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WORLD MARITIME UNIVERSITY
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THE ENERGY EFFICIENCY OF MARITIME AUTONOMOUS SURFACE SHIP (MASS)

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A dissertation submitted to the World Maritime University in partial fulfilment of the requirements for the reward of the degree of

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in
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(MARITIME ENERGY MANAGEMENT)

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Declaration

I certify that all the material in this dissertation that is not my own work has been identified, and that no material is included for which a degree has previously been conferred on me.

The contents of this dissertation reflect my own personal views, and are not necessarily endorsed by the University.

(Signature): **..**

(Date): **...**

Supervised by: **Professor Dr. Aykut Ölcer**

Supervisor's affiliation: **Head of Maritime Energy Management Specialization**

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Abstract

Title of Dissertation: **The energy efficiency of Maritime Autonomous Surface Ship (MASS)**

Degree: **Master of Science**

The world is facing a tangible threat from climate change caused by the overconcentration of greenhouse gas (GHG) emissions in the atmosphere. The Paris Agreement, which came into force in 2016, has promoted the world's efforts in GHG reduction to keep the earth's temperature increase below 1.5 °C compared to the pre-industrial level. As a result, "Initial IMO strategy on reduction of GHG emissions from ships" was adopted by the International Maritime Organization (IMO), targeting to reduce annual GHG emissions by at least 50% in 2050 compared to 2008 and to phase them out as soon as possible in this century. Various technical and operational energy saving measures were proposed for application onboard ships. The recent development of an autonomous ship also promises a significant advantage in energy savings and the minimization of GHG emissions.

The Energy Efficiency Design Index (EEDI) analysis was carried out for ships of three types: bulk carrier, oil/chemical tanker and container ship in two cases, when they are conventional ships and autonomously operated. Data was collected from 49 existing ships of those types built from 1977 to 2012 and had a deadweight ranging from 3,000 to 105,000 tons. The analysis was based on a general knowledge of naval architecture and assumption of equivalency in safety and operation between autonomous and conventional ships. The radical deviation of the autonomous ship from the conventional ship was investigated to find out that the autonomous ship is more energy-efficient than the conventional ship on one hand, but on the other hand, it may have some disadvantages that decrease the efficiency due to stricter rules which may be applied to compensate the crew's absence. However, the calculation has shown that the advantage of the autonomous ship is more prominent. Considerable EEDI reduction was achieved for autonomous ships of all types and sizes. Nevertheless, the larger the ship is, the less energy efficiency (EE) autonomous operation will bring. Besides, the autonomous ship is also seen to have more potential in improving its energy efficiency.

The autonomous ship's role was also discussed in the context of the IMO ambition for GHG reduction. Although the autonomous ship is seen to attain more energy efficiency than the conventional ship, it is not really a game-changer. That means, to phase out the GHG emissions from shipping, additional measures such as alternative fuels or electrical energy are still required.

KEYWORDS: MASS, Autonomous ship, EEDI, Energy efficiency, Ship design

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List of Abbreviations

ABS	American Bureau of Shipping
AI	Artificial Intelligence
COLREGS	International Regulations for Preventing Collisions at Sea
CS	Conventional Ship
DWT	Deadweight
EE	Energy efficiency
EEDI	Energy Efficiency Design Index
EEOI	Energy Efficiency Operational Indicator
EEXI	Energy Efficiency Existing Ship Index
FRP	Fiber-Reinforced Plastic
GHG	Greenhouse Gas
GT	Gross Tonnage
HP	Horse Power
IEA	Agency International Energy
IMO	International Maritime Organization
LNG	Liquefied Natural Gas
Load Lines	International Convention on Load Lines
MARPOL	International Convention for the Prevention of Pollution from Ships
MASS	Maritime Autonomous Surface Ship
MBM	Market-Based Measure
MCR	Maximum Continuous Rating
MEPC	Marine Environment Protection Committee

PDCA	Plan, Do, Check and Act
S&DH	Superstructure and Deck house
SOLAS	The International Convention for the Safety of Life at Sea
UNCTAD	United Nations Conference on Trade and Development
UNFCCC	United Nations Framework Convention on Climate Change
VR	Vietnam Register

Chapter 1 - Introduction

1.1 Background information

Greenhouse Gas (GHG) comprising natural and anthropogenic GHG is believed to be the most active driver of global warming, which causes the rising of the earth's temperature and sea level. In turn, global warming has resulted in climate change, which is observed to cause natural disasters of heavy consequence like floods and super storms (IEA, 2015). Therefore, quickly abating GHG from human activities is one of the top priorities in this Century to keep the earth's temperature at a safe limit.

Shipping is seen to be a very fuel-efficient means of transport with respect to GHG emission. More than ninety percent of global trade by volume is conducted by seaborne transportation (Oceana, 2018). Conversely, international shipping is responsible for only 2.02% of the world anthropogenic GHG emission, estimated to be 740 million tons of CO2 equivalent in 2018 (Faber, et al., 2020). However, GHG from ships is predicted to continually increase in the near future. Faber, et al. (2020) argue that CO2 emission from shipping in 2050 will be equal to 1.9 to 2.3 times that of 2008, while, previously, Hoen et al. (2017) estimated the emission increase rate at about 1.2 to 2.2 times in 2050 compared to 2012, depending on the world economic situation and the management of maritime energy. If a scenario of no effective abatement measures is adopted, Cames et al. (2015) predict that, by 2050, CO2 emissions from international shipping will account for around 17% of the global total.

To abate GHG from anthropogenic sources, global scale actions have been triggered by international institutions in general and the IMO in particular. The Paris Agreement was adopted in 2015 by UNFCCC members and came into force in 2016. This Agreement's long-term goal is to keep the earth's average temperature increase at less than 2 °C higher than the pre-industrial level and to find measures to keep this temperature increase well below 1.5 °C. The IMO first took shipping GHG reduction targets into consideration at MEPC 59 and 60 but then postponed to MEPC 68 in 2015 (IMO, 2015a). Among the follow-up actions, MEPC 70 approved a "Roadmap for developing a comprehensive IMO strategy on the reduction of GHG emissions from ships" (IMO, 2016a). Following the roadmap, an “Initial IMO strategy on reduction of GHG emissions from ships” was adopted by MEPC 72 (IMO, 2018a).

One of the most noticeable IMO instruments in reducing GHG emissions from ships is the regulation on the Energy Efficiency Design Index (EEDI). These regulations were introduced into Chapter 4 of Annex VI of MARPOL at MEPC 62 and entered into force on 1 January 2013. EEDI has become a standard criterion by which to evaluate the energy efficiency (EE) of a newly built ship based on its design characteristics and sea trial results (IMO, 2011a).

EEDI requirements have encouraged the ship building industry to improve the EE of new ships by utilizing new technologies and the ship owners are completely free in choosing the energy saving measures as long as the ship’s required EEDI is satisfied. McMillan and Jabaro (2011) have investigated all feasible energy saving measures applicable for new ship design with percentage of savings ranging from 2% to 30%. The three best candidate measures are Flettner rotors (30%), towing kite (26%) and engines running on LNG (20%). The IMO has also carried out an assessment on the availability and readiness of most applicable energy saving measures where the reduction in CO2 emission can reach 22% for ships installed with gas-fueled engines (IMO, 2015b).

Due to the Fourth Industrial Revolution's impact, autonomous shipping is day by day becoming a reality, triggered by several prototype tests in recent years. The autonomous operation of ships is expected to increase EE, and hence it promises a prospect for a sustainable shipping industry (Johns, 2018; WMU, 2019).

1.2 Problem statements/ motivation

In the past, cargo ships were designed to meet their purposes, maximize the deadweight and, foremost, satisfy the safety criteria. However, today, under the pressure of environmental protection, constant development of science and higher standard for human’s livings, the design and operation of cargo ships have to address many issues and there is no space for the business-as-usual trade-off. Besides, due to the explosion of the Fourth Industrial Revolution, where smart machines will replace humans in every aspect of life, the future domination of Maritime Autonomous Surface Ships (MASS) in shipping is inevitable.

The IMO first set its targets on GHG emission reduction by revising MARPOL Annex VI at MEPC 62. This amendment of Annex VI entered into force from 1 January 2013, concentrated on the EE of new ships (by an instrument of EEDI requirements) and EE in operations of all ships (by an instrument of SEEMP). Newly built ships are required to have a reduction in CO2 emissions per transport work of up to 30% from 1 January 2025 compared to the reference line (IMO, 2011a). The IMO is also ambitious to reduce total CO2 emissions from shipping in 2050 to 50% of the 2008 level (IMO, 2018a). This ambition has presented a big challenge for naval architects worldwide to design new ships with satisfactory EE. Several EE improving measures for ships were identified at MEPC 68 (IMO, 2015b) but the application of those was challenging. Thus more measures should be found to actualize the IMO's ambition.

The EE is believed to play an essential role in the abatement of anthropogenic CO2 emissions. To achieve the 450-scenario, in which the CO2 content in the atmosphere must be kept at 450 parts per million to limit the global temperature increase to 2 °C, the EE should contribute almost 50% to the CO2 reduction (IEA, 2010). Therefore, it would not be an exaggeration to say that the future ship will have an energy-efficiency-oriented design. Wijnolst and Wergeland (2009) have used an S-curve to describe the development of technology and innovation in ship design. For example, the development of ships' propulsion systems has drawn four S-curves, in which the first is human and wind power, the second is steam power, the third is internal combustion engine and the last is alternative fuel. Likewise, the said S-curve theory may also be applied to the evolution of a ship's automation. A conventional ship (CS) is seen to be more and more automated and digitally supported. Whereas on the ships of old days all onboard jobs were done manually, modern ships have reduced-to-the-most-extent crews and are highly automated. The automation is found to be one of the factors that can contribute to an energy-efficient ship (Kabir, 2017). If considering the CS as being on the first S-curve of automation, whether a MASS will start a new S-curve may raise questions that require answers.

Due to the need for better well-being of seafarers, the Maritime Labour Convention, 2006 came into force on 20 August 2013 (ILO, 2013) to provide decent working condition for seafarers. The regulations of this Convention, inter alia, require a ship to have a larger and better equipped accommodation area, which makes the ship's superstructures and deckhouses heavier and hence reduces the EE of the ship.

Along with the history of the shipping industry, most maritime casualties are related to human factors. The US Coast Guard estimated that about 75 to 96 percent of ship-related accidents are wholly or partially caused by humans (Rothblum, 2000). The development of technologies supporting navigation is believed to decrease the frequency of marine accidents involving human error (Hetherington et al. , 2006).

The operation of a MASS without crew onboard is expected to address at least the above-mentioned issues. This dissertation is motivated by the potential capability of a MASS to be more energy efficient than a CS and by a belief that the MASS will create a new S-curve in ship automation and lay the foundation for a future of sustainable and carbon neutralized shipping industry.

1.3 Aims and Objectives

This dissertation aims to determine how much more energy-saving a MASS can attain than a CS of the same size and purpose based on attained EEDI of the ships.

Additionally, assessment is also made on the contribution of MASS to the fulfillment of the IMO GHG reduction targets.

1.4 Research questions and hypothesis

This research will answer the following questions:

- How much energy efficiency can a MASS attain compared to CS in terms of attained EEDI?

- How can a MASS feasibly comply with the IMO's EE regulations and GHG cut-down road map?
- How much potential is there for a MASS to improve its EE in the future?

A set of existing CSs is chosen for the analysis. Subsequently, a model of MASS is built up based on a hypothesis that a MASS should have equivalent safety and operational capability compared to a CS.

1.5 Research Scope

The research focuses on the EE in design (operational aspect is outside the scope) of MASS compared to CS regarding the following three types:

- Bulk carriers: Ships defined in regulation 2.25 of MARPOL Annex VI;
- Oil/chemical tankers: Tankers defined in regulation 2.27 of MARPOL Annex VI;
- Container ships: Ships defined in regulation 2.28 of MARPOL Annex VI.

MASSs of levels 3 and 4 (no crew onboard) in accordance with the IMO's classification of MASSs (see section 2.4) are the objects of this study.

In the context of the ultimate purpose to abate anthropogenic GHG, the EE of a ship in this dissertation is interpreted by the possibility to reduce the amount of CO2 emitted when carrying out one transport work. Alternatively speaking, the EEDI of a ship is used as a benchmark for the analysis.

1.6 Research Outline

This dissertation employs a quantitative method, the steps of which are as follows:

- Analyzing the differences in design characteristics of MASSs and CSs.
- Collecting data on CSs of three types: bulk carrier, oil/chemical tanker and container ship.
- Building up the model of MASS with equivalency in operational capability and safety.
- Calculating the reduction in attained EEDI between MASS and CS.

- Identifying energy-saving measures that can be feasibly applied to MASS in the future and assessing its role in the context of the IMO GHG reduction roadmap.
- Drawing out the conclusions.

The outline of the research steps is illustrated in Figure 1 below.

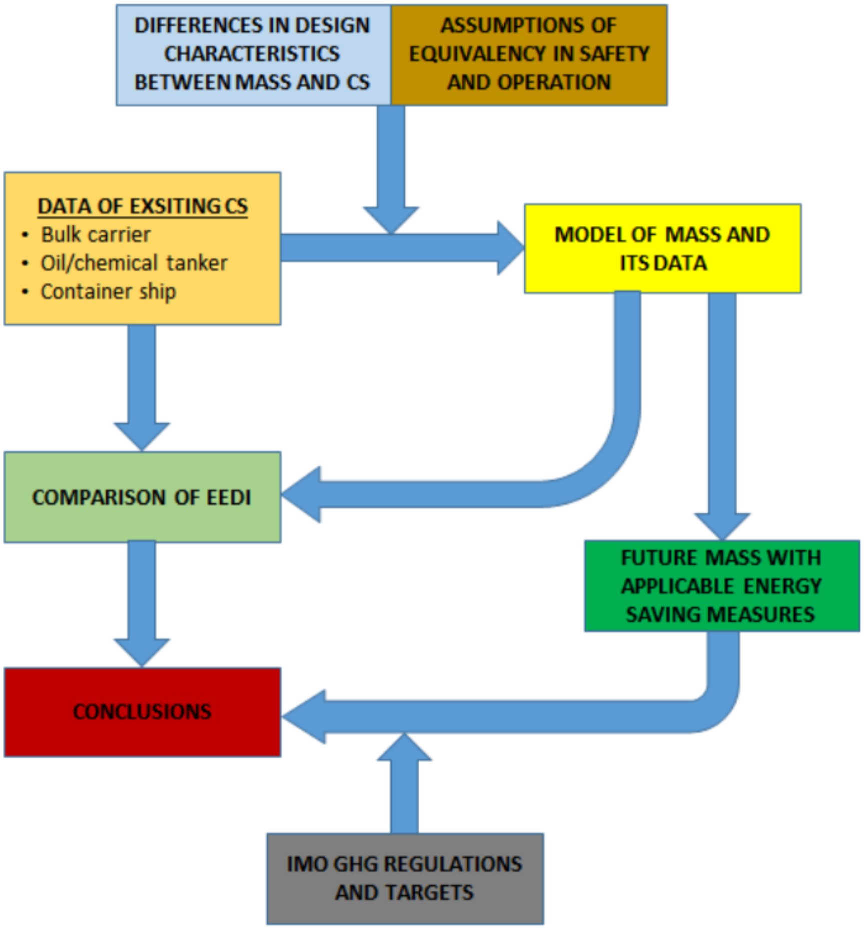


Figure 1 – Research outline

Chapter 2 – Literature Review

2.1 General

This Chapter discusses the IMO ambition and road map in reducing GHG emissions from shipping and how emissions are being and will be regulated with respect to ship design. This literature review will provide the IMO GHG legal framework context to analyze the role of MASS.

The discussion also extends to feasible measures to increase the EE of cargo ships in the design stage. From this review, a comparison will be made between the energy saving of MASS and those measures. In addition, this is also a base to assess their applicability to MASS and estimate the EE of the future MASS.

Finally, the evolution of MASS from the past to the present is summarized together with its prospects in attaining a significant energy saving compared to CS. Based on this, a comprehensive overview of MASS development and trends will be provided.

2.2 The IMO regulations and targets on GHG emission

In the context of growing evidence that carbon dioxide causes global warming, the international community is acting to address GHG emissions from anthropogenic sources. The IMO took its first step in September 1997 when the MARPOL 1997 Conference took place. Resolution 8 of the Conference recognized the adverse effect of CO2 on the earth and further realized that the current Annex VI of MARPOL did not yet regulate CO2 emissions from shipping. Based on the facts above, the IMO promoted and urged member states to join the studies on CO2 emissions and assigned MEPC to identify feasible measures and strategies to reduce seaborne CO2 emissions (IMO, 1997). Since then, many milestones have been passed, as presented in Table 1.

Table 1 – Timeline of the IMO efforts on abatement of GHG from shipping

Time milestone	MEPC meeting	The IMO actions	Remarks
Sept. 1997		Res. 8 of the 1997 MARPOL Conference on CO2 from ship	Initiation of IMO actions on reduction of GHG emission from shipping

Time milestone	**MEPC meeting**	**The IMO actions**	**Remarks**
June 2000	MEPC 45	First IMO GHG study 2000	
Dec. 2003		Res. A.963(23) for the Policies and practices to reduce GHG from shipping	
June 2005	MEPC 53	MEPC/Circ.471: interim guidelines for CO2 operation index	
June 2008		GHG working group 1	
Feb. 2009		GHG working group 2	
July 2009	MEPC 59	• MEPC.1/Cir.681: Interim Guidelines Calculation of EEDI for New Ships • MEPC.1/Cir.682: Interim Guidelines for Verification of EEDI (voluntary) • MEPC.1/Cir.683: Guidance for establishment of SEEMP • MEPC.1/Cir.684: Guidelines for voluntary use of EEOI • Second IMO GHG study 2009	
June 2010		Energy Efficiency working group	
July 2011	MEPC 62	Res. MEPC.203(62): Amendments to MARPOL (new Chapter 4 and related amendments to other chapters)	Mandatory requirements on EEDI and SEEMP are adopted
Mar. 2012	MEPC 63	• Res.MEPC.212(63): Guidelines on the Calculation EEDI for New Ships • Res.MEPC.213(63): Guidelines for the establishment of SEEMP • Res.MEPC.214(63): Guidelines on Survey and Certification EEDI	
1 Jan. 2013		Regulations on Energy Efficiency for Ships (Res. MEPC.203(62)) came into force	
May 2013	MEPC 65	• Res.MEPC.231(65): Guidelines for Reference Lines of EEDI • Res.MEPC.232(65): Interim Guidelines for Minimum Propulsion Power of ships • Res.MEPC.233(65): Guidelines for Reference Lines of EEDI for Cruise Passenger Ships with Non-Conventional Propulsion • MEPC.1/Cir.815: Guidance on Treatment of Innovative EE Technologies for Attained EEDI • MEPC.1/ Cir.816: Guidance on Survey and Certification of the EEDI	
Mar. 2014	MEPC 66	• Res.MEPC.251(66): Amendments to MARPOL • Res.MEPC.245(66) – Guidelines on the Calculation of the EEDI for New Ships	
Oct. 2014	MEPC 67	Third IMO GHG study 2014	
May 2015	MEPC 68	Debate on Monitoring, Reporting and Verification (MRV)	

Time milestone	MEPC meeting	The IMO actions	Remarks
Oct. 2016	MEPC 70	• IMO Roadmap for GHG emission was approved. • Res.MEPC.278(70): – Amendments to MARPOL (Data collection system for fuel oil consumption of ships)	Ships having GT of 5000 and above are required to report the fuel oil consumption and associated data (traveled distance, cargo weight carried…)
April 2018	MEPC 72	Res.MEPC.304(72): Initial IMO strategy on reduction of GHG emissions from ships	
Oct. 2018	MEPC 73	Program of follow-up actions for the Initial IMO Strategy up to 2023 was approved	

Note:

1 Data in the Table is retrieved from Bazari (2016) and IMO (2020).

2 Green rows are important milestones.

The first significant milestone is the adoption of a new Chapter IV in Annex VI of MARPOL in July 2011, aiming to improve the EE of ships through technical and operational measures. The legal framework includes EEDI for new-built ships of specific sizes and types, and SEEMP for all ships in operation having a gross tonnage of 400 and above. EEDI regulations require the new ships to attain a specified reduction in EEDI compared to the base index and are implemented in phases. The ships shall reduce CO2 emissions by up to 10% from 1/1/2015, 20% from 1/1/2020 and 30% from 1/1/2025. SEEMP can be understood as an energy plan in which a mechanism is established for the operators to improve the ship's energy consumption through cost-effective measures. Approaches are also recommended to monitor the energy performance of ships over time. It is expected that SEEMP will have a positive effect mainly in the short and medium-term. In contrast, EEDI will significantly impact long-term CO2 abatement once the energy-inefficient fleet is replaced by an EEDI compliance one. It is estimated that, if those regulations are effectively implemented, a yearly CO2 emission saving of 1.3 gigatons will probably be attained by 2050 compared to the business-as-usual scenario. This amount of savings is equivalent to around 3.6% of the global CO2 emission in 2012 (IMO, 2011b; IMO, 2011a; UNCTAD, 2018).

At the MEPC 70 meeting in October 2016, the IMO stepped to a more methodical and strategic approach in GHG abatement from shipping by adopting a roadmap for the reduction of GHG. Activities and further GHG studies with associated timelines of the roadmap provide a way toward the adoption of a 2023 revised strategy (IMO, 2016a). Also, on this occasion, a crucial amendment was made to the existing Regulation 22 of Annex VI to require ships with GT of 5,000 and above to include in the SEEMP a methodology to collect and report to the administration fuel consumption data, which is called SEEMP Part II. Regulation 22A was also supplemented to give instructions on the collection and reporting of ship's fuel consumption (IMO, 2016b). These amendments would facilitate further IMO GHG studies by providing input for the bottom-up analysis and are the basis for a transparent, objective and inclusive policy debate of the MEPC (UNCTAD, 2018).

The latest important milestone was marked by the adoption of "Initial IMO Strategy on reduction of GHG emissions from ships" in the MEPC 72 meeting, the vision of which is to urgently phase out seaborne GHG emissions in the 21st century. The IMO's ambition is targeted by the average reduction of CO2 per transport work of 40% by 2030 and 70% by 2050, corresponding to the 2008 level. Annual GHG emissions from international shipping are targeted to peak and decline as soon as possible to at least 50% by 2050 in relation to 2008 (IMO, 2018a).

In addition to the afore-mentioned adopted GHG abatement measures, new regulations may be approved and come into force in the near future. Among those, the IMO is considering to strengthen and expand the scope of existing regulations. EEDI regulations may be enhanced by increasing the GHG reduction percentage for phase 3 of implementation, especially for container ships, which have a significant potential for EEDI reduction due to their relatively high service speed (IMO, 2018b). Furthermore, the coverage of EEDI requirements is also being considered by the proposal for the introduction of phase 4 (IMO, 2019a) and EEDI for existing ships which is called EEXI (IMO, 2019b). Apart from current technical and operational measures, a new one based on the principle of "polluter pays" is expected to be an effective long term measure, known as a market-based measure (MBM) (Ölçer et al., 2018).

2.3 Energy efficiency of a ship and feasible technical saving measures

In general, EE means the possibility to save the energy consumed for a specific operation. A ship attaining EE means a ship consumes the least energy while carrying a certain amount of cargo along a certain shipping distance. So the most reasonable benchmark to assess the EE of a ship should be the amount of energy consumed per transport work (e.g., MJ/ton-mile), based on which the less is the better.

EE in shipping has a number of benefits. Firstly, the operator will save on fuel costs. Secondly, it will have a positive externality on the global environment, which is proportional to the amount of fuel cut-down. In the context of the IMO's effort to reduce GHG emissions from the shipping industry, the EE of a ship is also interpreted as the saving in the amount of CO2 emitted per transport work (gCO2/ton-mile). So it can be said that the ship nowadays is not only designed to reduce energy consumed but also aims to abate CO2 emissions. As already discussed in section 2.2, the IMO has been using EEDI to indicate the energy-saving capability of a ship.

Attained EEDI of a ship is provided in Regulation 20 of Annex VI of MARPOL, and the detailed guidance for the calculation is given in Resolution MEPC.245(66) (IMO, 2014). Attained EEDI is expressed by the following formula.

$$\frac{\left\{\begin{array}{c} \left(\prod_{j=1}^{n} f_i\right)\left(\sum_{i=1}^{nME} P_{ME(i)}\, CF_{ME(i)} SFC_{ME(i)}\right) + \left(P_{AE} CF_{AE} SFC_{AE}\right) \\ +\left[\left(\prod_{j=1}^{n} f_i \cdot \sum_{i=1}^{nPTI} P_{PTI(i)} - \sum_{i=1}^{neff} f_{eff(i)} \cdot P_{AEeff(i)}\right) CF_{AE} \cdot SFC_{AE}\right] \\ -\left(\sum_{i=1}^{neff} f_{eff(i)} \cdot P_{eff(i)} \cdot CF_{ME} \cdot SFC_{ME}\right) \end{array}\right\}}{f_i \cdot f_c \cdot f_l \cdot Capacity \cdot f_w \cdot V_{ref}} \tag*{Equation 1}$$

The explanations of elements in the above formula can be found in Resolution MEPC.245(66). Briefly speaking, attained EEDI is the mass of CO2 emitted for each unit of transport work that the ship finishes (generally expressed as grams of CO2 per ton-mile). The above formula numerator is called "environmental cost" while the denominator is called "Benefit for Society".

For simplification and easy understanding, attained EEDI can be expressed by the following formula (Bazari, 2016).

$$Attained\ EEDI = \frac{CO_2\ emission}{transport\ work} = \frac{Engine\ power \times SFC \times C_F}{DWT \times speed} \qquad Equation\ 2$$

Where:

SFC is the fuel consumption of the engines taken into account;

C_F is the carbon factor, depending on the fuel type used by the engine;

DWT represents the ship's carrying capacity.

It can be seen from *Equation 2* above that attained EEDI depends on the power of all machines that may emit CO2 during the normal operation of a ship, as well as the fuel consumption and type of fuel they use. In addition, attained EEDI can be reduced when the ship carries more and runs faster at the pre-set EEDI condition.

Theoretically, the less attained EEDI, the more EE of a ship is achieved. This section will identify probable technical measures to get a better EEDI and classify them into five groups of approaching methods presented in the following sections from 2.3.1 to 2.3.5.

2.3.1 Measures to increase the deadweight (DW) of the ship

As we know, DW of a ship is estimated by subtracting lightweight (LW) from the ship's displacement (Disp.), as follows:

$$DW = Disp. - LW$$

Based on the above formula, DW can be increased by generating a larger displacement or reducing the lightship's weight. In the context of the ship's EE, the increase of DW is only considered to be effective when other parameters of the ship are kept unchanged. In other words, with a particular ship of specific dimensions, the lighter the ship is, the more its EE is attained.

In ship design, there may be a number of ways to decrease the LW of a ship, e.g., utilizing light material for the construction of the ship or optimizing the ship's structural scantlings. Indicatively, it is supposed that a hull weight reduction of 20% may potentially result in a 9% decrease in engine power and up to 7% reduction in fuel consumption (Crist, 2009).

The reduction in LW can rely on using a material with better strength or smaller specific mass. On a cargo ship, the typical higher strength material for constructing the hull is high tensile steel. This will help reduce the scantling (thickness and dimensions) of the hull's structural members and, consequently, reduce the LW. It is estimated that the hull steel weight can be reduced by about 12% if the ship is constructed entirely of high tensile steel instead of mild steel (ABS, 2017). Materials that are lighter in specific mass and widely used in the ship construction are aluminum and fiber-reinforced plastic (FRP). Those light materials are more suitable for small fast crafts and the superstructures of cargo ships (McMillan & Jabaro, 2011).

2.3.2 Measures to increase the ship's speed

The advance speed of a ship in water is expressed by the following formula (Lewis, 1988):

$$V = \frac{P_E}{R_T}$$

Where:

P_E is the effective power, depending on the rated power of the main engine(s), the efficiency of transmission arrangement and propulsion device(s), as well as the intended safety margin.

R_T is the total resistance of the ship at speed V.

Looking at the afore-mentioned formula, V increases when P_E increases and/or R_T decreases. However, as P_E is proportional to the third exponent of V (Lewis, 1988), the increase of P_E will increase the engine power and, hence, the reduction in EEDI of ship will not be achieved. The most probable measures to decrease EEDI by improving speed V are to decrease the ship's total resistance R_T and how to do so will be discussed in this section.

A ship's total resistance can be decomposed into four main components: frictional resistance (R_F), wave-making resistance (R_W), eddy resistance (R_E) and air resistance (R_A), as expressed in the following formula (Lewis, 1988):

$$R_T = R_F + R_W + R_E + R_A$$

The friction resistance is caused by the motion of the ship's hull in a viscous liquid environment, while the wave-making component corresponds to the energy loss to create the wave system on the surface of the water. These two components constitute the major part of the total resistance. The remaining minor part is contributed by eddy resistance, characterized by the energy carried away by eddies shed from the appendages or even the hull, and air resistance created when the above-waterline parts of the ship move through the air (Lewis, 1988). To reduce the ship's total resistance, several technical measures can be used to minimize the aforementioned resistance components.

Regarding the reduction of the frictional resistance, hull dimensions can be optimized to achieve up to 10% reduction in fuel consumption (McMillan & Jabaro, 2011). With an optimized set of ship’s main dimensions, the ship’s form (or also called ship’s lines) can be further optimized to obtain more reduction in fuel consumption of about 5-8% (ABS, 2017). Ship’s speed can be considerably improved by an innovative technology using air bubbles to reduce the hull’s frictional resistance and hence, may result in a reduction of up to 15% for fuel consumption. Besides, special hull coating also reduces the resistance and achieves about 5% energy saving (McMillan & Jabaro, 2011).

The most popular measure to reduce wave-making resistance is to fit a bulbous bow in the forepart of the ship, resulting in a fuel-saving of up to 10% for ships having high Froude numbers. Furthermore, aft waterline extension, which is called "ducktail", is also an effective solution. This kind of appendage redistributes the pressure on the aft part of the hull, and hence, if properly applied, it will positively affect the wave system and help reduce propulsion power demand by 4-10% (McMillan & Jabaro, 2011).

A reduction in the ship's eddy resistance can be achieved by optimizing appendages (e.g. shaft line arrangement) or openings on the ship's hull (e.g. bow thruster tunnel, sea chest…). The fuel-saving for these measures is estimated to be from 1-5% (McMillan & Jabaro, 2011).

Air resistant (R_A) of a ship can be reduced considerably by optimizing the superstructure shape leading to a fuel saving of up to 5%. However, this measure is the most effective for a fast ship like high-speed craft where 2-5% energy saving may be attained. The application on slow cargo ships is more limited (around 1-2% saving may be achieved) due to the low speed of the ship and few alternatives in superstructure arrangement (IMO, 2015b).

2.3.3 Measures to decrease the engine power

As the propulsion engine's power is proportional to exponent three of ship's speed V in water (Lewis, 1988), a decrease in V will result in a greater decline in engine power. Hence the ship is more energy efficient in terms of EEDI. In other words, decreasing V is the most simple and effective way to save engine power and help the ship to attain better EEDI. Indicatively, a few knots reduction in speed may bring up to 23% reduction in fuel consumption (Crist, 2009). However, this section discusses only technical measures that allow the designer to choose less powerful engines while still keeping the ship's speed unchanged.

The needed power of a ship's main engine(s) depends partly on the propulsion devices' working efficiency. The more efficient the device is, the less engine power is demanded. Thus, increasing the working efficiency of those devices is a measure to gain better EEDI. If the hull and propeller interface is correctly optimized, the ship can obtain up to 4% saving in fuel consumption. The proper combination between the propeller and a rudder bulb may increase the efficiency of both and 6% power saving may be attained. Advanced propellers, e.g. those with winglets or contra-rotating ones, may have 3-6% higher efficiency than conventional propellers (McMillan & Jabaro, 2011).

The power demand on board a ship can be considerably relaxed by the support from external renewable energy like wind and solar. A towing kite tethered to the bow of a ship can pull the ship forward in a preferable wind condition and help to reduce fuel consumption by 2-3% for smaller ships and up to 26% for bigger ships. Fixed sail (or rigid wing sail) is another type of propulsion supportive device which is estimated in some studies to save fuel consumption from a few percent up to 30% during the ship's lifetime. The Flettner rotor is a vertical rotating cylinder, combined with the proper wind direction, producing the thrust to support the main propulsion. This technology is expected to save ship's fuel consumption by about 3.6% to 12.4%. In addition to wind energy, solar panels may be used to convert solar energy to electrical energy, which is then provided to the ship's general grid. It is estimated that solar energy can contribute up to 4% of the shipboard auxiliary power (Ariffin & Hannan, 2020; McMillan & Jabaro, 2011; Crist, 2009).

2.3.4 Measures to decrease the specific fuel consumption (SFC)

SFC depends on two factors that are engine quality and the combusted fuel type. The more energy content the fuel has, the less SFC is obtained. Likewise, a better engine will consume less fuel and hence obtains a smaller SFC. In this section, only measures that help increase the shipboard engine's EE are discussed.

By far, there are some technological measures to improve the EE of an engine. "Common Rail" is a technology where fuel injection is electronically controlled across all cylinders to yield greater atomization of fuel prior to its combustion. Thanks to this, fuel is completely burned, and the fuel can be saved up to 1%. Fuel additives can reduce soot produced in the combustion of the fuel and through this, fuel consumption is improved by up to 2% (McMillan & Jabaro, 2011).

2.3.5 Measures to decrease the carbon factor (C_F)

As carbon factors depend on the fuel type, C_F can only decrease when fuel is alternated. However, some issues need to be considered for alternative fuel relating to its EE and GHG abatement. Firstly, if the fuel has lower C_F but also lower energy content, the fuel consumption will increase and, hence, the GHG reduction may not be attained as expected. Secondly, life-cycle GHG emission also needs to be considered.

In the literature, there are many candidates for future marine alternative fuels. One of those is Liquefied Natural Gas (LNG), which has higher energy content and low carbon to hydrogen ratio and is expected to save approximately 20% in CO2 emissions. However, if the methane slip is not well managed, LNG's impact on GHG will not be as positive as it should be (McMillan & Jabaro, 2011). In addition to LNG, hydrogen is also a potential marine alternative fuel as it is totally free from carbon. Hydrogen can be produced by electrolysis of water using electrical energy from renewable sources and used in fuel cell technology or directly burned in the engine combustion chamber (Momirlan & Veziroglu, 2005). Similar to hydrogen, ammonia (NH3) is also a zero CO2 emitting fuel and is seen to be used with HFO as dual fuel to save 27% of CO2 emissions per ship's transport work if a full life cycle is considered (Bicer & Dincer, 2018). Another potential candidate for the marine alternative fuel is methanol, which is claimed to have a life cycle impact on global warming of about 25% compared to HFO when produced from biomass (Brynolf et al., 2014). The most advantageous property of the four mentioned alternative fuels is that they can all be synthesized from renewable sources. Therefore, from the lifecycle GHG emission perspective, all of them may be considered carbon neutral in certain cases (Kirstein et al., 2018).

2.4 Development of Maritime Autonomous Surface Ship and its energy efficiency

Human history has completely passed through three industrial revolutions and the fourth one is being formed. The first revolution was triggered by the steam engine's invention between the 18th and 19th centuries, resulting in a partial replacement of human labor by machinery. From the late 19th century to the beginning of the 20th, the invention of mass production and electricity marked the formation of the second industrial revolution. Not so long after that, by the second half of the 20th century, human life was once again radically changed by the application of automation, electronics and IT systems, which was called the third industrial revolution. The fourth one (or Industry 4.0) was born in the early 21st century with completely new concepts, such as the internet of things, big data, artificial intelligence and autonomous devices (Popkova et al., 2019).

As a result of Industry 4.0 and Artificial Intelligence (AI), smart machines are replacing human labor. Therefore, the trend of the unmanned remote-controlled vehicle in general and ship, in particular, is inevitable.

First of all, the concept of an autonomous ship should be made clear. Generally, autonomy can be understood as the capability of a system to do a specific task independently. Therefore, in the shipping context, an autonomous ship implies a ship that can carry the cargo between seaports without human support during the operation of the ship (Rødseth, 2017). As the autonomous ship is a technological breakthrough in naval architecture, current international technical regulations need to be reviewed and updated. To do that, a so-called "scoping exercise" is being carried out by the IMO and the term "Maritime Autonomous Surface Ship" (MASS) is used to refer to those kinds of ships. Depending on the degree of autonomy, MASSs can be divided into four levels (IMO, 2018c) as follows:

- Level 1: Ship has a certain number of automated systems but the crew is maintained on-board to take control when needed.
- Level 2: Ship is remotely controlled with crew on-board to assume the control in case of an emergency.
- Level 3: Ship is completely remotely controlled without crew on-board.
- Level 4 (Autonomous): The ship can make a decision and react by itself. The onshore operators only intervene in case of the system on-board fails.

Since the last decade, a considerable number of autonomous cargo ship projects have been deployed, including container ships, bulk carriers and general cargo ships.

According to Rødseth (2017), MUNIN ("Maritime Unmanned Navigation through Intelligence in Networks") is the first autonomous ship project, which began in 2012. Besides the financial saving for crew costs, the project's benefit on the environment is also pointed out. It is supposed that the ship's EE is generated by the automatic energy management system and improvement in routing and navigational capability. Besides, the omission of superstructures and deckhouses also promises a large contribution to the ship's EE (MUNIN, 2016). Figure 2 shows the concept of the project's autonomous ship.

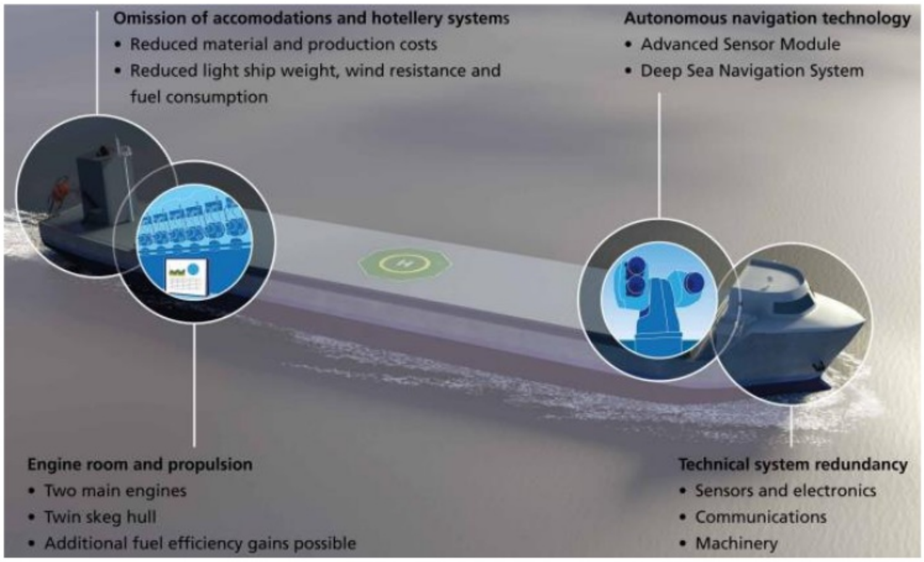


Figure 2 – A concept of autonomous ship of MUNIN (Source: MUNIN (2016))

ReVolt is another project on an autonomous 100 TEU container carrier developed by DNV-GL, initiated in 2013. This project focused on short sea shipping with an operational range of 100 nautical miles. As the absence of crew facility on-board creates an increase in carrying capacity and decrease in annual operational cost, the ship is claimed to save up to $34 million in its lifetime of 30 years (DNV-GL, 2014).

The world's first project on a fully electrical autonomous ship is the YARA Birkeland, a 120 TEU container ship. It is designed to be a zero-emission ship and has no ballast tank, using battery packs as permanent ballast. The ship is expected to be put into service as a semi-autonomous ship by 2020 and fully autonomous from 2022 (Kongsberg, 2017).

Rolls-Royce plans to launch a remote-controlled ship with a reduced crew and certain functions supported from shore in 2020. Moreover, the corporation has the ambition to operate un-crewed short sea ships in 2025 and deep-sea ships in 2030. A fully autonomous ocean-going ship is expected to be put in service in 2035 (Rolls-Royce, 2016).

A project of a remotely supported 2,500 TEU feeder ship developed by "Green Ship of the Future and Odense Maritime Technology" is claimed to achieve a 30% reduction in EEDI compared to an equivalent conventional ship. This project ship is expected to go beyond the phase-3 EEDI requirements, which come into effect from 2025. To obtain such an EE, the ship (see Figure 3) is designed with a reduced accommodation area for the crew, combined with other measures such as main engines using LNG, air lubrication, and PTO shaft generator (GreenShip, 2016).

Figure 3 – The concept of level 3 autonomous ship (Source: GreenShip (2016))

According to Daffey (2017), a 20,000 DWT autonomous general cargo ship designed by Rolls-Royce can have a reduction of from 700 to 1,000 tons in its lightweight, 1% in wind resistance and from 200 to 270 kW in the hotel load. This design is claimed to save 10% to 15% fuel compared to an equivalent conventional ship. The ship is described with no accommodation block, redundant machinery, increased automation and sensors, more cargo carried and lower power demand.

Few pieces of research are seen to investigate the MASS's EE in detail. Most of them tend to point out the economic benefit of the MASS's operation. However, the MASS's EE can be partially revealed when its operational cost is evaluated. Kretschmann et al. (2017) estimated the cost of an autonomous Panamax bulk carrier to determine the cost reduction compared to the conventional ship of the same size and safety level. Kretschmann et al.'s MASS model was based on the previously mentioned MUNIN concept. In the calculation of fuel cost reduction, it was found that 6% of fuel consumption could be saved due to three main characteristics of a MASS, including air resistance reduction, hotel load elimination and less lightship weight.

Ait Allal et al. (2018) demonstrated the EE of a MASS by investigating the equipment that may not be needed on board or consume less energy. The evaluation is based on the equipment's rated power consumption and the weight of the ship's superstructures and deckhouses that will be eliminated if MASS is implemented. Specifically, this study shows that only by omitting the superstructures and deckhouses, an autonomous container ship of 212.6 m in length can save 0.83 tons of fuel per day, while an autonomous general cargo ship having a length of 106 m can save 0.063 tons per day. Besides, MASS is evaluated to save up to 74.5% in the sum of electrical energy consumed by all electrical devices. However, it should be noted that this study assumes MASS is designed with the non-ballast operation and no mooring equipment.

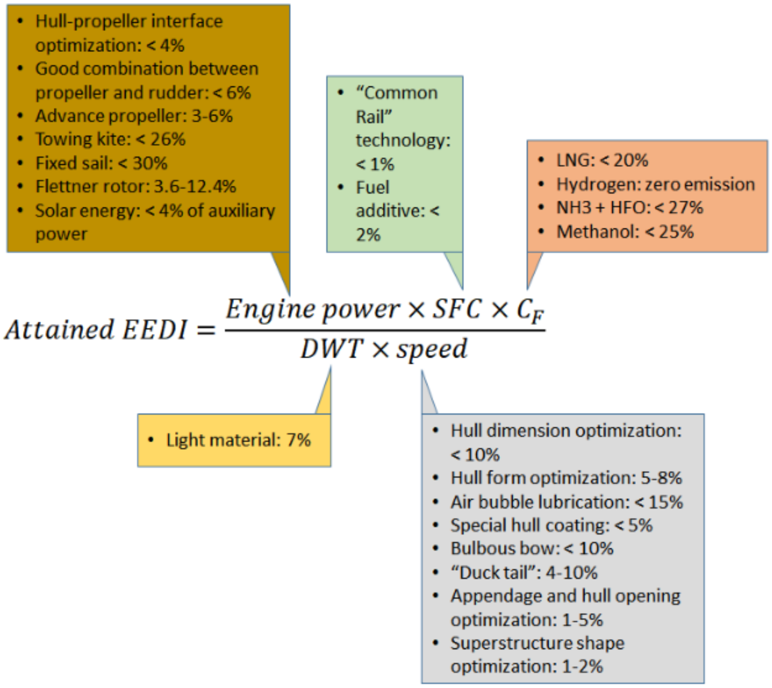
It is asserted by Lysyy et al. (2018) that MASS can help the operators to attain both environmental and economic goals by implementing slow steaming methods because, in the operation of a MASS, cost of the crew may be neglected. For CS, slow steaming's economic benefit is not high due to the extra cost for the crew to spend more time at sea.

2.5 Summary

By far, the only mandatory legal framework on GHG emission cut down is Chapter 4 of Annex VI MARPOL, in which EEDI requirements are applied to new ships of certain sizes and types and SEEMP to all ships having GT of 400 and above in operation. The current active phase of EEDI is phase 2, when every newly built ship is required to reduce the CO2 emissions by up to 20% compared to the baseline. The reduction percentage will be raised to 30% after 1 January 2025. For existing ships, in addition to the shipboard energy management plan (SEEMP Part I), data collection on fuel oil consumption is required (SEEMP Part II). In the near future, the IMO will consider strengthening and expanding the scope of these regulations and adopting new ones for long-term strategy. It may be said that the IMO's regulations will be more and more stringent for the ultimate target of phasing out CO2 emissions from the shipping industry in this century. Therefore, the ship must be designed and built with more and more EE.

In can be seen that the latest approach of the IMO on the GHG issue is in line with a PLAN-DO-CHECK-ACT (PDCA) cycle. The PLAN phase is formed by the IMO's strategy, targets and action plans based on the reported ship's fuel consumption review. The DO phase will implement those proposed actions through mandatory regulations and guidelines. Finally, the CHECK phase is carried out mainly by the data collecting system and the ACT phase (or review phase) is done through periodical IMO GHG studies. This PDCA cycle will ensure continual improvement in addressing GHG emission issues of shipping.

The investigated GHG reduction measures can be categorized into five groups, as illustrated in Figure 4. Among those measures, ones that are related to the engine itself for improving the SFC are seen to be the least effective (just a few percent of saving). In contrast, measures that come from renewable energy (like wind and solar) show their high potential with up to 30% energy saving. It can be explained that diesel engine technology has been at its mature phase of development while the application of renewable energy onboard the ship is just at the infancy phase. Additionally, almost all abating measures in the literature review are seen to reduce GHG emissions to a certain extent. To decarbonize the shipping industry, alternative fuels may be one of the best options.



$$Attained\ EEDI = \frac{Engine\ power \times SFC \times C_F}{DWT \times speed}$$

Figure 4 – Summary of ship's GHG reduction measures and their estimated saving

The literature review has also revealed that MASS may attain some fuel consumption reductions, which are mainly the result of the ship's crew accommodation elimination. However, in most of the literature, the amount of ships' energy-saving is not quantified specifically through detailed approaches.

The study of Ait Allal et al. (2018) was one of the most notable ones, which has included quite a detailed energy-saving calculation. Nevertheless, the comparison was made between CS and MASS integrated with more energy-saving measures (e.g. no ballast and windlass design) but not on the correlation between the two kinds. It should be noted that MASS and CS have many characteristics in common, and the fundamental differences between them are to be manned or unmanned. Hence, any energy-saving measures which are applicable to MASS are also likely to be compatible with CS. Ait Allal et al.'s study has not considered the factors that may make the

MASS less efficient than the CS, e.g. the duplication of important equipment like main engine and steering equipment. Furthermore, an overall relative energy saving amount was not determined.

The comparison between the MASS and the CS was fairer in the work of Kretschmann et al. (2017) because no ship was more favorably treated. That means the MASS was assessed based on an assumption of equivalent safety level, and the fuel-saving was resulted only by the MASS's nature, which is the elimination of crew onboard. However, the redundancy of important systems is only taken into account for the estimation of the capital cost but not for the impact on the ship's EE. Kretschmann et al.'s approach is somewhat similar to the one used in this dissertation. Therefore, their result can be used as a reference for the present study.

The MASS's final evolution is expected to be fully autonomous, where no crew is needed onboard and less personnel on standby onshore for emergency cases. As electrical energy is more compatible with the autonomous control system, future MASS is expected to be operated fully relying on electrical energy, promising a future carbon free shipping industry.

Chapter 3 – Comparison between MASS and conventional ship with regard to design characteristics

3.1 General

This Chapter investigates in detail the differences in design characteristics between MASS and CS, which may affect the EE of ships. The comparison-based advantages or disadvantages regarding EE of MASS are also assessed in parallel. The comparison is made to the most applicable and reasonable extent relying on the general knowledge of naval architecture and relevant regulations and standards of safety and navigation. Besides, quantification is made for every difference to understand better how it will affect the EE of the MASS.

The comparison is made based on equivalency in safety and operation between MASS and CS. For this dissertation's purpose, equivalency in safety means MASS and CS are both in compliance with applicable safety requirements of relevant international conventions, e.g. SOLAS. In other words, the two kinds of ships shall satisfy the same or equivalent safety standards. Equivalency in operation means the two ships are assumed to attain the same operational performances, for instance, carrying capacity and/or design speed. One example of the equivalency in operation is that if the MASS's lightweight is decreased due to the omission of accommodation structures for crews, the MASS's deadweight will increase by a corresponding quantity to make MASS have the same displacement with CS.

3.2 Superstructure and Deck house

On present-day CS, superstructures and deckhouses (S&DHs) are seen to be located aft of the ship. This arrangement helps to cover the engine room opening, leave more continuous spaces for cargo in the middle and make it easier to attain aft trim in ballast conditions. These structures provide rooms and spaces for ships' equipment, such as air conditioner, CO2 bottles for engine room fire extinguishing and steering gear, and for crew accommodations like sleeping rooms, WC, galley and mess room. The heart of the structure is the wheelhouse where navigational and radio equipment is arranged.

As MASS does not have crews living onboard, the S&DHs we normally see on CS that provide for crew hotel facilities become useless. Hence, those structures can be omitted on MASS. In addition, on MASS of level 3 and 4, the wheel house may also be eliminated. Instead, a smaller room may be situated on the main deck, providing sufficient navigating facility, with livestream video from surveillance cameras for the pilot or special personnel in case of MASS emergency.

On CS, S&DHs do not only provide functional rooms for ship's operation but also have other important effects. These structures often support the exhaust gas piping arrangement through the so-called engine well and finally through the funnel to a level higher than the top deck. In addition, S&DHs provide a platform on top of wheelhouse for the arrangement of navigational instruments, e.g., radar, compass and navigational light mast.

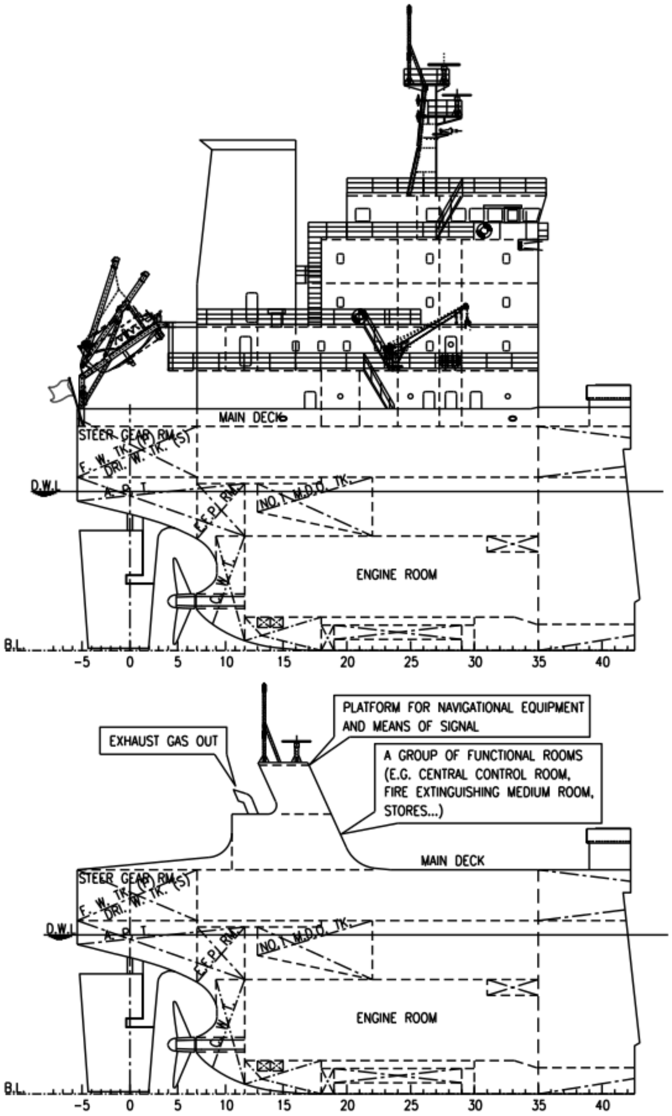
On MASS, due to the omission of the S&DHs, alternative arrangement of exhaust gas piping, navigational instruments and light mast may be employed. Firstly, exhaust gas may lead to a suitable position higher than ship's main deck or to the ship's either sides, as often seen on high speed crafts. Secondly, navigational equipment and navigational lights can be arranged on a raised platform located aft most of the ship. The arrangement of navigational lights is regulated by International Regulations for Preventing Collisions at Sea (COLREGS), in which, the aft masthead light of ships having a length of 50 meters and more shall be exhibited higher than the forward one (Rule 23 of COLREGS). The said raised platform which is not as high as conventional S&DH may not assure this regulation is met but the Administration can exempt the ship from exhibiting the second mast head light as often seen on offshore supply vessels, or this regulation will be reviewed and amended suitably.

The elimination of rooms for crew's needs and alternative arrangement of other spaces in a typical S&DH of ship are summed up in Table 2.

Table 2 – Alternative arrangement of rooms and spaces in a ship's S&DH

Name of room or space	**Purposes**	**Possible alternative arrangement**
Wheel house	Display data from navigational instruments, provide navigator with sufficient sea surface view and means of control, working stations for radio communication and chart, fire control station, central control station	A room with sufficient area on main deck where necessary navigational data, display of camera view and means of control are provided (for emergency and pilotage)
Sleeping room, WC and bath room	For crew accommodation	Eliminated
Hospital	For the first aid of the crew	Eliminated
Laundry	Serve the need of the crew	Eliminated
Mess room, clubs	For crew's dining and meeting each other	Eliminated
Galley	For preparation of meals	Eliminated
Central air conditioner room	For cooling or heating accommodation spaces	Eliminated
Store	For storage of crew's stuff, food and provision, firefighting equipment…	Partly eliminated or reduced in size
CO2 room	For storage of CO2 bottles to extinguish the fire in engine room and cargo holds	CO2 bottles will be contained in a room on main deck of the ship
Engine opening, engine wells, funnel	The space containing exhaust gas piping, silencer, scrubber (if fitted)…	Exhaust gas can be lead to the ship's sides while silencer may be arranged in the engine room. Exhaust gas can also be lead to a position above the main deck of ship or to either sides
Steering gear room	For arrangement of steering gear, emergency steering gear	Can be a room on main deck or under main deck with reduced area due to no frequent access of crew

In sum, the elimination of S&DH on MASS and the proposed alternative arrangement are illustrated in Figure 5, where the superstructures look more simple, compact and light in weight.



Note:

The above is a typical S&DH of a bulk carrier while the below is a probable alternative arrangement of S&DH on MASS.

Figure 5 – Probable alternative arrangement for S&DH on MASS

The elimination of S&DH on MASS results in the reduction in the ship's lightweight. So if MASS and CS in consideration have the same displacement, the deadweight of

MASS will be sur-added an amount equal to the weight of eliminated S&DH, in comparison with CS.

The weight of the S&DH, W_{SHD}, includes the weight of steel, W_{SDH-ST}, and other components (e.g. paneling, ventilation, lighting equipment, interior…), W_{SDH-O}, as in the following formulas (Papanikolaou, 2014)

$$W_{SDH} = W_{SDH-ST} + W_{SDH-O}$$

The steel weight depends on the location (tier) of S&DH and is characterized by coefficient of volumetric weight (Papanikolaou, 2014). Presuming that the average height of S&DH is 2.5 m, the steel weight of S&DH per square meter is calculated in Table 3.

Table 3 – Steel weight of S&DH per square meter

Location	**Weight per cubic meter of S&DH (ton/m^3)** (Source: Papanikolaou (2014))	**Weight per square meter of S&DH (ton/m^2)**	**Remarks**
Poop	0.075	0.1875	Average height of S&DH is assumed to be 2.5 m
Tier 1	0.057	0.1425	
Tier 2	0.055	0.1375	
Tier 3	0.052	0.13	
Tier 4 and above	0.053	0.1325	
Wheelhouse	0.04	0.1	

The remaining weight of S&DH, W_{SDH-O}, can be taken as 0.17 ton/m2 for every location of S&DH (Papanikolaou, 2014). Hence, the total weight for S&DH is calculated in Table 4 below.

Table 4 – Total weight of S&DH per square meter

Location	**Steel weight (ton/m^2)**	**Weight of the remainder (ton/m^2)**	**Total weight (ton/m^2)**
Poop	0.1875	0.17	0.3575
Tier 1	0.1425	0.17	0.3125
Tier 2	0.1375	0.17	0.3075
Tier 3	0.13	0.17	0.3
Tier 4 and above	0.1325	0.17	0.3025
Wheelhouse	0.1	0.17	0.27

3.3 Air resistance

Air resistance of a ship moving with speed V in still air depends on the transverse projected area of the ship's portion above the waterline, expressed by the following formula (Lewis, 1988):

$$R_A = C_A \frac{1}{2} \rho A_T V^2$$

Where:

C_A is the coefficient depending on the shape of the hull above the waterline and the S&DH;

ρ is the air density;

A_T is the transverse projected area of ship's portion above the waterline, mainly comprised of the ship's hull and S&DH.

On CS, due to the streamlined shape of the hull above waterline and the flat surface of the S&DH's fore bulkhead which is normal to the ship's speed direction, A_T is contributed by 100% of the projected area of S&DH and 30% of the projected area of the main hull (Lewis, 1988), as in the following formula:

$$A_T = 0.3A_1 + A_2$$

Where:

A_1 is the transverse projected area of the hull above water line, simply equal to $B \times F$, with B and F are ship's breadth and freeboard, respectively;

A_2 is the transverse projected area of the S&DH.

From the above formula, total air resistance can be separated into air resistance of the main hull and the S&DH as follows:

$$R_A = C_A \frac{1}{2} \rho (0.3A_1 + A_2) V^2 = C_A \frac{1}{2} \rho (0.3A_1) V^2 + C_A \frac{1}{2} \rho (A_2) V^2$$

Where:

The first term of sum is the air resistance of the main hull;

The second term of sum is the air resistance of the S&DH.

The percent that the air resistance of the S&DH (R_{A2}) account for in the total air resistance (R_A):

$$\frac{R_{A2}}{R_A}100\% = \frac{C_A\frac{1}{2}\rho(A_2)V^2}{C_A\frac{1}{2}\rho(0.3A_1)V^2 + C_A\frac{1}{2}\rho(A_2)V^2}100\% = \frac{A_2}{0.3A_1 + A_2}100\%$$

Based on the evaluation of all bulk carriers and oil/chemical tankers in consideration (see appendices 1 and 2), the air resistance of the S&DH shares at least 81.7% and 72.0% of the total air resistance for bulk carriers and oil/chemical tankers, respectively.

As the S&DH can be omitted on autonomous bulk carrier and oil/chemical tanker, the windage area A_2 and resistance R_{A2} may also be disregarded. Based on the previous estimation, it is conservative to say that MASS's air resistance can be reduced by 81.7% and 72.0% in the case of bulk carrier and oil/chemical tanker, respectively.

Air resistance is approximated by Molland et al. (2017) for some conventional oil tankers, bulk carriers, passenger ships, resulting in the share of air resistance in the total resistance of 2% for slow vessels like oil tankers to 6% for faster ships like passenger ships. Air resistance of a CS is also reported by Wartsila (2016) to be responsible for 2% of the total resistance. Therefore, in this dissertation, it is conservative to consider air resistance accounting for 2% of a ship's total resistance. That means MASS can reduce ship's total resistance by 81.7% × 2% = 1.63% in the case of a bulk carrier and 72.0% × 2% = 1.44% in the case of an oil/chemical tanker.

The main engine power is linearly proportional to the ship's total resistance (Lewis, 1988). Therefore, in the case of bulk carriers and oil/chemical tankers, MASS's main engine power can be reduced by 1.63% and 1.44%, respectively, but still maintain the same propulsive capability equivalent to CS.

Unlike other types of cargo vessels, the MASS carrying containers does not attain such air resistance reduction because on container ships, the air resistance is caused by the main hull and the container stacks carried on the main deck, in front of the S&DH. Thus, the main engine does not gain any savings in power regarding ship's resistance reduction.

3.4 Means for protection of the crew

As MASS carries no crew onboard, protective equipment can be omitted as investigated in detail from 3.4.1 to 3.4.3 below. To quantify the relative weight deduction, a 53,000 DWT bulk carrier (name: Ocean Queen) and a 16,800 DWT oil tanker (name: Glory Star) are chosen for the case studies (see Appendix 1 and 2).

3.4.1 Live-saving appliances

As per SOLAS requirements (Chapter III), conventional cargo ships shall carry sufficient life-saving appliances for the crew to use in emergencies. These appliances include radio equipment (2-way VHF radio apparatus, EPIRB, radar transponder…), personal life-saving apparatus (life-jacket, immersion suit, lifebuoy…), survival craft, rescue boat and life raft. Most of these are insignificant in weight. The life-saving apparatuses that have considerable weight are listed in Table 5.

Table 5 – Investigation of life-saving apparatuses that are significant in weight

Name of life-saving appliance	Quantity (1)	Weight per one item, in ton (2)	Weight (ton)
Oil/chemical tanker			
Lifeboat (free fall type)	1	3.90	3.90
Life raft	2	0.15	0.30
Rescue boat	1	1.50	1.50
Total			**5.70**
Ships other than oil/chemical tanker			
Lifeboat (one of them can be used as rescue boat)	2	2.50	5.00
Life raft	2	0.15	0.30
Total			**5.30**

Note:

(1) The ship is assumed to be equipped for a crew of 20 persons. The Table is prepared for ships having length of 85 meter or more.

(2) The weight of life-saving apparatus is estimated in reference with some life-saving equipment manufacturers.

Based on the above weight calculation, it can be further estimated that the life-saving appliances account for around 0.05% and 0.10% of the lightweight of a 53,000 DWT bulk carrier and a 16,800 DWT oil tanker, respectively. Therefore, in this dissertation, they can be considered to be negligible.

3.4.2 Crew protection structures

The structures investigated in this section are those required by the Load Lines Convention (Regulations 25 and 25-1 of Chapter II Annex I) to protect the crew. Those structures include bulwarks, guard rails or gangways on oil/chemical tankers, which may be omitted in whole or in most part on MASS. Walkways may only be needed for frequent surveys or have alternative simpler and lighter-in-weight arrangements.

The omission of those protective structures may result in occasions for MASS to gain more deadweight. To quantify the weight of those structures, calculations are made for case studies of a 53,000 DWT bulk carrier and a 16,800 DWT oil tanker.

The handrail and bulwark are required to be of at least 1 meter in height. According to the two ships' designs in the case studies, the weight of handrail is about 0.0137 tons per meter, while that of bulwark is about 0.11 tons per meter. For oil/chemical tankers, the weight of the gangway that provides safe passage for the crew from stern to bow is estimated at 0.196 tons per meter.

The weight calculations of those crew protective structures for a 53,000 DWT bulk carrier and a 16,800 DWT oil tanker are shown in Table 6 and Table 7, respectively.

Table 6 – Estimation of handrail and bulwark weight on a 53,000 DWT bulk carrier

Length of ship	183.05	m
Light ship weight	11562.1	ton
Length of handrail	526.37	m
Percent of handrail's length to ship's length	287.56	%
Weight of handrail	7.18	ton

Length of bulwark	60.83	m
Percent of bulwark's length to ship's length	33.23	%
Weight of bulwark	6.64	ton
Total bulwark & handrail weight	**13.82**	**ton**
Percent of bulwark & handrail to lightship weight	0.12	%

Table 7 – Estimation of handrail, bulwark and gangway weight on a 16,800 DWT oil tanker

Length of ship	134.50	m
Light ship weight	5525.4	ton
Length of handrail	407.53	m
Percent of handrail's length to ship's length	303.00	%
Weight of handrail	5.56	ton
Length of bulwark	42.15	m
Percent of bulwark's length to ship's length	31.34	%
Weight of bulwark	4.60	ton
Length of gangway	96.25	m
Percent of gangway's length to ship's length	71.56	%
Weight of gangway	18.87	ton
Total bulwark, handrail & gangway weight	**29.03**	**ton**
Percent of bulwark & handrail to lightship weight	0.53	%

The above weight calculation does not take into account the ladders associated with those structures. However, it can be seen from the above calculation that the weights of those protective structures are minor compared to the lightweight. Hence, they are considered to be omitted in further computation.

3.4.3 Fight-fighting appliances for accommodation area

The fire-fighting appliances investigated in this section are those required by the SOLAS (Chapter II-2) for the extinction of fire in the accommodation area (e.g. portable fire extinguishers). As crew is absent on-board the MASS, fire-fighting equipment is no longer needed and, hence, a certain weight may be deducted from the lightship weight and MASS may gain more deadweight accordingly.

To see how this equipment omission can contribute to MASS's deadweight increase, estimation is made for a case study of a 53,000 DWT bulk carrier mentioned in the previous section. The results are shown in Table 8.

Table 8 – Estimation of fire-fighting equipment weight on a 53,000 DWT bulk carrier

Light ship weight	11562.1	ton
Number of CO2 extinguishers (5 kg type)	1	piece
Number of dry powder extinguishers (8 kg type)	14	pieces
Number of CO2 extinguishers (for spare)	1	piece
Number of dry powder extinguishers (for spare)	14	pieces
Gross weight of one CO2 extinguisher	0.014	ton
Gross weight of one dry powder extinguisher	0.012	ton
Total weight of CO2 extinguishers	0.03	ton
Total weight of dry powder extinguishers	0.34	ton
Total weight of portable fire extinguishers in accommodation area	**0.36**	**ton**
Percent of portable fire extinguishers to lightship weight	0.003	%

Note:

The number of fire extinguishers is based on the ship's fire control plan. The weights of the extinguishers are retrieved from Survitec (2020).

Again, it can be seen that the above-estimated weights are minor compared to the lightweight. Hence, they may be considered to be negligible in further computation.

3.5 Energy for crew accommodation

On the MASS, the energy serving crew's accommodation is not needed. This is mainly electrical energy providing for air conditioning, freshwater pump, cooking, recreation, and lighting.

As the crew number on a CS is normally seen to be from 20 to 25 and not so dependent on the ship's size, the hotel load is, therefore, predictable based on the data of existing ships. It is recommended by Resolution MEPC.245(66) (IMO, 2014) that the hotel load can be taken as 250 kW for ships having total propulsion power of 10,000 kW and upward. For ships of which the power is less than 10,000 kW, the Resolution does not point out how much specifically the hotel load is. Instead, the sum of energy for crew accommodation and for serving the main engine operation is as follows:

$$P_{AE} = 0.05 \times \sum (Propulsion\ power) \qquad \textit{Equation 3}$$

It is unreasonable to take hotel load as 250 kW in this case because if the ship's propulsion power is equal to or less than 5,000 kW, the energy serving the operation of propulsion engine is equal to zero or negative. Therefore, it is better and more conservative to consider hotel load is half of the value in the formula of P_{AE} above.

On this basis, an assumption can be made in this study that the energy for crew accommodation that a MASS can save is 250 kW for ships with total propulsion power from 10,000 kW and $0.025 \times \sum(Propulsion\ power)$ for other cases.

3.6 Systems serving the crew

For a CS, many systems are designed to serve the everyday human needs of the crew. Those are the freshwater system, sewage system and air conditioning system. For the proper working of the systems, a number of equipment and facilities are fitted, e.g. freshwater pumps, sewage tank and central air conditioning machine, most of which are arranged in the ship's engine room.

Onboard a MASS, the previously mentioned system and associated equipment can be omitted to save a certain lightship weight and contribute to MASS's EE. Based on a case study of an existing 53,000 DWT bulk carrier, the deducted equipment and weights are quantified in Table 9.

Table 9 – Weight of equipment and facilities serving the crew on a 53,000 DWT bulk carrier

Length of ship	183.05	m
Light ship weight	11562.1	ton
F.W. generator	0.16	ton
Fresh water pump	0.01	ton
Central air conditioner	1.96	ton
Sewage treatment plant	1.55	ton
Sewage tank	0.56	ton
Total weight	**4.24**	**ton**
Percent compared to lightship weight	0.037	%

Note:

The weights of equipment are retrieved from Wartsila (2019); (Carrier, 2019).

The above weight calculation has not taken into account the piping system associated with the equipment. However, according to the above results, it can be said that those systems are minor in weight and hence will be ignored in further assessment.

3.7 Alternative design of important system onboard MASS

Although MASS has advantages in reducing lightweight as investigated in 3.2, 3.4 and 3.6 above, due to the absence of humans onboard, some important systems and related equipment (e.g. propulsion equipment, anchorage equipment) should be selected and arranged so that the ship can still operate at an acceptable level when any single piece of equipment malfunctions. The alternative design may be the redundancy of the equipment or dividing the system into multi independent subsystems. This alternative design may make MASS's lightship weight increase correspondingly.

The most important system onboard a ship is the propulsion system, which pushes the ship forward or sometimes pulls it aft. This system is also the most energy-consuming one, generally including one or more main engines driving respective propellers via the shafting systems. The propulsion system is supported by associated equipment, such as fuel pumps, piping and fuel purifiers. Conventional bulk carriers, oil tankers and container ships normally have one main engine driving one propeller. If these ships are autonomously operated, the said propulsion system should be at least divided into two relatively independent subsystems, so in the case that one subsystem malfunctions, the rest will take the ship to the designated shelter.

Assuming the energy efficiencies of propulsion systems with one or two main engines are the same, each main engine's power onboard the MASS will be half of that on the CS. To investigate the change in weight between MASS and CS regarding the alternative design of the propulsion system, the main engine's weight comparison is made between two cases, one engine and a combination of two engines of the same maker but half in power. The results are shown in Table 10 and Figure 6.

Table 10 – Main engine weight increment (in %) when one engine is replaced by two having half power

Maker	Engine name	Rated power (kW)	Weight (ton)	Weight increase (%)
Wärtsilä	8L32	9,280	71	23.9
	16V32	4,640	44	
	12V32	6,960	57	22.8
	6L32	3,480	35	
	14V46F	16,800	216	4.6
	7L46F	8,400	113	
	12V46F	14,400	177	9.6
	6L46F	7,200	97	
	16V31DF & SG	8,800	94	20.7
	8V31DF & SG	4,400	57	
MAN B&W	8S26MC	2,200	53	20.8
	4S26MC	1,100	32	
	12L35MC	7,800	126	6.3
	6L35MC	3,900	67	

Note:

1 Particulars of the engines in the Table are retrieved from Wartsila (2020) and Marengine (2002).

2 Weight increase is the increase of weight, in percentage, when two engines (each having half power) are used instead of one engine.

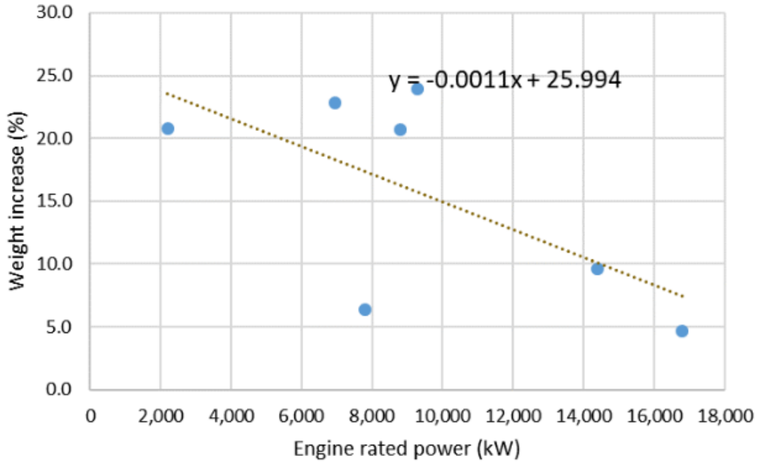


Figure 6 – Estimation of weight increasing (in %) when one engine is replaced by two having half power

The increasing percentage in Table 10 is investigated only for the change in weight of the main engine itself. However, in an approximate way, it is assumed by this study that the increase in weight of the whole propulsion plant will be at the same rate if that plant is separated into two.

According to Papanikolaou (2014), the weight of a ship's propulsion system is composed of three components, as in the following formula:

$$W_M = W_{MM} + W_{MS} + W_{MR} \qquad \textit{Equation 4}$$

Where:

W_{MM} is the weight of main engine and its gear box, if provided;

W_{MS} is the weight of shafting system and associated propellers;

W_{MR} comprises weight of supporting equipment (e.g. fuel pumps and lubricating oil pump), piping system, funnel, exhausting pipes, electrical system etc.

For cargo ship and tanker using low speed diesel engines, the three above-mentioned weight components, in kg, can be determined by the following empirical formulas (Papanikolaou, 2014):

$$W_{MM} = (30 \sim 40) \times MCR \qquad \textit{Equation 5}$$

$$W_{MS} = (5 \sim 10) \times MCR \qquad \textit{Equation 6}$$

$$W_{MR} = (25 \sim 50) \times MCR \qquad \textit{Equation 7}$$

Where MCR is the maximum continuous rating of the main engine, in horse power (HP).

Therefore, it can be deduced from *Equation 5* to *Equation 7* that:

$$W_M = (60 \sim 100) \times MCR \qquad \textit{Equation 8}$$

From *Equation 5* and *Equation 8*, we have:

$$W_M = (2 \sim 2.5) \times W_{MM}$$

Based on the above argument, it is assumed by this dissertation that:

$$W_M = 2.25 \times W_{MM} \qquad \textit{Equation 9}$$

The weight of the main engine, W_{MM}, in case of a single one on the CS, is more realistic to be derived from the statistics in Table 10, depending on the rated power of the main engine. The relationship between W_{MM} and rated power is shown in Figure 7.

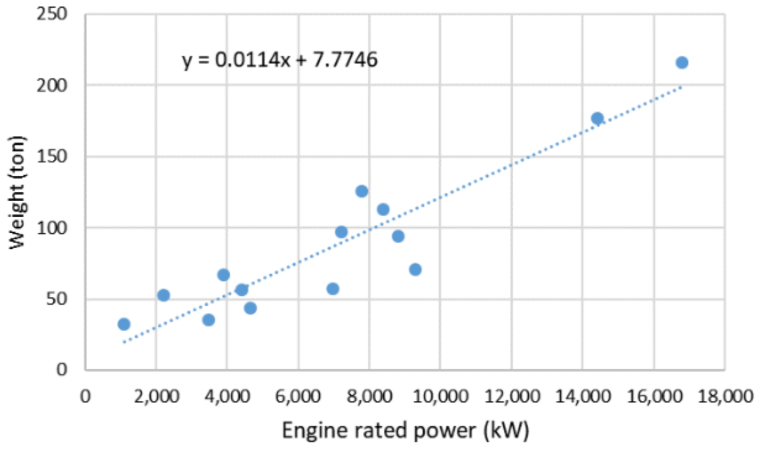


Figure 7 – Relation between weight of main engine and its rated power

From Figure 7, we have:

$$W_{MM}(ton) = 0.0114 \times MCR(kW) + 7.7746 \qquad \textit{Equation 10}$$

It can be deduced from *Equation 9* and *Equation 10* that the total weight of propulsion system of CS (in case of one main engine) is:

$$W_M = 2.25 \times (0.0114 \times MCR + 7.7746)$$

Hence:

$$W_M(ton) = 0.02565 \times MCR(kW) + 17.49285 \qquad \textit{Equation 11}$$

From Figure 6, we have the weight increase (in percent) of the MASS's propulsion system compared to CS's:

$$W_{increase}(\%) = -0.0011 \times MCR(kW) + 25.994 \qquad \textit{Equation 12}$$

From *Equation 11* and *Equation 12*, we have the weight increase (in ton) of the MASS's propulsion system compared to the CS's:

$$W_{increase}(ton) = (-0.0011 \times MCR(kW) + 25.994) \times (0.02565 \times MCR(kW) + 17.49285)/100 \qquad \textit{Equation 13}$$

Equation 13 will be used in the calculation of MASS's EE in Chapter 4.

Another important system that needs to be alternatively designed is the steering system. On a single-screw ship, this system includes one rudder mechanically turned by hydraulic, electric or electro-hydraulic steering gear. On a CS, the steering gear is made redundant by the complement of an auxiliary steering gear that will be deployed if the main one fails to operate correctly. As a MASS should have at least two independent propulsion systems, it can be easily arranged with at least two independent steering systems. The steering capacity of a ship is characterized by the total area of rudders. Therefore, if a single steering system is replaced by two independent ones, the capacity of each will be allowed to be decreased to a half. Like the propulsion system, the weight of two smaller systems will be greater and thus decrease MASS's carrying capacity. However, as the steering system is a minor-weight system on a ship, its alternative design on a MASS does not significantly affect its EE.

The anchorage system is also considered one of the important ones which assure the ship's safety. The anchor is dropped when a ship needs to be held at the desired location, e.g. waiting for the port's availability. The anchorage system can help the ship obtain better intact stability when the ship is not moving by its propulsion system or increase maneuverability in shallow water. In emergency cases where the ship's steering system fails, leading to a potential collision, dropping down an anchor will effectively decrease the ship's speed to avoid collision. Due to this system's importance, a CS is provided with two separate anchors that are dropped and recovered by two independent windlasses, constituting two independent anchoring systems. This arrangement is redundant enough in the case of a MASS and, therefore, an alternative design of the anchoring system is not needed.

3.8 Equipment doing human's job onboard

Onboard a CS, the crew must carry out many tasks relating to the ship's operation, some of which are very important. Those tasks may be navigation and look out, monitoring engines and equipment operations, and checking the ship's stability and trim. Therefore, the MASS with the omission of a crew must be fitted with new systems to perform the same tasks as mentioned previously.

To support the navigation and look out, special cameras are fitted at certain positions onboard the MASS to have a full picture of the ship's surroundings. For the MASS of level 3, the information will be sent to the remote navigators for their assessment and response. In the case of a level-4 MASS, the information will be processed by the ship itself with the help of AI, and autonomous responses will be made correspondingly. The needed number and weight of those cameras is not possible to be determined exactly in this study. However, based on the cameras that are manufactured today, it can be assumed that the MASS gains inconsiderable weight due to the installation of the monitoring camera system.

Another important job that needs the support of technology is monitoring the operational status of the shipboard engines like main engine(s), auxiliary engine(s) and other equipment. This can be done by systems of sensors that are also believed to have a very small weight compared to thousands of tons of lightship weight.

On the CS, the ship's trim & stability and longitudinal strength are manually verified by the officer in charge using the Longitudinal Strength and Stability Booklet provided by the designer. For large cargo ships, this job is supported by the loading computer as required by SOLAS and also by classification societies. On the MASS, this job will be carried out remotely by the onshore operators or by the onboard computer system using AI. The inputs for the calculation, e.g. sounding of fuel tanks, ballast tanks and position of cargo, are read by the sensors. Based on the outcome of the assessment, the ship's loading will be adjusted correspondingly (e.g. fill in or discharge ballast water, or change the position of the cargo onboard). The computation and assessment are supported by a computer system connected to relevant sensors and other functional equipment like ballast pumps and cargo handling gears. Therefore, the MASS will gain some more weight compared to the CS, including the computer system and the associated sensors. However, those weights are significantly small compared to the lightship weight and may be considered to be disregarded in this dissertation.

3.9 Summary

Due to the omission of the crew, the MASS is seen to have not only advantages but also disadvantages compared to the CS in terms of ship's EE. The factors that help the MASS to be more energy efficient or vice versa are summarized and illustrated in Figure 8.

As analyzed, the biggest disadvantage of MASS is the separation of the propulsion system. This definitely makes the MASS lightship weight increase considerably due to the significant weight of the propulsion system. However, it can be observed that three major factors can help MASS to gain remarkable EE. Those are the elimination of S&DH's weight, reduction in ship's air resistance and cut-off of energy serving the crew's needs.

All the above major negative and positive factors are quantifiable and will be taken into EEDI analysis in Chapter 4. Other minor factors are assumed to be disregarded by this study because they are insignificant and may compensate each other.

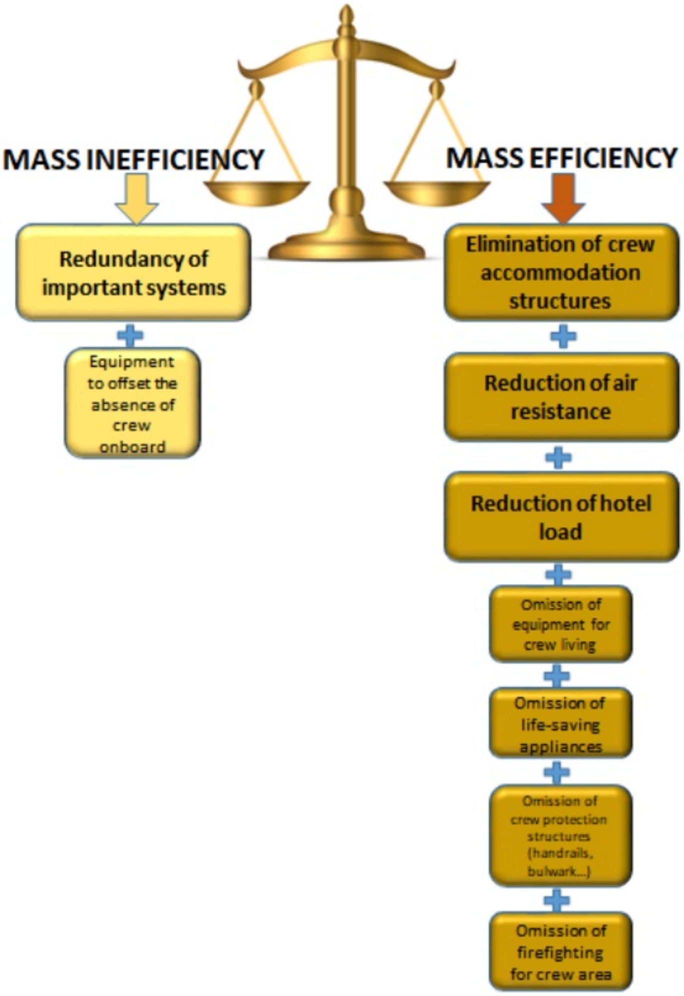


Figure 8 – Advantages and disadvantages of the MASS compared to the CS in terms of EE

Chapter 4 – Analysis of reduction in attained EEDI of the MASS

4.1 General

This Chapter calculates the EEDI reduction (in percentage) of the MASS with reference to the CS. The analysis is carried out based on the detailed comparison between the two kinds of ships carried out in Chapter 3.

To simplify the calculation, it is assumed that the ship has no shaft generator or motor and no innovative EE technology. The attained EEDI (hereinafter, in this Chapter, referred to as EEDI) formula in Resolution MEPC.245(66) (IMO, 2014) can be shortened as follows:

$$EEDI = \frac{\left(\prod_{j=1}^{n} f_i\right)\left(\sum_{i=1}^{nME} P_{ME(i)}\, CF_{ME(i)} SFC_{ME(i)}\right) + \left(P_{AE} CF_{AE} SFC_{AE}\right)}{f_i \cdot f_c \cdot f_l \cdot Capacity \cdot f_w \cdot V_{ref}}$$

If other minor factors are neglected, the above formula can be written as:

$$EEDI = \frac{\left(\sum_{i=1}^{nME} P_{ME(i)}\, CF_{ME(i)} SFC_{ME(i)}\right) + \left(P_{AE} CF_{AE} SFC_{AE}\right)}{Capacity \cdot V_{ref}}$$

Or:

$$EEDI = \frac{P_{ME} CF_{ME} SFC_{ME} + P_{AE} CF_{AE} SFC_{AE}}{Capacity \cdot V_{ref}}$$

So we have:

$$EEDI \cdot V_{ref} = \frac{P_{ME} CF_{ME} SFC_{ME} + P_{AE} CF_{AE} SFC_{AE}}{Capacity}$$

In which:

P_{ME} is 75% of the total power of all main engines.

The following assumption is also made based on the assumption for the EEDI base line calculation of IMO (2011c):

- The carbon factor is taken to be the same for main engine and auxiliary engine $CF_{ME} = CF_{AE} = 3.1144\, gCO2/gfuel$
- The specific fuel consumption for main engine is $SFC_{ME} = 190\ g/kWh$
- The specific fuel consumption for auxiliary engine is $SFC_{AE} = 215\ g/kWh$

As the simplification has the same effect in computing the EEDI of the MASS and the CS, the EEDI reduction result, which is derived from the ratio between EEDIs of the two ships, will not be considerably affected.

The afore-mentioned values of $EEDI \cdot V_{ref}$ are calculated for both CS and MASS and compared to each other to obtain the reduction in EEDI of MASS, as follows:

$EEDI\ reduction = 1 - \frac{EEDI_{MASS}}{EEDI_{CS}} = 1 - \frac{EEDI_{MASS} \cdot V_{ref}}{EEDI_{CS} \cdot V_{ref}}$ (be noted that MASS and CS are assumed to run at same reference speed).

In calculation of $EEDI_{MASS} \cdot V_{ref}$, the followings are noted:

- $Capacity$ is increased and decreased taking into account the evaluations in 3.2 and 3.7, respectively.
- P_{ME} is reduced taking into account the evaluations in 3.3.
- P_{AE} is reduced taking into account the evaluations in 3.5.

The calculation flow chart is illustrated in Figure 9.

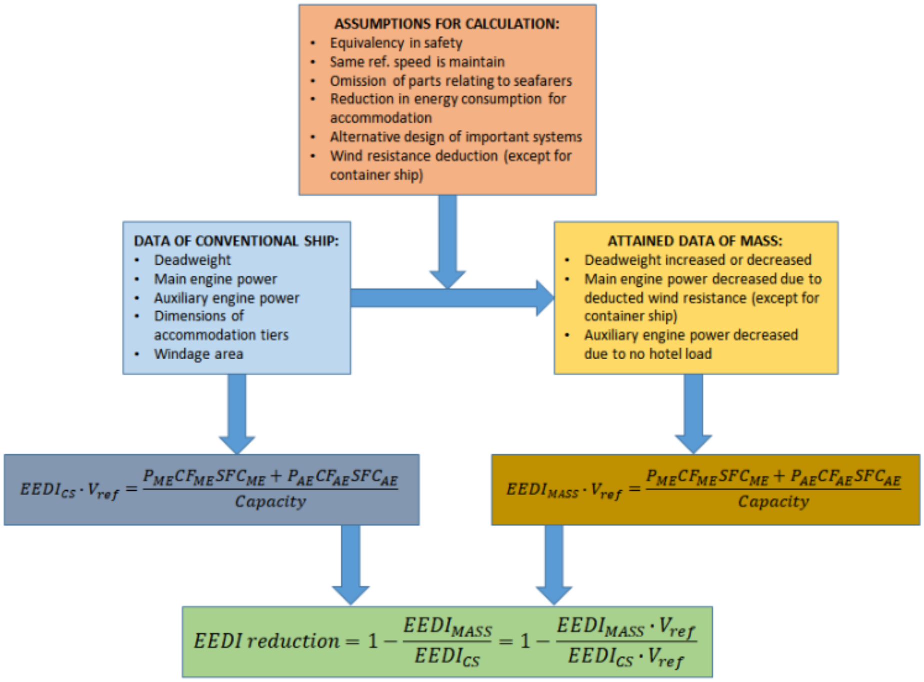


Figure 9 – Calculation flow chart for the EEDI reduction of the MASS

Input data for the analysis is collected from existing ships that are classed by the Vietnam Register (VR). The ships' particulars are all published on the website of the organization (VR, 2020).

4.2 Bulk carrier

The EEDI reduction analysis of bulk carriers is carried out based on 21 existing ships, built from 1990 to 2012 with their DWTs ranging from 8184.5 to 68591.0 tons. All of the ships are equipped with a single diesel engine and screw propulsion. The detailed calculation is shown in Appendix 1 and the reduction, in percent, of MASS's EEDI compared to CS's is presented in Figure 10, together with the function of the regression line.

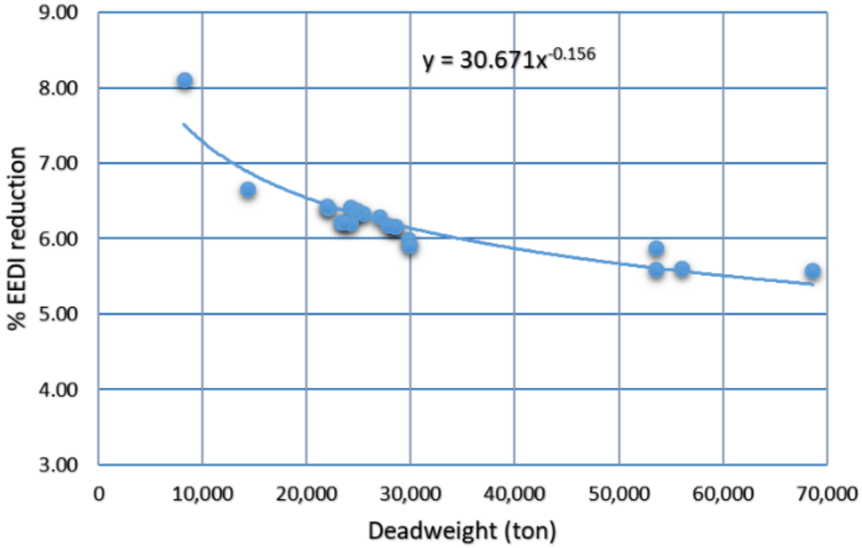


Figure 10 – EEDI reduction (in percent) for bulk carriers

4.3 Oil/Chemical tanker

The EEDI reduction analysis of oil/chemical carriers is carried out based on 15 existing ships, built from 1977 to 2012 with their DWTs ranging from 3411.4 to 105,465.0 tons. All of the ships are equipped with a single diesel engine and screw propulsion. The detailed calculation is shown in Appendix 2 and the reduction, in percent, of MASS's EEDI compared to CS's is presented in Figure 11, together with the function of the regression line.

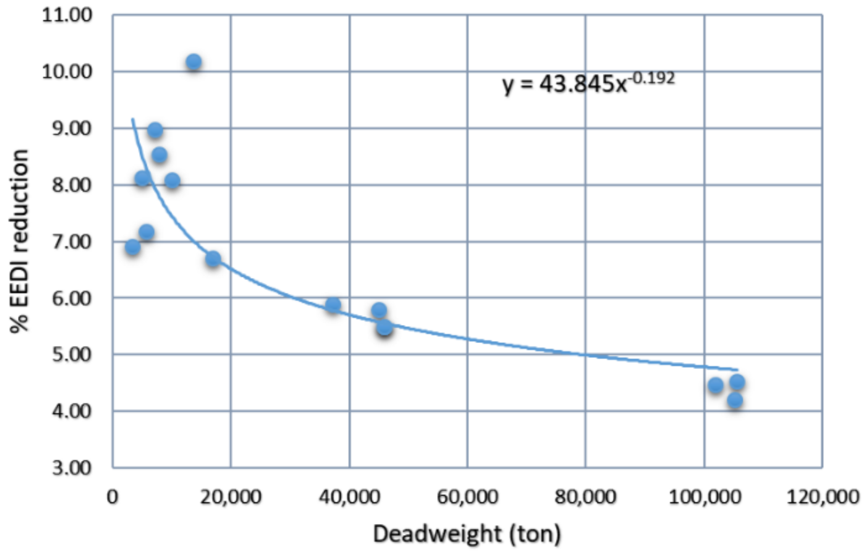


Figure 11 – EEDI reduction (in percent) for oil/chemical tanker

4.4 Container ship

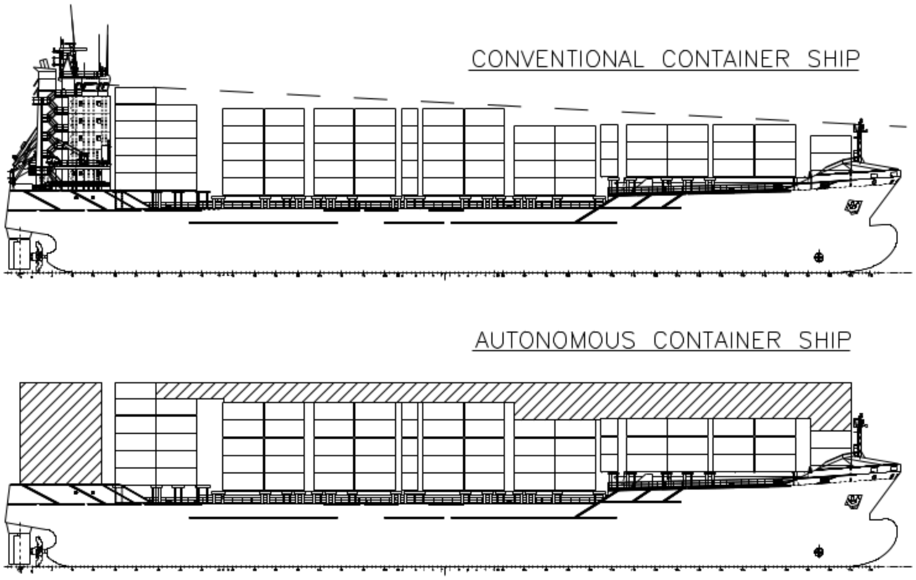
The EEDI reduction analysis of container ships is carried out based on 13 existing ships, built from 1996 to 2012 with their DWTs ranging from 3200.8 to 18,409.0 tons. All of the ships are equipped with a single diesel engine and screw propulsion. The detailed calculation is presented in Appendix 3 and the reduction, in percent, of MASS's EEDI compared to CS's is shown in Figure 13, together with the function of the regression line.

Different from bulk carriers and oil/chemical tankers, in the attained EEDI calculation of container ships, it is instructed by the IMO Resolution MEPC.245(66) (IMO, 2014) that the $Capacity$ in the EEDI formula shall be 70% of the ship's deadweight.

As discussed in Chapter 3, the ship's DWT may gain more due to the elimination of the S&DH. Unlike other regular cargo ships, a container ship is a ship carrying boxes. In other words, a container ship is a ship carrying a volume rather than carrying a mass. How can a container ship increase its carrying capacity in this case?

The question above can be answered that, on a conventional container ship, the containers' arrangement has some limitations due to the IMO requirements on ship's navigational bridge visibility (Regulation 22 of Chapter V of SOLAS). Accordingly, the on-deck containers are not allowed to block the view from some specified positions on the navigation bridge deck. Besides, the S&DH also occupies a certain space for the arrangement of the on-deck containers.

However, on an autonomous container ship, a number of container stacks can be placed at the position left by the omitted S&DH. Furthermore, container tiers can also be added to the bays located forward of the omitted S&DH. This will definitely raise the ship's vertical center of gravity and impair the ship's stability. In return, this safety aspect is compensated by the removal of quite a tall and heavy S&DH block and can also be solved by the ballast operations and container loading plan. The potential for improving the box carrying capacity of an autonomous container ship is illustrated in Figure 12.



Note:

1 Above is the typical arrangement of on-deck containers on conventional container ship where container allocation is seen to be limited due to the required visibility of the navigator.

2 The below is a probable on-deck container arrangement on an autonomous container ship. Hatched areas are the spaces where additional containers can be arranged to take advantage of the increase in weight carrying capacity.

Figure 12 – Improvement in box carrying capacity of autonomous container ship

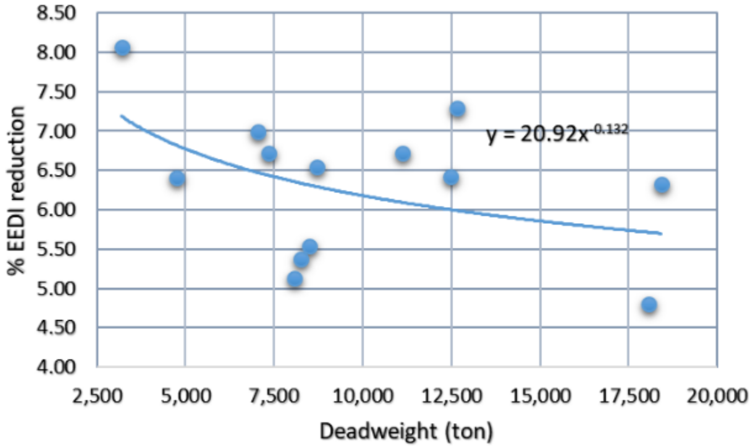


Figure 13 – EEDI reduction (in percent) for container ship

Chapter 5 – Discussion

5.1 Energy efficiency of the MASS

Generally, all three types of ships are observed to have a certain improvement in attained EEDI if the MASS is used instead of the CS. In all cases, the percentage reduction is from about 5% to less than 10%. The MASS's GHG reduction is presented in Figure 14 in conjunction with the reviewed measures in section 2.3. The Figure shows the ranges of GHG savings in percent, which can be attained by the ships. For measures, the lower margins of which were not identified in the literature, zero is taken to sketch this Figure. It can be seen that autonomous operation can bring significant savings compared to most of the investigated abating measures.

From Figure 10, Figure 11 and Figure 13, the EEDI reduction is found to be less for larger ships and vice versa. This problem can be explained based on the factors that significantly impact the MASS's EE. The EE of MASS is mostly attained by the elimination of the crew's S&DH and hotel load. It is seen in the fact that the crew complement is not subject to variation when the ship size changes. The need for living conditions and energy consumption of a fixed number of crew members results in the less varying weight of S&DH and hotel load against the ship's size. Figure 15 shows that the ratio between S&DH's weight and ship's deadweight declines with the increase of the ship's size. As the ship gets larger, the influence of this saving becomes minor, and therefore the less EE is attained when the ship is autonomously operated.

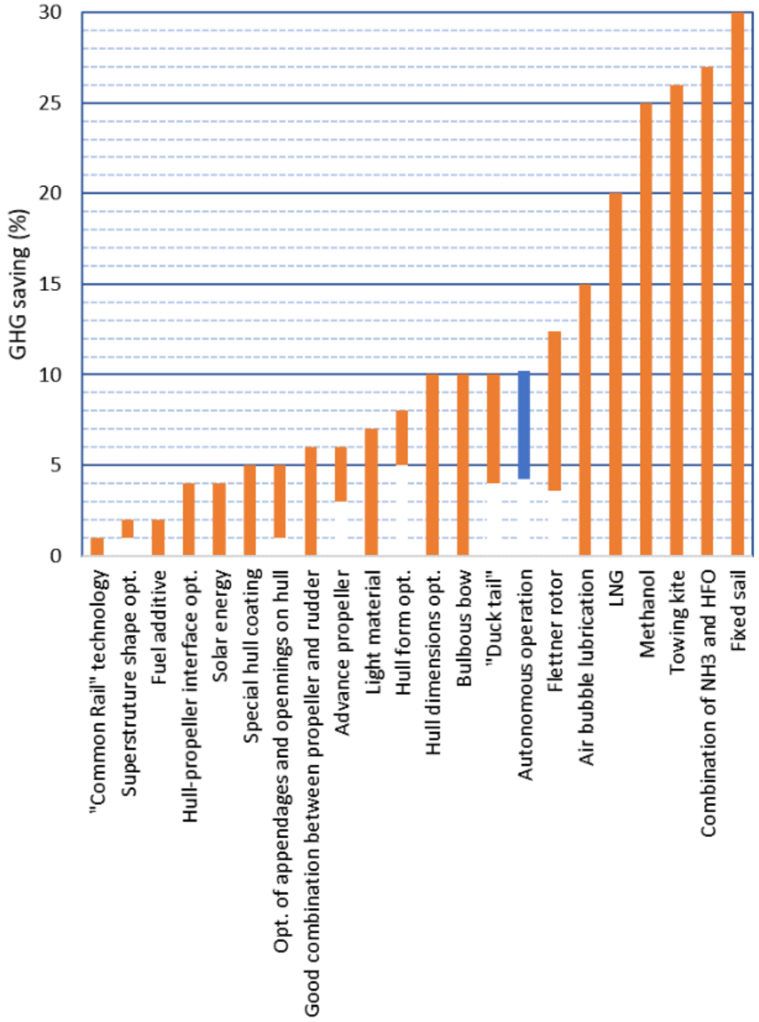


Figure 14 – The EE of the MASS (blue bar) in relation to other saving measures

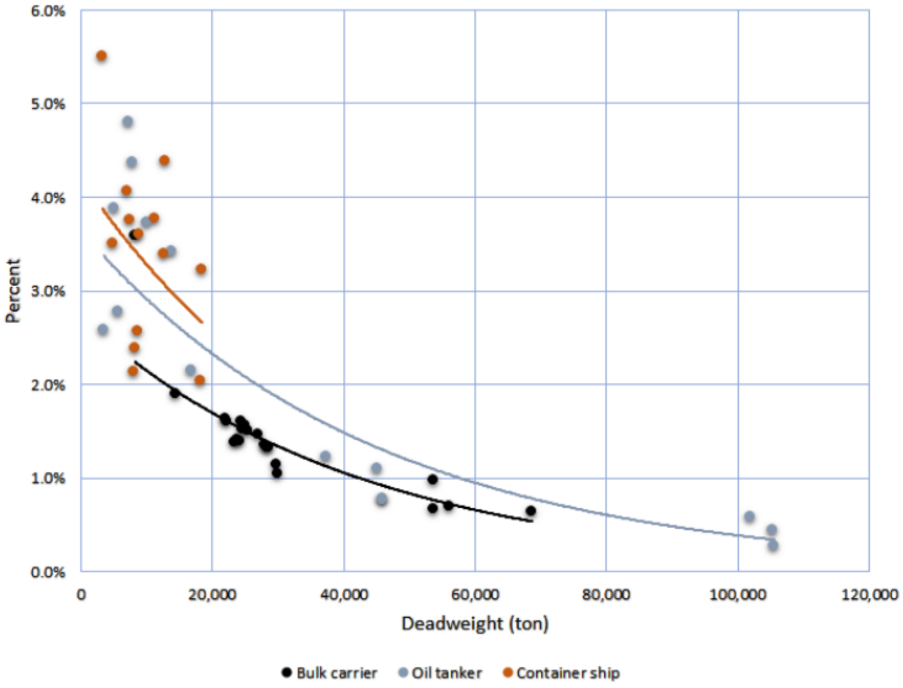


Figure 15 – The relation between S&DH's weight/ship's DWT (%) and ship's DWT

For bulk carriers and oil/chemical tankers, the EEDI reduction data is seen to be more scattered for ships of lower DWT and consistent for larger ships. This can be explained by the fact that although the crew complement is almost fixed for ships with varying DWT, the accommodation area may have slight differences due to the applicable requirements (e.g. built after or before an effective date of a relevant rule) or the need of the ship owners (e.g. the ship built for European owner is often seen to have more spacious accommodation area than Asian). The difference becomes relatively more significant for smaller ships and vice versa for larger ones. As the elimination of accommodation area contributes considerably to the reduction in attained EEDI of MASS, the calculated results for small ships will definitely deviate largely from each other. For container ships, the scattering of the data is observed for the whole investigated deadweight range because those ships' sizes correspond to the fore-said lower deadweight ranges of bulk carriers or oil/chemical tankers.

To compare the EEDI's reduction of three ship types, a consolidated graph has been drawn for the three trend lines in Figure 10, Figure 11 and Figure 13 against a range of DWT which those types of ships have in common (see Figure 16).

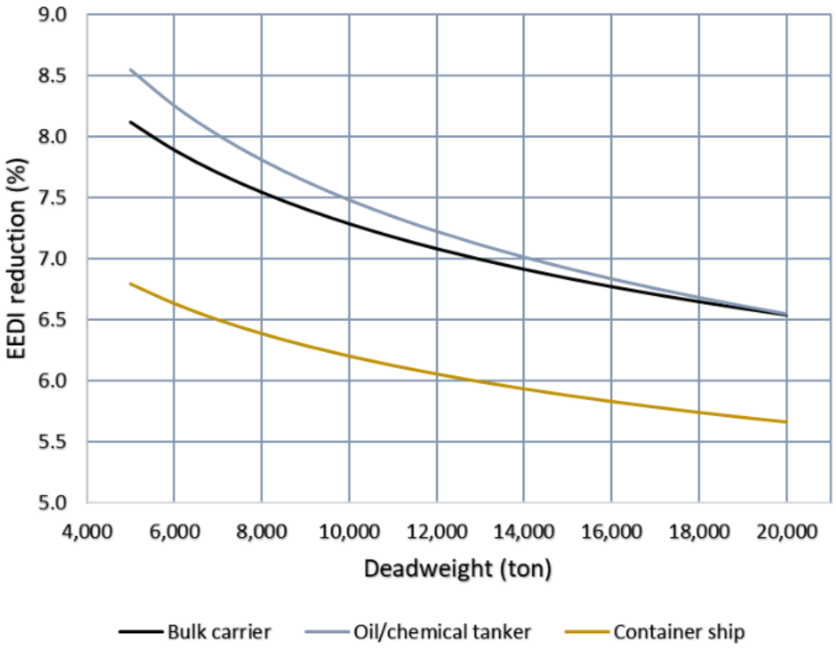


Figure 16 – Comparison between three ship types

It can be seen that although the autonomous oil/chemical tanker is observed to be more effective than the bulk carrier, the difference is not much. It may be explained that the design of those two ship types is almost identical, e.g., relatively low speed, similar hull form and structural design with double hull for oil/chemical tanker and double bottom, large bilge hopper and topside tank for bulk carrier. Their structural design is so similar that most classification societies provide common structural rules for oil tankers and bulk carriers. The difference in energy-saving capability may come from the gap between their S&DH's weights (see Figure 15).

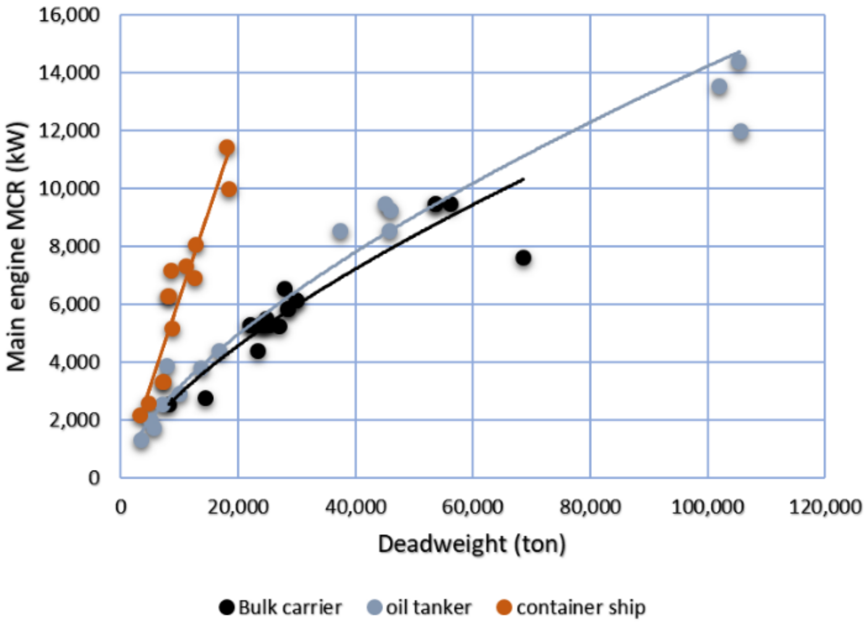


Figure 17 – Main engine power versus deadweight of 3 ship types

Compared to oil/chemical tanker and bulk carrier, the EEDI reduction of autonomous container ships is significantly lower (see Figure 16), equal to around 80% if considering the same size of ship. The explanation is that the container ship has a comparatively higher speed than the others, and hence it needs a more powerful propulsion engine that consumes much more energy. Figure 17 shows that the container ship needs a much larger engine than the others of the same deadweight. When becoming autonomous, the elimination of S&DH and hotel load will have a lower impact on the total GHG emission per transport work. Furthermore, the autonomous container ship is not subject to the air resistance reduction, and thus a reduction in main engine power is not attained.

It is seen in Figure 15 and Figure 17 that the coverage of the collected container ships' data is more narrow than the two other types of ships. This is because of the data shortage as no really large container ship is being classed by the Vietnam Register from which the data is collected. However, the EEDI reduction trend of container ships is believed to be similar to the oil/chemical tanker and bulk carrier.

The EEDI reduction of the autonomous bulk carriers found by this study is seen to be reasonable compared to Kretschmann et al. (2017) research. A six percent fuel-saving was demonstrated by Kretschmann et al. for an autonomous Panamax bulk carrier, the deadweight of which is normally from 60,000 to 80,000 tons. This saving is equivalent to a 6% reduction in EEDI. Figure 10 shows that the autonomous bulk carrier of the same size in this study also attains a similar reduction.

The MASS's EE in this dissertation has been evaluated based on the general knowledge of naval architecture and subjective assessments on the equivalency of safety and operation between and the MASS and the CS. The efficiency, in reality, may differ from this evaluation, depending on several factors. Firstly, the alternative designs of important systems mentioned in section 3.7 are demonstrated to decrease the MASS's EE, but how much it is decreased relies on the stringency of the applied rules. In other words, it depends on the future rule makers' safety equivalency definitions. This study presumes that two independent propulsion systems are safe enough for the MASS's operation. However, if the rule maker thinks two is not enough, but requires three or more, the MASS's EE will be another matter. Secondly, the deviation from CS to MASS is not as straight forward as described in this study. One example is that the arrangement of two main engines may result in a different hull form of the MASS than the CS. The change in hull form and tandem operation of thrusting equipment may either positively or negatively affect the propulsion system's efficiency. Besides, the smaller engine and/or smaller propeller's efficiency is also different from the larger one. The hull form is also a matter of ship's total resistance, which directly affects the ship's energy consumption. All those factors are very complicated if they are put together in one study. Therefore, in this dissertation, they are assumed to have insignificant effect on the EEDI reduction evaluation and are not taken into account.

The obtained EEDI reduction of MASS in this study comes from the differences in nature of the two kinds of ships but not from any additional energy-saving measures applied to one of the ships only. Therefore, it can be said that the results are always reasonable at any development level of the conventional shipping industry. If any technical measures are applied to a CS to curb emissions, the MASS may employ the same to have the same emission reduction rate in combination with the one estimated by this study. The terms "infrastructure" and "superstructure" may be used in this case to describe the relation between the ship type and the energy-saving measure. Saying so, the change from CS to MASS is the change in the infrastructure, while the other energy-saving measures can be considered the superstructures which can be built on those infrastructures.

5.2 Future MASS and its role in context of the IMO GHG reduction ambition

The IMO GHG reduction ambition is reflected in the Initial IMO strategy, as discussed previously in section 2.2. The ultimate aim is to phase out GHG emissions from shipping as soon as possible in this century. The initial targets are set in relation to the 2008 level, including two aspects, carbon intensity and total GHG emission. The measures for improving carbon intensity are to strengthen the EEDI requirements, and the expected outcome is quantified by the reduction in CO2 emission per transport work of 40% by 2030 and 70% by 2050. Another aspect is the total GHG emission from international shipping, aimed to peak quickly and decline to 50% by 2050. These two aspects are interrelated. The total GHG emission depends both on the carbon intensity and the scale of the fleet (or also the scale of the world seaborne trade). Therefore, if seaborne trade is increased beyond the expectation, the carbon intensity target should be adjusted accordingly.

The above-mentioned GHG emission per transport work should represent the whole fleet, including ships built in different years. The earlier the ship was built, the higher carbon intensity the ship has. So, to reduce CO2 emission per transport work by 70% in 2050, ships built at this time should achieve an EEDI reduction of more than 70% to balance with the existing less efficient ones. However, a specific EEDI reduction rate for ships built in 2050 and onward has not been pointed out by the IMO yet. In this section, the possibility of a MASS to attain 70% EEDI reduction and its role in phasing out the GHG will be discussed.

The calculation model of MASS in this study is based on existing ships built from 1977 to 2012, the EEDIs of which may be considered equivalent to the index values of phase 0 reference line specified in Regulation 21 of Annex VI MARPOL. According to the EEDI reduction estimated in sections from 4.2 to 4.4, it can be said that the application of MASS will help to decrease the attained EEDI by between 4.21% and 10.18% without any additional saving measures. Optimistically speaking, the autonomous operation can make a certain number of ships, especially smaller ships, immediately fulfill phase-1 EEDI or partially achieve phase-2 EEDI, which requires up to 10% and 20% reduction, respectively, compared to the baseline.

To attain further EEDI reduction, the future MASS should incorporate applicable energy-saving measures investigated in section 2.3. For that purpose, the compatibilities of those with the MASS are analyzed in Table 11.

Table 11 – MASS and the applicability of the energy saving measures

No.	Energy saving measures	Compatible with the MASS?	Expected energy saving	Remarks
1	Light material of hull structures	Yes	< 7%	
2	Hull dimensions optimization	Yes	< 10%	
3	Hull form optimization	Yes	5-8%	
4	Air bubble lubrication	Yes	< 15%	
5	Special hull coating	Yes	< 5%	
6	Bulbous bow	Yes	< 10%	
7	"Duck tail"	Yes	4-10%	
8	Optimization of appendages and openings on hull	Yes	1-5%	
9	Optimization of superstructure shape	No	1-2%	The MASS has no S&DH
10	Hull-propeller interface optimization	Yes	< 4%	

No.	Energy saving measures	Compatible with the MASS?	Expected energy saving	Remarks
11	Good combination between propeller and rudder	Yes	< 6%	
12	Advance propeller	Yes	3-6%	
13	Towing kite	No	< 26%	Towing kite is too complicated to manipulate without human especially when recovering the kite. Therefore, it is not feasible to apply to the MASS
14	Fixed sail	Yes	< 30%	
15	Flettner rotor	Yes	3.6-12.4%	
16	Solar energy	Yes	< 4%	
17	"Common Rail" technology	Yes	< 1%	
18	Fuel additive	Yes	< 2%	
19	LNG	Yes	< 20%	
20	Hydrogen	Yes	100%	
21	Combination of NH3 and HFO	Yes	< 27%	
22	Methanol	Yes	< 25%	

It is observed from the above that all of the energy-saving measures are applicable to the MASS, except the towing kite and the optimization of S&DH. The MASS with no crew onboard may have advantages in the application of some technical measures. For instance, most of the exposed deck areas are suitable for installing solar panels because the walkway is not needed during the MASS operation on the sea. Besides, the erection of rigid sails on the deck is also more favorable without any limitations related to the navigational bridge view, and the MASS can more easily afford long voyage times caused by the effect of using sails.

To investigate the feasibility of attaining 70% EEDI reduction, it is assumed that the MASS is integrated with several applicable saving measures which are selected from Table 11. The chosen ones and their assumed efficiencies are presented in Table 12. It should be kept in mind that the applied measures should not interfere with each other in working. For example, the bulbous bow and the “duck tail” should not be used together in one design because they make the same effect of minimizing the energy loss for the wave system created by the ship when moving.

Table 12 – The chosen technical measures to be applied to the MASS and their assumed efficiencies

No.	Applied saving measures	Efficiencies in the literatures	Assumed efficiencies
1	Hull form optimization	5-8%	8%
2	Air bubble lubrication	< 15%	15%
3	Optimization of appendages and openings on hull	1-5%	5%
4	Advance propeller	3-6%	6%
5	Fixed sail	< 30%	30%
6	Solar energy	< 4%	4%
7	LNG	< 20%	20%
8	Light material of hull structures	< 7%	7%
9	Bulbous bow	< 10%	10%

The GHG reduction (in percent) when all the above measures are combined can be estimated by the following formula.

$$Overall\ reduction = 1 - (1 - eff_1)(1 - eff_2) \dots (1 - eff_n)(1 - eff_{MASS}) \qquad \textit{Equation 14}$$

Where:

eff_i is the efficiency of the measure i, in percent;

eff_{MASS} is the efficiency of the MASS over the CS, in this study, assuming $eff_{MASS} =$ 8%.

So we have:

$$Overall\ reduction = 1 - (1 - 8\%)(1 - 15\%)(1 - 5\%)(1 - 6\%)(1 - 30\%)(1 - 4\%)(1 - 20\%)(1 - 7\%)(1 - 10\%)(1 - 8\%) = \mathbf{71\%}$$

According to the result, it can be said that the future MASS equipped with those technical measures listed in Table 12 can fulfill the IMO's GHG intensity target in 2050. However, it is seen in Table 12 that all the efficiencies are assumed to take the highest values reported by the reviewed literature. So, in this scenario, the MASS can achieve 70% GHG reduction only in the ideal condition. Therefore, the MASS can really attain the IMO’s GHG intensity goal when more energy-efficient measures are used in addition to or in place of the chosen ones.

To obtain further CO2 emission reduction or decarbonize the ship, alternative fuels or electrical energy may all be feasible solutions provided that they are produced in a sustainable way. Among those measures, electrical energy is believed to facilitate the autonomous control of the ship. Hence, the future MASS will likely run on electrical energy, and the shipping industry will be zero-emission.

Chapter 6 – Conclusions and associated issues

6.1 Energy efficiency of the MASS and its role in addressing the IMO GHG emission issues

The MASS is seen to have a significant EEDI reduction, from about 5% to 10%, compared to the CS. However, the larger the ship is, the less EE is attained. Among those types of ships of the same DWT in the investigation, oil/chemical tankers and bulk carriers are found to have larger EEDI reductions if the autonomous operation is applied, while that of container ships is considerably lower.

With respect to existing energy-saving measures applicable to cargo ships, the MASS is found to be a relatively effective one. Nevertheless, the application of MASS only helps to abate CO2 emission to a certain extent. This research also revealed that the IMO's 2050-target on the ship's carbon intensity would not be easily achieved by the application of the MASS itself, even when additional potential energy-saving measures are employed. To meet the target or completely eliminate the air emissions, the shipping industry must rely on clean solutions like alternative fuels or electrical energy.

One of the factors deciding the MASS's EE, in reality, is the IMO's technical regulations on the MASS because they will affect its design characteristics. The stricter the regulations are, the less efficient the MASS is. As the IMO's regulations are being reviewed and subjected to modification, the actual EE of MASS is still a big question.

In comparison with published research in the literature review, this study is the first one to investigate in detail the differences between the MASS and the CS with respect to EE. This is also the only study in which the MASS's EE is approached based on the EEDI values and the differences in nature between the MASS and the CS in terms of design characteristics. Therefore, the results remain reasonable for any development levels of the CS regarding the EE. In other words, whenever the MASS becomes a reality, it will attain such an EE compared to the CS at the time of autonomy application.

The developed framework in this research can easily be applied to other types of ships by taking those ships' characteristics into consideration. This might be very beneficial for the relevant stakeholders to be able to see the big picture with regard to the impact of autonomous ships on the EE.

6.2 Potential in improving energy efficiency of MASS

In addition to the EEDI reduction previously concluded in section 6.1, MASS may still have the potential to improve its EE more. Firstly, due to the absence of humans onboard the ship, the ship's safety, the carried cargo and the time at sea can be considered for trading off against the EE of the ship. One of the possible trade-offs may be the decrease of the ship's freeboard to increase the carrying capacity provided that relevant safety criteria are met (e.g. intact and damage stability, hull strength). Another trade-off may be the relaxation of the safety requirements. For instance, if the requirements on subdivision and damage stability are less stringent, MASS may have fewer watertight bulkheads leading to a lighter lightweight, and then the MASS will attain more EE due to the improvement of ship's deadweight.

For the CS with crew on board, the voyage time should not be too long to frustrate the seafarers and violate some of the basic human rights. Oppositely, MASS can sustain on the sea for as long as it is designed for and intended to be, depending on several factors like cargo preservation, and supply-demand of cargo carrying. Given the fact that slow steaming is applicable to both type of ships, however, in some cases where the demand of cargo carrying is low, the commodity is not spoiled during a long voyage (e.g. some types of ore) and arrival time is not a crucial issue, relatively slower steaming can be applied to the MASS to attain more fuel-saving than the CS.

In addition to the afore-mentioned trade-offs, there may be other opportunities for the designers to improve the EE of MASS. Principally, the buoyancy force acting on a certain section of the ship's hull is proportional to that section's immersed area. Consequently, the buoyance force is normally the greatest in the middle part of the ship and decreases toward both ends of the ship. The hull girder stress will not be excessive if the ship's weight is distributed similarly to the buoyancy. That means the more weight is distributed in the midship area or the less weight at the two ends of the ship, the less hull girder stress is (e.g. in case of laden condition where cargo holds are located in the middle part of the ship). Therefore, the omission of quite a heavy accommodation structure at the aft end brings more advantages in the MASS's longitudinal strength. An evaluation in Appendix 4 shows that the MASS's bending moment can be reduced by around 20% compared to the CS. The shearing force is also seen to have a significant reduction. This will help the designers optimize the scantling of the ship's structural members resulting in a lighter ship weight and increasing the ship's EE.

6.3 Future work

In the autonomous ship era, the port operation and the interaction between ship and port may all be autonomous. This will harmonize the arrivals of all ships intending to call at the port, and hence each ship’s speed will be optimized to make the just-in-time arrival. This scenario leads to the potential in saving energy of the world fleet in operation.

The future work will investigate the differences in nature between the MASS and the CS in operation, especially in the target of just-in-time arrival, based on which, the energy-saving of MASS in operation will be analyzed.

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Appendix 1 – Bulk carrier analysis

Ship's particulars (Source: VR (2020))

No.	Ship name	IMO number	Year of built	Place of built	Lightship (ton)	Deadweight (ton)	Length (m)	Breadth (m)
1	TAN BINH 134	9236858	2001	Japan	5097	24,600.00	149.99	26
2	PACIFIC 01	9248198	2001	Japan	6095	28,494.00	160.4	27.2
3	PVT-HN	9237395	2001	Japan	6210.3	28,379.00	160.4	27.2
4	HAI NAM 39	9276755	2003	Japan	6086	29,794.00	163.5	27
5	VOSCO UNITY	9290983	2004	Japan	8400	53,552.00	182	32
6	VINALINES SUNRISE	9331878	2006	Japan	8500	56,057.00	182.00	32.26
7	HTK SUNRISE	9316957	2006	Japan	6052	29,828.00	163.50	27.00
8	VINACOMIN HALONG	9581813	2011	Vietnam	2890.7	8,184.50	107.24	17.20
9	OCEAN QUEEN	9331751	2012	Vietnam	11562.1	53,532.90	183.05	32.26
10	VIET THUAN 235	9527362	2012	Vietnam	7714	23,255.50	156.25	25.00
11	MY THINH	8915304	1990	Japan	3169	14,348.00	127.00	21.20
12	OCEAN STAR	9008677	1990	Japan	6407	27,000.00	164.00	27.50
13	VEGA STAR	9061588	1994	Japan	5219	22,035.00	148.00	25.00
14	ORIENTAL GLORY	9104469	1995	Japan	9789	68,591.00	215.00	32.20
15	PEACE STAR	9085663	1995	Japan	5306	21,967.00	148.00	25.00
16	NEPTUNE STAR	9136553	1996	Japan	5471	25,398.00	149.80	26.00
17	VTB ACE	9143049	1996	Japan	5689.7	24,157.00	151.00	25.80
18	VINASHIP PEARL	9114488	1996	Japan	5451	24,241.00	144.99	26.00
19	VINASHIP SEA	9168350	1998	Japan	7060	27,841.00	162.00	27.00
20	VTC GLORY	9168752	1998	Japan	5112	23,620.00	143.00	26.00
21	TAN BINH 59	9191436	1999	Japan	5599	24,838.00	146.00	26.20

Ship's particulars (Source: VR (2020)) (continued):

No.	Ship name	Depth (m)	Draft (m)	Freeboard (m)	Speed (kt)	Main engine (kW)	Auxiliary engine (kW)
1	TAN BINH 134	13.3	9.53	3.77	14	5340	800
2	PACIFIC 01	13.6	9.76	3.84	14	5850	1500
3	PVT-HN	13.6	9.761	3.839	14	5850	1500
4	HAI NAM 39	13.8	9.7	4.1	14.2	6150	1000
5	VOSCO UNITY	17	12	5.02	15	9480	1320
6	VINALINES SUNRISE	17.90	12.55	5.35	14.5	9480	1650
7	HTK SUNRISE	13.80	9.70	4.1	16.1	6150	1365
8	VINACOMIN HALONG	9.20	7.05	2.15	12	2574	720
9	OCEAN QUEEN	17.53	12.62	4.91	15	9480	2310
10	VIET THUAN 235	12.00	8.68	3.32	10.5	4412	1620
11	MY THINH	10.80	7.92	2.881	12.2	2795	1059
12	OCEAN STAR	13.15	9.20	3.95	13.5	5273	883
13	VEGA STAR	12.70	9.11	3.591	14	5296	883
14	ORIENTAL GLORY	18.20	13.29	4.911	14	7634	1980
15	PEACE STAR	12.70	9.10	3.6	14	5295	882
16	NEPTUNE STAR	13.50	9.82	3.685	14	5295	1200
17	VTB ACE	13.30	9.40	3.9	15.8	5383.86	1102
18	VINASHIP PEARL	13.30	9.53	3.77	14.5	5296	882.6
19	VINASHIP SEA	13.80	9.65	4.15	13	6545	1059.12
20	VTC GLORY	13.20	9.55	3.65	16.3	5295	882
21	TAN BINH 59	13.30	9.68	3.62	14	5516	1000.28

Dimensions of ship's S&DH (Source: VR (2020))

Note:

- L (m) is the length
- W (m) is the width
- Poop is defined in Regulation 3(10)(f) Annex I of Loadlines Convention.
- Tier refers to the tier of the deckhouse.

No.	Ship name	Poop		Tier 1		Tier 2		Tier 3		Tier 4	
		L (m)	W (m)	L (m)	W (m)	L (m)	W (m)	L (m)	W (m)	L (m)	W (m)
1	TAN BINH 134	27.3	17.35	18.7	15.85	9.66	15.85	9.62	15.85		
2	PACIFIC 01	26.3	19	16.7	14.3	14.4	14.3	10.5	14.3		
3	PVT-HN	26.3	19	16.7	14.3	14.4	14.3	10.5	14.3		
4	HAI NAM 39	17.3	17.53	9.79	27	9.79	27	9.79	17.85		
5	VOSCO UNITY	15.8	19	12.9	19	12.9	19	12.9	19		
6	VINALINES SUNRISE	19	19	15.7	19	12.58	19	12.58	19		
7	HTK SUNRISE	18.04	17.6	9.6	27	9.6	17.5	9.6	17.5		
8	VINACOMIN HALONG	23.8	17	13.7	11.1	11	11.1	11	11.1		
9	OCEAN QUEEN	13.6	23.8	13.6	23.8	12	23.8	12	23.8	12	23.8
10	VIET THUAN 235	18.8	18.05	18.7	15.4	9.6	15.4	9.6	15.4		
11	MY THINH	23.2	15.9	10.7	12.9	10.7	12.9	10.7	12.9		
12	OCEAN STAR	18.7	17.72	18.8	17.72	15.9	17.72	14.4	17.72		
13	VEGA STAR	17.1	15.4	17.1	15.4	17.1	15.4	17.1	15.4		
14	ORIENTAL GLORY	19.2	20.6	17.5	20.6	15.9	20.6	10.5	20.6		
15	PEACE STAR	17.4	15.4	17.4	15.4	17.4	15.4	17.4	15.4		
16	NEPTUNE STAR	20.56	26	17.6	14.3	12.9	14.3	10.4	14.3		
17	VTB ACE	16.7	15	16.7	15	16.7	15	16.7	15		
18	VINASHIP PEARL	27.4	18.4	18.7	16.3	9.7	16.3	9.7	16.3		
19	VINASHIP SEA	20	17.3	20	17.3	16.7	17.3	7.9	17.3		
20	VTC GLORY	14.4	18.4	14.4	18.4	11.4	18.4	11.4	18.4		
21	TAN BINH 59	17.8	25	17.64	15.9	17.64	15.9	8.24	15.9		

Dimensions of ship's S&DH (Source: VR (2020)) (continued) and windage areas

Note:

- Accom. weight is the weight of S&DH which is calculated based on the weight factors of S&DH given in Table 4 of section 3.2 and the covering area of the S&DH which is equal to $L \times W$.
- Windage area of accom. is the fore end bulkhead area of S&DH which can be estimated by summing up each tier of S&DH (equal to $\sum(W \times 2.5)$, where W is the width of the tier and 2.5 is the average height of all tier.
- Windage area of the main hull can be roughly estimated by the equation $F \times B$, where F and B are the freeboard and breadth of ship, respectively.

No.	Ship name	Wheelhouse		Accom. weight (ton)	Windage area of accom. (m2)	Windage area of main hull (m2)
		L (m)	W (m)			
1	TAN BINH 134	7.18	11.28	376.6	190.5	98.0
2	PACIFIC 01	6.9	9.61	379.5	178.8	98.0
3	PVT-HN	6.9	9.61	379.5	178.8	104.4
4	HAI NAM 39	6.4	10.02	342.0	248.5	99.0
5	VOSCO UNITY	10.5	10.5	362.6	216.3	161.9
6	VINALINES SUNRISE	8.2	10.2	390.1	215.5	100.0
7	HTK SUNRISE	6.6	9.4	313.3	222.5	110.7
8	VINACOMIN HALONG	10.5	9.1	293.8	149.0	101.0
9	OCEAN QUEEN	10.6	17.6	527.1	341.5	158.4
10	VIET THUAN 235	7.9	10.4	323.3	186.6	102.0
11	MY THINH	5.22	10.02	273.0	161.6	61.1
12	OCEAN STAR	5	8.1	396.7	197.5	103.0
13	VEGA STAR	6.5	10.7	355.2	180.8	89.8
14	ORIENTAL GLORY	6.7	11.2	439.9	234.0	104.0
15	PEACE STAR	6.5	10.6	360.9	180.5	90.0
16	NEPTUNE STAR	5.3	9.5	384.7	196.0	105.0
17	VTB ACE	6.1	10.4	337.1	176.0	100.6
18	VINASHIP PEARL	6.1	11.7	390.8	197.5	106.0
19	VINASHIP SEA	6.4	9	377.2	195.5	112.1
20	VTC GLORY	9.6	11.1	333.7	211.8	107.0
21	TAN BINH 59	5.5	11.1	388.8	209.5	94.8

Calculation of $EEDI_{attained} \cdot V_{ref}$ for CS

Note:

For the detailed explanations, see section 4.1.

No.	Ship name	Conventional ship						
		PME (kW)	CFME	SFCME	PAE (kW)	CFAE	SFCAE	EEDI*Vref
1	TAN BINH 134	4005.0	3.1144	190	267	3.1144	215	103.6
2	PACIFIC 01	4387.5	3.1144	190	292.5	3.1144	215	98.0
3	PVT-HN	4387.5	3.1144	190	292.5	3.1144	215	98.4
4	HAI NAM 39	4612.5	3.1144	190	307.5	3.1144	215	98.5
5	VOSCO UNITY	7110.0	3.1144	190	474	3.1144	215	84.5
6	VINALINES SUNRISE	7110.0	3.1144	190	474	3.1144	215	80.7
7	HTK SUNRISE	4612.5	3.1144	190	307.5	3.1144	215	98.4
8	VINACOMIN HALONG	1930.7	3.1144	190	128.7125	3.1144	215	150.1
9	OCEAN QUEEN	7110.0	3.1144	190	474	3.1144	215	84.5
10	VIET THUAN 235	3309.0	3.1144	190	220.6	3.1144	215	90.5
11	MY THINH	2096.2	3.1144	190	139.745	3.1144	215	93.0
12	OCEAN STAR	3954.8	3.1144	190	263.65	3.1144	215	93.2
13	VEGA STAR	3971.7	3.1144	190	264.78	3.1144	215	114.7
14	ORIENTAL GLORY	5725.5	3.1144	190	381.7	3.1144	215	53.1
15	PEACE STAR	3971.3	3.1144	190	264.75	3.1144	215	115.0
16	NEPTUNE STAR	3971.3	3.1144	190	264.75	3.1144	215	99.5
17	VTB ACE	4037.9	3.1144	190	269.193	3.1144	215	106.4
18	VINASHIP PEARL	3972.0	3.1144	190	264.8	3.1144	215	104.3
19	VINASHIP SEA	4908.8	3.1144	190	327.25	3.1144	215	112.2
20	VTC GLORY	3971.3	3.1144	190	264.75	3.1144	215	107.0
21	TAN BINH 59	4137.0	3.1144	190	275.8	3.1144	215	106.0

Calculation of $EEDI_{attained} \cdot V_{ref}$ for MASS

Note:

For the detailed explanations, see section 4.1.

No.	Ship name	MASS					
		PME (kW)	CFME	SFCME	PAE (kW)	CFAE	SFCAE
1	TAN BINH 134	3939.72	3.1144	190	133.5	3.1144	215
2	PACIFIC 01	4315.98	3.1144	190	146.25	3.1144	215
3	PVT-HN	4315.98	3.1144	190	146.25	3.1144	215
4	HAI NAM 39	4537.32	3.1144	190	153.75	3.1144	215
5	VOSCO UNITY	6994.11	3.1144	190	237	3.1144	215
6	VINALINES SUNRISE	6994.11	3.1144	190	237	3.1144	215
7	HTK SUNRISE	4537.32	3.1144	190	153.75	3.1144	215
8	VINACOMIN HALONG	1899.22	3.1144	190	64.35625	3.1144	215
9	OCEAN QUEEN	6994.11	3.1144	190	237	3.1144	215
10	VIET THUAN 235	3255.06	3.1144	190	110.3	3.1144	215
11	MY THINH	2062.01	3.1144	190	69.8725	3.1144	215
12	OCEAN STAR	3890.29	3.1144	190	131.825	3.1144	215
13	VEGA STAR	3906.96	3.1144	190	132.39	3.1144	215
14	ORIENTAL GLORY	5632.17	3.1144	190	190.85	3.1144	215
15	PEACE STAR	3906.52	3.1144	190	132.375	3.1144	215
16	NEPTUNE STAR	3906.52	3.1144	190	132.375	3.1144	215
17	VTB ACE	3972.08	3.1144	190	134.5965	3.1144	215
18	VINASHIP PEARL	3907.26	3.1144	190	132.4	3.1144	215
19	VINASHIP SEA	4828.74	3.1144	190	163.625	3.1144	215
20	VTC GLORY	3906.52	3.1144	190	132.375	3.1144	215
21	TAN BINH 59	4069.57	3.1144	190	137.9	3.1144	215

Calculation of $EEDI_{attained} \cdot V_{ref}$ for MASS (continued) and EEDI reduction

Note:

- (Capacity +) is the increase of deadweight due to the elimination of S&DH (see section 3.2).
- (Capacity –) is the decrease in deadweight due to the alternative arrangement of the ship's propulsion system (see section 3.7).
- For other explanations in detail, see section 4.1.

No.	Ship name	MASS				EEDI reduction (%)
		Capacity +	Capacity -	Capacity	EEDI*Vref	
1	TAN BINH 134	376.6	31.08	24945.6	97.0	6.34
2	PACIFIC 01	379.5	32.77	28840.8	91.9	6.2
3	PVT-HN	379.5	32.77	28725.8	92.3	6.17
4	HAI NAM 39	342.0	33.70	30102.3	92.6	6.0
5	VOSCO UNITY	362.6	40.57	53874.0	79.8	5.59
6	VINALINES SUNRISE	390.1	40.57	56406.5	76.2	5.6
7	HTK SUNRISE	313.3	33.70	30107.6	92.6	5.91
8	VINACOMIN HALONG	293.8	19.35	8459.0	138.0	8.1
9	OCEAN QUEEN	527.1	40.57	54019.5	79.6	5.88
10	VIET THUAN 235	323.3	27.62	23551.2	84.9	6.2
11	MY THINH	273.0	20.44	14600.5	86.8	6.67
12	OCEAN STAR	396.7	30.84	27365.8	87.3	6.3
13	VEGA STAR	355.2	30.92	22359.3	107.4	6.40
14	ORIENTAL GLORY	439.9	37.53	68993.4	50.2	5.6
15	PEACE STAR	360.9	30.92	22297.0	107.6	6.43
16	NEPTUNE STAR	384.7	30.92	25751.8	93.2	6.3
17	VTB ACE	337.1	31.23	24462.9	99.8	6.21
18	VINASHIP PEARL	390.8	30.93	24600.9	97.6	6.4
19	VINASHIP SEA	377.2	34.84	28183.4	105.3	6.18
20	VTC GLORY	333.7	30.92	23922.8	100.3	6.2
21	TAN BINH 59	388.8	31.68	25195.1	99.2	6.37

Calculation of reduction (in %) of air resistance

Note:

The percentage reduction of air resistance is calculated by the formula:

$$\frac{A_2}{0.3A_1 + A_2}100\%$$

Where:

A_2 is the windage area of the S&DHs;

A_1 is the windage area of the main hull.

For the detailed explanation, see section 3.3.

No.	Ship name	Breadth (m)	Freeboard (m)	Windage area of accom. (m2)	Windage area of main hull (m2)	Air resist. Reduction
1	TAN BINH 134	26	3.77	190.5	98.0	86.6%
2	PACIFIC 01	27.2	3.84	178.8	98.0	85.9%
3	PVT-HN	27.2	3.839	178.8	104.4	85.1%
4	HAI NAM 39	27	4.1	248.5	99.0	89.3%
5	VOSCO UNITY	32	5.02	216.3	161.9	81.7%
6	VINALINES SUNRISE	32.26	5.35	215.5	100.0	87.8%
7	HTK SUNRISE	27.00	4.1	222.5	110.7	87.0%
8	VINACOMIN HALONG	17.20	2.15	149.0	101.0	83.1%
9	OCEAN QUEEN	32.26	4.91	341.5	158.4	87.8%
10	VIET THUAN 235	25.00	3.32	186.6	102.0	85.9%
11	MY THINH	21.20	2.881	161.6	61.1	89.8%
12	OCEAN STAR	27.50	3.95	197.5	103.0	86.5%
13	VEGA STAR	25.00	3.591	180.8	89.8	87.0%
14	ORIENTAL GLORY	32.20	4.911	234.0	104.0	88.2%
15	PEACE STAR	25.00	3.6	180.5	90.0	87.0%
16	NEPTUNE STAR	26.00	3.685	196.0	105.0	86.2%
17	VTB ACE	25.80	3.9	176.0	100.6	85.4%
18	VINASHIP PEARL	26.00	3.77	197.5	106.0	86.1%
19	VINASHIP SEA	27.00	4.15	195.5	112.1	85.3%
20	VTC GLORY	26.00	3.65	211.8	107.0	86.8%
21	TAN BINH 59	26.20	3.62	209.5	94.8	88.0%

Appendix 2 – Oil/chemical tanker analysis

Ship’s particulars (Source: VR (2020))

No.	Ship name	IMO number	Year of built	Place of built	Lightship (ton)	Deadweight (ton)	Length (m)	Breadth (m)
1	GREAT WALRUS	9450179	2007	China	4333.10	13708	129.50	20.80
2	THANH CHAU 26	7709813	1977	Japan	991.60	3411	80.25	11.00
3	DYNAMIC OCEAN 05	9656515	2012	Vietnam	1724.20	4990	84.97	15.30
4	AN PHU 16	9561681	2010	Vietnam	1758.10	5645	90.56	15.60
5	GREAT LADY	9525766	2009	China	2813.40	7130	110.00	17.60
6	LONGHUNG 2	9236925	2001	Japan	2769.30	7786	104.05	18.60
7	AULAC DRAGON	9311309	2003	China	4002.90	10000	123.32	19.50
8	GLORY STAR	9463528	2007	China	5525.40	16820	134.50	23.00
9	PETROLIMEX 10	9239642	2003	Korea	8778.90	37256	168.00	31.00
10	HAI LINH 03	9258351	2002	Japan	9283.00	45798	171.00	32.00
11	PVT DOLPHIN	9288277	2004	Japan	8898.00	45888	172.00	32.20
12	VINALINES GLORY	9337303	2006	Korea	10113.30	44999	174.00	32.20
13	APOLLO	9321964	2006	Japan	16008.00	105465	229.00	42.00
14	PVT MERCURY	9426946	2012	Vietnam	20485.00	101900	236.00	43.00
15	PVT ATHENA	9208136	2000	Korea	17740.00	105177	234.00	42.00

Ship's particulars (Source: VR (2020)) (continued)

No.	Ship name	Depth (m)	Draft (m)	Freeboard (m)	Speed (kt)	Main engine (kW)	Auxiliary engine (kW)
1	GREAT WALRUS	10.80	8.10	2.70	12.60	3824	806.00
2	THANH CHAU 26	6.40	4.98	1.42	11.00	1323.90	440.00
3	DYNAMIC OCEAN 05	7.90	6.34	1.56	12.00	2000.00	552.00
4	AN PHU 16	8.65	6.75	1.90	10.00	1765.00	396.00
5	GREAT LADY	9.00	6.60	2.40	12	2574.00	626.00
6	LONGHUNG 2	9.60	7.00	2.60	14.40	3900.00	1200.00
7	AULAC DRAGON	9.78	6.87	2.91	12.00	2940.00	588.00
8	GLORY STAR	12.60	8.95	3.65	13.00	4400.00	1209.00
9	PETROLIMEX 10	17.20	10.50	6.70	17.00	8561.22	2430.00
10	HAI LINH 03	18.80	12.10	6.70	14.50	8580.00	1650.00
11	PVT DOLPHIN	18.70	12.02	6.68	15.10	9267.00	2400.00
12	VINALINES GLORY	19.10	13.02	6.08	15.00	9485.00	2910.00
13	APOLLO	21.30	14.85	6.45	14.80	12000.00	2130.00
14	PVT MERCURY	20.00	14.10	5.90	13.70	13560.00	2340.00
15	PVT ATHENA	22.00	14.92	7.08	13.5	14415.80	414.00

Dimensions of ship's S&DH (Source: VR (2020))

Note:

- L (m) is the length
- W (m) is the width
- Poop is defined in Regulation 3(10)(f) Annex I of Loadlines Convention.
- Tier refers to the tier of the deckhouse.

No.	Ship name	Poop		Tier 1		Tier 2		Tier 3		Tier 4	
		L (m)	W (m)	L (m)	W (m)	L (m)	W (m)	L (m)	W (m)	L (m)	W (m)
1	GREAT WALRUS	28.5	20.8	18.5	15.5	11.2	14	11.2	14	11.2	14
2	THANH CHAU 26	10.8	11	10.8	7.6	4.1	10.8				
3	DYNAMIC OCEAN 05	20.7	15.3	13.79	9.7	10.1	8.7				
4	AN PHU 16	18.34	13.52	11.6	9.4	10.55	8.07				
5	GREAT LADY	25.1	16.5	18	14.4	16.8	10.12	13.3	10.2		
6	LONGHUNG 2	26	16.2	16	11.9	14.4	13.1	14.4	13.1		
7	AULAC DRAGON	23.27	19.5	16.5	15.1	15.6	12.8	10.5	14.8		
8	GLORY STAR	20.7	23	16.6	15.1	9.7	15.14	9.8	15.14		
9	PETROLIMEX 10			22.84	20.8	16.1	20.8	12.88	20.8	12.88	20.8
10	HAI LINH 03			16.96	17.82	14.51	17.82	14.51	17.82	14.51	17.82
11	PVT DOLPHIN			20	18.5	12.9	18.5	12.9	18.5	12.9	18.5
12	VINALINES GLORY			15.2	24.2	20.4	24.2	13.4	24.2	13.4	24.2
13	APOLLO			12.4	24.8	12.4	24.8	12.4	24.8		
14	PVT MERCURY			17.9	30	14.3	30	14.3	30	14.3	30
15	PVT ATHENA			14.3	25	14.3	25	14.3	25	14.3	25

Dimensions of ship’s S&DH (Source: VR (2020)) (continued) and windage areas

Note:

- Accom. weight is the weight of S&DH which is calculated based on the weight factors of S&DH given in Table 4 of section 3.2 and the covering area of the S&DH which is equal to $L \times W$.
- Windage area of accom. is the fore end bulkhead area of S&DH which can be estimated by summing up each tier of S&DH (equal to $\sum(W \times 2.5)$, where W is the width of the tier and 2.5 is the average height of all tier.
- Windage area of the main hull can be roughly estimated by the equation $F \times B$, where F and B are the freeboard and breadth of ship, respectively.

No.	Ship name	Wheelhouse		Accom. weight (ton)	Windage area of accom. (m2)	Windage area of main hull (m2)
		L (m)	W (m)			
1	GREAT WALRUS	7.7	12.6	470.4	227.3	56.2
2	THANH CHAU 26	4.2	5.88	88.4	88.2	98.0
3	DYNAMIC OCEAN 05	6.14	7.3	194.1	102.5	23.9
4	AN PHU 16	4.2	7.45	157.3	96.1	99.0
5	GREAT LADY	9.9	7.8	342.9	147.6	42.2
6	LONGHUNG 2	7.1	8.3	340.6	156.5	100.0
7	AULAC DRAGON	11.2	8.5	373.8	176.8	56.7
8	GLORY STAR	7.88	11.6	362.9	200.0	101.0
9	PETROLIMEX 10	11.13	14.85	457.5	245.1	207.7
10	HAI LINH 03	11.2	8.16	354.4	198.6	102.0
11	PVT DOLPHIN	10.4	9.5	359.5	208.8	215.0
12	VINALINES GLORY	8.5	15	496.6	279.5	103.0
13	APOLLO	9.2	9.2	305.8	209.0	270.9
14	PVT MERCURY	10.6	14	598.3	335.0	104.0
15	PVT ATHENA	12.7	10.8	474.1	277.0	297.4

Calculation of $EEDI_{attained} \cdot V_{ref}$ for CS

Note:

For the detailed explanations, see section 4.1.

No.	Ship name	Conventional ship						
		PME (kW)	CFME	SFCME	PAE (kW)	CFAE	SFCAE	EEDI*Vref
1	GREAT WALRUS	2868	3.1144	190	345.6	3.1144	215	140.7
2	THANH CHAU 26	992.925	3.1144	190	66.2	3.1144	215	185.2
3	DYNAMIC OCEAN 05	1500	3.1144	190	100.0	3.1144	215	191.3
4	AN PHU 16	1323.75	3.1144	190	88.3	3.1144	215	149.2
5	GREAT LADY	1930.5	3.1144	190	128.7	3.1144	215	172.3
6	LONGHUNG 2	2925	3.1144	190	195.0	3.1144	215	239.1
7	AULAC DRAGON	2205	3.1144	190	147.0	3.1144	215	140.3
8	GLORY STAR	3300	3.1144	190	220.0	3.1144	215	124.9
9	PETROLIMEX 10	6420.915	3.1144	190	428.1	3.1144	215	109.7
10	HAI LINH 03	6435	3.1144	190	429.0	3.1144	215	89.4
11	PVT DOLPHIN	6950.25	3.1144	190	463.4	3.1144	215	96.4
12	VINALINES GLORY	7113.75	3.1144	190	474.3	3.1144	215	100.6
13	APOLLO	9000	3.1144	190	550.0	3.1144	215	54.0
14	PVT MERCURY	10170	3.1144	190	589.0	3.1144	215	62.9
15	PVT ATHENA	10811.85	3.1144	190	610.4	3.1144	215	64.7

Calculation of $EEDI_{attained} \cdot V_{ref}$ for MASS

Note:

For the detailed explanations, see section 4.1.

No.	Ship name	MASS					
		PME (kW)	CFME	SFCME	PAE (kW)	CFAE	SFCAE
1	GREAT WALRUS	2826.7	3.1144	190	172.8	3.1144	215
2	THANH CHAU 26	978.6	3.1144	190	33.0975	3.1144	215
3	DYNAMIC OCEAN 05	1478.4	3.1144	190	50	3.1144	215
4	AN PHU 16	1304.7	3.1144	190	44.125	3.1144	215
5	GREAT LADY	1902.7	3.1144	190	64.35	3.1144	215
6	LONGHUNG 2	2882.9	3.1144	190	97.5	3.1144	215
7	AULAC DRAGON	2173.2	3.1144	190	73.5	3.1144	215
8	GLORY STAR	3252.5	3.1144	190	110	3.1144	215
9	PETROLIMEX 10	6328.5	3.1144	190	214.0305	3.1144	215
10	HAI LINH 03	6342.3	3.1144	190	214.5	3.1144	215
11	PVT DOLPHIN	6850.2	3.1144	190	231.675	3.1144	215
12	VINALINES GLORY	7011.3	3.1144	190	237.125	3.1144	215
13	APOLLO	8870.4	3.1144	190	300	3.1144	215
14	PVT MERCURY	10023.6	3.1144	190	339	3.1144	215
15	PVT ATHENA	10656.2	3.1144	190	360.395	3.1144	215

Calculation of $EEDI_{attained} \cdot V_{ref}$ for MASS (continued) and EEDI reduction

Note:

- (Capacity +) is the increase of deadweight due to the elimination of S&DH (see section 3.2).
- (Capacity –) is the decrease in deadweight due to the alternative arrangement of the ship's propulsion system (see section 3.7).
- For other explanations in detail, see section 4.1.

No.	Ship name	MASS				EEDI reduction (%)
		Capacity +	Capacity -	Capacity	EEDI*Vref	
1	GREAT WALRUS	470.4	25.18	14152.74	126.4	10.18
2	THANH CHAU 26	88.4	12.62	3487.18	172.4	6.9
3	DYNAMIC OCEAN 05	194.1	16.37	5167.88	175.8	8.12
4	AN PHU 16	157.3	15.10	5787.55	138.5	7.2
5	GREAT LADY	342.9	19.34	7453.84	156.8	8.98
6	LONGHUNG 2	340.6	25.51	8101.08	218.6	8.5
7	AULAC DRAGON	373.8	21.14	10352.66	129.0	8.09
8	GLORY STAR	362.9	27.57	17155.71	116.5	6.7
9	PETROLIMEX 10	457.5	39.30	37674.27	103.2	5.90
10	HAI LINH 03	354.4	39.33	46113.09	84.5	5.5
11	PVT DOLPHIN	359.5	40.32	46207.15	91.1	5.50
12	VINALINES GLORY	496.6	40.58	45454.98	94.8	5.8
13	APOLLO	305.8	41.62	105729.15	51.5	4.53
14	PVT MERCURY	598.3	40.47	102457.50	60.1	4.5
15	PVT ATHENA	474.1	39.25	105611.82	62.0	4.21

Calculation of reduction (in %) of air resistance

Note:

The percentage reduction of air resistance is calculated by the formula:

$$\frac{A_2}{0.3A_1 + A_2}100\%$$

Where:

A_2 is the windage area of the S&DHs;

A_1 is the windage area of the main hull.

For the detailed explanation, see section 3.3.

No.	Ship name	Breadth (m)	Freeboard (m)	Windage area of accom. (m2)	Windage area of main hull (m2)	Air resist. Reduction
1	GREAT WALRUS	20.80	2.70	227.3	56.2	93.1%
2	THANH CHAU 26	11.00	1.42	88.2	98.0	75.0%
3	DYNAMIC OCEAN 05	15.30	1.56	102.5	23.9	93.5%
4	AN PHU 16	15.60	1.90	96.1	99.0	76.4%
5	GREAT LADY	17.60	2.40	147.6	42.2	92.1%
6	LONGHUNG 2	18.60	2.60	156.5	100.0	83.9%
7	AULAC DRAGON	19.50	2.91	176.8	56.7	91.2%
8	GLORY STAR	23.00	3.65	200.0	101.0	86.8%
9	PETROLIMEX 10	31.00	6.70	245.1	207.7	79.7%
10	HAI LINH 03	32.00	6.70	198.6	102.0	86.6%
11	PVT DOLPHIN	32.20	6.68	208.8	215.0	76.4%
12	VINALINES GLORY	32.20	6.08	279.5	103.0	90.0%
13	APOLLO	42.00	6.45	209.0	270.9	72.0%
14	PVT MERCURY	43.00	5.90	335.0	104.0	91.5%
15	PVT ATHENA	42.00	7.08	277.0	297.4	75.6%

Appendix 3 – Container ship analysis

Ship's particulars (Source: VR (2020))

No.	Ship name	IMO number	Year of built	Place of built	Lightship (ton)	Deadweight (ton)	Length (m)	Breadth (m)
1	HAIAN PARK	9207560	2000	Japan	4875.00	12649.00	134.00	22.40
2	HAIAN SONG	9236585	2001	Poland	6805.00	18409.00	145.00	24.00
3	HAIAN TIME	9245158	2001	Japan	5563.00	18055.00	150.00	25.60
4	VIETSUN INTEGRITY	9264776	2003	China	3927.30	8059.90	123.4	19.20
5	PHUC KHANH	9318905	2004	China	3748.50	8238.00	122.54	19.20
6	BIENDONG MARINER	9279214	2004	Vietnam	5341.00	12474.00	140.64	22.30
7	TAN CANG GLORY	9334105	2005	Germany	3663.00	8489.00	126.80	19.40
8	TRUONG HAI STAR 2	9419606	2007	Vietnam	3014.20	3200.80	84.80	15.40
9	NASICO SKY	9560883	2012	Vietnam	2074.40	4751.60	95.80	15.80
10	NICOLE	9122320	1996	Korea	2495.80	7345.10	105.02	18.20
11	TAN CANG FOUNDATION	9122332	1996	Korea	2446.40	7040.00	105.00	18.20
12	PACIFIC EXPRESS	9167851	1997	Japan	4115.00	11117.00	119.04	22.40
13	PROSPER	9159268	1997	Japan	3613.90	8716.10	110.00	18.20

Ship's particulars (Source: VR (2020)) (continued)

No.	Ship name	Depth (m)	Draft (m)	Freeboard (m)	Speed (kt)	Main engine (kW)	Auxilary engine (kW)
1	HAIAN PARK	11.00	8.20	2.80	17.30	8098	1560
2	HAIAN SONG	13.90	10.20	3.70	18.60	10010	3060
3	HAIAN TIME	12.90	9.07	3.84	18.50	11440	2880
4	VIETSUN INTEGRITY	9.20	7.20	2.00	17.00	6300	1000
5	PHUC KHANH	9.20	7.22	1.98	17.00	6300	740
6	BIENDONG MARINER	11.10	8.26	2.85	18.00	6930	1599
7	TAN CANG GLORY	9.45	7.36	2.09	17.00	7200	1030
8	TRUONG HAI STAR 2	7.30	5.75	1.55	12.00	2207	660
9	NASICO SKY	7.70	5.70	2.00	12.50	2610	672
10	NICOLE	8.70	6.90	1.80	14.00	3353	882.6
11	TAN CANG FOUNDATION	8.70	6.70	2.00	14.00	3354	883
12	PACIFIC EXPRESS	11.20	8.20	3.00	17.00	7355	1650
13	PROSPER	11.00	7.84	3.17	16.00	5177	1192

Dimensions of ship's S&DH (Source: VR (2020))

Note:

- L (m) is the length
- W (m) is the width
- Poop is defined in Regulation 3(10)(f) Annex I of Loadlines Convention.
- Tier refers to the tier of the deckhouse.

No.	Ship name	Poop		Tier 1		Tier 2		Tier 3		Tier 4	
		L (m)	W (m)	L (m)	W (m)	L (m)	W (m)	L (m)	W (m)	L (m)	W (m)
1	HAIAN PARK	29	19.8	14	16	12.6	14.8	12.6	14.8	12.6	14.8
2	HAIAN SONG	23.2	24	15.4	18	15.4	18	8.8	18	8.8	18
3	HAIAN TIME			20.1	14.9	20.1	14.9	11.9	16.32	11.9	16.32
4	VIETSUN INTEGRITY			12.64	9.8	9.04	9.8	7.5	9.8	7.5	9.8
5	PHUC KHANH			11.8	12.1	9.1	9.74	9.1	9.74	9.1	9.74
6	BIENDONG MARINER	20.25	22.3	13.1	14.9	13.1	14.9	6.9	14.9	6.9	14.9
7	TAN CANG GLORY	14.7	19.4	8.9	9.9	6.4	9.9	6.4	9.9	6.4	9.9
8	TRUONG HAI STAR 2	15.2	14	12.1	10.22	8.5	9.4	8.5	10.2		
9	NASICO SKY	15.2	15.8	9.5	9.8	9.5	9.8	4.9	9.8		
10	NICOLE	18.6	16.2	12.7	12.7	8.88	12.7	8.88	12.7	8.88	12.7
11	TAN CANG FOUNDATION	18.51	16.29	13.8	13.2	8.8	13.2	8.8	13.2	8.8	13.2
12	PACIFIC EXPRESS	23.95	19.55	14.2	14	14.2	14	8	14	8	14
13	PROSPER	15.6	18.2	9.9	14.3	8.6	14.3	8.6	14.3	8.6	14.3

Dimensions of ship's S&DH (Source: VR (2020)) (continued)

Note:

Accom. weight is the weight of S&DH which is calculated based on the weight factors of S&DH given in Table 4 of section 3.2 and the covering area of the S&DH which is equal to $L \times W$.

No.	Ship name	Tier 5		Tier 6		Wheelhouse		Accom. weight (ton)
		L (m)	W (m)	L (m)	W (m)	L (m)	W (m)	
1	HAIAN PARK	12.6	14.8	7.7	14.8	6.5	10.8	554.8
2	HAIAN SONG	8.8	18	8.8	18	7.7	15.7	594.8
3	HAIAN TIME	9.55	16.32			8.3	8.6	369.1
4	VIETSUN INTEGRITY	7.5	9.8	7.5	9.8	5.44	12	172.3
5	PHUC KHANH	9.1	9.74	9.1	9.74	5.6	11.8	196.7
6	BIENDONG MARINER	6.9	14.9	6.9	14.9	6.3	10.6	424.6
7	TAN CANG GLORY	6.4	9.9			5.3	8.83	218.9
8	TRUONG HAI STAR 2					4.2	8.6	176.1
9	NASICO SKY					4.9	6.9	167.1
10	NICOLE					6.6	8.8	276.4
11	TAN CANG FOUNDATION					6.66	9.12	286.8
12	PACIFIC EXPRESS	8	14			7.4	14	420.0
13	PROSPER	8.6	14.3			6.7	10.7	314.2

Calculation of $EEDI_{attained} \cdot V_{ref}$ for CS

Note:

- In case of container ship, Capacity is 70 percent of ship's deadweight.
- For the detailed explanations, see section 4.1.

No.	Ship name	Conventional ship							
		PME (kW)	CFME	SFC ME	PAE (kW)	CFAE	SFC AE	Capacity	EEDI* Vref
1	HAIAN PARK	6073.5	3.1144	190	404.9	3.1144	215	8854.3	436.5
2	HAIAN SONG	7507.5	3.1144	190	500.25	3.1144	215	12886.3	370.7
3	HAIAN TIME	8580	3.1144	190	536	3.1144	215	12638.5	430.1
4	VIETSUN INTEGRITY	4725	3.1144	190	315	3.1144	215	5641.93	533.0
5	PHUC KHANH	4725	3.1144	190	315	3.1144	215	5766.6	521.4
6	BIENDONG MARINER	5197.5	3.1144	190	346.5	3.1144	215	8731.8	378.8
7	TAN CANG GLORY	5400	3.1144	190	360	3.1144	215	5942.3	578.3
8	TRUONG HAI STAR 2	1654.9	3.1144	190	110.33	3.1144	215	2240.56	470.0
9	NASICO SKY	1957.5	3.1144	190	130.5	3.1144	215	3326.12	374.5
10	NICOLE	2514.8	3.1144	190	167.65	3.1144	215	5141.57	311.3
11	TAN CANG FOUNDATION	2515.4	3.1144	190	167.69	3.1144	215	4928	324.8
12	PACIFIC EXPRESS	5516.3	3.1144	190	367.75	3.1144	215	7781.9	451.1
13	PROSPER	3882.8	3.1144	190	258.85	3.1144	215	6101.27	405.0

Calculation of $EEDI_{attained} \cdot V_{ref}$ for MASS

Note:

- In case of autonomous container ship, no air resistance reduction is made and therefore main engine power is not subject to the reduction.
- For the detailed explanations, see section 4.1.

No.	Ship name	MASS					
		PME (kW)	CFME	SFCME	PAE (kW)	CFAE	SFCAE
1	HAIAN PARK	6073.5	3.1144	190	202.45	3.1144	215
2	HAIAN SONG	7507.5	3.1144	190	250.25	3.1144	215
3	HAIAN TIME	8580.0	3.1144	190	286	3.1144	215
4	VIETSUN INTEGRITY	4725.0	3.1144	190	157.5	3.1144	215
5	PHUC KHANH	4725.0	3.1144	190	157.5	3.1144	215
6	BIENDONG MARINER	5197.5	3.1144	190	173.25	3.1144	215
7	TAN CANG GLORY	5400.0	3.1144	190	180	3.1144	215
8	TRUONG HAI STAR 2	1654.9	3.1144	190	55.1625	3.1144	215
9	NASICO SKY	1957.5	3.1144	190	65.25	3.1144	215
10	NICOLE	2514.8	3.1144	190	83.825	3.1144	215
11	TAN CANG FOUNDATION	2515.4	3.1144	190	83.847	3.1144	215
12	PACIFIC EXPRESS	5516.3	3.1144	190	183.875	3.1144	215
13	PROSPER	3882.8	3.1144	190	129.425	3.1144	215

Calculation of $EEDI_{attained} \cdot V_{ref}$ for MASS (continued) and EEDI reduction

Note:

- (DWT +) is the increase of deadweight due to the elimination of S&DH (see section 3.2).
- (DWT –) is the decrease in deadweight due to the alternative arrangement of the ship's propulsion system (see section 3.7).
- Capacity of autonomous container ship is equal to 70% of ship's deadweight.
- For other explanations in detail, see section 4.1.

No.	Ship name	MASS					EEDI reduction (%)
		DWT+	DWT-	DWT	Capacity	EEDI*Vref	
1	HAIAN PARK	554.8	38.5	13165.3	9215.7	404.7	7.29
2	HAIAN SONG	594.8	41.1	18962.7	13273.9	347.3	6.3
3	HAIAN TIME	369.1	41.7	18382.4	12867.7	409.4	4.81
4	VIETSUN INTEGRITY	172.3	34.1	8198.1	5738.7	505.6	5.1
5	PHUC KHANH	196.7	34.1	8400.6	5880.4	493.4	5.38
6	BIENDONG MARINER	424.6	35.9	12862.8	9003.9	354.5	6.4
7	TAN CANG GLORY	218.9	36.5	8671.4	6070.0	546.3	5.54
8	TRUONG HAI STAR 2	176.1	17.5	3359.5	2351.6	432.1	8.1
9	NASICO SKY	167.1	19.5	4899.2	3429.4	350.5	6.41
10	NICOLE	276.4	23.1	7598.4	5318.9	290.3	6.7
11	TAN CANG FOUNDATION	286.8	23.1	7303.7	5112.6	302.1	6.99
12	PACIFIC EXPRESS	420.0	36.9	11500.1	8050.0	420.8	6.7
13	PROSPER	314.2	30.5	8999.8	6299.9	378.5	6.55

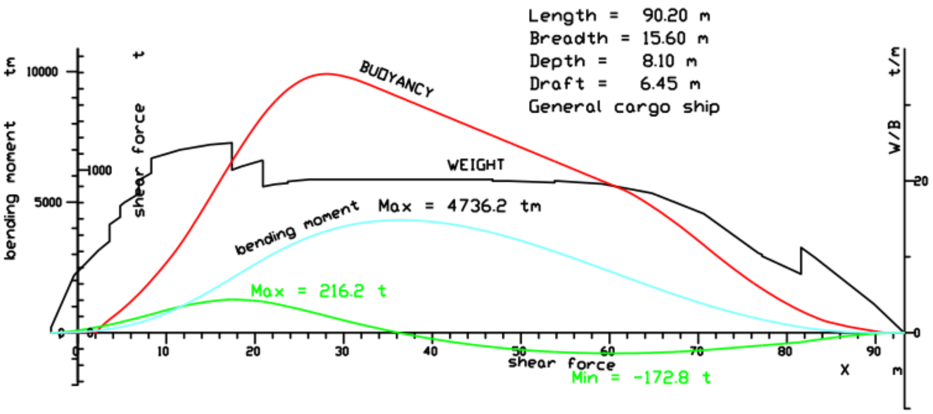
Appendix 4 – Longitudinal strength of ship with and without superstructure

Theoretically, a ship's longitudinal strength depends on the longitudinal distribution of the ship's weight elements and buoyancy. The more similar these two distributions are, the less bending moment and shearing force the ship will bear. A ship's buoyancy is the integration of its wetted transverse sectional areas along the wetted length. Therefore, the buoyancy is seen to attain maximum values in the middle part of the ship, where the sectional areas are the largest and tapper toward both ends. Ship's weight elements include lightweight and deadweight (cargo, bulker, fresh water, ballast water etc.). For CS of light condition, due to the heavy weights of superstructure and engine room equipment, the aft part is seen to have more weight distributed than the middle. If cargo is carried, the middle will be distributed with more weight from cargo. Hence, it can be said that the weight distribution of a ship is more similar to the buoyance distribution in cases where cargo is carried, and a ship often reaches its ultimate longitudinal strength in ballast or light condition.

The longitudinal strength is analyzed by the NAPA program for a 5,300 DWT general cargo ship in light condition for two cases, CS with its business-as-usual superstructure and the same ship without superstructure which is expected to reflect the longitudinal strength of a MASS. The results are shown in Figure 18.

It is seen in Figure 18 that the maximum bending moment of the MASS is just equal to around 82% of the CS, while minimum and maximum shearing force are reduced to 64% and 81%, respectively. The significant reduction in the MASS's longitudinal stress is expected to help the designers more optimize ship's scantling and reduce the lightship weight.

STRENGTH CURVES WITH SUPERSTRUCTURE



STRENGTH CURVES WITHOUT SUPERSTRUCTURE

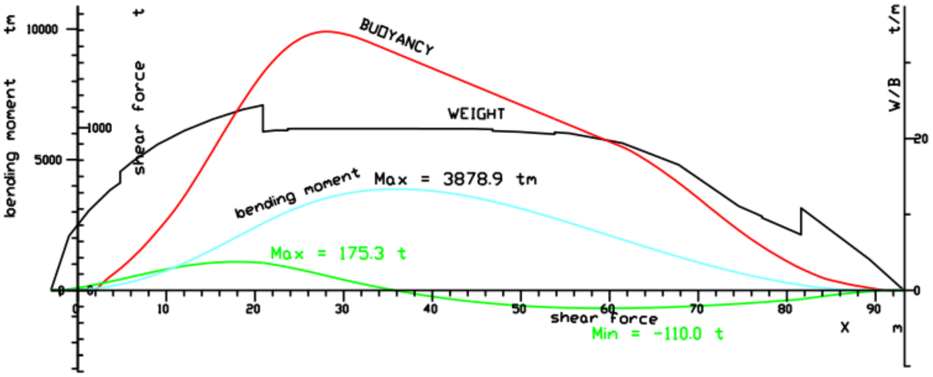


Figure 18 – Bending moments and shearing forces of ships with (above) and without superstructure (below)