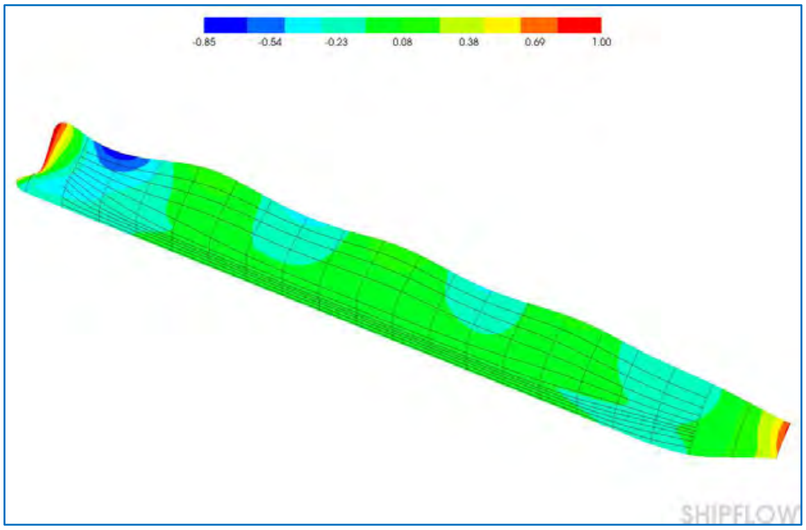

Figure. 4.8: Pressure distribution and streamlines of MV Madina-5 (Parent Hull)

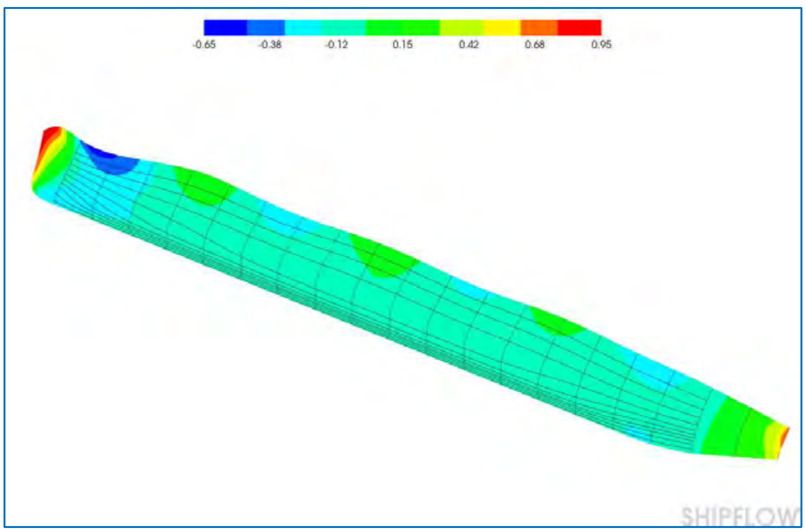

Figure. 4.9: Pressure distribution and streamlines of MV Madina-5 (Improved Hull)

The change in resistances coefficients are presented in Table 4.21 below:

Table 4.21: Comparison between parent and improved hull of MV Madina-5

	Parent Design	**Improved Design**	**Change (%)**
Frictional Resistance Coeff., C_F	0.001592	0.001653	3.83%
Wave Resistance Coeff., C_W	0.001474	0.000972	-34.06%
Viscous pres. resist. Coeff., C_{PV}	0.0005366	0.0005109	-4.79%
Viscous resist. Coeff., C_V	0.002129	0.002163	1.60%
Total Resistance Coeff., C_T	0.003603	0.003135	-13.00%

As explained in Section 4.2.4 and Table 4.15, the frictional resistance coefficient increased because of the increase in length. However, increasing the L_{WL}/B ratio and lowering block coefficient has made the improved ship slender and fine. This has reduced the wave-making resistance to a great extent. The viscous pressure resistance coefficient has also reduced because of this change, but the viscous resistance coefficient has been increased, mainly because of the increase in length. Overall, the improved design has 13% less resistance than the parent design.

The total resistance coefficient of the improved hull of MV Madina-5 was obtained from CFD software (Ship flow). Related values of propulsion part were obtained from Holtrop-Mennen (1982) method and thus required engine power is found. The detailed calculation has been presented in Appendix I.

Table 3.1, 3.2 and 3.3 of Section 3.3.1 present the measured fuel consumption data of 15 ships. The fuel consumption was measured in liter per hour and converted to a gram per kilowatt-hour (SFC). The average of measured SFC for each category was used for the vessels that had undergone CFD analysis. The required fuel consumption of the improved design has also been presented in Appendix I. To check the CO_2 emission as well as the fuel consumption, Table 4.22 has been presented below.

Table 4.22: Comparisons of $EEDI_{BD}$ and fuel consumptions of MV Madina-5

	Parent hull	Improved hull	Improvement (%)
$EEDI_{BD}$ baseline value (gm-CO_2/tonne-mile)	23.55	23.55	-
Attained $EEDI_{BD}$ (gm-CO_2/tonne-mile)	16.97	14.24	16.10%
Fuel Consumption (Liter/hour)	142.10	127.73	10.11%

Improved design, focusing on the reduction of $EEDI_{BD}$ value must satisfy the stability criteria. For this reason, the improved design's stability has been tested. To do that, commercial software 'Hydromax' (Stability module of the ship design software 'Maxsurf') was used. Table 4.23 shows the gist of the stability results for the improved design of MV Madina-5. Details of stability calculation are presented in Appendix-J.

Table 4.23: Stability for improved design of MV Madina-5

Code	Criteria	Limit Value	Units	Full Load Departure Condition	Full Load Arrival Condition	Ballast Departure Condition	Ballast Arrival Condition	Remarks
A.749(18) Ch3 - Design criteria applicable to all ships	3.1.2.1: Area 0 to 30	3.1513	m.deg	11.3868	11.6678	23.0131	23.3438	Criteria satisfied
A.749(18) Ch3 - Design criteria applicable to all ships	3.1.2.1: Area 0 to 40	5.1566	m.deg	17.1978	17.6553	36.2645	36.7456	Criteria satisfied
A.749(18) Ch3 - Design criteria applicable to all ships	3.1.2.1: Area 30 to 40	1.7189	m.deg	5.8110	5.9875	13.2514	13.4018	Criteria satisfied
A.749(18) Ch3 - Design criteria applicable to all ships	3.1.2.2: Max GZ at 30 or greater	0.200	m	0.581	0.600	1.337	1.354	Criteria satisfied
A.749(18) Ch3 - Design criteria applicable to all ships	3.1.2.3: Angle of maximum GZ	25.0	deg	30.0	45.0	45.0	45.0	Criteria satisfied
A.749(18) Ch3 - Design criteria applicable to all ships	3.1.2.4: Initial GMt	0.150	m	2.203	2.208	3.517	3.578	Criteria satisfied

The improved cargo ship based on the ship design suggestion seems to reduce $EEDI_{BD}$ and fuel consumption by 16.10% and 10.11% respectively (Table 4.22). In addition to that, the improved design meets the stability criteria (Table 4.23). Hence the design propositions made in this research are validated and justified.

4.3.3 Implementing design suggestions on MT. Saima-1 (Oil Tanker)

Similar to the process described in Section 4.3.2, investigated oil tanker, 'MT Saima-1' has been redesigned. The change made to improve the design of 'MT Saima-1' from the parent design is presented in Table 4.24.

Table 4.24: Comparison between parent and improved design of MT. Saima-1

Design Particulars	**Parent Design**	**Improved Design**	**Change (%)**	**Efficient Ranges (From design suggestion)**
Water line length, L_{WL} (meter)	59.6	69.94	14.78%	-
Moulded Breadth, B (meter)	10.67	11	3.00%	-
L_{WL}/B	5.58	6.36	12.26%	5.33-6.73
Loaded Draft, T(meter)	3.2	3.35	4.48%	-
B/T	3.33	3.28	-1.52%	2.38-3.28
Block Coefficient, C_B	0.76	0.6	-26.67%	Lowest possible C_B that meets capacity and stability requirements
Propeller Diameter, D (meter)	1.525	1.525	0%	-
Displacement (Tonne)	1546	1546	0.00%	-
Deadweight (Tonne)	1100	1100	0.00%	-
Speed (Knot)	10	10	0.00%	8.00-11.00
Froude Number, F_N	0.213	0.196	-8.67%	0.16-0.21

Figures 4.10 and 4.11 shows the free surface wave, Figures 4.12 and 4.13 shows the wave height along the hull, and Figures 4.14 and 4.15 show the pressure coefficient distribution for parent and improved hull, respectively. Details of the CFD software output is presented in Appendix H.

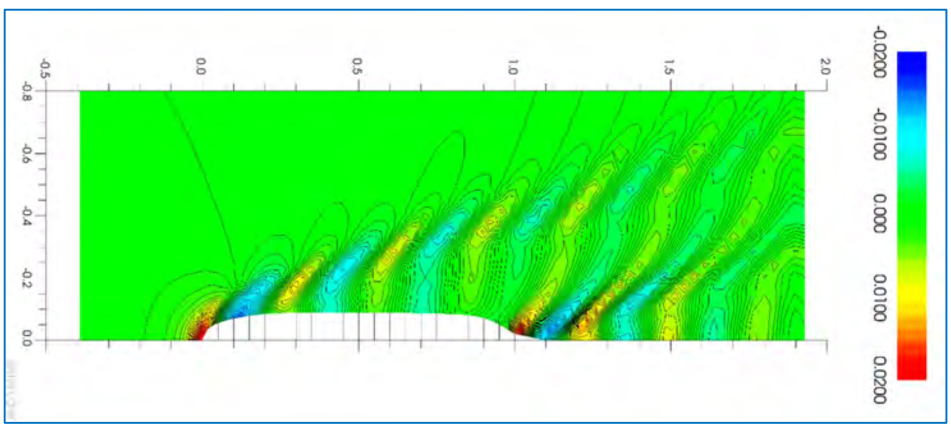

Figure 4.10: Free surface wave of MT Saima-1 (Parent Hull)

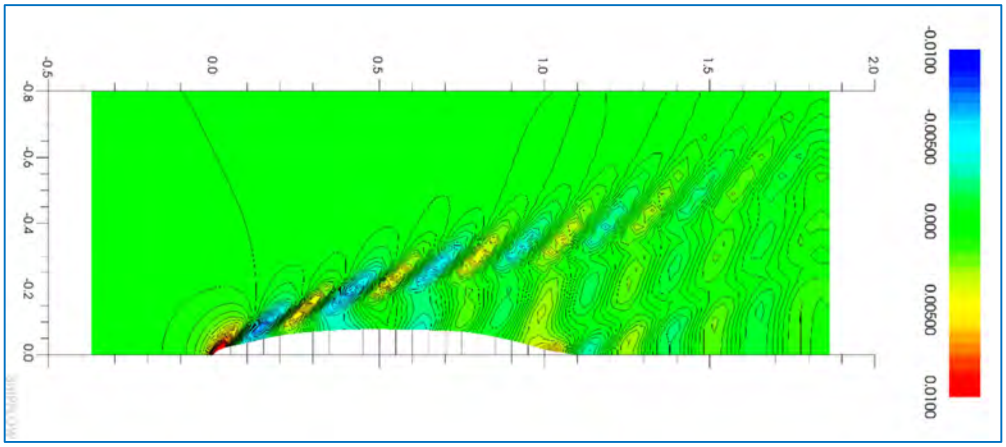

Figure 4.11: Free surface wave of MT Saima-1 (Improved Hull)

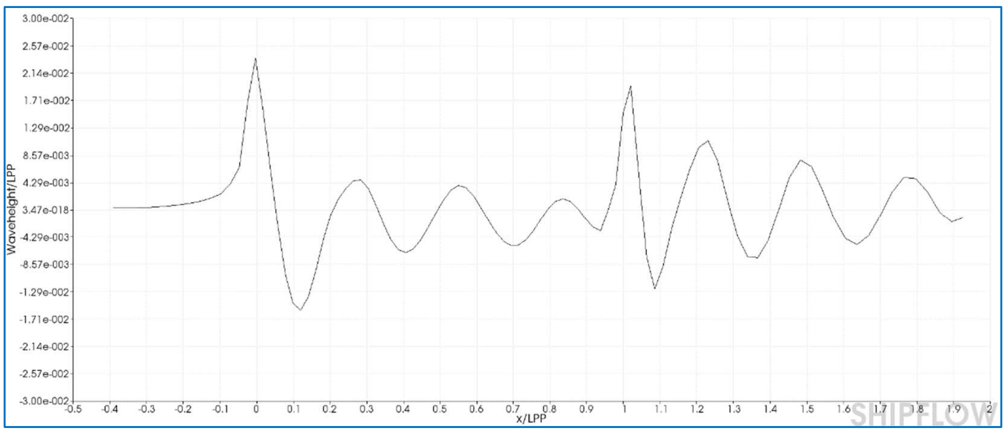

Figure. 4.12: Wave height along the hull of MT Saima-1 (Parent hull)

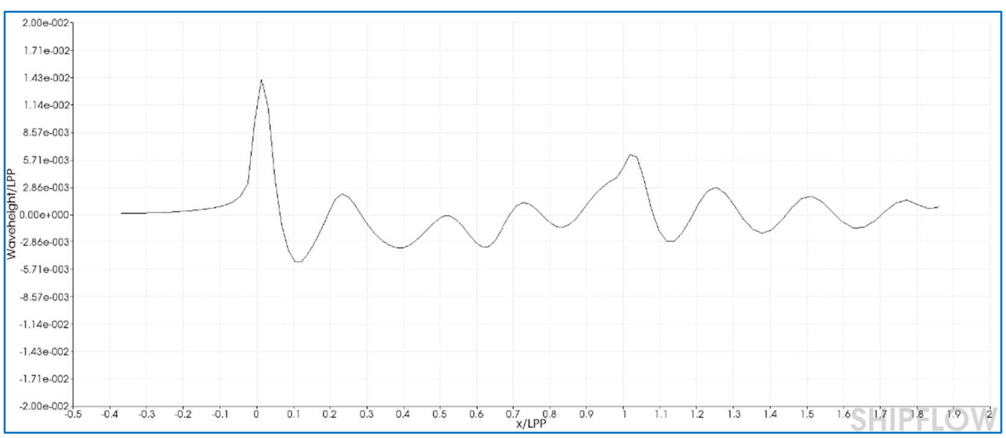

Figure. 4.13: Wave height along the hull of MT Saima-1 (Improved Hull)

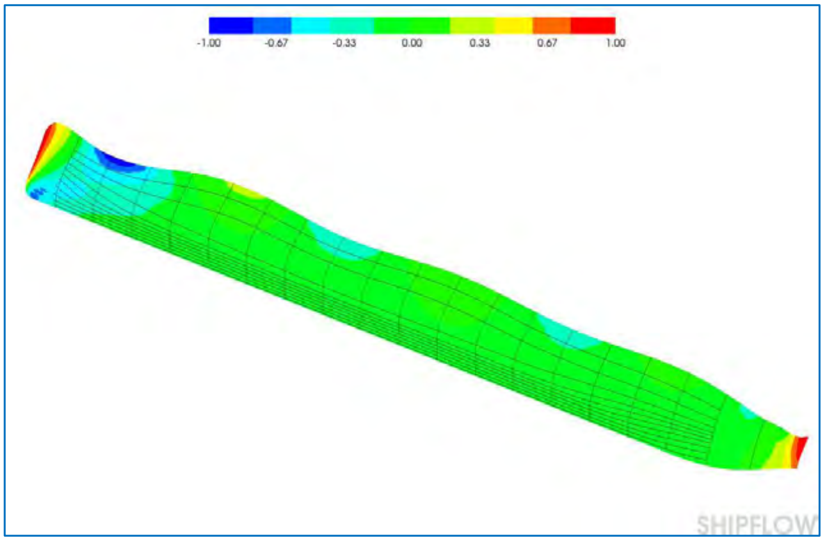

Figure. 4.14: Pressure distribution and streamlines of MT Saima-1 (Parent Hull)

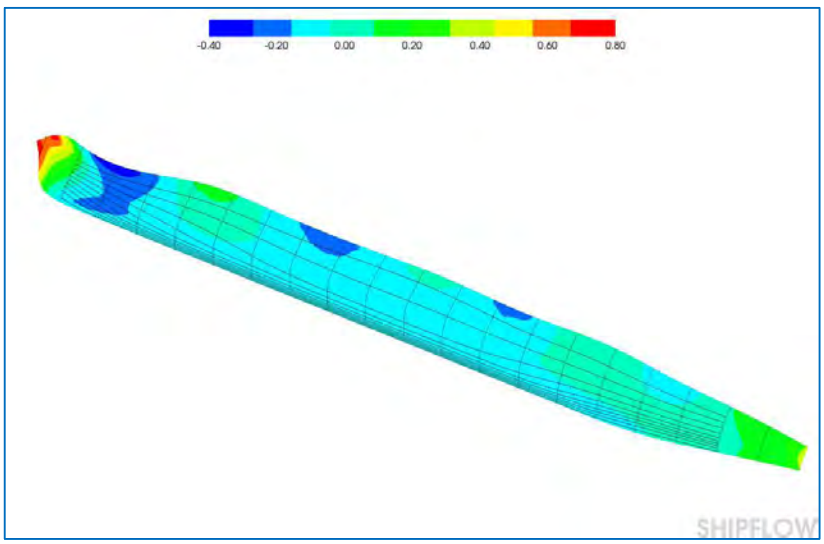

Figure. 4.15: Pressure distribution and streamlines of MT Saima-1 (Improved Hull)

The change in resistances coefficients is presented in Table 4.25 below:

Table 4.25: Comparison between parent and improved hull of MT Saima-1

Design Particulars	Parent Design	Improved Design	Change (%)
Frictional Resistance Coeff., C_F	0.001604	0.001676	4.49%
Wave Resistance Coeff., C_W	0.001492	0.000912	-38.87%
Viscous pres. resist. Coeff., C_{PV}	0.00042	0.000591	40.84%
Viscous resist. Coeff., C_V	0.002023	0.002267	12.06%
Total Resistance Coeff., C_T	0.003515	0.003163	-10.00%

For the case of ‘MT Samia-1’, the frictional resistance coefficient increased because of the increase in length. However, increasing the L_{WL}/B ratio and lowering block coefficient has made the improved ship slender and fine. This has reduced the wave-making resistance to a great extent. The viscous pressure resistance coefficient and viscous resistance coefficient has been increased, mainly because of the increase in length. Overall, the improved design has 10% less resistance than the parent design.

Similar to M.V. Madina-5, the total resistance coefficient of the improved hull of MT Saima-1 was obtained from CFD software (Ship flow). Related values of propulsion part were obtained from Holtrop-Mennen method and thus required engine power is found. To check the CO_2 emission as well as the fuel consumption, Table 4.26 has been presented below. The detailed calculation has been presented in Appendix I.

Table 4.26: Comparisons of $EEDI_{BD}$ and fuel consumptions of MT. Saima-1

	Parent hull	**Improved hull**	**Improvement (%)**
$EEDI_{BD}$ baseline value (gm-CO_2/tonne-mile)	36.19	36.19	-
Attained $EEDI_{BD}$ (gm-CO_2/tonne-mile)	29.803	19.40	34.91%
Fuel Consumption (Liter/hour)	130.70	91.15	30.26%

Improved design for MT Saima-1 has also gone under the stability check. Table 4.27 shows the gist of the stability results for the improved design of MT. Saima-1. Details of stability calculation are presented in Appendix-J.

The improved oil tanker based on the ship design suggestion seems to reduce $EEDI_{BD}$ and fuel consumption by 34.91% and 30.26% respectively (Table 4.26). In addition to that, the improved design meets the stability criteria as well (Table 4.27). Hence the design propositions made in this research are validated and justified.

Table 4.27: Large Angle Stability for improved design of MT. Saima-1

Code	Criteria	Value	Units	Full Load Departure Condition	Full Load Arrival Condition	Ballast Departure Condition	Ballast Arrival Condition	Remarks
A.749(18) Ch3 - Design criteria applicable to all ships	3.1.2.1: Area 0 to 30	3.1513	m.deg	11.1295	11.3776	24.1632	24.4268	Criteria satisfied
A.749(18) Ch3 - Design criteria applicable to all ships	3.1.2.1: Area 0 to 40	5.1566	m.deg	16.2996	16.7185	36.9038	37.3018	Criteria satisfied
A.749(18) Ch3 - Design criteria applicable to all ships	3.1.2.1: Area 30 to 40	1.7189	m.deg	5.1701	5.3409	12.7406	12.8750	Criteria satisfied
A.749(18) Ch3 - Design criteria applicable to all ships	3.1.2.2: Max GZ at 30 or greater	0.200	m	0.550	0.566	1.330	1.339	Criteria satisfied
A.749(18) Ch3 - Design criteria applicable to all ships	3.1.2.3: Angle of maximum GZ	25.0	deg	30.0	30.0	30.0	30.0	Criteria satisfied
A.749(18) Ch3 - Design criteria applicable to all ships	3.1.2.4: Initial GMt	0.150	m	2.003	2.009	3.985	4.048	Criteria satisfied

4.3.4 Implementing design MV Takwa-1 (Passenger Ship)

As per the suggestion provided in Tables 4.15 and 4.18, investigated passenger ship ‘MV Takwa-1’ has been redesigned. The change made to improve the design of ‘MV Takwa-1’ from the parent design is presented in Table 4.28.

Table 4.28: Comparison between parent and improved design of MV Takwa-1

Design Particulars	Parent Design	Improved Design	Change (%)	Efficient Ranges (From design suggestion)
Waterline length, L_{WL} (meter)	57.05	60.9	8.68%	-
Moulded Breadth, B (meter)	9.76	9.54	-2.25%	-
L_{WL}/B	5.84	6.5	11.30%	5.01-6.39
Loaded Draft, T(meter)	1.6	1.68	5.00%	-
B/T	6.1	5.68	-6.89%	3.39-8.47
Block Coefficient, C_B	0.67	0.611	-10.45%	Lowest possible C_B that meets capacity and stability requirements
Propller Diameter, D (meter)	1.525	1.525	0%	-
Displacement (Tonne)	597	597	0.00%	-
Gross Tonnage	733	733	0.00%	-
Speed (Knot)	11.5	11.5	0.00%	10.00-14.00
Froude Number, F_N	0.25	0.24	-4.00%	0.21-0.27

The resistance of both parent and the improved ship has been analysed by CFD software. Figures 4.16 and 4.17 shows the free surface wave, Figures 4.18 and 4.19 show the wave height along the hull and Figures 4.20 and 4.21 show the pressure coefficient distribution for parent and improved hull, respectively. Details of the CFD software output is presented in Appendix H.

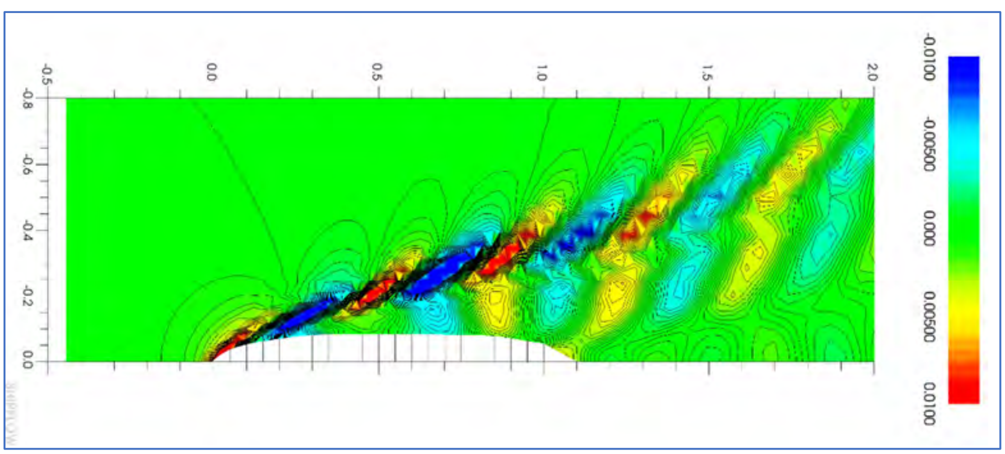

Figure 4.16: Free surface wave of MV Takwa-1 (Parent Hull)

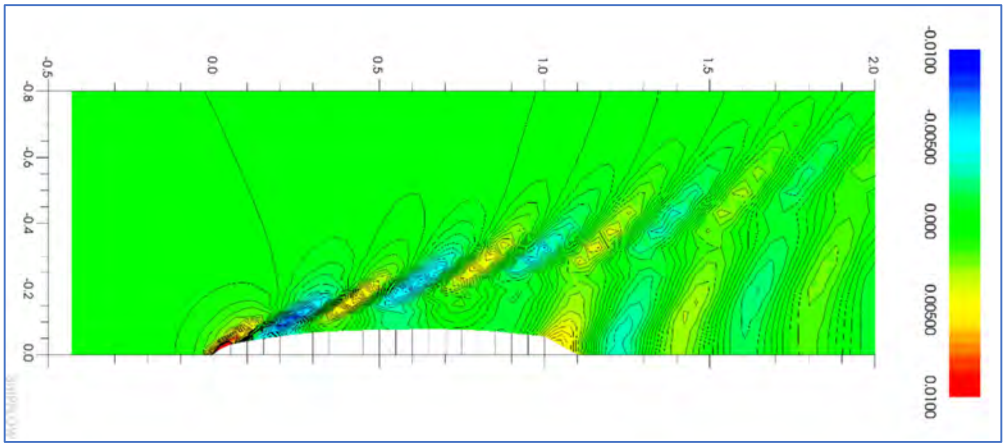

Figure 4.17: Free surface wave of MV Takwa-1 (Improved Hull)

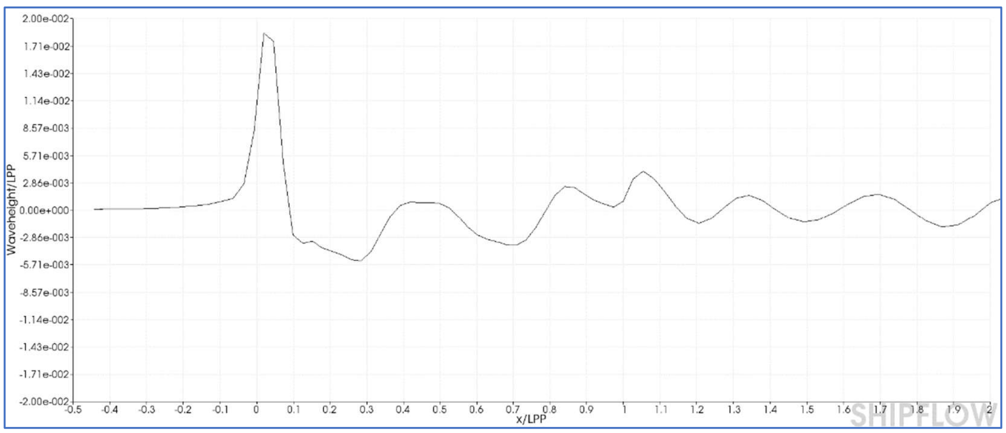

Figure. 4.18: Wave height along the hull of MV Takwa-1 (Parent hull)

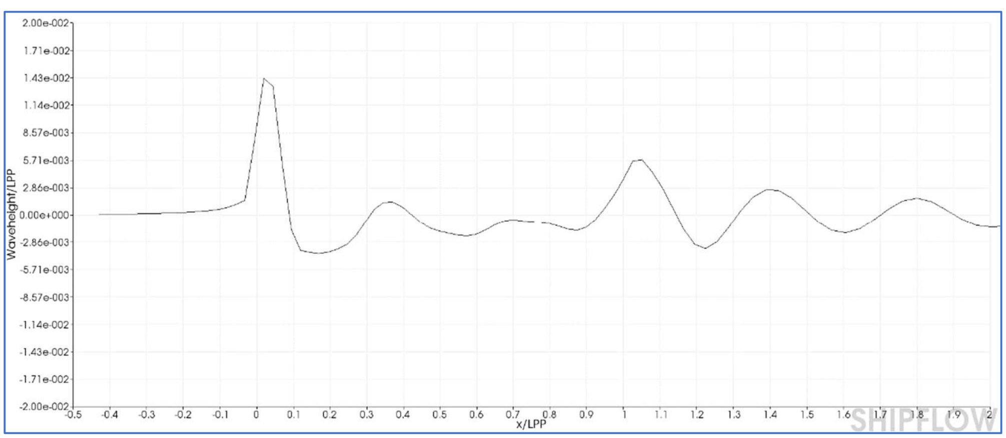

Figure. 4.19: Wave height along the hull of MV Takwa-1 (Improved Hull)

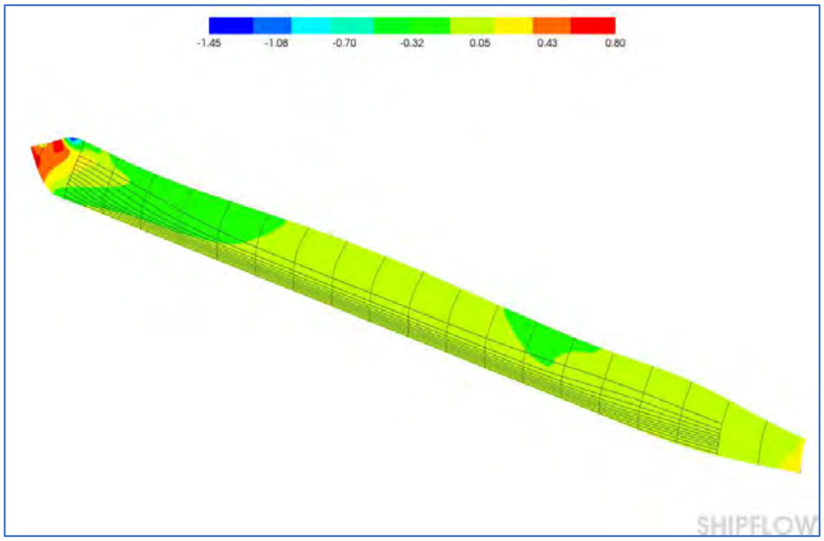

Figure. 4.20: Pressure distribution and streamlines of MV Takwa-1 (Parent Hull)

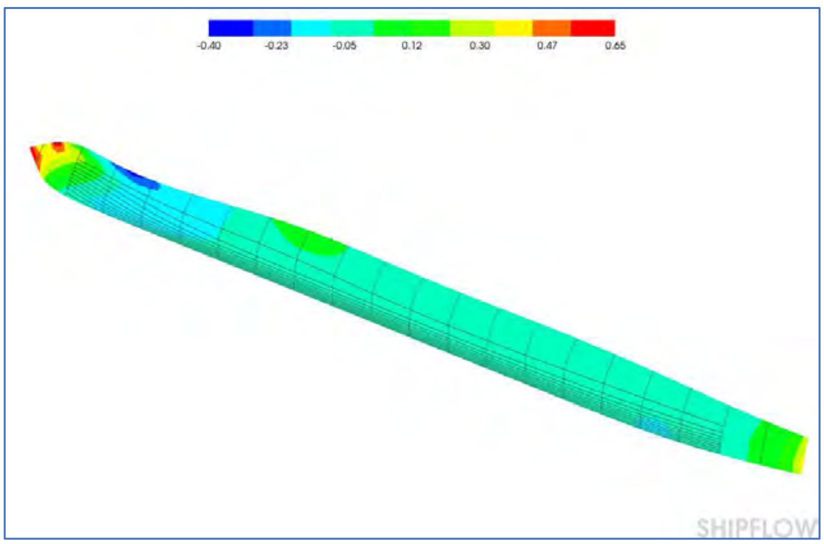

Figure. 4.21: Pressure distribution and streamlines of MV Takwa-1 (Improved Hull)

The change in resistance coefficients is presented in Table 4.29 below:

Table 4.29: Comparison between parent and improved hull of MV. Takwa-1

	Parent Design	**Improved Design**	**Change (%)**
Frictional Resistance Coeff., C_F	0.001693	0.001717	1.42%
Wave Resistance Coeff., C_W	0.001483	0.001064	-28.25%
Viscous pres. resist. Coeff., C_{PV}	0.0002003	0.0001319	-34.15%
Viscous resist. Coeff., C_V	0.001893	0.001853	-2.11%
Total Resistance Coeff., C_T	0.003376	0.002917	-13.60%

As explained in Section 4.4.4 and Table 4.15, the frictional resistance coefficient increased because of the increase in length. However, increasing the L_{WL}/B ratio and lowering block coefficient has made the improved ship slender and fine. This has reduced the wave-making resistance to a great extent. Viscous pressure resistance coefficient and viscous resistance coefficient were reduced as well because of the change. Overall, the improved design has 13.89% less resistance than the parent design.

Similar to M.V. Madina-5 and M.T. Saima-1, the total resistance coefficient of the improved hull of M.V. Takwa-1 was obtained from CFD software (Ship flow). Related values of propulsion part were obtained from Holtrop-Mennen method and thus required engine power is found. To check the CO_2 emission as well as the fuel consumption, Table 4.30 has been presented below. The detailed calculation has presented in Appendix I.

Table 4.30: Comparisons of $EEDI_{BD}$ and fuel consumptions of MV. Takwa-1

	Parent hull	Improved hull	Improvement (%)
$EEDI_{BD}$ baseline value (gm-CO_2/tonne-mile)	49.29	49.29	-
Attained $EEDI_{BD}$ (gm-CO_2/tonne-mile)	27.87	20.96	24.79%
Fuel Consumption (Liter/hour)	107.026	75.48	29.48%

Improved design for MV. Takwa-1 has also gone under the stability check. Following Table 4.31 shows the gist of the stability results for the improved design of MV Takwa-1. Details of stability calculation are presented in Appendix-J.

The improved passenger ship based on the ship design suggestion will reduce $EEDI_{BD}$ and fuel consumption by 24.79% and 29.48% respectively (Table 4.30). In addition to that, the improved design meets the stability criteria as well (Table 4.31). Hence the design propositions made in this research are validated and justified.

Table 4.31: Large Angle Stability for improved design of MV Takwa-1

Code	Criteria	Value	Units	Full Load Departure Condition	Full Load Arrival Condition	Ballast Departure Condition	Ballast Arrival Condition	Remarks
A.749(18) Ch3 - Design criteria applicable to all ships	3.1.2.1: Area 0 to 30	3.1513	m.deg	20.3475	20.9374	20.2956	20.9608	Criteria satisfied
A.749(18) Ch3 - Design criteria applicable to all ships	3.1.2.1: Area 0 to 40	5.1566	m.deg	30.5355	31.6919	29.9681	31.2594	Criteria satisfied
A.749(18) Ch3 - Design criteria applicable to all ships	3.1.2.1: Area 30 to 40	1.7189	m.deg	10.1880	10.7545	9.6725	10.2986	Criteria satisfied
A.749(18) Ch3 - Design criteria applicable to all ships	3.1.2.2: Max GZ at 30 or greater	0.200	m	1.116	1.169	1.079	1.138	Criteria satisfied
A.749(18) Ch3 - Design criteria applicable to all ships	3.1.2.3: Angle of maximum GZ	25.0	deg	30.0	30.0	30.0	30.0	Criteria satisfied
A.749(18) Ch3 - Design criteria applicable to all ships	3.1.2.4: Initial GMt	0.150	m	3.118	3.211	3.193	3.288	Criteria satisfied
A.749(18) Ch3 - Design criteria applicable to all ships	3.1.2.5: Passenger crowding: angle of equilibrium	10.0	deg	0.0	0.0	0.0	0.0	Criteria satisfied
A.749(18) Ch3 - Design criteria applicable to all ships	3.1.2.6: Turn: angle of equilibrium	10.0	deg	0.0	0.0	0.0	0.0	Criteria satisfied

CHAPTER 5

CONCLUSIONS AND FUTURE WORKS

5.1 Concluding Remarks

Before any attempt of design improvement based on fuel consumption and CO_2 emission, it is necessary to know where those ships stand now. Since EEDI by IMO quantifies the CO_2 emission per tonne mile for seagoing ships, the establishment of EEDI baselines for inland ships of Bangladesh (Termed as $EEDI_{BD}$) is necessary. After screening and verifying 2,247 ship data, incorporating shallow water effect and evaluating the carbon content of fuel used in the maritime sector of Bangladesh, $EEDI_{BD}$ baselines have been established for inland general cargo, oil tanker and passenger ships of Bangladesh. In the process of this establishment, EEDI formulation by IMO has been modified and made useful for inland ships of Bangladesh.

Hydrodynamic improvement of a ship can be done in different ways; however, this research focuses on the hydrodynamic improvement of the design based on fuel consumption and CO_2 emission. Since $EEDI_{BD}$ informs us of the benefit to the society (by carrying cargo) at the cost of the environment (as they emit CO_2 to the environment by burning fossil fuel), dependency of $EEDI_{BD}$ on ship design particulars was identified by sensitivity analysis. The outcome of the sensitivity analysis is a set of ship design suggestions that will reduce the value of $EEDI_{BD}$.

Those ship design suggestions had been implemented on an existing inland general cargo, oil tanker and passenger ships of Bangladesh. Existing ships' hull lines were prepared after physical investigation and measurement. These ships' designs were improved based on the ship design suggestions. Both the parent and improved ships' resistances have been computed by CFD software.

The result of CFD analysis has shown 13%, 10% and 13.60% improvement in ship resistance for investigated inland cargo, oil tanker and passenger ships respectively. Since the effective power of a ship is a product of total ship resistance and speed, more than

10% of fuel consumption can be reduced by the improved ship based on the design suggestion provided.

In this research, the improvement of designs was presented as a comparison with existing vessels. For fare comparison, deadweight, speed and DWT/Displacement were kept the same for both the parent and the improved vessel. Only the most important details were changed as a result of the sensitivity study. Simple adjustments to those primary characteristics enhanced the vessel's hydrodynamic performance, lowering the overall resistance coefficient. More reduction of $EEDI_{BD}$ is possible with the improved hull form, propeller design and other improved efficiency enhancement measures.

Another crucial consideration is the economic impact on each country. It is a fact that the total CO_2 emissions from inland shipping account for a very small portion of global CO_2 emissions. However, from the perspective of a single country, the economic impact is significant. Since this research has proved that it is possible to reduce CO_2 emissions by more than 10% concerning their current rate in Bangladesh, a large quantity of fuel can be saved per trip. This will have a market impact as well because any decrease in carrying costs will result in a fall in commodity prices. The implementation of this law will not increase the ship's building costs, but it will significantly reduce operations costs, in addition to the immediate environmental advantages.

5.2 Future works and recommendations

This research work mainly focused on the possible design modification of inland ships of Bangladesh based on fuel consumption and emission control. To do so, the prime effort was provided to achieve the research objective, which includes the existing EEDI formulation modification, establishment of $EEDI_{BD}$ baselines for Bangladesh and providing suggestions to design inland ships of Bangladesh through sensitivity analysis. One research opens a new research window and this research feels that following future works are necessary for total understanding of the problem and solutions.

5.2.1 Economic analysis

Energy consumption defines countries economic growth and development. An increase in energy consumption clearly will mean the progressive growth of a country's economy, however, economic growth will boost with the efficient handling of energy and power. Every sector that consumes energy and plays a role in the economy of the country, should maintain its progressive growth, as well as use power more efficiently. For example, digitalization and automation save millions of man-hours and money for a country. Therefore, implementing energy-saving measures in any industry or sector will help the economy of any country. Improved energy efficiency at the national level means fewer energy imports. This will not only lower the foreign exchange pressures but also improve the availability of scarce energy resources for others to use.

5.2.2 Practical implementation of suggestion

A hypothesis becomes a theory after being proven by an experiment. The ship design suggestion provided in this research should be implemented practically to check the accuracy and reliability of the provided suggestion. This can be done in 2 ways. First, a full-scale ship at the desired capacity and speed of the owner can be designed and constructed based on the design suggestion. After the trial, the design suggestion can be compared with another typically designed ship. Second, a model test in a towing tank can be done for 2 ships having the same capacity and speed. One of them shall be designed based on the design suggestion and the other shall be a conventionally designed ship. A comparison of these two ships will justify the validity of the design suggestion.

5.2.3 Implementation of other improved efficiency enhancement measures

This research only focused on the ship's main hull design modification to improve the EEDI value by reducing total resistance. There are many other energy-efficient measures available that can be implemented to inland ships of Bangladesh. Some measures may cost and some of them may cost less or nothing. This study has not been done in this research. Therefore, implementation of all available energy enhancement measures to inland ships and quantifying the social benefit would be important future work. This will define the following two issues:

a. What would be the maximum amount of CO_2 that can be removed from inland ships of Bangladesh.
b. The cost-effectiveness of other measures' implementation.

5.2.4 Implementation of Life Cycle Assessment (LCA)

Life cycle assessment of a ship concerning the EEDI will be able to assess the actual influence of energy-efficient measures on the CO_2 emission. A new ship with new Engine(s), Genset(s) and other equipment(s) will not be able to maintain the same efficiency level as time goes on. Refit docking, painting and repairing will increase the efficiency, but it will not be as good as the new ship. Since EEDI is calculated for new ships, the effectiveness of energy-efficient measures on the ship shall be evaluated for the lifespan of the ship. In addition to that, the EEDI value may be changed as the older ship speed may decrease at the same MCR of the engine. The true success of the implementation of EEDI for new ships and energy-efficient measures to improve EEDI depends upon the life cycle analysis. Therefore, a Life Cycle Assessment (LCA) of the ship concerning EEDI would be a very important analysis.

5.2.5 Restricted channel effects for future consideration

As mentioned in Chapter 2 under Section 2.2.9 the effect of the width of narrow riverbanks on ship resistance has not been considered. The assumption is seemed fairly all right and explained in the same Section. However, for future research, these effects can be taken into consideration to justify the assumption.

In this research, 15 vessels' speeds have been measured on board. However, the water depth could not be measured physically. For this reason, river depth data from different government organizations have been taken into consideration. The river depth data were correct, however, the number of water depth data, were not sufficient. More data is required to finalize the average effect of shallow water on ship resistance.

The water depth of a certain route is not uniform. For this reason, the effect of shallow water will not be uniform as well. This research relies on the river water depth data at certain points only, which are measured daily by different government organizations of Bangladesh. In addition to that, the measured highest speed in each case has been considered as the achieved speed without any effect of shallow water, because in these routes there may be certain regions where the depth of water may be quite high than the measured depth at different locations. Therefore, in this research, the average speed as measured in a certain route has been considered as the gained speed after overcoming the average effect of shallow water.

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1 message

Mon, Aug 28, 2017 at 4:45 PM

Dear Hasan,

I am glad that you are interested in this promising topic - the energy efficiency of inland waterway vessels. Nowadays, these ships are neglected compared to various types of marine vessels. However, for economies of some countries, inland waterway ships are highly important. Therefore I would like to encourage you to continue with your work.

Of course that you can use any figure from my paper in your thesis, but please specify the source in the reference list. In the attachment, you can find clear figure 20.

By the way, I would like to suggest to you to check the following paper (see the attachment), that was presented at the RINA conference in 2014. In this paper, you will find suggested EEDI reference curves, based on actual ship speed, for vessels navigating on the Danube and on the Rhine, which might be considered as the most significant European rivers.

If you need anything else please do not hesitate to ask.

Best regards,

Aleksandar

Dear Dr Aleksandar Simić,

Good Day.

https://mail.google.com/mail/u/0?ik=a89d2df9458&view=pt&search=all&permthid=thread-f%3A1576857543969825099%7Cmsg-f%3A1576871483688192225&sim 1/2

I am a Ph.D student at the Bangladesh University of Engineering and Technology and currently working on the establishment of EEDI reference lines for the inland ships of Bangladesh. In this regard, I found your paper 'On Energy Efficiency of Inland Waterway Self-Propelled Cargo Vessels' very valuable. I seek permission to use your published results as reference. Also, I want to use figure 20 of the paper in my thesis. If you have clear view of figure 20, send me please if you decide to permit to use that figure.

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Regards,

S.M. Rashidul Hasan

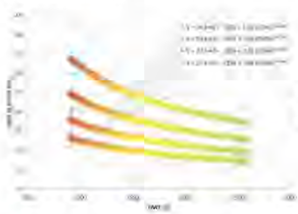
Ph.D Student (ID: 1014124001)

Bangladesh University of Engineering & Technology

Dhaka, Bangladesh.

---

2 attachments



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>>
>> Chelsea
>>
>> On Tue, Jun 30, 2020 at 5:33 AM Rashidul Hasan <rashed.navalarch@gmail.com> wrote:
>>
>>> Dear Qinxian (Chelsea),
>>>
>>> Hope you are fine and in good health.
>>>
>>> I am Rashidul Hasan, PhD Candidate from the Bangladesh University of Engineering & Technology, Bangladesh. I am a Naval Architect and a part of my research includes sensitivity analysis. In this regard, I have found your thesis (attached) and I would like to add some part of chapter 3 to my thesis, if you parmit. To be specific, theoretical text from the section 3.1 and 3.1.3.
>>>
>>> Therefore, you are kindly requested to allow us to use section 3.1 and 3.1.3 for your thesis as attached with this email. I assure you, the source of the text will be inserted in my thesis.
>>>
>>> Looking forward to your answer.
>>>
>>> With best regards
>>> S M Rashidul Hasan
>>> PhD Candidate
>>> Bangladesh University of Engineering & Technology

https://mail.google.com/mail/u/0?ik=a89d2df945&view=pt&search=all&permthid=thread-a%3Ar8373464969937119204%7Cmsg-f%3A1671019303877261130&si... 1/2

Appendix-B

Details of travelled route

The travelled route, distance and SFC curve of investigated 5 number Inland General Cargo Ships of Bangladesh

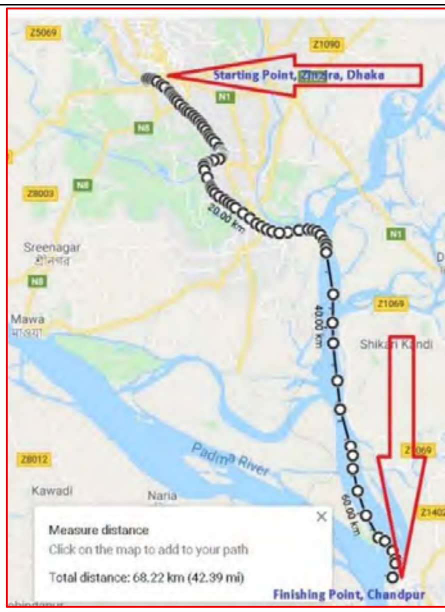

Figure B-1: Dhaka to Chandpur by G.C-1

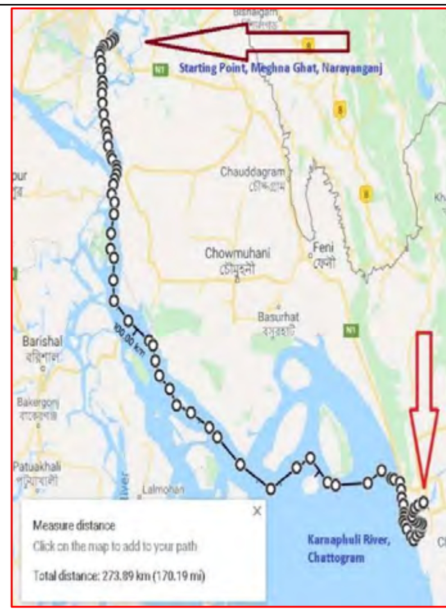

Figure B-2: Meghna Ghat to Chattogram by G.C-2 and G.C-5

Figure B-3: Rupshi, Narayanganj to Chattogram by G.C-2

Figure B-4: Fatullah, Narayanganj to Baghabari by G.C-4

The travelled route, distance and SFC curve of investigated 5 number Inland Oil Tankers of Bangladesh

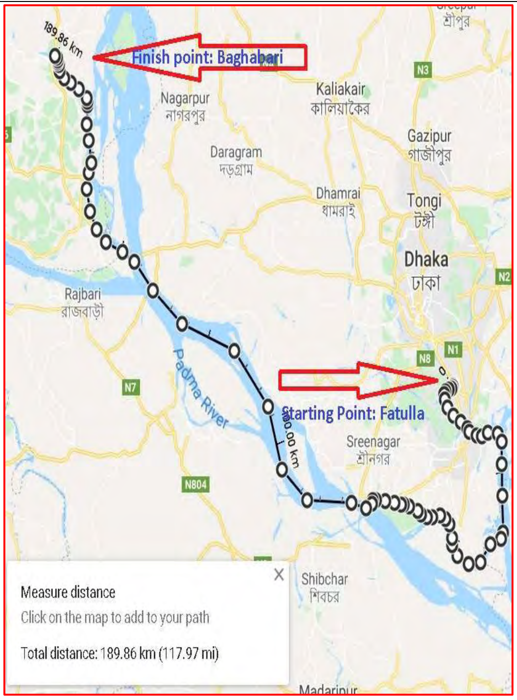

Figure B-5: Fatullah, Narayanganj to Baghabari by O.T-1

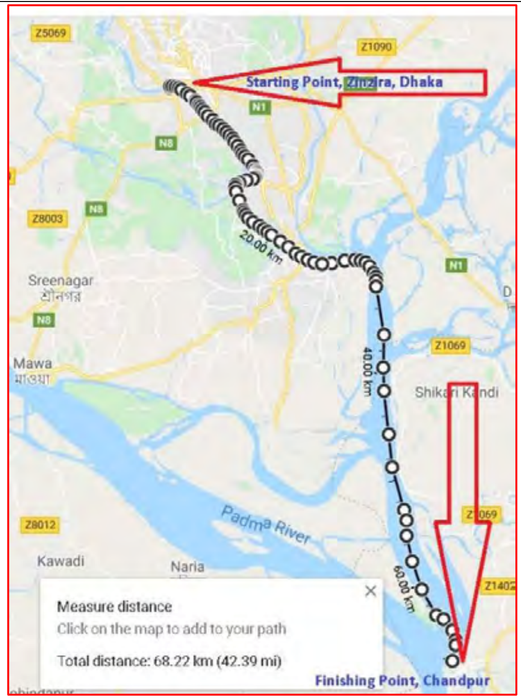

Figure B-6: Dhaka to Chandpur by O.T-2

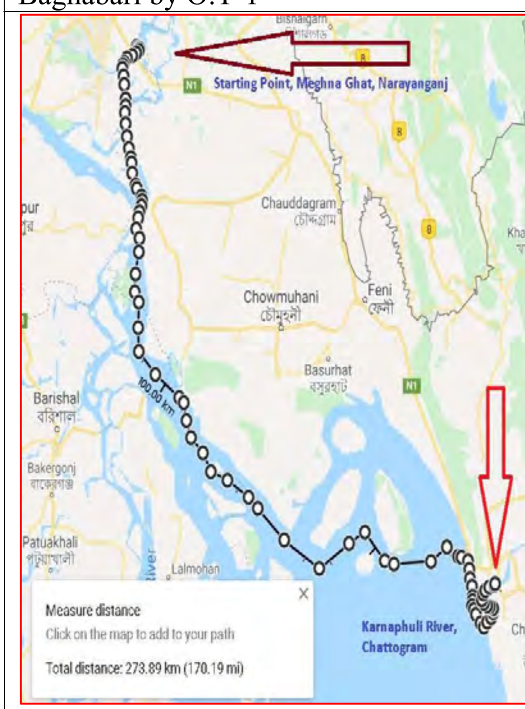

Figure B-7: Meghnaghat, Narayanganj to Chattogram by O.T 3

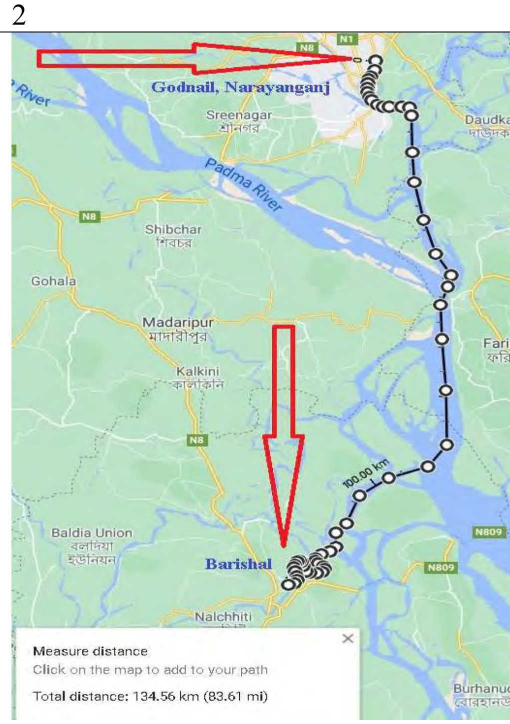

Figure B-8: Godnail, Narayanganj to Barishal by O.T.-4

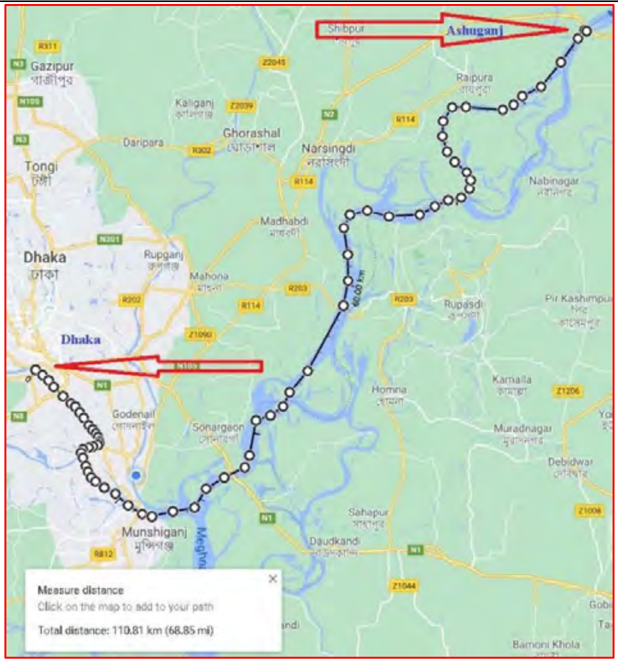

Figure B-9: Dhaka to Ashuganj by O.T.-5

The travelled route, distance and SFC curve of investigated 5 number Inland Passenger Ships of Bangladesh

Figure B-10: Dhaka to Sureshor, Shariatpur by PV-1

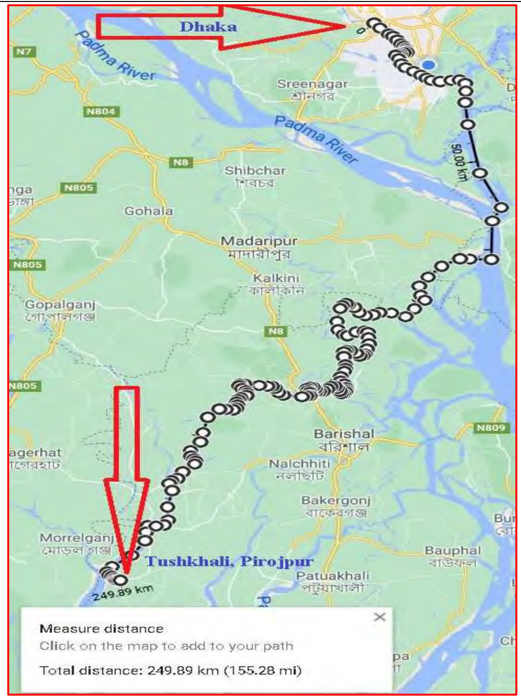

Figure B-11: Dhaka to Tushkhali, Pirojpur by P.V-2

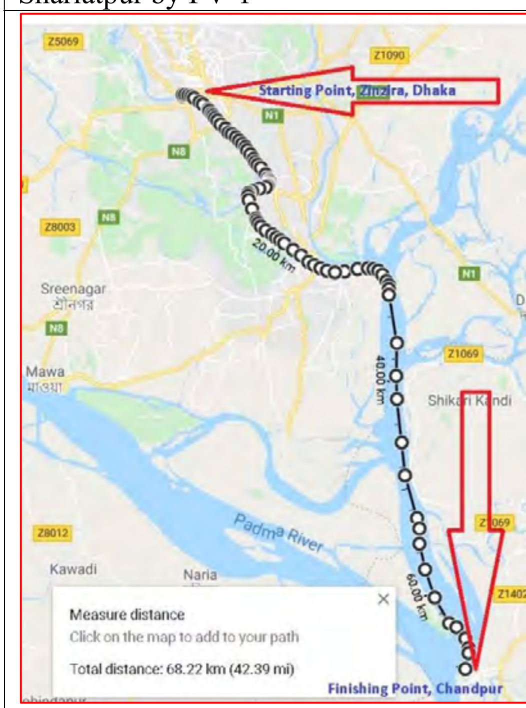

Figure B-12: Dhaka to Chandpur by P.V -3

Figure B-13: Dhaka to Patuakhali by P.V-4

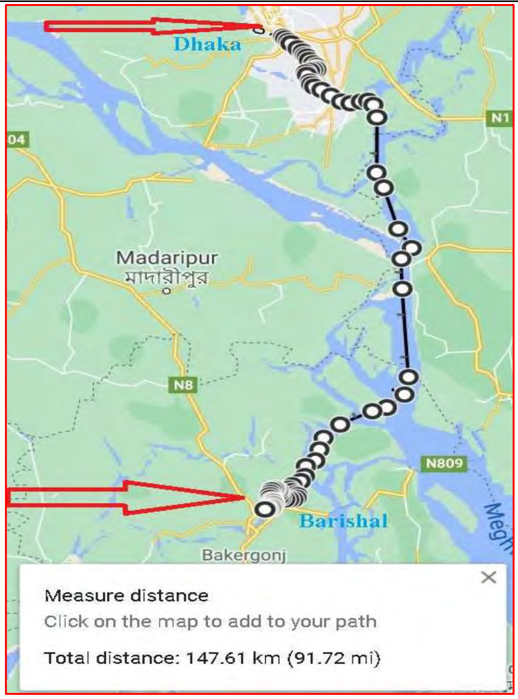

Figure B-14: Dhaka to Barishal by PV-5

Appendix-C
Calculation of shallow water effect

Speed loss calculation according to Lackenby (1963) method:
According to Lackenby (1963), reduced speed due to the shallow water effect is

$$\partial V = V(0.1242\left(\frac{A_M}{H^2} - 0.05\right) + 1 - \sqrt{\tanh\left(\frac{gH}{V^2}\right)})$$

Where,

V = Open water speed (m/s)
∂V = Reduced speed due to shallow water effect (m/s)
A_M = Midship Sectional Area under water (m^2)
= Midship Section coefficient (C_M) X Breadth (B) X Draft (T)
C_M = 0.977+0.085 (Block Coefficient-0.6)
H = Water depth (m)
g = Gravitational Force (m/s^2)

When,
V = 9.50 knot = 4.887 m/s
$A_M = C_M$ X B X T = 0.9872 X 7.95 X 2.55 = 20.01 m^2.
H = 3.88 meter
g = 9.81 m/s^2

$$\partial V = 4.887\left(0.1242\left(\frac{20.01}{3.88^2} - 0.05\right) + 1 - \sqrt{\tanh\left(\frac{9.81x3.88}{4.887^2}\right)}\right)$$

$$= 4.887\left(0.1242\left(\frac{20.01}{5^2} - 0.05\right) + 1 - \sqrt{\tanh(1.594)}\right)$$

$$= 0.972$$

Hence, ship speed will be reduced from 09.50 knots to (09.50x0.5144-0.972)/0.5144 = 7.61 knot. The shallow water effect on ship speed is 19.93%.

Dr C.B. Barras (2004) has quantified the effect of shallow water as a function of water depth (H)/Ship draft (T) ratio.

According to him, when
H/T = 1.1-1.15, % of loss in speed = 60-(25 x H/T)
H/T = 1.5-3.0, % of loss in speed = 36-(9XH/T)

Following Table C1, C2 and C3 present the effect of shallow water according to Lackenby (1963) and Barras (2004) method for the investigated ships based on the above sample calculation.

Table C.1: Shallow water effect of investigated general cargo ships by Lackenby (1963) and Barras (2004) method

Vessel ID	H (m)	B (m)	T (m)	C_M	$A_M = C_M$ X B X T	V (m/s)	∂V (m/s)	% of speed loss (Lackenby)	% of speed loss (Barras)
GC-1	3.88	7.95	2.55	0.98	20.01	4.89	0.97	19.93%	22.31%
GC-2	4.81	11.60	3.00	0.98	34.35	5.14	1.06	20.61%	21.57%
GC-3	4.09	10.98	3.00	0.97	32.18	5.40	1.59	29.47%	25.92%
GC-4	4.78	7.77	2.29	0.98	17.47	4.89	0.53	10.83%	17.21%
GC-5	4.97	13.00	4.00	0.99	51.47	5.40	1.55	28.73%	28.94%

Table C.2: Shallow water effect of investigated tankers by Lackenby (1963) and Barras (2004) method

Vessel ID	H (m)	B (m)	T (m)	C_M	$A_M = C_M$ X B X T	V (m/s)	∂V (m/s)	% of speed loss (Lackenby)	% of speed loss (Barras)
OT-1	4.02	10.68	1.80	0.98	19.03	4.89	0.86	17.62%	15.90%
OT-2	3.75	10.00	1.80	0.99	17.94	4.37	0.76	17.33%	17.25%
OT-3	4.93	12.50	4.00	0.99	49.62	5.40	1.53	28.30%	29.19%
OT-4	3.23	11.00	1.80	0.99	19.62	4.89	1.45	29.55%	19.85%
OT-5	3.50	10.00	2.00	0.99	19.83	4.37	0.97	22.20%	20.25%

Table C.3: Shallow water effect of investigated passenger ships by Lackenby (1963) and Barras (2004) method

Vessel ID	H (m)	B (m)	T (m)	C_M	$A_M = C_M$ X B X T	V (m/s)	∂V (m/s)	% of speed loss (Lackenby)	% of speed loss (Barras)
PV-1	3.38	8.75	1.62	0.98	13.91	5.92	1.69	28.56%	17.22%
PV-2	3.38	9.15	1.40	0.97	12.45	6.17	1.80	29.16%	14.27%
PV-3	4.14	10.98	1.70	0.98	18.40	6.94	2.07	29.83%	14.08%
PV-4	3.48	10.84	1.60	0.98	17.03	5.14	1.24	24.16%	16.43%
PV-5	3.96	13.57	1.80	0.99	24.25	6.43	2.11	32.85%	16.20%

Appendix-D
Investigated ship's main engine load and SFC

Cargo Ships

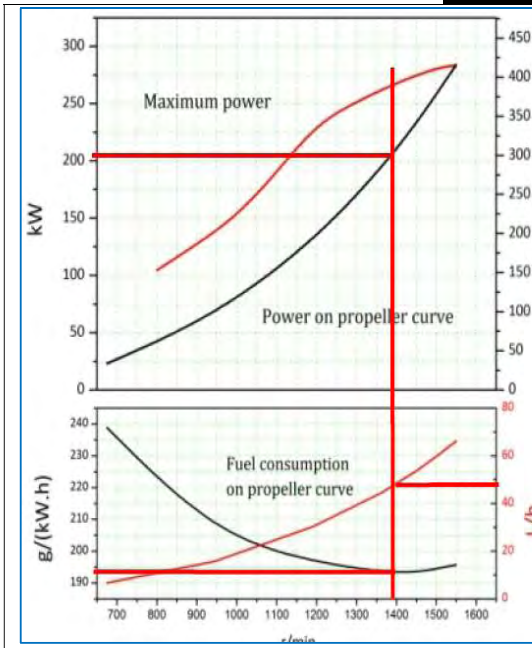

Figure D1: Fuel consumption of G.C-1, Weichei Engine, model: WP12C350-15

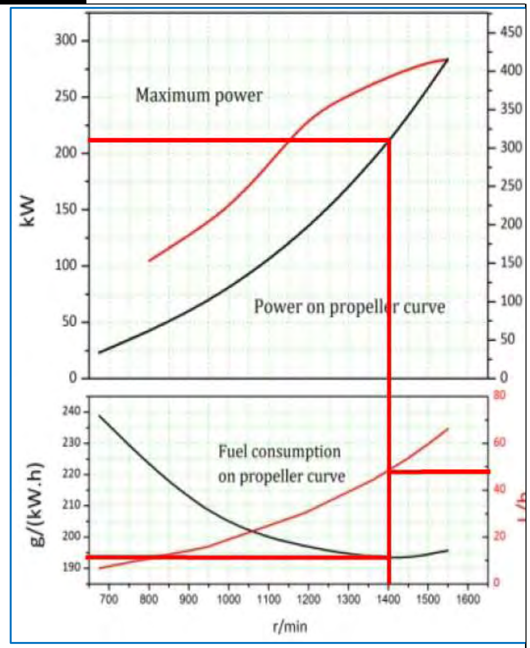

Figure D2: Fuel consumption of G.C-2, Weichei Engine, model: WP12C350-15

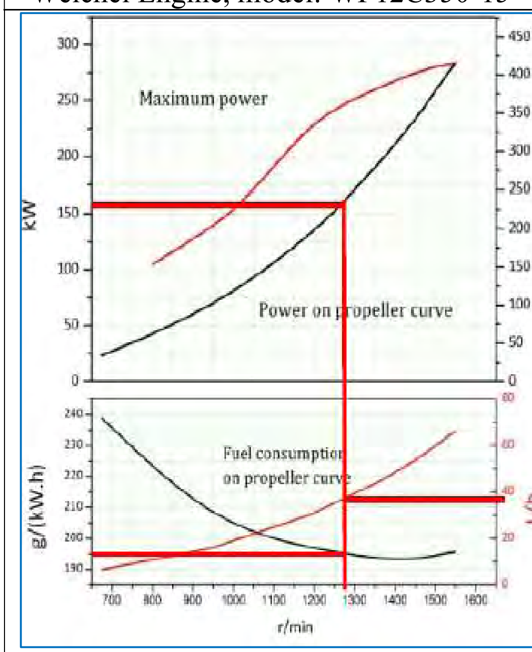

Figure D3: Fuel consumption of G.C-3, Weichei Engine, model: WP12C350-15

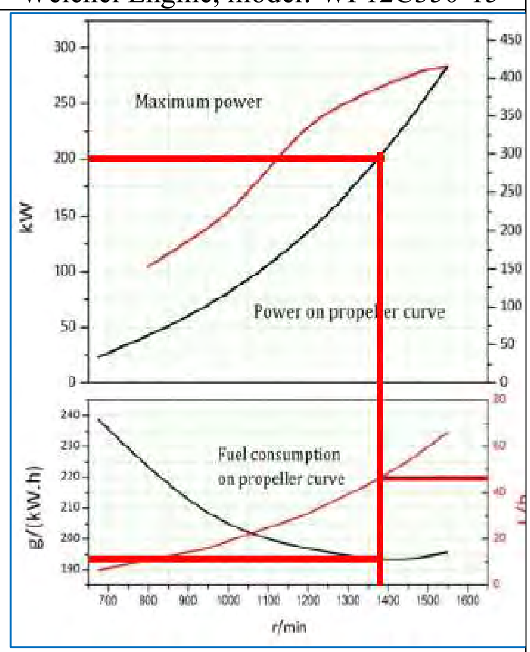

Figure D4: Fuel consumption of G.C-4, Weichei Engine, model: WP12C350-15

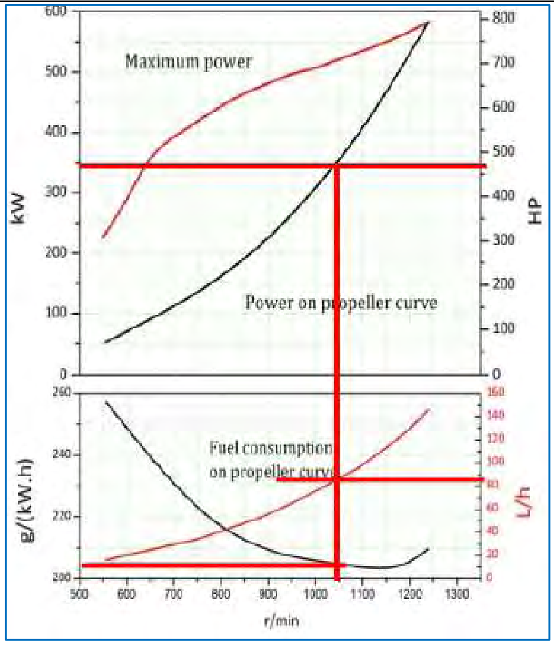

Figure D5: Fuel consumption of G.C-5, Weichei Engine, model: 8170ZC720-2

Oil Tankers

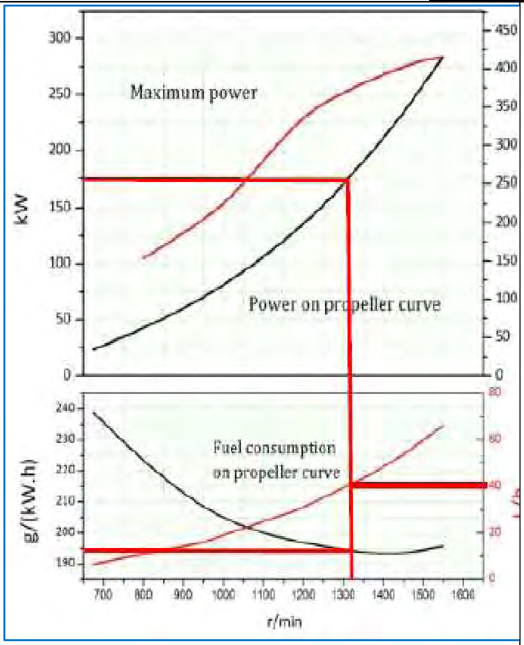

Figure D6: Fuel consumption of O.T-1, Weichei Engine, model: WP12C350-15

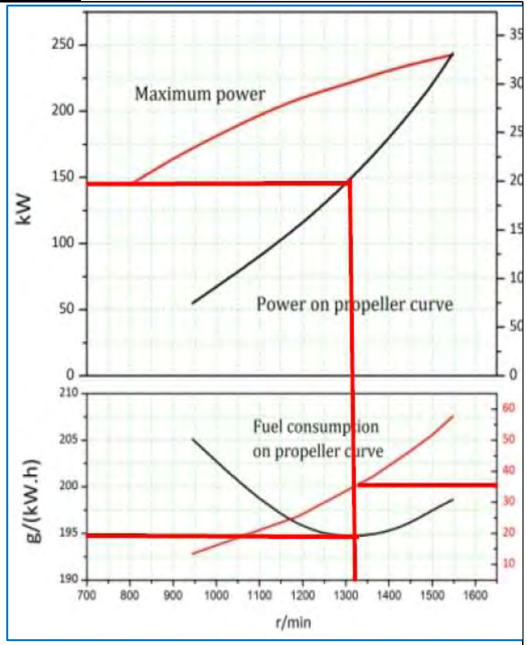

Figure D7: Fuel consumption of O.T-2, Weichei Engine, model: WP12C300-15

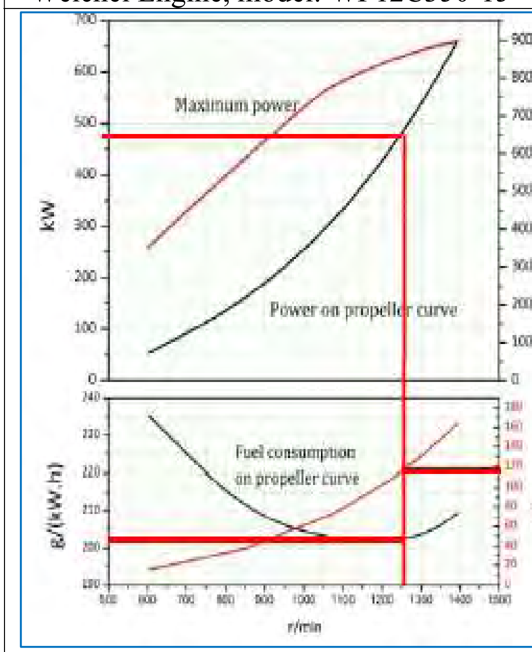

Figure D8: Fuel consumption of O.T-3, Weichei Engine, model: 8170ZC818-3

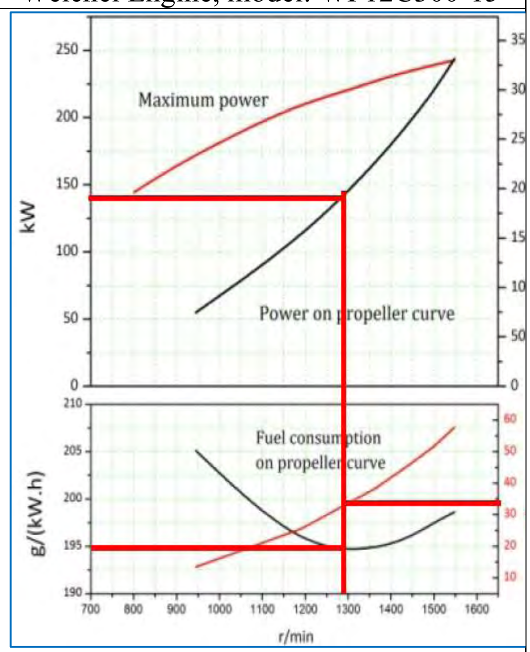

Figure D9: Fuel consumption of O.T-4, Weichei Engine, model: WP12C300-15

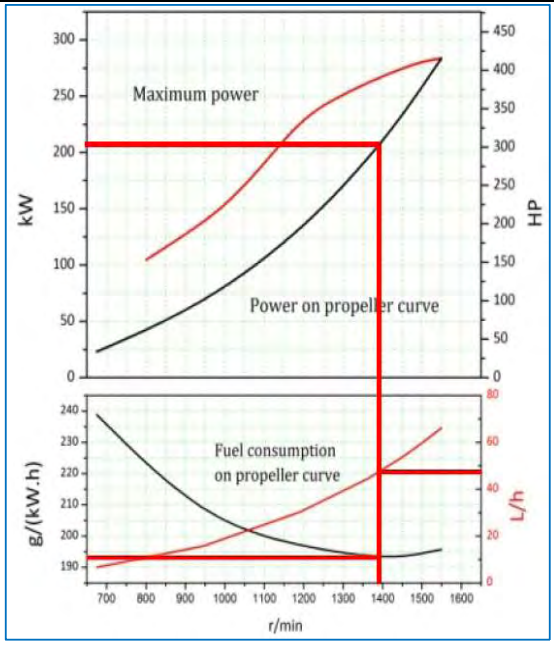

Figure D10: Fuel consumption of O.T-5, Weichei Engine, model: WP12C350-15

Passenger Ships

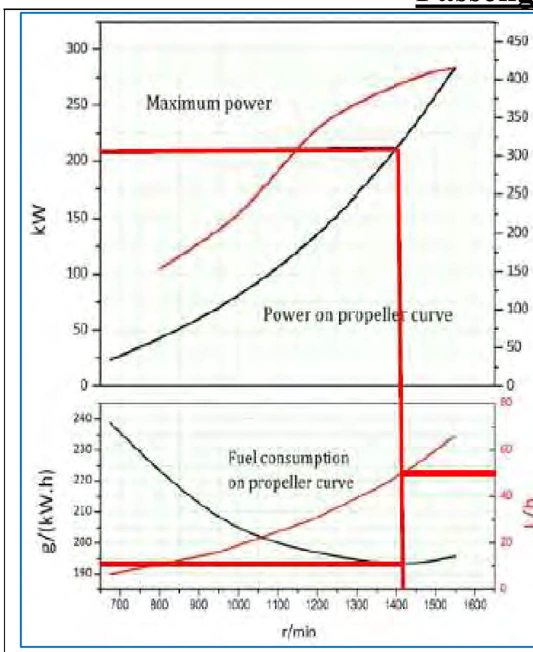

Figure D11: Fuel consumption of P.V-1, Weichei Engine model: WP12C350-15

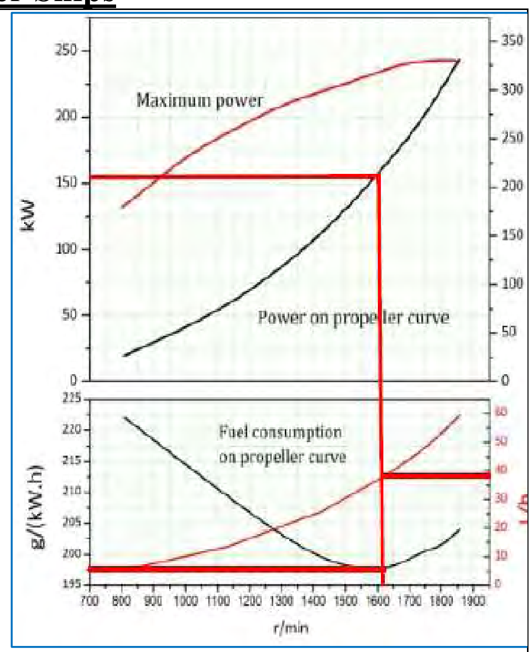

Figure D12: Fuel consumption of P.V-2, Weichei Engine, model: WD12C300-18

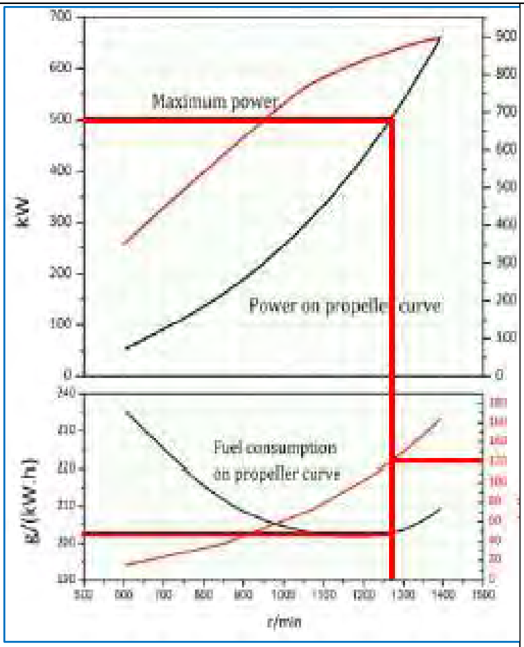

Figure D13: Fuel consumption of P.V-3, Weichei Engine, model: 8170ZC818-3

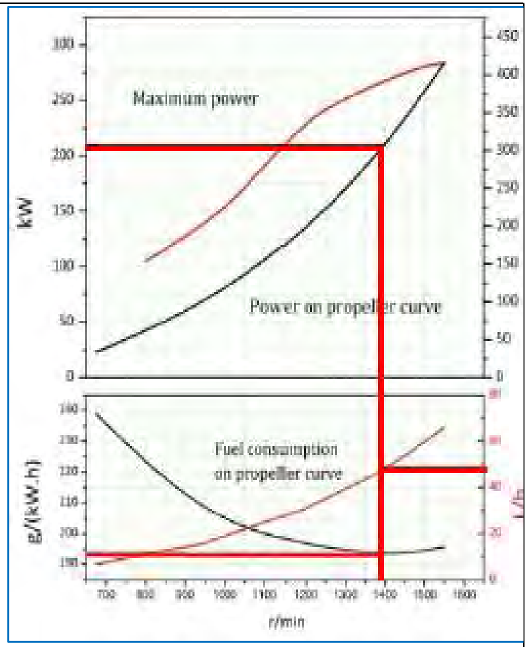

Figure D14: Fuel consumption of P.V-4, Weichei Engine, model: WP12C350-15

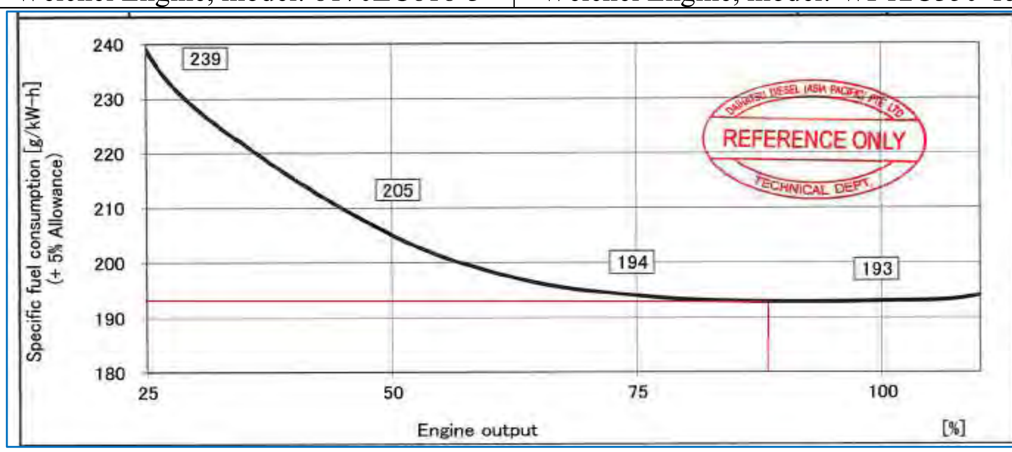

Figure D15: Fuel consumption of P.V-5, Daihatsu Engine, model: 6DEM-18(L)

Appendix-E

Fuel quality analysis results from CARS, Dhaka University

Centre for Advanced Research in Sciences (CARS)
University of Dhaka
Dhaka 1000
Phone: + 880-2-9661920-59 (ext. 4618)

Date: 01. 01. 2018

Centre for Advanced Research in Sciences, University of Dhaka
Dhaka-1000
CARS

Analysis Report

Name of the person requested	: S.M. Rashidul Hasan
Name of the Department	: Department of Naval, Architecture and Marine Engineering, Bangladesh University of Engineering and Technology
Analysis requested for	: Elemental Analysis (CHNS)
Category	: C
No. of samples	: 1
No. of analysis has been carried out	: 1
Reference No.	: CHNS-63
Date of analysis	: 27-12-2017
Nature of samples	: Organic

Assay specifications

Sample pan	: Tin boat
Combustion temp.	: 1150 °C
Reduction temp.	: 850 °C
Gas flow rate	: Helium-200 mL/min, Oxygen-14 mL/min
Time for analysis	: 800 sec/sample
Detector	: Thermal conductivity detector (TCD)

The analysis was carried out with CHNS elemental analyzer, varioMicro V1.6.1, GmbH, Germany.

Comment

The spectrum and result of the sample are attached herewith.

Sultana
Rajia Sultana
Research Fellow

Sultan
Dr. Md. Zakir Sultan
Principal Scientist

08 JAN 2018

Prof. Dr. Golam Mohammed Bhuiyan
Director

Director
Centre for Advanced Research
in Sciences, University of Dhaka
Dhaka-1000

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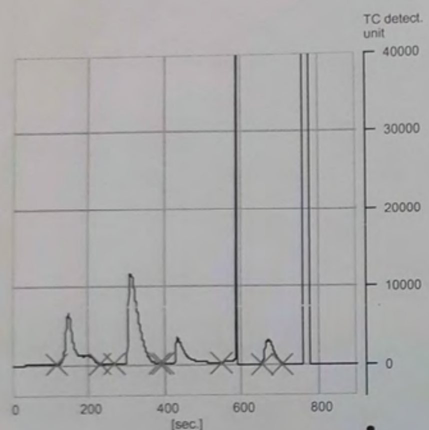
Document: 171227_Cal (VarioMICRO) from: 8/18/2017 12:46:38 PM

Centre for Advanced Research in Sciences,University of Dhaka
varioMICRO CHNS
serial number: 15082030

Graphic report

	Weight [mg]	Name	Method	N Area	C Area	H Area	S Area	N [%]	C [%]	H [%]	S [%]	C/N ratio	N Factor	C Factor	H Factor	S Factor	N Blank	C Blank	H Blank	S Blank	Date	Time	C/H ratio	Humidity [%]
2	[illegible]	sulfanilic acid	2mgChem80s	18.917	54.539	8.281	8.022	8.09	41.81	4.070	18.500	5.1434	0.5567	1.1057	1.2748	0.9022	0	0	0	0	18.08.2017	01:08	10.2236	0.00



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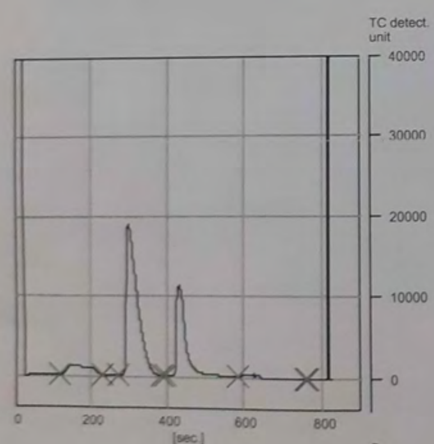
6	3.8750	Res_01	2mgChem80s	9.437	62.975	30.819	0	3.86	72.36	12.262	0.000	18.7761	0.5567	1.1057	1.2748	0.9022	0	0	0	0	18.08.2017	01:22	5.9031	0.00



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Elementar Analysensysteme GmbH

Page 1 (of 3)

Centre for Advanced Research in Sciences (CARS)

University of Dhaka

Dhaka 1000

Phone: + 880-2-9661920-59 (ext. 4618)

Dhaka-1000 CARS

Date: 19. 03. 2018

Analysis Report

Name of the person requested	: S.M. Rashidul Hasan
Name of the Department	: Department of Naval Architecture Marine Engineering, BUET
Analysis requested for	: Elemental Analysis (CHNS)
Category	: C
No. of samples	: 02
No. of analysis has been carried out	: 02
Reference No.	: CHNS-75
Date of analysis	: 08/03/2018
Nature of samples	: Organic

Assay specifications

Sample pan	: Tin boat
Combustion temp.	: 1150 °C
Reduction temp.	: 850 °C
Gas flow rate	: Helium-200 mL/min, Oxygen-14 mL/min
Time for analysis	: 800 sec/sample
Detector	: Thermal conductivity detector (TCD)

The analysis was carried out with CHNS elemental analyzer, varioMicro V1.6.1, GmbH, Germany.

Comment

The spectra and results of the samples are attached herewith.

Sultana

Rajia Sultana
Research Fellow

Sultan

Dr. Md. Zakir Sultan
Principal Scientist

Prof. Dr. Golam Mohammed Bhuiyan
Director

Director
Centre for Advanced Research
in Sciences, University of Dhaka
Dhaka-1000

1

Document: 08.03.2018_Cal (VarioMICRO) from: 8/19/2017 10:54:03 PM

Centre for Advanced Research in Sciences,University of Dhaka
varioMICRO CHNS
serial number: 15082030

Graphic report

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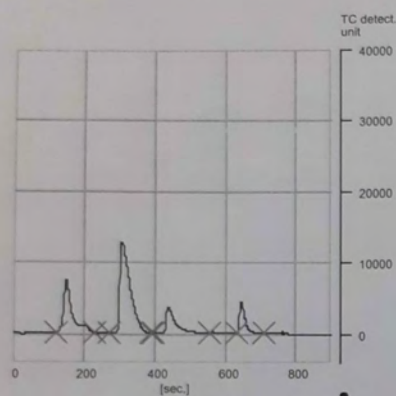
7	4.5850	sulfanilic acid	2mgChem80s	21 422	43 514	11 614	7 788	8.09	41.81	4.070	18.500	5.1434	0.8109	1.0890	1.2773	1.1552	0	0	0	0	19.08.2017 18:58	10.2238	0.00



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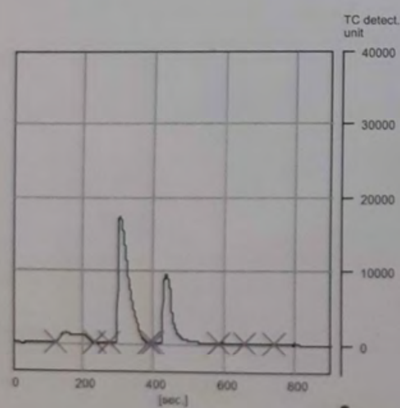
8	4.5600	PM	2mgChem80s	9 581	61 145	29 183	206	3.65	58.82	9.910	0.308	16.1194	0.8109	1.0890	1.2773	1.1552	0	0	0	0	19.08.2017 19:08	5.9357	0.00



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Elementar Analysensysteme GmbH

Page 1 (of 2)

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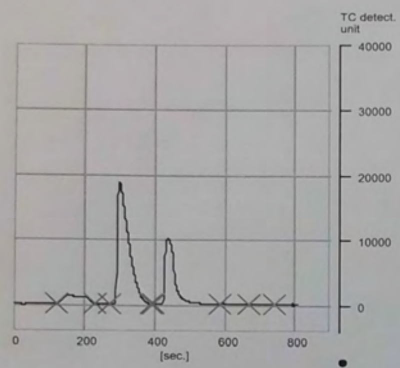
Centre for Advanced Research in Sciences,University of Dhaka
varioMICRO CHNS
serial number: 15082030

Graphic report

	Weight [mg]	Name	Method	N Area	C Area	H Area	S Area	N [%]	C [%]	H [%]	S [%]	C/N ratio	N Factor	C Factor	H Factor	S Factor	N Blank	C Blank	H Blank	S Blank	Date	Time	C/H ratio	Humidity [%]
9	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	33 340	117	4.42	80.74	13.611	0.712	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	0	0	0	[illegible]	[illegible]	[illegible]	[illegible]



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Elementar Analysensysteme GmbH

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Appendix-F

Accepted and rejected ship data (detailed report presented to the attached CD)

Appendix-G

Sample calculation of different values of EEDI by IMO and $EEDI_{BD}$.

Table G-1: Sample calculation of different values of EEDI by IMO and $EEDI_{BD}$.

Vessel's Basic parameters: Length: 64 m, Breadth: 11 m, Draft: 3.5 m, Block Coefficient: 0.70				
	Unit	**EEDI by IMO**	**EEDI $_{BD}$**	**Data Source**
Installed Engine Power	Kilowatt	448	448	Ship data
P_{ME}	Kilowatt	336	308	Calculated
MCR	% of Main Engine Power	75%	70%	Engine SFC Curve
Main Engine RPM at MCR	As a per centage of total RPM	90.60%	88%	Calculated
Shallow water effect	As a percentage of speed loss	0%	20%	Assumed (For $EEDI_{BD}$), which is considered as average as per Section 2.2.10
C_{FME}	$gmCO_2$/gmFuel	3.206	2.787	Table 2.6
SFC_{ME}	gm/kWhr	195	195	SFC curve
P_{AE}	Kilowatt	22.38	22	Calculated as per IMO
C_{FAE}	$gmCO_2$/gmFuel	3.206	2.787	Table 2.6
SFC_{AE}	gm/kWhr	205	205	SFC curve
$P_{PT(i)}$, $f_{eff(i)}$, $P_{AEeff(i)}$, $P_{eff(i)}$	Kilowatt	0	0	Assumed that no shaft motor or energy-efficient technology is used
f_j	Unitless	1	1	When a specific design element (such as an ice-class ship) is used, otherwise 1 as per IMO regulation
f_i	Unitless	1	1	Assumed that there is no technical/regulatory limitation. Therefore $f_i = 1$
f_c	Unitless	1	1	Cubic capacity factor assumed to be 1.
f_l,	Unitless	1	1	Assumed 1
f_W	Unitless	1	1	Assumed 1
Capacity	Tonne	1206	1025	1025 for EEDIBD, which 85% of EEDI by IMO as per Table 2.6
V_{REF}	Knot	9.5	9.2	9.2 knot is at 70% MCR of the engine. This becomes 7.36 knot after shallow water effect correction
EEDI	gm/Tonne.	19.63	23.87	Calculated

Table G-2: Sample Main Engine Power Prediction of 'M.V. Greatwall logistics-2' by Holtrop-Mennen (1982, 1984) method

Sl	Symbol	Definition	Unit	Value	Data Source
1	L_{WL}	Water Length	Meter (m)	61.47	General Arrangement Drawing
2	B_{MLD}	Moulded Breadth	Meter (m)	10.36	General Arrangement Drawing
3	T	Loaded Draft	Meter (m)	3.97	General Arrangement Drawing
4	C_B	Block Coefficient	Unitless	0.77	Stability booklet
5	C_{stern}	Specific shape Coefficient of the after body	Unitless	0	Lines plan
6	A_T	Immersed Transom Area (Loaded)	Square meter (m^2)	0	General Arrangement Drawing
7	A_{BT}	Transverse Section area of the bulb where still water intersects with the stem.	Square meter (m^2)	0	Lines plan
8	h_b	Center of the transverse section of the bulb	Meter (m)	0	Lines plan
9	Z	Number of propeller blades	Nos.	4	Assumed
10	L_{CB}	Longitudinal Center of Buoyancy from amidship (Forward of amidship is +Ve)	Meter (m)	1.25	Stability booklet
11	ρ	Water Density	Kg/m^3	1000	Assumed
12	S_{app}	Wetted area appendages	Square meter (m^2)	22.55	General Arrangement Drawing
13	C_{bto}	A coefficient to calculate resistance due to thruster tunnel opening	Unitless	0	General Arrangement Drawing
14	T_A	Difference between forward and aft Draft	Meter (m)	0	Lines plan
15	T_F	Forward Draft of the ship	Meter (m)	3.97	Lines plan
16	C_P	Prismatic Coefficient	Unitless	0.78	Stability booklet

17	C_M	Midship Coefficient	Unitless	0.99	Stability booklet
18	C_{WP}	Water Plan Area Coefficient	Unitless	0.86	Stability booklet
19	∇	Volume Displacement of Ship	Tonne	1946	Stability booklet
20	c13	Coefficient accounts for the specific shape of after body of the ship	Unitless	1	Lines plan
21	c12	Coefficient accounts for calculating form factor	Unitless	0.54	Lines plan
22	Lr	A parameter reflecting the length of the run	Meter (m)	15.54	Lines plan
23	1+k1	Form Factor	Unitless	1.27	Holtrop-Mennen (1982, 1984) formula
24	S	Wetted Area of the Ship	Square meter (m^2)	899.675	Stability booklet
25	Rn	Reynold's number	Unitless	343275 570.5	Calculated
26	C_F	The coefficient of the frictional resistance of the ship according to the ITTC 1957 formula	Unitless	0.00175 6	ITTC 1957 formula
27	R_F	Frictional resistance of the ship according to ITTC 1957 formula	Kilo Newton (kN)	20.46	ITTC 1957 formula
28	R_{bow}	Additional pressure resistance of bulbous bow near the water surface	Kilo Newton (kN)	0	Holtrop-Mennen (1982, 1984)
29	Rapp	Resistance of appendages	Kilo Newton (kN)	1.18	Holtrop-Mennen (1982, 1984)
30	c7	Coefficient accounts for the wave resistance	Unitless	0.17	Holtrop-Mennen (1982, 1984)
31	i_E	The half-angle of the entrance, which is the angle of the waterline at the bow in degrees regarding the centre plane but	Degree	36.83	Holtrop-Mennen (1982, 1984)

		neglecting the local shape at the stern.			
32	c1	Coefficient accounts for the wave resistance	Unitless	3.94	Holtrop-Mennen (1982, 1984)
33	c3	The coefficient that determines the influence of the bulbous bow on the wave resistance	Unitless	0	Holtrop-Mennen (1982, 1984)
34	c2	Coefficient accounts for the wave resistance	Unitless	1	Holtrop-Mennen (1982, 1984)
35	c5	Coefficient accounts for the wave resistance	Unitless	1	Holtrop-Mennen (1982, 1984)
36	c16	Coefficient accounts for the wave resistance	Unitless	1.18	Holtrop-Mennen (1982, 1984)
37	m1	Coefficient accounts for the wave resistance	Unitless	-2.13	Holtrop-Mennen (1982, 1984)
38	c15	Coefficient accounts calculating the coefficient	Unitless	-1.69	Holtrop-Mennen (1982, 1984)
39	m2	Coefficient accounts for the wave resistance	Unitless	-0.095	Holtrop-Mennen (1982, 1984)
40	λ	Coefficient accounts for the wave resistance	Unitless	0.945	Holtrop-Mennen (1982, 1984)
41	m4	Coefficient accounts for the wave resistance	Unitless	-0.001347	Holtrop-Mennen (1982, 1984)
42	R_W	Wave resistance	Kilo Newton (kN)	10.782	Holtrop-Mennen (1982, 1984)
43	P_B	A measure for the emergence of the bow	Unitless	0	Holtrop-Mennen (1982, 1984)
44	F_{NI}	Froude number based on the immersion	Unitless	0.771	Holtrop-Mennen (1982, 1984)
45	R_B	Additional resistance due to the presence of a bulbous bow	Kilo Newton (kN)	0	Holtrop-Mennen (1982, 1984)
46	F_{NT}	Froude number based on the transom immersion	Unitless	0	Holtrop-Mennen (1982, 1984)

47	R_{TR}	Additional pressure resistance due to the immersed transom	Kilo Newton (kN)	0	Holtrop-Mennen (1982, 1984)
48	c4	Coefficient accounts for the correlation allowance coefficient	Unitless	0.04	Holtrop-Mennen (1982, 1984)
49	Ca	Correlation allowance coefficient	Unitless	0.00061	Holtrop-Mennen (1982, 1984)
50	Ra	Model ship correlation resistance	Kilo Newton (kN)	7.11	Holtrop-Mennen (1982, 1984)
51	R_T	Total resistance of the ship	Kilo Newton (kN)	45.14	Holtrop-Mennen (1982, 1984)
52	P_E	Required effective power at specific speed	Kilo Watt (kW)	227.57	Holtrop-Mennen (1982, 1984)
53	c8	Coefficient accounts for the coefficient c_9	Unitless	23.23	Holtrop-Mennen (1982, 1984)
54	c9	Coefficient accounts for the wake of the ship	Unitless	23.23	Holtrop-Mennen (1982, 1984)
55	c20	Coefficient accounts for the wake of the ship	Unitless	1	Holtrop-Mennen (1982, 1984)
56	Cv	Viscous resistance coefficient	Unitless	0.002848	Holtrop-Mennen (1982, 1984)
57	c11	Coefficient accounts for the wake of the ship	Unitless	2.44	Holtrop-Mennen (1982, 1984)
58	Cp1	Coefficient required for thrust deduction factor	Unitless	0.78	Holtrop-Mennen (1982, 1984)
59	c19	Coefficient required for wake	Unitless	0.1	Holtrop-Mennen (1982, 1984)
60	wake	Wake of the ship	Unitless	0.2	Holtrop-Mennen (1982, 1984)
61	t	Thrust deduction factor	Unitless	0.2	Holtrop-Mennen (1982, 1984)
62	hr	Relative rotative efficiency	Unitless	1.01	Holtrop-Mennen (1982, 1984)
63	J	The advanced ratio of the prop when it is exposed to a water speed Up (water speed seen at the propeller)	Unitless	0.41	Holtrop-Mennen (1982, 1984)

64	KT-Bseries	Thrust coefficient	Unitless	0.21	Wageningen B-screw series
65	KQ-B-series	Torque coefficient	Unitless	0.03	Wageningen B-screw series
66	Δ_{CD}	The drag coefficient of the profile Section	Unitless	0	Holtrop-Mennen (1982, 1984)
67	KT-ship	Corrected Thrust coefficient	Unitless	0.21	Holtrop-Mennen (1982, 1984)
68	KQ-ship	Corrected Torque coefficient	Unitless	0.03	Holtrop-Mennen (1982, 1984)
69	$T_{required}$	Required Thrust	Kilo Newton (kN)	56.5	Holtrop-Mennen (1982, 1984)
70	D	Diameter of the propeller	Meter (m)	1.68	Propeller drawing
71	Gear Ratio	Gear Box Ratio of the Main Propulsion Engine	Unitless	1:03	Interview with the master
72	P/D	Pitch Diameter Ratio of Propeller	Unitless	0.8	Assumed
73	P_{RPM}	Rotation Per Minute (RPM) of the propeller	Rotation per minute (RPM)	352	@ 70% MCR
74	AE/Ao	The blade area ratio	Unitless	0.51	Holtrop-Mennen (1982, 1984)
75	(t/c)0,75	Thickness chord length ratio of the propeller	Unitless	0.05	Holtrop-Mennen (1982, 1984)
76	Vs	Speed over an unrestricted channel at 70% MCR	Knot	9.8	Achieved speed at 70% MCR
77	ν	Kinematic viscosity	m^2/s	9.027×10^{-7}	Calculated at 25^0 C
78	F_N	Froude Number	Unitless	0.21	Calculated
79	$T_{generated}$	Generated thrust by the propeller	Kilo Newton (kN)	56.15	Holtrop-Mennen (1982, 1984)
80	Q	Torque	Kilo Newton Meter (kNm)	12.76	Holtrop-Mennen (1982, 1984)
81	P_D	Developed Horse Power	Kilo Watt (kW)	470.27	Holtrop-Mennen (1982, 1984)
82	P_S or P_{ME}	Shaft Horse Power	Kilo Watt (kW)	470.27	Holtrop-Mennen (1982, 1984)
83	MCR	Maximum Continuous Rating	Unit less	70%	
84	ME	Installed Main Engine Power	kW	671.4	
			HP	900	

Appendix-H

CFD Analysis (detailed report presented to the attached CD)

Appendix-I
Improvement of fuel consumption

MV Madina-5 (General Cargo), MT Saima-1 (Oil Tanker) and MV Takwa-1 (Passenger's vessel), these three vessels have been physically measured at the Highspeed Shipbuilding and Engineering Co. Ltd. Existing hull shapes have been physically measured and redrawn in the software 'Rhino'. Following Table, J1 presents the principal particulars of those investigated vessels.

Table I-1: Investigated vessels for validation

Principal Particulars	**MV. Madina-5 (General Cargo Ship)**	**MT. Saima-1 (Oil Tanker)**	**MV. Takwa-1 (Passenger Ship)**
Overall Length	76.21 meter	62.50 meter	59.76 meter
Waterline length	72.024 meter	59.60 meter	57.05 meter
Breadth	11.58 meter	10.67 meter	9.76 meter
Depth	5.20 meter	3.66 meter	2.59 meter
Draft	4.88 meter	3.20 meter	1.60 meter
Dead Weight (or Gross Tonne)	2100 tonne	1100 tonne	733
Maine Engine	550 BHP×2	480 BHP×2	350 BHP×2
Service speed	10 knots	10 knots	11.50 knots

These three ships hulls have been redesigned based on the suggestions provided in Tables 4.15, 4.16, 4.17 and 4.18. Redesigned vessels have the same capacity and speed as the parent hulls.

Using the ship design software 'Maxsurf', hulls have been redesigned. These new hulls have been analyzed by the CFD software 'Shipflow' to find the required resistance at the specified speed and draft. The total resistant coefficients of each new hull found by the CFD analysis have been used further to find the required power. To do that, ITTC-1978, ITTC-2002 methods (ITTC, 1978 and ITTC, 2002) and Holtrop-Mennen (1982) methods were used.

Table I2 has been extracted from Tables 3.1, 3.2 and 3.3 and the average SFC from the measured ships (5 from each category) are presented. The calculation processes, formula and required ship data with sources are presented to calculate required ship power in Table I3. Average SFC data in Table I2 have been used to estimate the fuel consumptions per hour for the ships under investigation of Table I1.

Table I-2: Measurement of ship's fuel consumption at actual for 5 Inland Cargo Vessels, 5 Oil Tankers and 5 Passenger ships

Ship ID	**SFC of measured ship (gm/kW.hr)**	**Average SFC (gm/kW.hr)**
G.C-1	198	208.00
G.C-2	201	
G.C-3	219	
G.C-4	203	
G.C-5	218	
O.T-1	221	219.00
O.T-2	219	
O.T-3	220	
OT-4	219	
OT-5	216	
P.V-1	212	215.00
P.V-2	214	
P.V-3	238	
P.V-4	210	
P.V-5	202	

Table I-3: Ship data, formula and results for the improved designs of each type of vessel.

Ship data	**Brief description**	**Data source**	**MV. Madina-5 (General Cargo)**	**MT. Saima-1 (Oil Tanker)**	**MV. Takwa-1 (Passenger Ship)**
ρ	Water density (kg/$m^{3)}$	Average standard value	1000	1000	1000
S	Ship's wetted surface area (m^2)	Analysis result from CFD Software	1233.56	834.51	539.35
V	Ship's speed (knot)	Same as parent hull	10.00	10.00	11.50

C_B	Block Coefficient	Software 'Maxsurf'	0.72	0.60	0.60
C_P	Prismatic coefficient of ship	Software 'Maxsurf'	0.729	0.617	0.68
LCB	Longitudinal centre of buoyancy of ship (meter)	Software 'Maxsurf'	1.998	1.998	0.623
P	Propeller pitch (meter)	Assumed in the new design	1.504	1.219	1.220
D	Propeller diameter (meter)	Same as the parent hull	1.88	1.525	1.525
L	Waterline length of the ship (meter)	As per the ship design suggestion of this thesis	75.00	69.94	61.50
B	The moulded breadth of the ship (meter)	As per the ship design suggestion of this thesis	11.54	11.00	9.624
d	Ship draft (meter)	As per the ship design suggestion of this thesis	4.88	3.35	1.68
n	Propeller RPM	From Engine curve against the required power	297	372	397
Z	Number of propeller blade	4 bladed propellers considered	04	04	04
C_{stern}	After body form factor (-10 for 'V' shaped, 0 for normal shaped and 10 for 'U' shaped with Sections with Hogner stern)	Normal shape considered	0	0	0
K_p	Propeller blade surface roughness	Holtrop-Mennen (1982)	0.00003	0.00003	0.00003
K	A constant of the blade area ratio formula	Holtrop-Mennen (1982)	0 to 0.1 for twin screw propeller, 0.05 considered	0 to 0.1 for twin screw propeller, 0.05 considered	0 to 0.1 for twin screw propeller, 0.05 considered
p_o	Atmospheric pressure (Pa)	Average standard value	101325	101325	101325
p_v	Vapour pressure (Pa)	Average standard value	133.322	133.322	133.322

$\rho g h$	Static pressure at the shaft centreline (Pa)	Static pressure at h = Ship Draft-Propeller Radius, considered.	38653.34	25388.26	9000.675
Relative rotative efficiency, η_R	0.9922 – 0.05908 A_E/A_o+ 0.07424 (C_P – 0.0225lcb)	Holtrop-Mennen (1982) for single-screw ship	N/A	N/A	N/A
	0.9737 + 0.111 (C_P-0.0225lcb) – 0.06325 P/D	Holtrop-Mennen (1982) for twin-screw ship	1.004	0.99	0.99
Propeller open water efficiency, η_0	$\frac{P_T}{P_D}=\frac{J}{2\pi}\frac{K_{T-ship}}{K_{Q-ship}}=\frac{1}{2\pi}\frac{V_A}{nD}\frac{K_{T-ship}}{K_{Q-ship}}=\frac{1}{2\pi}\frac{V(1-w)}{nD}\frac{K_{T-ship}}{K_{Q-ship}}$	Holtrop-Mennen (1982)	0.52	0.532	0.573
$K_{T\text{-B-series}}$	Thrust Coefficient	B-Series propeller polynomial	0.191	0.186	0.165
$K_{Q\text{-B-series}}$	Torque Coefficient	B-Series propeller polynomial	0.0255	0.025	0.023
Propeller Thrust coefficient, K_{T-ship}	$K_{T-B\ Series}+\Delta C_D 0.3\frac{Pc_{0.75}Z}{D^2}$	Holtrop-Mennen (1982)	0.1906	0.185	0.164
Propeller Torque coefficient, K_{Q-ship}	$K_{Q-B\ Series}-\Delta C_D 0.25\frac{c_{0.75}Z}{D}$	Holtrop-Mennen (1982)	0.0263	0.026	0.024
Drag coefficient, ΔC_D	$(2+4(\frac{t}{c})_{0.75})\left\{0.003605-(1.89+1.62\log\left(\frac{c_{0.75}}{k_p}\right))^{-2.5}\right\}$	Holtrop-Mennen (1982)	-0.002089	-0.002643	-0.002564
Propeller chord length at a radius of 75% of	2.073 x (A_E/A_0) x D/Z	Holtrop-Mennen (1982)	0.447	0.347	0.358

propeller diameter, $C_{0.75}$					
Blade thickness-chord length ratio, $(t/c)_{0.75}$	$(0.0185-0.00125\ Z)\ D/c_{0.75}$	Holtrop-Mennen (1982)	0.057	0.059	0.057
Blade area ratio, A_E/A_0	$K + \frac{(1.3+0.3Z)*T}{D^2(p_o+\rho gh-p_v)}$	Holtrop-Mennen (1982)	0.459	0.439	0.453
Propeller thrust, T	$R_T/(1-t)$ (N)	Holtrop-Mennen (1982)	62916.73	40973.00	31386.00
Thrust deduction factor, t	$0.25014\ (B/L)^{0.28956} \times (\sqrt{(Bd)}/D)^{0.2624}/((1-C_P + 0.0225 \times lcb)^{0.01762} + 0.0015C_{stern})$	Holtrop-Mennen (1982) for single-screw ship	N/A	N/A	N/A
	$0.324 \times C_B - 0.1885\ D/\sqrt{(Bd)}$, (for twin screw ship)	Holtrop-Mennen (1982) for twin-screw ship	0.187	0.148	0.123
Wake fraction (w) can be calculated by	$0.3C_B + 10C_VC_B-0.1$	Holtrop-Mennen (1982) for single-screw ship	N/A	N/A	N/A
	$0.3095C_B + 10C_VC_B -0.23D/\sqrt{(BT)}$	Holtrop-Mennen (1982) for twin-screw ship	0.184	0.144	0.11
Total ship resistance, R_T	$0.5 \times C_T \times \rho \times S \times V^2$ (kN)	Hydrodynamic rule of ship	51164.72	34.922	27.528
Effective ship power, P_E	$R_T \times V$ (kW)	Hydrodynamic rule of ship	263	180	163
Shaft Efficiency (η_s)	Varies from 0.97-0.99	Average considered	0.98	0.98	0.98
Hull Efficiency (η_H)	$\eta_H = (1-t)/(1-w)$	Calculated value	0.997	0.995	0.985
Required Engine Shaft Power, P_S	$P_E/(\eta_R \times \eta_o \times \eta_S \times \eta_H)$ (kW)	Hydrodynamic rule of ship	516.00	350.00	295.00

Required main engine power, ME (kW)	ME = Ps/0.8 (for passenger ships) ME = Ps/0.7 (for cargo and oil tanker)		645.00	437.00	368.00
SFC	gm/kW.hr	Average value from the measured fuel consumption	208.00	219.00	215.00
Fuel Consumption of parent hull (liter/hour)	MCR_{ME} x AVG SFC/ (1000 x 0.84)	MCR_{ME} = 70% of main engine power for cargo and oil tanker and 80% for passenger ships	142.24	130.70	107.026
Fuel Consumption of improved hull (liter/hour)	Ps x SFC/(1000*0.84)	Specific gravity of diesel is considered 0.84	127.73	91.15	75.48
Improved hull Attained $EEDI_{BD}$ ($gmCO_2$/Tonne-mile)			14.24	19.40	20.96
Parent hull Attained $EEDI_{BD}$ ($gmCO_2$/Tonne-mile)			16.97	29.803	27.87

Appendix-J

Stability calculation for M.V Madina-5 (Improved Design)

(Detailed report presented to the attached CD)

Load case 1- Full Load Departure Condition 100% Fuel and Freshwater
Damage Case - Intact
Free to Trim
Specific gravity = 1; (Density = 1 tonne/m^3)
Fluid analysis method: Use corrected VCG

Item Name	Quantity	Unit Mass tonne	Total Mass tonne	Unit Volume m^3	Total Volume m^3	Long. Arm m	Trans. Arm m	Vert. Arm m	Total FSM tonne.m	FSM Type
Lightship	1	700.000	700.000			36.000	0.000	3.500	0.000	User Specified
APT	0%	33.506	0.000	33.506	0.000	3.977	0.000	1.844	0.000	Maximum
FORT	100%	7.745	7.745	9.221	9.221	4.999	0.000	4.176	0.000	Maximum
FOST-P	100%	1.890	1.890	2.250	2.250	13.250	-2.500	2.750	0.000	Maximum
FOST-S	100%	1.890	1.890	2.250	2.250	13.250	2.500	2.750	0.000	Maximum
Complements	12	0.075	0.900			15.000	0.000	6.000	0.000	User Specified
Store	1	3.000	3.000			12.000	0.000	6.000	0.000	User Specified
Freshwater	1	2.000	2.000			10.000	0.000	9.000	0.000	User Specified
Hold-1	1	782.575	782.575			23.000	0.000	2.300	0.000	User Specified
Hold-2	1	700.000	700.000			42.000	0.000	2.300	0.000	User Specified
Hold-3	1	600.000	600.000			60.000	0.000	2.300	0.000	User Specified
FPT	0%	44.855	0.000	44.855	0.000	73.015	0.000	0.000	0.000	Maximum
Total Load case			2800.000	92.082	13.721	38.842	0.000	2.616	0.000	
FS correction								0.000		
VCG fluid								2.616		

Load case 2- Full Load Arrival Condition 10% Fuel and Freshwater
Damage Case - Intact
Free to Trim
Specific gravity = 1; (Density = 1 tonne/m^3)
Fluid analysis method: Use corrected VCG

Item Name	**Quantity**	**Unit Mass tonne**	**Total Mass tonne**	**Unit Volume m^3**	**Total Volume m^3**	**Long. Arm m**	**Trans. Arm m**	**Vert. Arm m**	**Total FSM tonne.m**	**FSM Type**
Lightship	1	700.000	700.000			36.000	0.000	3.500	0.000	User Specified
APT	0%	33.506	0.000	33.506	0.000	3.977	0.000	1.844	0.000	Maximum
FORT	10%	7.745	0.775	9.221	0.922	5.000	0.000	3.118	4.480	Maximum
FOST-P	10%	1.890	0.189	2.250	0.225	13.250	-2.500	2.075	0.105	Maximum
FOST-S	10%	1.890	0.189	2.250	0.225	13.250	2.500	2.075	0.105	Maximum
Complements	12	0.075	0.900			15.000	0.000	6.000	0.000	User Specified
Store	0.1	3.000	0.300			12.000	0.000	6.000	0.000	User Specified
Freshwater	0.1	2.000	0.200			10.000	0.000	9.000	0.000	User Specified
Hold-1	1	782.575	782.575			23.000	0.000	2.300	0.000	User Specified
Hold-2	1	700.000	700.000			42.000	0.000	2.300	0.000	User Specified
Hold-3	1	600.000	600.000			60.000	0.000	2.300	0.000	User Specified
FPT	0%	44.855	0.000	44.855	0.000	73.015	0.000	0.000	0.000	Maximum
Total Load case			2785.128	92.082	1.372	39.003	0.000	2.604	4.690	
FS correction								0.002		
VCG fluid								2.606		

Load case 3- Ballast Departure Condition 100% Fuel and Freshwater
Damage Case - Intact
Free to Trim
Specific gravity = 1; (Density = 1 tonne/m^3)
Fluid analysis method: Use corrected VCG

Item Name	Quantity	Unit Mass tonne	Total Mass tonne	Unit Volume m^3	Total Volume m^3	Long. Arm m	Trans. Arm m	Vert. Arm m	Total FSM tonne.m	FSM Type
Lightship	1	700.000	700.000			36.000	0.000	3.500	0.000	User Specified
APT	0%	33.506	0.000	33.506	0.000	3.977	0.000	1.844	0.000	Maximum
FORT	100%	7.745	7.745	9.221	9.221	4.999	0.000	4.176	0.000	Maximum
FOST-P	100%	1.890	1.890	2.250	2.250	13.250	-2.500	2.750	0.000	Maximum
FOST-S	100%	1.890	1.890	2.250	2.250	13.250	2.500	2.750	0.000	Maximum
Complements	12	0.075	0.900			15.000	0.000	6.000	0.000	User Specified
Store	1	3.000	3.000			12.000	0.000	6.000	0.000	User Specified
Freshwater	1	2.000	2.000			10.000	0.000	9.000	0.000	User Specified
Hold-1	0	782.575	0.000			23.000	0.000	2.300	0.000	User Specified
Hold-2	0	700.000	0.000			42.000	0.000	2.300	0.000	User Specified
Hold-3	0	600.000	0.000			60.000	0.000	2.300	0.000	User Specified
FPT	100%	44.855	44.855	44.855	44.855	73.250	0.000	3.198	0.000	Maximum
Total Load case			762.280	92.082	58.575	37.577	0.000	3.513	0.000	
FS correction								0.000		
VCG fluid								3.513		

Load case 4 - Ballast Arrival Condition 10% Fuel and Freshwater
Damage Case - Intact
Free to Trim
Specific gravity = 1; (Density = 1 tonne/m^3)
Fluid analysis method: Use corrected VCG

Item Name	Quantity	Unit Mass tonne	Total Mass tonne	Unit Volume m^3	Total Volume m^3	Long. Arm m	Trans. Arm m	Vert. Arm m	Total FSM tonne.m	FSM Type
Lightship	1	700.000	700.000			36.000	0.000	3.500	0.000	User Specified
APT	0%	33.506	0.000	33.506	0.000	3.977	0.000	1.844	0.000	Maximum
FORT	10%	7.745	0.775	9.221	0.922	5.000	0.000	3.118	4.480	Maximum
FOST-P	10%	1.890	0.189	2.250	0.225	13.250	-2.500	2.075	0.105	Maximum
FOST-S	10%	1.890	0.189	2.250	0.225	13.250	2.500	2.075	0.105	Maximum
Complements	12	0.075	0.900			15.000	0.000	6.000	0.000	User Specified
Store	0.1	3.000	0.300			12.000	0.000	6.000	0.000	User Specified
Freshwater	0.1	2.000	0.200			10.000	0.000	9.000	0.000	User Specified
Hold-1	0	782.575	0.000			23.000	0.000	2.300	0.000	User Specified
Hold-2	0	700.000	0.000			42.000	0.000	2.300	0.000	User Specified
Hold-3	0	600.000	0.000			60.000	0.000	2.300	0.000	User Specified
FPT	100%	44.855	44.855	44.855	44.855	73.250	0.000	3.198	0.000	Maximum
Total Load case			747.407	92.082	46.227	38.150	0.000	3.486	4.690	
FS correction								0.006		
VCG fluid								3.493		

<u>Stability calculation for M.T Saima-1 (Improved Design)</u>
(Detailed report presented to the attached CD)

Load case 1- Full Load Departure Condition 100% Fuel and Freshwater
Damage Case - Intact
Free to Trim
Specific gravity = 1; (Density = 1 tonne/m^3)
Fluid analysis method: Use corrected VCG

Item Name	Quantity	Unit Mass tonne	Total Mass tonne	Unit Volume m^3	Total Volume m^3	Long. Arm m	Trans. Arm m	Vert. Arm m	Total FSM tonne.m	FSM Type
Lightship	1	446.000	446.000			33.000	0.000	3.300	0.000	User Specified
APT	0%	18.539	0.000	18.539	0.000	3.977	0.000	1.946	0.000	Maximum
FORT	100%	4.160	4.160	4.953	4.953	5.000	0.000	3.634	0.000	Maximum
FOST-P	100%	1.890	1.890	2.250	2.250	13.250	-2.500	2.750	0.000	Maximum
FOST-S	100%	1.890	1.890	2.250	2.250	13.250	2.500	2.750	0.000	Maximum
Complements	12	0.075	0.900			15.000	0.000	6.000	0.000	User Specified
Store	1	2.000	2.000			12.000	0.000	6.000	0.000	User Specified
Freshwater	1	1.000	1.000			10.000	0.000	9.000	0.000	User Specified
Hold-1	1	450.000	450.000			23.000	0.000	2.300	0.000	User Specified
Hold-2	1	350.000	350.000			42.000	0.000	2.300	0.000	User Specified
Hold-3	1	288.160	288.160			58.000	0.000	2.300	0.000	User Specified
FPT	0%	18.983	0.000	18.983	0.000	67.023	0.000	0.161	0.000	Maximum
Total Load case			1546.000	46.976	9.453	36.610	0.000	2.604	0.000	
FS correction								0.000		
VCG fluid								2.604		

Load case 2 - Full Load Arrival Condition 10% Fuel and Freshwater

Damage Case - Intact
Free to Trim
Specific gravity = 1; (Density = 1 tonne/m^3)
Fluid analysis method: Use corrected VCG

Item Name	**Quantity**	**Unit Mass tonne**	**Total Mass tonne**	**Unit Volume m^3**	**Total Volume m^3**	**Long. Arm m**	**Trans. Arm m**	**Vert. Arm m**	**Total FSM tonne.m**	**FSM Type**
Lightship	1	446.000	446.000			33.000	0.000	3.300	0.000	User Specified
APT	0%	18.539	0.000	18.539	0.000	3.977	0.000	1.946	0.000	Maximum
FORT	10%	4.160	0.416	4.953	0.495	5.006	0.000	3.065	4.480	Maximum
FOST-P	10%	1.890	0.189	2.250	0.225	13.250	-2.500	2.075	0.105	Maximum
FOST-S	10%	1.890	0.189	2.250	0.225	13.250	2.500	2.075	0.105	Maximum
Complements	12	0.075	0.900			15.000	0.000	6.000	0.000	User Specified
Store	0.1	2.000	0.200			12.000	0.000	6.000	0.000	User Specified
Freshwater	0.1	1.000	0.100			10.000	0.000	9.000	0.000	User Specified
Hold-1	1	450.000	450.000			23.000	0.000	2.300	0.000	User Specified
Hold-2	1	350.000	350.000			42.000	0.000	2.300	0.000	User Specified
Hold-3	1	288.160	288.160			58.000	0.000	2.300	0.000	User Specified
FPT	0%	18.983	0.000	18.983	0.000	67.023	0.000	0.161	0.000	Maximum
Total Load case			1536.154	46.976	0.945	36.784	0.000	2.594	4.690	
FS correction								0.003		
VCG fluid								2.597		

Load case 3- Ballast Departure Condition 100% Fuel and Freshwater
Damage Case - Intact
Free to Trim
Specific gravity = 1; (Density = 1 tonne/m^3)
Fluid analysis method: Use corrected VCG

Item Name	Quantity	Unit Mass tonne	Total Mass tonne	Unit Volume m^3	Total Volume m^3	Long. Arm m	Trans. Arm m	Vert. Arm m	Total FSM tonne.m	FSM Type
Lightship	1	446.000	446.000			33.000	0.000	3.300	0.000	User Specified
APT	0%	18.539	0.000	18.539	0.000	3.977	0.000	1.946	0.000	Maximum
FORT	100%	4.160	4.160	4.953	4.953	5.000	0.000	3.634	0.000	Maximum
FOST-P	100%	1.890	1.890	2.250	2.250	13.250	-2.500	2.750	0.000	Maximum
FOST-S	100%	1.890	1.890	2.250	2.250	13.250	2.500	2.750	0.000	Maximum
Complements	12	0.075	0.900			15.000	0.000	6.000	0.000	User Specified
Store	1	2.000	2.000			12.000	0.000	6.000	0.000	User Specified
Freshwater	1	1.000	1.000			10.000	0.000	9.000	0.000	User Specified
Hold-1	0	450.000	0.000			23.000	0.000	2.300	0.000	User Specified
Hold-2	0	350.000	0.000			42.000	0.000	2.300	0.000	User Specified
Hold-3	0	288.160	0.000			58.000	0.000	2.300	0.000	User Specified
FPT	100%	18.983	18.983	18.983	18.983	68.122	0.000	3.444	0.000	Maximum
Total Load case			476.824	46.976	28.436	33.827	0.000	3.333	0.000	
FS correction								0.000		
VCG fluid								3.333		

Load case 4- Ballast Arrival Condition 10% Fuel and Freshwater
Damage Case - Intact
Free to Trim
Specific gravity = 1; (Density = 1 tonne/m^3)
Fluid analysis method: Use corrected VCG

Item Name	Quantity	Unit Mass tonne	Total Mass tonne	Unit Volume m^3	Total Volume m^3	Long. Arm m	Trans. Arm m	Vert. Arm m	Total FSM tonne.m	FSM Type
Lightship	1	446.000	446.000			33.000	0.000	3.300	0.000	User Specified
APT	0%	18.539	0.000	18.539	0.000	3.977	0.000	1.946	0.000	Maximum
FORT	10%	4.160	0.416	4.953	0.495	5.006	0.000	3.065	4.480	Maximum
FOST-P	10%	1.890	0.189	2.250	0.225	13.250	-2.500	2.075	0.105	Maximum
FOST-S	10%	1.890	0.189	2.250	0.225	13.250	2.500	2.075	0.105	Maximum
Complements	12	0.075	0.900			15.000	0.000	6.000	0.000	User Specified
Store	0.1	2.000	0.200			12.000	0.000	6.000	0.000	User Specified
Freshwater	0.1	1.000	0.100			10.000	0.000	9.000	0.000	User Specified
Hold-1	0	450.000	0.000			23.000	0.000	2.300	0.000	User Specified
Hold-2	0	350.000	0.000			42.000	0.000	2.300	0.000	User Specified
Hold-3	0	288.160	0.000			58.000	0.000	2.300	0.000	User Specified
FPT	100%	18.983	18.983	18.983	18.983	68.122	0.000	3.444	0.000	Maximum
Total Load case			466.977	46.976	19.929	34.338	0.000	3.312	4.690	
FS correction								0.010		
VCG fluid								3.322		

Stability calculation for M.V. Takwa-1 (Improved Design)
(Detailed report presented to the attached CD)

Load case 1- Full load departure-100% Fuel and Freshwater
Damage Case - Intact
Specific gravity = 1; (Density = 1 tonne/m^3)
Fluid analysis method: Use corrected VCG

Item Name	Quantity	Unit Mass tonne	Total Mass tonne	Unit Volume m^3	Total Volume m^3	Long. Arm m	Trans. Arm m	Vert. Arm m	Total FSM tonne.m	FSM Type
Lightship	1	475.770	475.770			29.000	0.000	2.750	0.000	Maximum
261 nos Passenger main deck	1	0.075	0.075			30.000	0.000	3.390	0.000	Maximum
154 nos Passenger Upper deck	1	0.075	0.075			40.000	0.000	5.790	0.000	Maximum
40 nos Passengers Bridge deck	1	0.075	0.075			35.000	0.000	8.190	0.000	Maximum
Cargo Hold -1	1	15.000	15.000			20.000	0.000	1.000	0.000	Maximum
Cargo Hold-2	1	25.000	25.000			36.000	0.000	1.000	0.000	Maximum
Cargo Hold-3	1	30.000	30.000			45.000	0.000	1.000	0.000	Maximum
Store	1	5.000	5.000			12.000	0.000	3.200	0.000	Maximum
Freshwater Tank	1	5.000	5.000			10.000	0.000	10.460	0.000	Maximum
APT	0%	24.967	0.000	24.967	0.000	2.734	0.000	1.121	0.000	Maximum
FORT	100%	7.319	7.319	7.319	7.319	3.526	0.000	1.876	0.000	Maximum
FOST-1	100%	1.573	1.573	1.573	1.573	13.325	-2.525	2.000	0.000	Maximum
FOST-2	100%	1.573	1.573	1.573	1.573	13.325	2.525	2.000	0.000	Maximum
FPT	0%	8.037	0.000	8.037	0.000	60.087	0.000	0.372	0.000	Maximum
Total Load case			566.459	43.468	10.464	29.186	0.000	2.592	0.000	
FS correction								0.000		
VCG fluid								2.592		

Load case 2- Full load Arrival-10% Fuel and Freshwater
Damage Case - Intact
Free to Trim
Specific gravity = 1; (Density = 1 tonne/m^3)
Fluid analysis method: Use corrected VCG

Item Name	Quantity	Unit Mass tonne	Total Mass tonne	Unit Volume m^3	Total Volume m^3	Long. Arm m	Trans. Arm m	Vert. Arm m	Total FSM tonne.m	FSM Type
Lightship	1	475.770	475.770			29.000	0.000	2.750	0.000	Maximum
261 nos Passenger main deck	1	0.075	0.075			30.000	0.000	3.390	0.000	Maximum
154 nos Passenger Upper deck	1	0.075	0.075			40.000	0.000	5.790	0.000	Maximum
40 nos Passengers Bridge deck	1	0.075	0.075			35.000	0.000	8.190	0.000	Maximum
Cargo Hold -1	1	15.000	15.000			20.000	0.000	1.000	0.000	Maximum
Cargo Hold-2	1	25.000	25.000			36.000	0.000	1.000	0.000	Maximum
Cargo Hold-3	1	30.000	30.000			45.000	0.000	1.000	0.000	Maximum
Store	0.1	5.000	0.500			12.000	0.000	3.200	0.000	Maximum
Freshwater Tank	0.1	5.000	0.500			10.000	0.000	10.460	0.000	Maximum
APT	0%	24.967	0.000	24.967	0.000	2.734	0.000	1.121	0.000	Maximum
FORT	10%	7.319	0.732	7.319	0.732	3.660	0.000	1.230	8.000	Maximum
FOST-1	10%	1.573	0.157	1.573	0.157	13.325	-2.525	1.550	0.448	Maximum
FOST-2	10%	1.573	0.157	1.573	0.157	13.325	2.525	1.550	0.448	Maximum
FPT	0%	8.037	0.000	8.037	0.000	60.087	0.000	0.372	0.000	Maximum
Total Load case			548.041	43.468	1.046	29.876	0.000	2.532	8.897	
FS correction								0.016		
VCG fluid								2.549		

Load case 3- Ballast departure-100% Fuel and Freshwater
Damage Case - Intact
Free to Trim
Specific gravity = 1; (Density = 1 tonne/m^3)
Fluid analysis method: Use corrected VCG

Item Name	**Quantity**	**Unit Mass tonne**	**Total Mass tonne**	**Unit Volume m^3**	**Total Volume m^3**	**Long. Arm m**	**Trans. Arm m**	**Vert. Arm m**	**Total FSM tonne.m**	**FSM Type**
Lightship	1	475.770	475.770			29.000	0.000	2.750	0.000	Maximum
261 nos Passenger main deck	0	0.075	0.000			30.000	0.000	3.390	0.000	Maximum
154 nos Passenger Upper deck	0	0.075	0.000			40.000	0.000	5.790	0.000	Maximum
40 nos Passengers Bridge deck	0	0.075	0.000			35.000	0.000	8.190	0.000	Maximum
Cargo Hold -1	0	15.000	0.000			20.000	0.000	1.000	0.000	Maximum
Cargo Hold-2	0	25.000	0.000			36.000	0.000	1.000	0.000	Maximum
Cargo Hold-3	0	30.000	0.000			45.000	0.000	1.000	0.000	Maximum
Store	1	5.000	5.000			12.000	0.000	3.200	0.000	Maximum
Freshwater Tank	1	5.000	5.000			10.000	0.000	10.460	0.000	Maximum
APT	100%	24.967	24.967	24.967	24.967	1.474	0.000	2.526	0.000	Maximum
FORT	100%	7.319	7.319	7.319	7.319	3.526	0.000	1.876	0.000	Maximum
FOST-1	100%	1.573	1.573	1.573	1.573	13.325	-2.525	2.000	0.000	Maximum
FOST-2	100%	1.573	1.573	1.573	1.573	13.325	2.525	2.000	0.000	Maximum
FPT	100%	8.037	8.037	8.037	8.037	60.922	0.000	2.352	0.000	Maximum
Total Load case			529.238	43.468	43.468	27.401	0.000	2.794	0.000	
FS correction								0.000		
VCG fluid								2.794		

Load case 4- Ballast Arrival-10% Fuel and Freshwater
Damage Case - Intact
Free to Trim
Specific gravity = 1; (Density = 1 tonne/m^3)
Fluid analysis method: Use corrected VCG

Item Name	Quantity	Unit Mass tonne	Total Mass tonne	Unit Volume m^3	Total Volume m^3	Long. Arm m	Trans. Arm m	Vert. Arm m	Total FSM tonne.m	FSM Type
Lightship	1	475.770	475.770			29.000	0.000	2.750	0.000	Maximum
261 nos Passenger main deck	0	0.075	0.000			30.000	0.000	3.390	0.000	Maximum
154 nos Passenger Upper deck	0	0.075	0.000			40.000	0.000	5.790	0.000	Maximum
40 nos Passengers Bridge deck	0	0.075	0.000			35.000	0.000	8.190	0.000	Maximum
Cargo Hold -1	0	15.000	0.000			20.000	0.000	1.000	0.000	Maximum
Cargo Hold-2	0	25.000	0.000			36.000	0.000	1.000	0.000	Maximum
Cargo Hold-3	0	30.000	0.000			45.000	0.000	1.000	0.000	Maximum
Store	0.1	5.000	0.500			12.000	0.000	3.200	0.000	Maximum
Freshwater Tank	0.1	5.000	0.500			10.000	0.000	10.460	0.000	Maximum
APT	100%	24.967	24.967	24.967	24.967	1.474	0.000	2.526	0.000	Maximum
FORT	10%	7.319	0.732	7.319	0.732	3.660	0.000	1.230	8.000	Maximum
FOST-1	10%	1.573	0.157	1.573	0.157	13.325	-2.525	1.550	0.448	Maximum
FOST-2	10%	1.573	0.157	1.573	0.157	13.325	2.525	1.550	0.448	Maximum
FPT	100%	8.037	8.037	8.037	8.037	60.922	0.000	2.352	0.000	Maximum
Total Load case			510.820	43.468	34.050	28.076	0.000	2.738	8.897	
FS correction								0.017		
VCG fluid								2.755		