SNAMES

Society of Naval Architects and Marine Engineers Singpore

38th Annual Journal 2018/2019

Time for a new maritime era

Society of Naval Architects and Marine Engineers Singapore

38th Annual Journal 2019

SNAMES

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President's Message

Dear Fellow Members,

My warmest greetings on behalf of the council members and welcome to our 38th Annual Journal.

It took great effort from the publication team, fellow members and industry members for their contribution towards another SNAMES Journal.

This year's journal title "TIME FOR A NEW MARITIME ERA", has the objective in mind of bringing togetherness in the industry to share ideas, resources and collaboration in today's competitive markets; not just primarily to survive but to ultimately grow. Leading companies in the industry have embarked on changes and innovations to cater for the technology advancements.

In light of digitalization, our Society has maintained and kept the same for this year's journal to be in digital format.

SNAMES had a busy year in 2018/19, with many events organized for our members and the maritime industry. We held technical talks at least once a month, as well as social networking events. Our Society has supported and collaborated with other maritime societies on issues of mutual interests, sharing of knowledge and experiences and providing networking opportunities for our members. These have facilitated the exchange of ideas and information, driving towards the objectives of our Society. The Council will continue to organize our annual dinner and annual golf tournament, and to co-organize technical talks with Joint-Branch and IMarEST.

This year, the council has also successfully signed a Memorandum of Understanding with the Republic of Singapore Yacht Club (RSYC) to enhance the benefits for our members. Our members are now able to enjoy the club facilities as a full paid member.

Last but not least, I would like to sincerely thank all our members and industry partners for their unwavering support to the Society over the years. Our role as a Society is to continue to nurture talents and advance the maritime profession, through good or challenging times. I believe the best is yet to come for SNAMES, and I hope you will continue to join me in supporting the growth of our Society and industry at large.

With best wishes

Koh Shu Yong
President SNAMES Council 2018/2019

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1974/1975	Mr Tan Kim Chuang	Mr Ho Ming Yeh
	Mr Ho Ming Yeh Mr	Keki R Vesuna
1975/1976	Mr Chua Chor Teck	Mr Alan Bragassam
1976/1977	Mr Chua Chor Teck	Mr Kalman E Nagy
1977/1978	Mr Chua Chor Teck	Mr Alan Bragassam
1978/1979	Mr Chua Chor Teck	Mr Alan Bragassam
1979/1980	Mr Chua Chor Teck	Mr Tan Kim Chuang
1980/1981	Mr Chung Chee Kit	Mr Lim Boon Heng

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1993/1994	Mr Zafrul Alam	Mr Ng Thiam Poh
1994/1995	Mr Ng Thiam Poh	Mr Dennis Oei
1995/1996	Mr Dennis Oei	Mr Kan Seng Chut
1996/1997	Mr Kan Seng Chut	Mr James Tan
1997/1998	Mr James Tan	Mr Phua Cheng Tar
1998/1999	Mr Phua Cheng Tar	Mr Leslie Low
1999/2000	Mr Leslie Low	Mr Wong Kin Hoong
2000/2001	Mr Wong Kin Hoong	Mr Leow Ban Tat
2001/2002	Mr Leow Ban Tat	Mr Ying Hing Leong
2002/2003	Mr Ying Hing Leong	Mr Tan Chor Hiong
2003/2004	Mr Tan Chor Hiong	Mr Dennis Chua
2004/2005	Mr Dennis Chua	Mr Ernest Wee
2005/2006	Mr Ernest Wee	Mr Fabian Chew
2006/2007	Mr Fabian Chew	Mr Goh Boon Guan
2007/2008	Mr Goh Boon Guan	Mr Chen Chin Kwang
2008/2009	Mr Chen Chin Kwang	Mr Simon Kuik
2009/2010	Mr Ronald M Pereira	Mr Kenneth Kee
	Mr Kenneth Kee	Mr David Kinrade
2010/2011	Mr Kenneth Kee	Mr Simon Kuik
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2014/2015	Prof Choo Yoo Sang	Dr Nigel Koh
2015/2018	Mr Foo Nan Cho	Mr Prem Shankar
2018/2019	Mr Koh Shu Yong	Mr Yeo Teck Chye

SNAMES Activities for Year 2018

45th Annual Dinner 2018

Held on 20th November 2018 at Shangri-La, Singapore

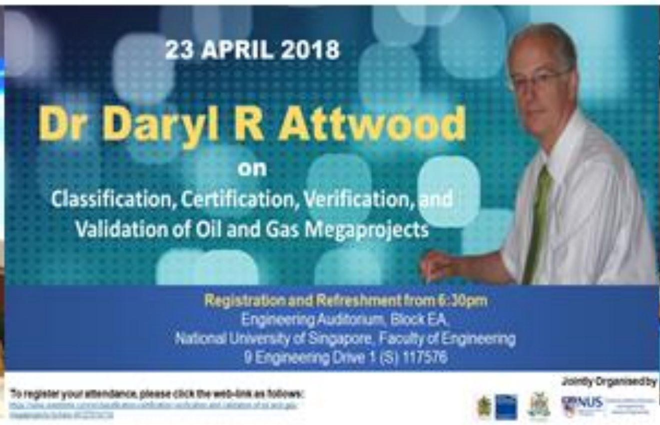
Guest of Honour
Dr KOH POH KOON
Senior Minister of State, Ministry of Trade & Industry

Technical Talks

Classification, Certification, Verification, and Validation of Oil and Gas Megaproject

Presented by
Dr Daryl Attwood

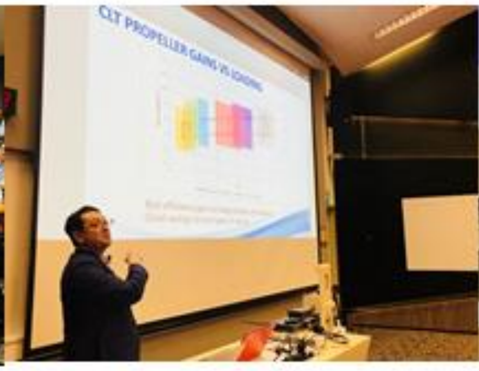
23rd April 2018
National University of Singapore

Ship Propulsion Optimization & Energy Efficiency: Experience with Unconventional High-efficiency Tip Plate Propellers

Presented by
Dr Giulio Gennaro

10th May 2018
Ngee Ann Polytechnic Singapore

Technical Talks

Visit to Additive Manufacturing Workshop

Presented by
Professor Chua Chee Kai

13th September 2018
Nanyang Technological University, Singapore

Maritime Cyber Security

Presented by
Mr Mark Milford

15th February 2019
Wärtsilä Acceleration Centre at PSA Vista Singapore

Member's Night

Member's Night at BREWERKZ
9 June 2018

Technical Papers

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Scrubber as a Compliance Alternative of Sulphur Capping in 2020

ABSTRACT

In the era of increasing sea-borne trade and worldwide awareness of global warming, the need for combating air emissions at sea has gathered pace. MARPOL Annex VI that entered into force on 19 May 2005 seeks to limit the air pollutants from the exhaust gases that are emitted from the merchant's vessels. MARPOL Annex VI has been amended over the years, in particular: a) pursuant to MEPC 63 adopted in March 2012, it mandates four sets mandatory regulations on Energy Efficiency for Ships in MARPOL Annex VI, and b) pursuant to MEPC 70 in October 2016; the fuel oil standard (0.50% sulphur limit) shall become effective on 1 January 2020. This complying fuel oil is available at a higher price in the market. At this stage, there is underlying uncertainty about the availability, as well, of such fuel notwithstanding at a higher price at most of the bunkering ports. This uncertainty has a potential to increase even further in light of increasing demand for such fuel. However, MARPOL Annex VI, Chapter 1, Regular 4 has provided ship owners and operators with an alternative path to the above-stated compliance by using exhaust gas cleaning systems also known as a SOx scrubber. There are equally important other alternatives to achieve compliance, for example, by changing the fuel composition through fuel blending, by improving & enhancing engines by replacing the fuel to LNG. At the same time, in many cases, such alternatives are not easy to implement due to various reasons.

In this paper, an attempt is made to provide guidance to distinct stakeholders, including ship owners, ship management companies, and others on the installation of scrubbers. The guidance in the context of scrubbers' performance and safety features will include inter alia, differing aspects involving manufacturing, engineering, installation on board the vessels, and effective supervision.

1. INTRODUCTION & REGULATORY REGIME

In the era of increasing sea-borne trade and world-wide awareness of global warming, the need for combating air emissions at sea has gathered pace. *MARPOL Annex VI* entered into force on 19 May 2005, and accordingly seeks to limit the air pollutants from the exhaust gases that are emitted from the merchant vessels. *MARPOL Annex VI* has been amended over the years, in particular: a) pursuant to Marine Environment Protection Committee (*MEPC 63)* adopted in March 2012, it decrees the four sets of mandatory regulations on Energy Efficiency for Ships in *MARPOL Annex VI*, and b) pursuant to *MEPC 70* in October 2016; the fuel oil standard (0.50% sulphur limit) shall become effective on 1 January 2020. This complying fuel oil is usually available at higher price; however, *MARPOL Annex VI*, Chapter 1, Regulation 4 has provided ship-owners and operators with an alternative path to the above stated compliance by using exhaust gas cleaning systems also known as a scrubber, which is the subject matter of this paper. The paper will first analyze the Regulatory regime and its evolution in context of regulations affecting merchant ships that operate on oceans and seas.

As the issues of global warming seize the human imagination, the issues associated with risks of pollution at sea take the center stage in the maritime sector of the industry. Risks for pollution at sea include air pollution at oceans due to movement of merchant ships in oceans. For many years, International Convention for the Prevention of Pollution from Ships (hereinafter "*MARPOL*") has set the framework for relevant regulations governing the Pollution from Ships. *MARPOL* has many Annexes and *Annex VI,* in particular, deals with the Regulations for Prevention of Air Pollution from Ships (hereinafter "*MARPOL Annex VI*"). This evolving framework is increasingly important in light of the fact that there has been increased in the size of the merchant fleet and volume of cargo that can be carried over the seas (please refer to Annex 1 to the Paper)

MARPOL ANNEX VI in relation to air pollution from ships was considered as far back in 1973 but was not included in the regulations. In 1979, in Geneva, the first international legally binding Convention on Long-range Transboundary Air Pollution by 34 governments and the European Community was agreed. It was followed by Protocols - on reducing sulphur emissions in 1985, controlling emissions of nitrogen oxides in 1988, controlling emissions of volatile organic compounds in 1991. It was followed later by further mandating requirements to reduce sulphur emissions in 1994. In 1987, the *Montreal Protocol* on substances that deplete the Ozone Layer was signed to cut consumption and production of ozone-depleting substances, including chlorofluorocarbons (CFCs) and halons in order to protect the ozone layer. This itself was followed by two Protocols to *Montreal Convention* banning ozone-depleting CFCs and HCFCs and methyl bromide. In 1980's, IMO's *Marine Environment Protection Committee* (hereinafter "MEPC") did consider air pollution in 1980s, but it was limited to the issue of fuel quality, and in respect to MARPOL Annex 1. In 1988, MEPC started discussing the issue of air pollution from ships more actively, and it led to the adoption in 1991, of an IMO Assembly Resolution A.719 (17) on *Prevention of Air Pollution from Ships*. It ultimately led to *Annex VI to MARPOL*. However, *Annex VI* to *MARPOL* pertaining to air pollution from the ships was first adopted in 1997, and thereafter entered into force 19 May 2005.

For the sake of completeness, MARPOL Annex VI was implemented in the United States through the Act to Prevent Pollution from Ships, *33 U.S.C. §§ 1901-1905 ("APPS").* The requirements pursuant to this Act apply to vessels operating in U.S. waters as well as ships operating within 200 nautical miles of the coast of North America, also known as the North American Emission Control Area (ECA).

It is important to highlight the main purpose of the *MARPOL Annex VI* is to set the guidelines to limit the air pollutants from the exhaust gas emitted from the merchant vessels. The gases that are contained in exhaust gas are Sulphur oxides (SOx) and Nitrous oxides (NOx), and such guidelines also prohibit deliberate emissions of ozone-depleting substances. The *MARPOL ANNEX VI* includes, in particular, the following:

- A global cap of 4.5% m/m on the sulphur content of fuel oil; and
- Allowed for special *SOx Emission Control Areas* (hereinafter "*SECAs*") to be established with more stringent controls on sulphur emissions, where the sulphur content of fuel oil used on board, the ships must not exceed 1.5% m/m; and
- New installations containing ozone-depleting substances are prohibited on all ships; and
- New installations containing hydro-chlorofluorocarbons (HCFCs) are permitted until 1 January 2020; and
- Annex VI also sets limits on emissions of nitrogen oxides (NOx) from diesel engines. A mandatory *NOx Technical Code*, was adopted by the Conference under the cover of Resolution 2; and
- The Annex also prohibits the incineration on board the ships of certain products, such as contaminated packaging materials and polychlorinated biphenyls (PCBs).

Revised MARPOL ANNEX VI

Over the years, there has been technological improvement and more awareness of risks of air pollution has evolved from the time *ANNEX VI to MARPOL* was adopted in 1997. *MEPC* in July 2005 agreed to revise *MARPOL Annex VI* and three years later, *MEPC 58* in October 2008 adopted the revised *MARPOL Annex VI* and the associated *NO_x Technical Code 2008*, which entered into force on 1 July 2010. The key changes introduced by the *Revised MARPOL Annex VI* were:

- Introduction of Emission Control Areas (ECAs) to reduce emissions of those air pollutants further in designated sea areas; and
- Progressive reduction of global emissions of SO_x, NO_x.; and
- The global sulphur cap will be reduced from current 3.50% that is in place from 1 January 2012 to 0.50%, effective from 1 January 2020; and
- The limits applicable in ECAs for SOx and particulate matter were reduced to 1.00%, beginning on 1 July 2010 (from the original 1.50%); being further reduced to 0.10 %, effective from 1 January 2015. For the sake of completeness, in many geographical areas, there are more stringent requirements, for example, in EU, where ships transiting EU ports y are subject to a 0.1% sulphur limit for a while.

- Progressive reductions in NOx emissions from marine diesel engines installed on ships are also included, with a "Tier II" emission limit for engines installed on or after 1 January 2011; then with a more stringent "Tier III" emission limit for engines installed on or after 1 January 2016 operating in ECAs. Marine diesel engines installed on or after 1 January 1990, but prior to 1 January 2000 are required to comply with "Tier I" emission limits, if an approved method for that engine has been certified by an Administration; and

- The revised *NOx Technical Code 2008* includes a new chapter based on the agreed approach for regulation of existing (pre-2000) engines established in *MARPOL Annex VI*, provisions for a direct measurement and monitoring method, a certification procedure for existing engines, and test cycles to be applied to Tier II and Tier III engines.

Emission Control Areas

MARPOL Annex VI, Chapter 3, Regulation 14 provides for General Requirements in relation to Sulphur Oxides ("Sox") and is as follows:

1) The sulphur content of any fuel oil used on board ships shall not exceed 4.5% m/m [emphasis added]; *and*
2) The world-wide average sulphur content of residual fuel oil supplied for use on board ships shall be monitored taking into account guidelines to be developed by the Organization.
In addition, same regulation provides for *SOx Emission Control Areas* as follows:
3) *For the purpose of this regulation, SO_x emission control areas shall include: the Baltic Sea area as defined in regulation 10(1)(b) of Annex I, the North Sea area as defined in regulation 5(1)(f) of Annex V; and b) any other sea area, including port areas, designated by the Organization in accordance with criteria and procedures for designation of SO_x emission control areas with respect to the prevention of air pollution from ships contained in appendix III to this MARPOL Annex VI.* (Please refer to Annex II to this paper)

Further Amendments to Revised MARPOL ANNEX VI

Over the years, amendments were made to *MARPOL ANNEX VI* that was adopted in 1997 and are in force from 19 May 2005. In addition, pursuant to the amendments to Revised MARPOL ANNEX VI provides:

- Resolution *MEPC 62* adopted in July 2011 and entered into force from 1 January 2013, with the amendments to *MARPOL Annex VI* (resolution *MEPC.203 (62)*, the *Energy Efficiency Design Index* (hereinafter "EEDI") was made mandatory for new ships and the *Ship Energy Efficiency Management Plan* (hereinafter "SEEMP") for all ships. EEDI mandates the use of energy-efficient equipment and engines on board the vessel and is measured by energy efficiency level per capacity mile. IMO has used a non-prescriptive approach for the industry to decide the design provides there is a gram CO2 reduction per mile with reference line being the ships built between 2000 and 2010. The requirements related to the EEDI will progressively become onerous every five years. Another aspect of the resolution is SEEMP, which is an operative measure that establishes a mechanism to improve the energy efficiency of a ship in a cost-effective manner using a voluntary use of the *Energy Efficiency Operational Indicator* (hereinafter "EEOI") pursuant to (*MEPC.1/Circ.684*).

O Pursuant to *MEPC 63* adopted in March 2012, it mandates four sets of important guidelines to assist in the implementation of the mandatory regulations on Energy Efficiency for Ships in *MARPOL Annex VI*:

O Pursuant to resolution *MEPC.212(63)* in 2012 - Guidelines on the method of calculation of the attained *Energy Efficiency Design Index* (EEDI) for new ships,

O Pursuant to resolution *MEPC.213(63)* in 2012 - *Guidelines for the development* of a Ship Energy Efficiency Management Plan (SEEMP),);

O Pursuant to resolution *MEPC.214(63)* in 2012 - *Guidelines on survey* and certification of the Energy Efficiency Design Index (EEDI), and

O Pursuant to resolution *MEPC.215(63) - Guidelines for calculation of reference* lines for use with the Energy Efficiency Design Index (EEDI),

O Pursuant to *MEPC 70* in October 2016 – It considered an assessment of fuel oil availability to inform the decision to be taken by the Parties to *MARPOL Annex VI*, and decided that the fuel oil standard **(0.50% sulphur limit) shall become effective on 1 January 2020.**

2. COMPLIANCE WITH NEW REGULATORY REGIME

On merchant ships ordinarily having large marine diesel engines, it is observed that typical heavy fuel oil has an average sulphur content of 2.7%. During the combustion process, the sulphur is oxidized to sulphur dioxide (SO2).

Regulatory regime applicable from 2020. Owners, in order to comply with the new regulations in relation to new fuel standard, will have to contemplate a switch to distillate fuel. These fuels complying with the regulations are available at higher prices, but also will raise additional concerns on board the ships, in particular, to the operating difficulties involving low viscosity, lubricity, lower flashpoints and catalytic fines. Fortunately, *IMO/MARPOL ANNEX VI, Chapter 1, Regulation 4* has provided ship-owners and operators with an alternative path to *MARPOL ANNEX VI* compliance by using exhaust gas cleaning systems also known as scrubbing.

For the sake of completeness, *MARPOL Annex VI,* Chapter 1, Regulation 4 provides:

The Administration of a Party may allow any fitting, material, appliance or apparatus, **such as SO_x scrubbers** [emphasis added], *to be fitted in a ship* ***or other procedures, alternative fuel oils, or compliance methods used as an alternative to that required by MARPOL Annex VI*** *[emphasis added]*.

3. THE FOUR MAIN WAYS TO OVERCOME 2020

As discussed above, pursuant to the amendments to *MARPOL Annex VI*, IMO will enforce a new 0.5% global sulphur cap on fuel content from 1 January 2020. This measure will ensure to limit the global air pollution and will also assist populations living close to ports or the coasts that are not within *Sulphur Emission Control Areas* ("SECAs"). SECAs restricts the mass of Sulphur Oxide to just 0.1% m/m. SECs being the Baltic Sea, the North Sea, the North American ECA, including most of US and Canadian coast and the US Caribbean ECA.

This will compel the ship owners and operators to modify and improve their ships to comply with the regulatory regime as discussed above. Pursuant to *MARPOL Annex VI, Chapter 1, Regulation 4*, there are four main common variations that ship owners and operators are currently employing - (1) use of low sulphur oxide fuel, (2) installation of SOx scrubber (sulphur oxides scrubber), (3) use of alternative fuels such as LNG, and (4) less commonly called as oil blending or solution blending.

In this paper, the authors will discuss the first more common options that are being employed, before moving to the option of scrubbers.

Option 1 – Low –Sulphur Oil

The use of low sulphur oxide fuels has the discernible and understandable advantage of the lowest investment cost, but the disadvantage is that the margins in operating the vessel can decrease considerably due to the rise in fuel price as a result of instability and/or unavailability of the fuel supply at various ports.

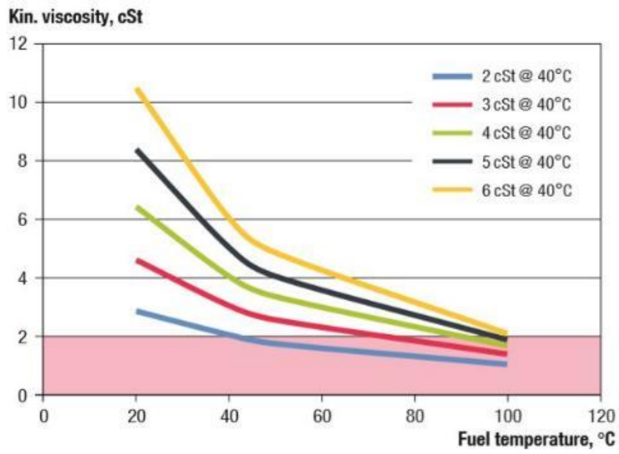
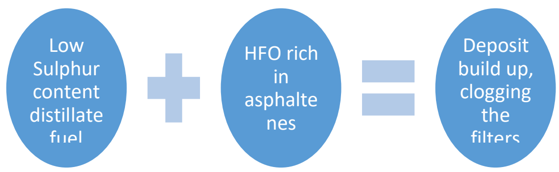


Figure 1. Temperature-Viscosity Relationship For Very Low Viscosity fuels

Additionally, altering to low sulphur fuels will lead to significant increase in fuel cost. Refineries worldwide need to change its existing production system to low sulphur fuel, which is estimated currently to take more than five years. As a result, it is predicted that there may be instability and/or unavailability of fuel supply at various ports for time being.

Technically, when switching from HFO to distillate oil, a slow changeover is necessary. This is because it will allow adequate time for the temperature of the fuel pump to drop from 150°C to 45°C. It will accordingly prevent pumping seize; as a result of insufficient viscosity of the distillate oil might stop the pump from working efficiently.



When mixing HFO with the distillate in the booster system, to have a smooth changeover, a good compatibility between the HFO & the distillate is essential. If the fuels are not compatible, it will result in the build-up of deposit, and thereby clogging filters. It can be seen as below:

Option 2 – LNG (Liquefied Natural Gas)

The use of alternative fuels such as LNG is basically an alternative that can lead to relatively low emission of nitrogen oxides and sulphur oxides. It has an added advantage of being available at relatively low fuel price. The complete removal of SOX and PM emissions and a reduction of NOX emissions of up to 85% can also reduce greenhouse gas (GHG) emissions by 10 to 20%, depending on engine technology.

However, the above advantages come with their own disadvantages. The installation costs for employing LNG fuels are extremely high. Additionally, the process of induction on board, the merchant ships is very complicated to execute, and not all ports currently have stations that can refill the LNG tanks.

Option 3 – Fuel Blending

Marine engineers and technologist are currently working on this option of solution blending or oil blending. Currently, it is unreliable and meanwhile, research has not reached the state where this option can comply with the regulatory regime.

Option 4 – Scrubber

HSFO can still be used after installation of a regulatory regime compliant SOx scrubber that is also known as an *exhaust gas cleaning plant*. No changes will have to be made to the engines or fuel treatment plants by ship owners and operators. Sox scrubber installations have the advantages of reducing exhaust emissions from ships by up to 90% m while still using heavy oil.

This alternative will, however, have a high initial cost, but due to use of low-cost HSFO, it will likely give a high return on investment over the years. It is estimated that the payback period of a scrubber is about one - two years based on oil price and amount of oil consumption on board the ships.

Due to excellent returns on the investment in short payback period, and with the new regulation coming, in 2020, it is widely seen that increasingly the stakeholders are opting to install the scrubbers. In turn, these installations of scrubbers on board, the vessels have resulted in the increase in the number of engineers, while also increasing the workload of the crew as they need to operate and maintain such installations.

Table 1. Comparative analysis of four options in tabular form

MAIN ALTERNATIVES	PRO	CON	APPLICATION
COMPLIANT SCRUBBER	It reduces exhaust emission by 98% High returns on investment	Additional equipment installation required Complexity of engine and funnel area.	New shipbuilding and Retrofit for Container, Bulk carrier, etc.
LOW-SULPHUR DISTILLED OIL (COMPLIANT FUEL)	Low investment cost	Oil prices fluctuate	Present ship operating available
LIQUEFIED NATURAL GAS	Low emission of NOx & Sox	High installation costs Unavailability of LNG at all ports	Future new shipbuilding available
FUEL BLENDING	High price oil cost relatively	Effect to engine maintenances by density of oil Still research is undergoing, and compliance is doubtful.	Blending solution

NOx-Nitrogen oxides,
SOx-Sulphur oxides,
LNG-Liquefied Natural Gas

4. PRINCIPLE AND TYPES OF SCRUBBER

A scrubber (or an exhaust gas scrubbing apparatus) is a desulfurization apparatus as it removes Sulphur Oxide (SO_x) from gas discharged from ship engines & boiler. The system is made using the principle that sulphuric acid is discharged; after the sulphuric acid is removed by the water stream in the apparatus, while passing through the scrubber. This alternative is considered fully compliant of *MARPOL Annex VI Regulation 4* with regards to compliance of Sulphur. Scrubbers have been in use in the marine industry since 2015, especially in the ECA zones in Europe and North America.

There are three main types of scrubbers: *Open, Closed & Hybrid.*

If one has installed an open scrubber, the marine engineers can replace bunkers when entering the port where open scrubbers are not permitted, for example, in Singapore port. If low sulphur fuel is used, it may cause performance deterioration due to low viscosity in the fuel pump, cylinder, etc., and viscosity should be increased to at least 2 cst and lubricant needs to be replaced. When using MGO, one need to apply oil cooler or chiller cooling system. There are separate guidelines that are available from different engine makers, but it is advised that the engine operator should operate with more stringent standards.

Open — Uses Seawater
- The salt components in Seawater is effective in diluting acid components of sulphuric acid. Once that is done it is dischraged into the sea.

Closed — Uses Purified water containing alkaline components
- The alkaline component (Caustic Soda or Magnesium hydroxide) will nuetralize the Sulphuric acid. After purifying the sulphuric acid, the water is reused and only an exceedingly small amount of water containing impurities is separated. These impurities are then removed before the water can be discharged into the sea.

Hybrid — Uses both seawater and alkaline components
- The Hybrid scrubber can switch between the two types (Open & Closed) of scrubber functions depending on the condition of the ship.

On the other hand, according to the analysis of advantages and disadvantages for the types of scrubbers, the open loop scrubber systems usually use a large amount of seawater, consume a relatively large amount of power, and are used mainly for ocean voyages. In addition, these have to be replaced with low sulphur oxide fuel in port.

However, the closed loop mainly uses fresh water and dosing unit to add NaOH for maintaining the PH values. The process tank, the water-treatment system and the heat exchange are additionally installed as compared with open loop scrubber systems so that it occupies a lot of space, but the power consumption is relatively small.

Hybrid scrubber systems are used as an open loop during ocean navigation and closed loop in port. It has a complicated system and requires a lot of installation space. However, it can be used while navigating in oceans and within the ports both. The scrubber market is moving from an open loop to a hybrid loop due to low operating costs after installation and due to no limitations of the operating area. Hybrid type market is expected to increase in particular, the increasingly stronger marine standards are driving the hybrid market, but in the case of a retrofit, the cost is about 30%. Installation cost will increase, and the level of difficulty will also increase.

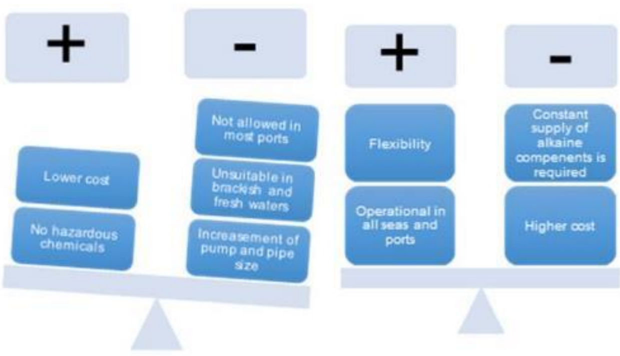


Table 2. The Advantages and Disadvantages of different types of scrubbers in the tabular forma

	Advantage	Disadvantage
Open	▪ Simple structure ▪ Simple installation/ operating with lower cost	▪ Increase of pump and pipe size ▪ Restriction on the Seawater condition (PH) and local discharge regulations
Closed	▪ Reduction of drive pump and piping size ▪ No restriction on the Seawater condition (PH) /local discharge regulations	▪ Complex structure ▪ Complicated installation/operating ▪ Higher cost ▪ Supplement of neutralizing (NaOH) needed
Hybrid	▪ Lower operating cost than closed type ▪ No restriction on the Seawater condition (PH) /local discharge regulations ▪ Need smaller amount of neutralizing (NaOH) than closed ▪ Flexible operation according to seawater condition	▪ Complex structure (Open/Closed scrubber) ▪ Complicated installation and operating ▪ Higher cost

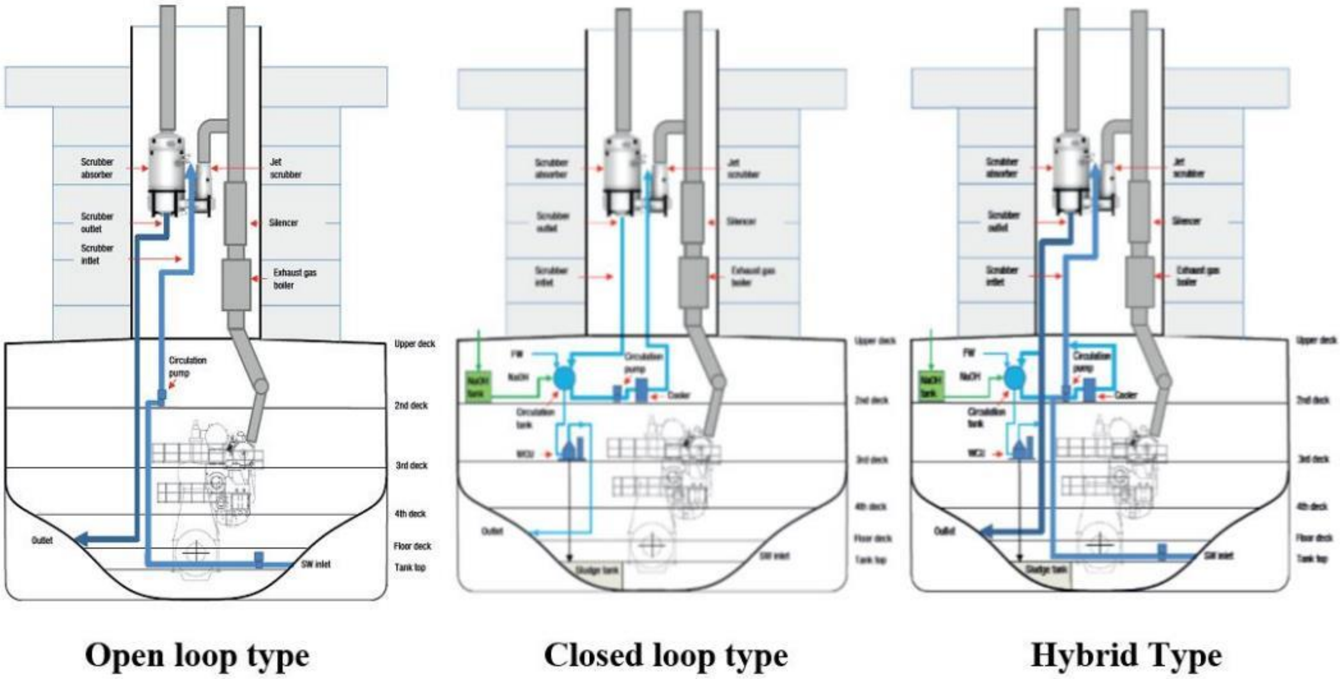


Figure 2. *Exhaust gas cleaning systems*

5. THE FUTURE PROSPECT OF SCRUBBER

Market Trends

As discussed in Section 1 of the paper that at the 70th meeting of MEPC in London in October 2016, the International Maritime Organization (IMO) will limit emissions of ships from 3.5% m/m to 0.5% m/m by 2020 concluded an agreement. According to the Clarkson and OECD surveys, currently, the most common options among ship owners are (1) use of low sulphur oxide fuel, (2) installation of SOx scrubber (sulphur oxides scrubber), (3) use of alternative fuels such as LNG.

The use of low sulphur oxide fuels has the advantage of the lowest investment cost, but the disadvantage is that the fuel price can rise due to instability and /or unavailability of the fuel supply. The scrubber installation has the advantages of reducing exhaust emissions from ships using heavy oil by up to 90% and the high return on investment. Due to the high initial investment costs or expectations for alternative technologies to replace them, the scrubber market has been underestimated.

As the year approaches 2020, ship owners are quickly moving into the scrubber market due to the uncertainty of oil prices and the absence of economical alternative technologies. A sharp rise in the price of a scrubber material and the delay in the material supply period proves this fact and has a great influence on the delivery period of the scrubber. In chartering contracts, it is known that the installation of the scrubber is the priority, and the main requirement of the ship owner's scrubber selection is frequently in relation to the delivery period.

The use of alternative fuels such as LNG can lead to relatively low emissions of nitrogen oxides and sulphur oxides. This is to be accompanied by a relatively low fuel price for the fuels that can be used in such systems. However, the installation cost of the LNG engine is remarkably high for installations and the process is extremely complicated to execute.

As a result, aggressive investment in scrubbers will be achieved by 2020. These agreements, market conditions and results of research are particularly good opportunities for scrubber manufacturers. Of cause, scrubbers are subject to an increased regulatory regime by the US Coast Guard and the EU, and accordingly they must be certified by Lions Clubs International), such as Lloyd's, DNV, and Bureau Veritas.

Table 3. Payback time of combined EGR/EGC scrubber system

Engine size	Operating time	CAPEX EGC scrubber and EGR	OPEX per year Fuel, EGR and EGC scrubber (SW)			Payback time
27MW	6000h/year		Ref.No EGC	OPEX (3%S)	Saving per year	
System	ECA share	Mio $	Mio $	Mio $	Mio $	Years
Combined	0% ECA	6.20	19.71	16.41	3.29	1.9
	20% ECA	6.20	20.74	16.61	4.12	1.5
	100% ECA	6.20	24.86	17.43	7.43	0.8
Reduced	0% ECA	5.30	19.71	16.63	3.08	1.7
	20% ECA	5.30	20.74	16.79	3.95	1.3
	100% ECA	5.30	24.86	17.43	7.43	0.7

Payback Period and Other Options

In the case of scrubbers, which are regarded as the most realistic solutions, the focus is on the payback period, or ROI (Return on Investment) based on the current oil price and the oil consumption of the ship. Even the same vessel can be affected by the trading route and operating method. Table 3 shows an example of calculating the payback period. The calculation of the payback period depends on whether the view of the oil market is pessimistic or optimistic, and there are considerable differences depending on the opinion of any party, such as the manufacturer of the scrubber and the classification. It depends on the type of scrubber as well, but it is generally considered to be around two years. Even considering the unpredictable oil price, ship owners still can expect safe operation as well as economic operation if they operate from 2 years after installing scrubber.

In order to do a thorough comparative analysis between the option of installing scrubber and another option of using low sulphur oxide fuel, there are many variables that cannot be overlooked, in particular, there are unexpected factors that may originate in the four industries from 2020 - scrubber company, refinery company, blending solution company and engine manufacturer. It is therefore, very hard to predict how these industries will respond to uncertainty while complying with the regulatory regime as discussed in the first section of this paper.

Refinery companies need to change its existing production system to low sulphur oxide fuel, which is likely to take more than five years. In this scenario of an increase in the price of low sulphur fuel, then it is likely that payback period can even be reduced to just one year. Accordingly, the installation of the scrubber has additional advantages.

As discussed earlier, the option of Blending solution is unreliable and currently not good enough to be a regulatory compliant option. Considering the current situation with the refineries, using a low sulphur fuel is a significant risk as well.

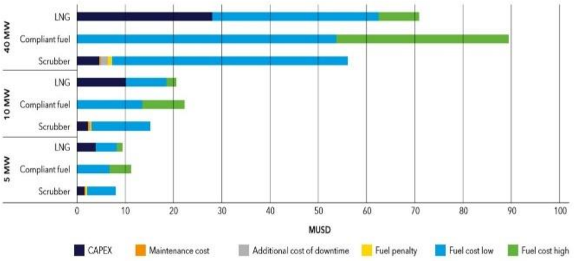


Figure 3. Comparative analysis in graphical form

<Accumulated costs over a period of five years at a 6% discount rate>

Scrubber systems will increase the ship's fuel consumption by approximately 2%. Downtime of the scrubber systems will introduce a cost for running these compliant fuels. Installation of scrubber system, and accordingly, it will increase the maintenance cost (more for closed loop scrubber systems). For closed loop systems, there will be an additional cost for alkali bunkering and sludge disposal system. It is expected that there will be an increase in demand for a Hybrid type which can not only avoid inconvenience due to the limitation of the operating area but also can operate at a low cost.

The Preparations and Procedures in Context of Scrubber

To design a scrubber system, it needs to fulfill the strict regulatory environment, in particular, the various geographical areas of operation of the ships. Sufficient information must be provided to installers of such as scrubber system such as fuel sulphur levels, the alkalinity of the seawater, any special conditions the ship would be operating in. The scrubber itself has its piping and cabling next to that, there is the heat exchanger, the separator, tanks, pumps, frequency converters, cabinets.

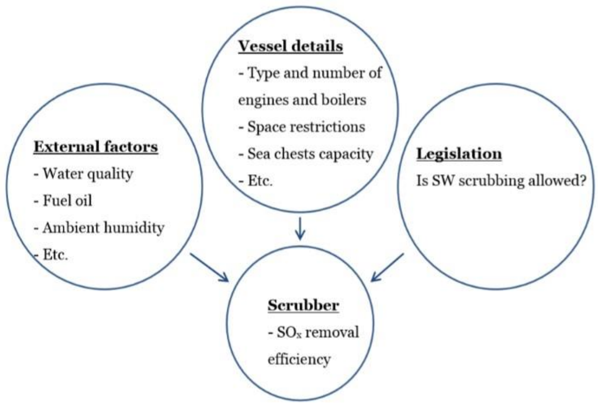


Figure 4. Main groups of design factors for an EGC scrubber system

The size of the scrubber is determined by the amount of exhaust gas, and the shape of the scrubber could be different depending on the manufacturer of such scrubber systems. In general, competitiveness is judged, when it has the optimum design with less installation space and low power consumption while satisfying the required performance expected on the ships. Most of all, it must be regulatory compliant.

Shipowners should request that these specific conditions that would include smaller scrubber size, washing water consumption, and power requirement be fully taken into account to achieve the goal of optimized scrubber equipment installation. A general scrubber configuration is as follows:

- After months of planning, the parts, pipes, and housings were prefabricated and delivered to the shipyard.
- Removal and repositioning of existing equipment began simultaneously at several places on board the ship.
- The various modifications that were required onboard took almost three weeks.
- There were new walkways, handrails as well as maintenance platforms.
- Space was created for the new equipment.
- Then once it was installed, the testing was carried out as to whether the equipment was working, the installation was working, and importantly whether the results were within the IMO legislation.

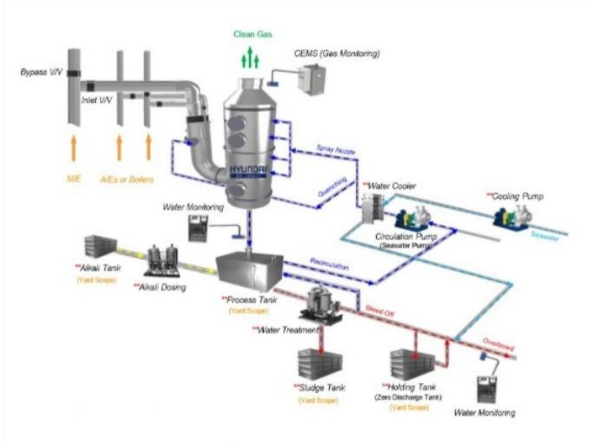


Figure 5. System layout of Hybrid loop system by Hyundai Materials

6. CONSIDERATIONS FOR EGCS INSTALLATION

Positioning and Structure of Scrubbers in engine room

SOx scrubber equipment does not have any special hazards, so it can be installed inside or outside the engine room depending on space availability. In the case of retrofit, one can also create a separate compartment if one does not have proper space. In this case, prevention of freezing of equipment and requirements for pipelines and cables through engine compartment bulkheads/decks should be considered.

For all these cases, it should be ensured that sufficient space is available for operation and maintenance. As well as ensuring space, the gross tonnage of the ship will be increased. Stability is also taken into consideration because the center of gravity of the vessel changes depending on the location of the SOx scrubber installation. The lower part of the place where the scrubber is installed should be adequately reinforced; vibration and noise should as well be considered. *I* type installations have fewer footprints than the *U* type, although stability should be considered carefully as there is a simultaneous increase in vertical length.

If the position of the end of the exhaust pipe were to be changed, the exhaust gas should not be reintroduced into the accommodation area. In particular, the exhaust gas part of high temperature should be heat-sealed to avoid fire hazard for safety at sea.

Where the engine room boundary is extended adjacent to the container cargo area, the isolation requirements that are required for the loading of dangerous goods shall be considered as met. From the viewpoint of installation of such systems, it is important to note that securing of space is often restricted depending on the condition of the vessel, and in the case of a retrofit, it is not easy to satisfy various demands of the owner or the operator.

Power Load

The additional power required to operate the scrubber must be analyzed. The load ratio of the sea-going merchant ship should be considered and how it is affected by the sum of the power of the scrubber. Should such a system be selected, it is important that the total power should not exceed 90% of generator capacity. If it were to exceed 90%, an additional generator should be installed.

Corrosion of Exhaust and Cleaning water

The ship is equipped with main engines, auxiliary engines, boilers, and so forth. Gas is exhausted from the connected exhaust lines from each of these pieces of equipment. Accordingly, the exhaust pipe of various devices is connected with a single scrubber to exhaust the gas; that is, the multi-stream is installed. Therefore, the maximum emission of exhaust gases from all such equipment must be considered. The scrubber increases the back pressure of the exhaust gas of the engine and can additionally affect the performance of the engine, and that can additionally affect the NOx emission limit. When installing the scrubber with the multi-stream method, there is a need for measures that are required to ease the flow by installing a separate exhaust fan to lower the back pressure. This is one of the complex parts of the scrubber technology that should be considered. The choice of equipment with a reliable technology is, therefore, paramount in this respect as it can directly affect the operation of marine engines of the ships.

Sulphuric acid in this altered spray state, which has become strongly acidic by sprayed seawater, has the potential to cause severe corrosion on top of the scrubber. Additionally, the inside of the wash-water discharge pipeline is strongly acidic, and is therefore installed under the water surface of the engine room to prevent the wash water from being reabsorbed through the other suction pipes of the engine room such as sea chest etc. It is done to prevent excessive corrosion to pipelines and connections. Since the scrubber body and the connected pipeline are large and long, the maintenance of the pipeline affects the performance of the scrubber device itself, and further affects the operation cost of the device after installation. Therefore, in the choice of the scrubber, the material from which the scrubber body and pipeline are manufactured is an important consideration because it affects the operations of the scrubber systems in long-term and in doing so provides required stability.

7. CONCLUSION

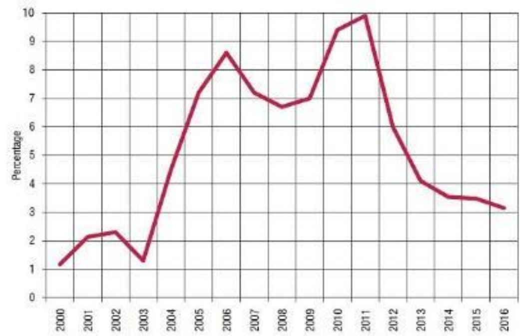
Due to the difficulties in forecasting the market for oil that can comply with the regulatory regime along with the fact that work is still in progress for other technologies that may be in compliance in the near future, it is observed in the maritime sector that many ship owners/ ship managers are moving rapidly to the scrubber market.

Depending on stakeholders, there are different viewpoints, for example, from manufacturers of engines, manufacturers of scrubber systems, shipbuilders, class societies, bunker companies, Port authorities, oil refineries and so forth. The authors agree that such views & opinions on the scrubber systems are rather varied and frankly, at times somewhat contradictory. However, considering the breakthrough in relevant technology at this point of time, the characteristics of the oil market and difficulties associated with changing the existing bunker lines on board the ships, it is the authors' view that the ship owners cannot delay the selection of the scrubber system for their ships.

However, since a relatively higher initial investment that is required to install scrubber systems, it is necessary for these stakeholders to make a reasonable and effective choice while taking into account the size and age of the ships, its trading areas and so forth. Particularly, durable materials should be selected for stable and long-term operation, and high-level of engineering and yard techniques should be introduced to facilitate pipeline maintenance. In the authors' view, no doubt the installation and operation of the correct scrubber systems will greatly contribute to and enhance the operations for ship owners & operators and other stakeholders. The expertise of engineers and commercial stakeholders is only going to increase in the future in relation to scrubber systems.

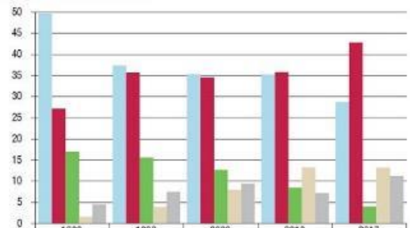
ANNEX I

Figure 2.1. Annual growth of world fleet, 2000–2016
(Percentage annual change)



Source: UNCTAD, *Review of Maritime Transport*, various issues.

Figure 2.2. World fleet by principal vessel type, 1980–2017
(Percentage share of dead-weight tonnage)



	1980	1990	2000	2010	2017
Oil tankers	49.7	37.4	35.4	35.3	28.7
Dry bulk carriers	27.2	35.6	34.6	35.8	42.8
General cargo ships	17.0	15.6	12.7	8.5	4.0
Container ships	1.6	3.9	8.0	13.3	13.2
Other	4.5	7.5	9.4	7.2	11.3

Sources: UNCTAD secretariat calculations, based on data from Clarksons Research and the *Review of Maritime Transport*, various issues.
Note: All propelled seagoing merchant vessels of 100 gross tons and above, not including inland waterway vessels, fishing vessels, military vessels, yachts and offshore fixed and mobile platforms and barges (with the exception of floating production, storage and offloading units, and drillships); beginning-of-year figures.

ANNEX II - Emission Control Areas in a tabular form that were designated pursuant to MARPOL VI and subsequent amendments are as follows:

Annex VI: Prevention of air pollution by ships (Emission Control Areas)				
	Emission Control Areas	Adopted By	Date of Entry in Force	In effect from
1	Baltic Sea (SOx) (NOx)	26 Sept 1997 7 July 2017	19 May 2005 1 Jan 2019	19 May 2006 1 Jan 2021 A ship constructed on or after 1 January 2021 and is operating in these emission control areas shall comply with NOX Tier III standards set forth in regulation 13.5 of MARPOL Annex VI.
2	North Sea (SOx) (NOx)	22 Jul 2005 7 July 2017	22 Nov 2006 1 Jan 2019	22 Nov 2007 1 Jan 2021 A ship constructed on or after 1 January 2021 and is operating in these emission control areas shall comply with NOx Tier III standards set forth in regulation 13.5 of MARPOL Annex VI.
3	North American ECA (SOx and PM) (NOx)	26 Mar 2010	1 Aug 2011	1 Aug 2012 1 Jan 2016 A ship constructed on or after 1 January 2016 and is operating in these emission control areas shall comply with NOx Tier III standards set forth in regulation 13.5 of MARPOL Annex VI.
4	United States Caribbean Sea ECA (SOx and PM) (NOx)	26 Jul 2011	1 Jan 2013	1 Jan 2014 1 Jan 2016 A ship constructed on or after 1 January 2016 and is operating in these emission control areas shall comply with NOx Tier III standards set forth in regulation 13.5 of MARPOL Annex VI.

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Gearing for New Ocean of Opportunities

ABSTRACT

– The Offshore & Marine (O&M) industry has seen one of the worst downturn of the decade. In order to ensure the sustainability of the O&M sector well into the future, businesses must equip itself with new capabilities to seize new opportunities. Amidst challenging market and intense competition, the Singapore O&M sector as a whole is reducing its reliance on oil exploration and diversifying into LNG, Offshore Renewables, and Green Technology. Such endeavour will likely involve development of new yard infrastructures, adoption of advanced manufacturing technology, and reskilling of the workforce to support the company's foray into new growth areas.

1. INTRODUCTION

Singapore has been a maritime nation since her founding in the 1800s, and has continued to play a key role on a global stage. As a major port state of a key waterway, Singapore has capitalised on its strategic location to build sophisticated port facilities and shipyards (13). However, this position is being threatened by challenging markets and regional developments. In 2018, the Singapore Government launched the Offshore and Marine (O&M) Industry Transformation Map (ITM) to transform the sector into a global leader for smart O&M engineering solutions (14).

In line with the ITM objectives, Sembcorp Marine has institutionalised its own programmes that are now in various stages of implementation. These programmes focus on:

- Improving productivity and reducing environmental footprint through technology adoption and investment in less energy-intensive facilities and equipment;
- Developing robust and cost-effective products and solutions across LNG, Offshore Renewables and Green Technology value chains;
- Forging closer collaborations with the industry, academia, and statutory bodies to facilitate technology test-bedding, translation, and adoption in the O&M sectors.

This paper discusses Sembcorp Marine's approach to economic and environmental sustainability, and the ongoing capabilities development to seize opportunities in new O&M growth areas.

2. IMPROVING PRODUCTIVITY AND REDUCING ENVIRONMENTAL FOOTPRINT

The O&M industry has encountered one of the worst downturns in recent history triggered by falling crude oil prices. Although oil prices have stabilised, earnings remain depressed due to intense competition from regional players and the lowered risk appetite of investors. Low charter rates and margins in new buildings and repairs are now seen as the 'new norm'. In order to remain globally competitive and sustain business growth for the next decades, holistic reassessment of a company's overall direction and its products and solutions life-cycle processes is necessary to identify and prepare for new opportunities. Amidst intense competition and tightened labour market, the O&M industry recognises the need to improve productivity through technology adoption.

2.1 Digitalisation and Advanced Manufacturing

Digitalisation enables the horizontal and vertical integration of all activities of the value chain, from design inception to post-production. The integration of products and solutions life-cycle processes facilitates a more robust and agile quasi-parallel approach to manufacturing than the conventional sequential approach. Digitalisation also enables the adoption of advanced data analytics which can potentially enhance the overall quality of decision-making leading to improved safety, quality, and productivity across the entire products and solutions life-cycle.

Alongside digitalisation, the adoption of advanced manufacturing (AM) technology in the O&M sector has also been identified as a key component of a coordinated Industry 4.0 (I4.0) strategy (2). AM, which includes robotics, additive manufacturing, internet-of-things (IoT) and automated production processes, will inevitably require an overhaul of the manufacturing model and significant investments to transform low-value, labour-intensive manufacturing to high-value, innovation-driven production. Adoption of smart and advanced manufacturing technologies is expected to endow the business with long-term competitive advantage on the global stage through new capabilities that position the business as a one-stop centre for O&M engineering solutions.

Sembcorp Marine's Tuas Boulevard Yard (TBY) is equipped with extensively-automated steel fabrication facility that spans a sprawling 120,000 m^2 area. This vertically-integrated facility operates with a suite of computerised systems that comprises pre-treatment, cutting, and robotic welding capabilities that optimise production efficiency and reduce man-hours. The TBY steel fabrication facility is not only able to efficiently deliver high quality welding, but also manufacture and assemble highly-customised steel components. In addition, major undertaking to break down individual silos of activities across the manufacturing value chain underpins Sembcorp Marine's ongoing development of TBY into a high-tech production hub.

Figure 1: R&D collaborators' visit to Sembcorp Marine's extensively automated steel fabrication facility at Tuas Boulevard Yard.

2.2 Safer and Smarter Operations

There is great potential to reduce cost of operations by adopting technologies such as drones and applied data analytics to improve safety and efficiency. Safety-related incidents are disruptive and costly, but such risks can now be mitigated by operationalising drone technology. For example, visual inspection for quality can utilise drones and eliminate the need for scaffolding. Adopting drones for certain operations present considerable savings in cost and time, thereby increasing efficiency and productivity. In addition, ongoing improvements in drone technology and wireless communication infrastructure will enable remote inspections of confined spaces and underwater structures from a safe position.

Sembcorp Marine's workplace safety and health (WSH) strategy emphasizes on enhancing HSE competencies and capabilities; building up commitment and leadership towards a better WSH culture; garnering support from stakeholders; and continuously improving its risk and safety management systems. In line with these objectives, Sembcorp Marine initiated a series of programmes to operationalise Unmanned Aerial Vehicles (UAV) for yard operations. Sembcorp Marine is the first in Singapore to have received the ABS External Specialist Certificate for the quality inspection of vessels using UAVs with certified pilots in various core departments. To ensure safe and authorised operations, the Group has relevant permits by the Civil Aviation Authority of Singapore (CAAS) to perform daily inspections alongside classification surveyors.

Figure 2: Collaborating with Classification Societies in the adoption of drones for remote inspections at height (top) and in confined spaces (bottom).

2.3 Reducing Environmental Footprint in Operations

Reducing the carbon footprint in operations can form a part of the company's long-term sustainability target. Annual target-setting and year-end review ensures decisions are made with sustainability in mind, while adequate flexibility is provisioned for manoeuvring around the market conditions. Realising the carbon footprint reductions goal may be achieved by various means: investing in less resource-intensive equipment and facilities when the time for renewal approaches; upgrading existing equipment and facilities to be more energy efficient and generating less waste; and investing in renewable energy systems to reduce consumption of non-renewable energy sources.

Singapore currently generates 95% of its energy from natural gas. Solar power accounts for only about 2% of the energy mix. In future, solar energy is expected to contribute up to 25% of the country energy needs and a series of nation-wide programmes have been launched to meet this target (3).

As of 2018, the total solar photovoltaics (PV) installed capacity is reported to be around 149 MWp, of which 50% were installed in the private sector (3). A number of high-profile private sector projects were announced in the same year, including the 2.4 GWh plants at 3M and REC manufacturing facilities, and the 6.8 GWh rooftop panels installed at Katoen Natie's Jurong Island warehouse.

Sembcorp Marine is also one of the major adopter of PV technology in Singapore; 5.38 GWh has been installed at the TBY steel fabrication facility with plans to expand the capacity to 10 GWh per year. The present 4.5 MWp plant at TBY steel fabrication facility is able to lower grid-supplied electricity by 30% at peak load, equivalent to 2500 tonnes of carbon emission reduction per year. These development reflect the commitment of private enterprises to reducing their carbon footprint.

Figure 3: Rooftop solar panels at Sembcorp Marine flagship Tuas Boulevard Yard.

3. DEVELOPING PRODUCTS AND SOLUTIONS FOR NEW GROWTH AREAS

The signing of the 2016 Paris Agreement signify the commitment of world leaders reduce carbon emissions in their respective economies. Transition to a low-carbon economy is considered one of the great challenges of the 21st century, which involves navigating complex political, economic, and technology barriers across numerous stakeholders. Looking ahead, all forms of energy will still be needed to meet the demands of a growing global population. Hence, meeting the global climate goals require emission reduction through more efficient use of resources as immediate priority, followed by elimination of non-essential disposable products such as plastic packaging. With increased adoption of more energy efficient engines, alternative fuels, and growing maturity in hybrid and fully-electric vehicles, demand for coal and crude oil will decline. Surviving O&M can no longer rely on oil exploration and drilling as a core business. Instead, new pivot points are now needed to diversify existing product portfolio in anticipation of a low-carbon and environment-conscious future. Sembcorp Marine has identified LNG, Offshore Renewables and Green Technology as new growth areas that can leverage on the Group's track-record in O&M engineering solutions, and the advanced capabilities of its smart and sustainable Tuas Boulevard Yard.

3.1 Seizing the LNG Opportunity

The demand for energy will continue to grow with increasing global population and rising income in emerging economies. Meanwhile, the energy mix will evolve as new technology advances and emerging technologies mature. Despite increasing demand for energy, the global community has taken steps to curtail carbon emissions.

Sembcorp Marine is committed to the adoption of natural gas as a greener alternative to conventional carbon fuel. As one of the leading technology company in the Offshore, Marine, and Energy sectors, Sembcorp Marine has developed a comprehensive suite of solutions that include cost-effective and modular near-shore gas terminal solutions, gas production and processing solutions, and a portfolio of O&M vessels powered by gas engines. In addition, the company is building 12 gas-battery hybrid tugboats to replace her existing diesel fleet as a reflection of her commitment to the environment. Sembcorp Marine will also design and construct a 12,000 m³ LNG bunkering vessel, the largest of its kind to be built in Singapore in terms of size and LNG tank capacity. These development signify rising confidence in gas technology and will help the O&M sector transition to cleaner and greener operations.

Figure 4: Sembcorp Marine LNG solutions under-construction: (from left to right) Gas-powered semi-submersible crane vessel (SSCV Sleipnir); 65t b.p. gas-battery hybrid tug; 12,000 m³ capacity LNG bunker vessel.

3.2 Preparing for Renewable Energy Future

Renewables are now the fastest-growing energy source since the industrial revolution. It is estimated that renewables could account for at least 14% of all energy consumption by 2040 (17). The academic circles are bolder in their estimates. A team of scientists predicted that transitioning to 100% renewables would be viable by 2050 (10), while more conservative estimates agreed that 80% is achievable within the same time-frame. Although these predictions may seem ambitious, recent development in the wind and solar energy industries have shown that maturity and cost reduction of renewables have exceeded conservative expectations (8).

In anticipation of a renewable-dominated future, the O&M industry should start to look into developing products and solutions across the renewables value chain. Such products will not only help customers reduce their carbon emissions, but also provide new opportunities for the O&M business.

Sembcorp Marine is currently executing EPCC projects to deliver two offshore windfarm substation topsides for deployment at the Hornsea 2 Offshore Wind Farm in the North Sea. This 1.4 GW facility will power over 1.3 million homes with clean energy when operational in 2022, reducing nearly 1.9 million tonnes of CO_2 and 46,000 tonnes of SO_2 emissions annually. In a further expansion to Sembcorp Marine's renewables value chain capabilities, the Group will design and construct three ROPAX ferries for deployment in Norwegian shortsea routes. These zero-emission vessels will operate on batteries rechargeable at hydroelectricity-based shore power points available along their service routes.

Figure 5: *Sembcorp Marine renewable solutions currently under-construction: Hornsea 2 offshore wind substations (top); Zero-emission ROPAX ferries (bottom).*

3.3 Contributing to More Sustainable Ocean

The ocean represents an estimated $1.5 trillion annual global value with regional and global economies relying on healthy oceans for aquaculture, subsistence fisheries, trade, and leisure (6). Unfortunately, the health of the ocean ecosystems is declining due to increasing pressure from human activities and climate change. In 2015, the United Nations member states adopted the 2030 agenda for sustainable development (18). The 17 sustainable development goals (UNSDG) form an integral component of this agenda, of which SDG 14 specifically addresses the state of our oceans and highlights the urgency for its conservation and sustainable use.

A legally binding Annex was added to the 1973 International Convention for the Prevention of Pollution from Ships (MARPOL) to address biological pollution from shipping. Since then, a number of conventions focused on protecting the health of our oceans have been ratified and enforced by member states. These statutory measures include: the prohibition of organotin in ship paints; requirements for ships to meet ballast water discharge standards; requirements for ships to limit their sulphur emissions to 0.5%; and requirement for new ships to meet the new efficiency targets defined by the Energy Efficiency Design Index (EEDI). Regulations are driving interest in more energy-efficient vessels, and ship designers are increasingly leveraging on artificial intelligence to automate the design and optimisation of hull forms to meet the EEDI targets (1).

In 2011, the Maritime Port Authority of Singapore (MPA) launched a series of voluntary programmes designed to recognise and incentivise maritime companies to adopt green shipping practices and fulfil the mandated environmental sustainability requirements. To date, the MPA programmes has benefited dozens of maritime companies and yielded direct CO_2 reductions of around 285,000 tonnes per year (12). Companies can take advantage of MPA funding platforms to defray some costs associated with their environmental sustainability activities.

Sembcorp Marine champions green shipping through its Semb-Eco green technology solutions to promote ocean sustainability. Products such as the non-chemical LUV ballast water management systems (BWMS), SembSOx exhaust gas cleaning systems (EGCS), and the non-chemical ElMag anti-corrosion solution help contribute to the health of our oceans and the environment.

Figure 6: Sembcorp Marine environmental products: Semb-Eco LUV ballast water management system (left); Semb-Eco ElMag Corrosion Protection System applied to VLCC stern tube (right).

4. FORGING CLOSER COLLABORATIONS WITH INDUSTRY AND ACADEMIC PARTNERS

It is no longer sufficient to merely invest in people, technology, and innovation; rather O&M companies must do so with objectives firmly rooted on sustainability in order to secure the company's survivability and relevance in the future ocean economy. There are various approaches to innovation. Most technology companies sets aside a certain percentage of their revenue towards R&D. For example, GE's investment in technology and innovation has more than doubled over the past two decades, reaching $4.9 billion in 2016 (4). A similar commitment to innovation needs to be adopted by the O&M industry in order to meet the challenges and opportunities of the future.

In addition, it is crucial that O&M innovation and technology centres be deeply connected with the entire value chain partners, from Classification Societies to Institute of Higher Learning and Government agencies. This multi-faceted approach strengthens the overall innovation capabilities, while refining and adapting the technology to address the unique needs of different markets around the world. It should lead to strategic development programmes that aim to produce a suite of safer, smarter and greener products and solutions that are also more robust to seize the new opportunities in the future ocean frontiers.

As a living lab, Tuas Boulevard Yard collaborates with various technology partners to test-bed innovative processes, advanced equipment and new technologies. Such endeavours strengthen Sembcorp Marine's operations and capabilities in developing and delivering new products and solutions for sustainable growth and with reduced environmental footprint.

5. CHAMPIONING SUSTAINABLE DEVELOPMENT

United Nations Member States have manifested their commitment to the United Nations Sustainability Development Goals (UNSDG) 2030 target in varying degrees (18). In Singapore, publicly-listed companies are now required to report their sustainability efforts as part of the listing requirements (16). Sustainability reporting has been guided primarily by recognised frameworks such as the Global Reporting Initiative (GRI), and the United Nations Global Compact (UNGC) Ten Principles. More specific to the O&M industry, the IPIECA framework (9) has deeply penetrated the Oil and Gas (O&G) value chain and has spilled over to the O&M sector.

Sembcorp Marine incorporates aspects of the 2030 goal as part of its ongoing transformation (see Figure 7) anchoring on its Corporate Environmental Policy (CEP). Sembcorp Marine's CEP identifies the key aspects of its environmental management systems, and encompasses all employees, contractors and customers. Regular audits for compliance with local regulations and international standards are undertaken as part of ISO 9001 and ISO 14001 requirements, and these are reviewed on a regular basis.

Sembcorp Marine's human capital strategy covers workforce development; competence-building and skills enhancement; organisational development; as well as cultivation of a strong company culture and identity. The Group seeks to offer a compelling employment experience, competitive compensation and benefits, opportunities for personal and professional development, as well as an enriching environment that promotes merit-based progression. Sembcorp Marine gears its people development systems towards business excellence to support the attainment of recognised accreditations, such as ISO 9001 and People Developer Standards, which involve structured review and evaluation processes.

Figure 7: *Notable Sembcorp Marine programmes and solutions for sustained business growth (Source: Sembcorp Marine Annual Report 2018).*

6. CONCLUSION

While the 21st Century present us with numerous challenges, there are also opportunities to be uncovered for Singapore O&M industry. Amidst challenging market and stiff competition from regional players, Singapore O&M business must leverage on technology to improve productivity and competitiveness. The sustainability of the O&M business also relies on the foresight of business leaders to identify future opportunities, and their will to steer the organisation towards the new objectives. As businesses focus on growth and seek new investment opportunities, there must be collective effort towards responsible and sustainable use of our ocean resources. Any business decisions must take into consideration the intersection of economic benefits, environmental health, and societal value in policies and best practices (6). With well-established frameworks available for sustainability reporting and a growing emphasis for companies to consider sustainability in their long-term approach, the climate for change is here. By combining purpose in innovation, competitiveness, productivity, profit and environmental benefits, the industry can lead sustainable development and realise economic benefits.

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Critical Analyses of Ballast Water Treatment Technologies

ABSTRACT

This article presents the critical analyses of different ballast water treatment systems to aid ship owners to select a system which is deemed most suitable for their vessels. Extracting 53 treatment systems data; system types, costs, power requirements and footprints from manufacturers and global markets to input under the Analytical Hierarchy Process (AHP) method for analysis.

The rankings of AHP criteria are made by ship owners themselves concerning the market data analysis for comparison. However, this is accurate to a certain extent due to some of the data obtained were overdue which are not updated. In all, the idea of the analysis is not to see which the best water ballast treatment system is. It is instead a guide to the owners on selecting a suitable treatment system for their vessels. Furthermore, buyers can obtain data conveniently and have a better view of the market through these analyses.

KEYWORDS

Analytic Hierarchy Process (AHP), AMS Type Approved, Ballast water treatment systems, Multi-criteria decision making, Global market, Pairwise comparison matrix

1. INTRODUCTION

Shipping activities transport more than 80% of the global commodities and transfer three to five billion metric tons of ballast water every year. Unintentional transfer and growth of marine organisms in ballast water tanks have been listed as one of the biggest threats to the world's ocean. Resulting in contamination of marine ecosystem, jeopardizing of human health and economic catastrophe.

According to the International Maritime Organization (IMO), adoption of the International Convention for the Control and Management of Ships' Ballast Water and Sediments in 2004 has been announced. Ballast Water Management Convention (BWMC) will be entering into force on 8 September 2017, which says that nations representing just over 35% of the world's merchant shipping tonnage have now ratified the convention. In regardless, ship owners must retrofit their vessels to meet the convention's standards within a five-year timeframe.

With modern technologies today, there are many promising treatments out in the market addressing this issue. However, many ship owners do not know what type of system are they looking for and which method is the most suitable for their operation.

Recent studies have shown that hybrid Fuzzy Stochastic Analytical Hierarchy Process (FSAHP) has been widely acknowledged for multi-criteria decision making than the traditional Analytical Hierarchy Process (AHP). In the absence or lacking data, these comparison decisions are made by experts with experiences and knowledge, which allow visible statistical information and figures to be seen. Also, it can detect biased opinions in group decision-making problems [1] and [2]. After all, FSAHP decision making is still made by human judgments and preferences without statistical data facts.

In this analysis, the traditional AHP approach was used to assist ship owners in identifying the most suitable ballast water treatment system. Therefore, with the sources of the market data analysis, owners can make comparison decision more accurately on selecting the right system.

2. METHODOLOGY

In this critical analysis, Microsoft Excel was utilised. All the market data and formulas were input into the spreadsheet to generate values and graphs. The process involves two principal stages; obtaining market data from manufacturers and application of data into the AHP in accordance to the owner's decision.

2.1 Market Data Analysis

There are a vast numerous ballast water treatment systems around the globe, but only 53 treatment systems are taken into considerations in this market analysis. These treatment systems have been approved by IMO and were given the Alternative Management System (AMS) type approval by United States Coastguard (USCG). In another word, these 53 systems have the warrant to sail on US ports with a period of five years from the approval date. Additionally, 19 systems have submitted to undergo the treatment system testing of USCG type approval as shown in Table 1.

Efficiency is an essential criterion for the comparison of ballast water treatment systems. However, it is negligible for this analysis because all the treatment systems have already complied with the G8 and G9 regulations.

In this market data, only four types of system are put to analyze. Figure 1 shows the capacity of different system types ranging from 500m3/h to more than 15,000m3/h.

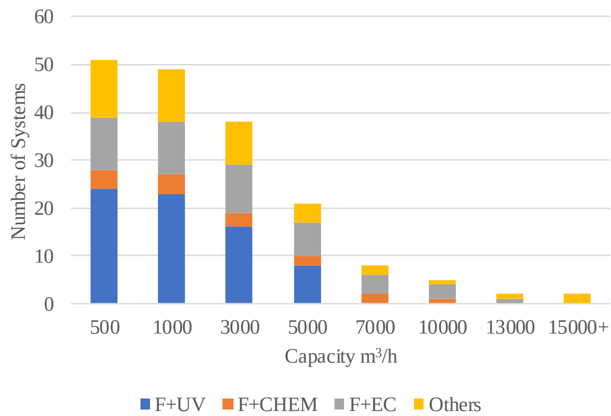

Figure 1: Different ranges of capacity over 53 systems

2.1.1 Costs

Cost is one of the significant factors that ship owners are looking out for. They should not allow the initial capital and installation costs to decide which treatment system to purchase, but also must take into consideration the operational expenditures (OPEX), such as maintenance and operational costs. Annual OPEX can be ranged from 3% to 15% of the capital cost. Additional charges on servicing and replacement of equipment would occur in later years with a significant fraction of these expenditures. Therefore, owners deciding to keep vessel for more than three to five years should take OPEX as an essential factor to be considered. Figures 2(a) to 2(d) presents the estimated cost on varies spending areas for different types of vessels according to its system type.

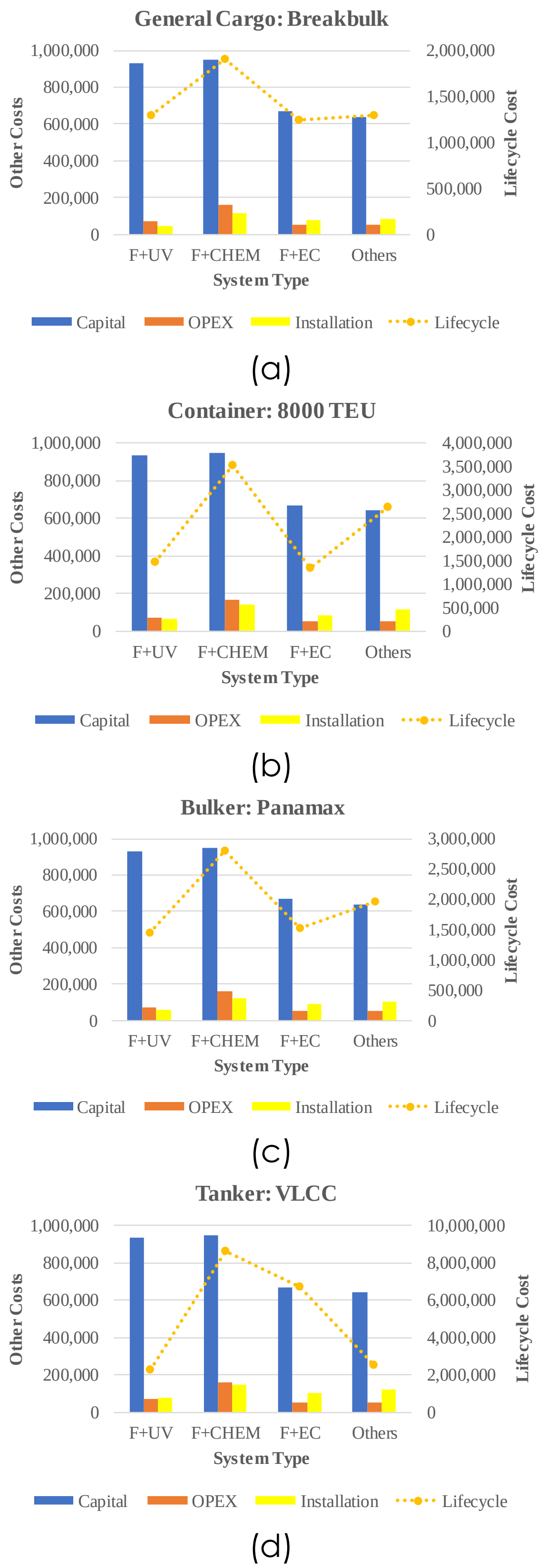

Figure 2: Overall estimated costs of different system types for 4 different vessels

(a)General Cargo: Breakbulk;(b) Container 8000 TEU;(c) Bulker: Cape Size Vessel;(d) Tanker: VLCC

Table 1 Detailed specification of 19 different ballast water treatment systems

Manufacturer	System Type	Does the system uses active substance?	USCG Type Approval	Capacity (m^3/h)	Footprint (m^2)	Max Height (m)	Power (kWh)	Sold	Installed	Retrofitted
						@5000m³/h			Units	
A	F+UV	NO	23/12/16	150-3000*i*	4.15@1000m³/h	2.5	150-301 @3000m³/h	>1100	900	200
B	F+UV	NO	Progressing	300-4000	44	3.2	393@4000m³/h	500	300	5
C	De+US*	NO	Progressing	20000-3456000	In Tank Treatment			-	1	1
D	F+CLO_2**	YES	Progressing	400-12000	21.9	3.4	12.4-33.8	62	7	4
E	F+UV	NO	Progressing	350-2100	9.7	3.06	205@2100m³/h	33	16	0
F	F+EC	YES	Progressing	75-10000	12.26	2.8	250	350	250	2
G	F+CL**	YES	Progressing	200-4500	~21	~2.7	18.25	1200	~160	~20
H	F+UV	NO	Progressing	200-6000	24.4@5100m³/h	3.7 @5100m³/h	804@5100m³/h	>120	>80	>10
I	F+UV	NO	Progressing	24-1400	-	-	150@1400m³/h	100	70	10
J	Oz*	YES	Progressing	300-8000	27.5	2.95	452.9	480	200	20
K	F+EC+De**	YES	6/2/17	200-7200	15.8	2.7	205	179	100	10
L	F+UV	NO	2/12/16	50-3000	5.28@3000m³/h	3.5 @3000m³/h	630@3000m³/h	428	264	84
M	F+EC	YES	Progressing	250-6500	9.5	2.4	76	250	44	1
N	F+UV	NO	Progressing	200-6000	23.22	3.7	325-480	300	>100	>50
O	F+UV	NO	Progressing	125-600	-	-	-	-	-	-
P	EC	YES	Progressing	150-1000*i*	3.8	2	34-73 @1000m³/h	976	769	11
Q	F+EC	YES	Progressing	250-13200	19	3.9	530@6000m³/h	5	1	1
R	F+UV	NO	Progressing	50-6000	43	2.6	495	118	80	23
S	HC+US+UV*	NO	Progressing	100-6000	25.7@3000m³/h	2.6 @3000m³/h	90@3000m³/h	224	175	27

CL=Chlorination CLO_2=Chlorine Dioxide De=Deoxygenation EC=Electrochlorination/Electrolysis
F=Filtration HC=Hydrocyclone Oz=Ozonation US=Ultrasound UV=Ultraviolet

i Able to increase capacity when install more components,
* Under 'Others' system type,
** Under 'F+CHEM' system type

2.2 Analytical Hierarchy Process (AHP)

AHP is a multi-criteria decision analysis developed by [3]. Basically, it uses human judgments to rank the alternatives to a decision. Rather than making the correct decision, this method helps owners to find one that best suit their goal and their understanding of the problem with the references to the market data.

2.2.1 AHP Procedure

The following steps are used for executing the AHP:

1. Define the problem and conclude the decisive goal.
2. Construct a hierarchy from the top with the decision goal, followed down by the criteria (intermediate level), then the list of alternatives (lowest level
3. Model a set of pairwise comparison matrices size (*n* x *n*) for each of the lower levels. Each element in an upper level (*j*) is used to compare the elements with the level directly below (*i*) concerning it, using the comparison scale in Table
4. There are $\frac{n(n-1)}{2}$ decisions to compare in step 3. In each pairwise comparison, reciprocals are automatically assigned. Then sum the column of each element.
5. Normalised the comparison matrix (divide each element of the column by the sum of that column). Average the total row of each element, known as the priority vector {*W*}. Sum of the column of each element should be equal to one.
6. To deem rankings are made with careful considerations, consistency check must be done to ensure consistency ratio is less than 0.1. If

consistency ratio is more or equal than 0.1 means rankings are not made appropriately. To check for consistency:

a. Determine weight sum vector,

$$\{Ws\} = [C]\{W\} \qquad (1)$$

b. Calculate the Eigen vector,

$$\{\lambda\} = \{Ws\}.\{\frac{1}{W}\} \qquad (2)$$

c. Average the total sum of Eigen value.

d. Calculate the consistency index,

$$CI = \frac{(\lambda - n)}{(n-1)} \qquad (3)$$

where *n* = matrix size.

e. Finally, determine the consistency ratio,

$$CR = \frac{CI}{RI} \qquad (4)$$

f. *RI* = Random Index is a standardized value presents in Table 3.

g. Combine the priority vectors from each system decision alternative criterion and the three criteria. Overall priority matrix will be formed with a (Decision alternatives x criteria) size matrix.

Table 2 AHP ranking scale for pairwise comparison

Intensity Ranking	Definition
1	Equally Important
2	In between 1&3
3	Moderate Importance
4	In between 3&5
5	Strong Importance
6	In between 5&7
7	Very Strong Importance
8	In between 7&9
9	Extremely Importance
Reciprocals	If *i* is less important than *j*

2.3 Case Study

A simulated case study was conducted for illustration purposes in addressing uncertainty in the context of the ship owner's decision making in the selection of a ballast water treatment system. 19 AMS type approved ballast water treatment systems were listed for this analysis showed in Table 1.

A ship-owner was assumed to have a breakbulk cargo with a 4000m3/h ballast pump capacity. In this case scenario, a typical customer beyond any doubt would go for the cheapest cost product, with the best benefits manufactured by a reputable company.

Referring to Figure 1(a), F+CHEM system type treatments have been eliminated because it has the highest estimated lifecycle cost, which does not meet the owner's requirements. Another 10 systems have been immediately discarded at the same time for apparent reason of capacity not meeting its condition.

In this illustration, power requirement, footprint and units are the criteria factors to be considered for the reminding systems as shown in Figure 3. However, other criteria can be added if necessary if there are relevant data for references.

Table 3 Random consistency index

Matrix Size	3	4	5	6	7	8	9
Random Index	0.58	0.9	1.12	1.24	1.32	1.41	1.45

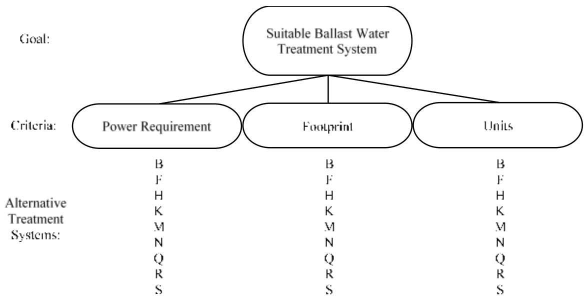

Figure 3 Hierarchy structure of ballast water treatment systems selection

Table 4 Pairwise comparison matrix[C] for power requirement

	j: B	F	H	K	M	N	Q	R	S
i: B	1	1/3	4	1/4	1/6	1/2	1/2	1/2	1/5
F	3	1	5	1/2	1/4	4	5	5	1/3
H	1/4	1/5	1	1/6	1/8	1/5	1/4	1/4	1/6
K	4	2	6	1	1/3	5	5	5	1/2
M	6	4	8	3	1	5	6	6	2
N	2	1/4	5	1/5	1/5	1	2	2	1/4
Q	2	1/5	4	1/5	1/6	1/2	1	1	1/5
R	2	1/5	4	1/5	1/6	1/2	1	1	1/5
S	5	3	6	2	1/2	4	5	5	1

By following the AHP procedure as described in *2.2.1*, the hierarchy structure was developed shown in Figure 3. Moving on to step 3, the ship-owner has to indicate priority rankings for each system decision alternative criterion matrix as shown in Table 4. Then steps 4 to 6 could be done using a spreadsheet to generate the values. Calculation of the values only will be done on element B and will be explained for illustration purposes.

After ship owner has indicated the rankings for the comparison, a size (9x9) matrix has been formed. Comparing of elements work in an 'L-shape' direction. Lower level elements in *i* rows will compare with the upper level elements in *j* column. Example, B*i*-B*j*=1 (Equally important); B*i*-F*j*=1/3 (F is moderately more important than B); B*i*-H*j*=4 (B is between 3&5 important than H).

By dividing each element of the matrix by its sum column element. Example, sum of B= (1+3+1/4+4+6+2+2+2+5) = 25.25 then 1/25.25 = 0.040

Priority vector is formed by averaging the rows in the normalised comparison matrix as shown in Table 5.

Table 5 Normalized comparison matrix for power requirement

		j				
		B	F	...	S	Priority Vector {*W*}
	B	0.040	0.030	...	0.041	0.040
	F	0.119	0.089	...	0.069	0.125
	H	0.001	0.018	...	0.034	0.020
	K	0.158	0.179	...	0.103	0.162
i	M	0.238	0.358	...	0.412	0.294
	N	0.079	0.022	...	0.052	0.063
	Q	0.079	0.018	...	0.041	0.046
	R	0.079	0.018	...	0.041	0.046
	S	0.198	0.268	...	0.206	0.204

λ = 9.745; *CI*= 0.093; *RI*= 1.45; *CR*= 0.064<0.1 OK

Table 6 Consistency check for power requirement

	Weighted Sum {Ws}		Eigen {λ}
B	0.369		9.306
F	1.282		10.239
H	0.188		9.438
K	1.670		10.312
M	2.957		10.066
N	0.601		9.517
Q	0.431		9.291
R	0.431		9.291
S	2.084		10.242
		Average λ=	9.745

Checking for consistency ratio as follows:

To obtain the weighted sum value of B= 0.3963 and so on, step 6(a) as applied.

$$(1x0.040) + (1/3x0.125) + (4x0.020) + (1/4x0.162) + (1/6x0.294) + (1/2x0.063) + (1/2x0.046) + (1/2x0.046) + (1/5x0.204) = 0.369 \quad (1)$$

Step 6(b) and (c) is performed to obtain the Eigen value presented in Table 6.

$$\{\lambda\} = \{Ws\}.\{\frac{1}{W}\} = \frac{0.369}{0.040} = 9.306 \quad (2)$$

Total the column and average out the Eigen value. Therefore, λ= 9.745

Now find consistency index by applying step 6d.

$$CI = \frac{(\lambda - n)}{(n-1)} = \frac{(9.745 - 9)}{(9-1)} = 0.093 \quad (3)$$

Selecting the matrix size 9 in Table 3, RI= 1.45. Lastly, consistency ratio can be calculated.

$$CR = \frac{CI}{RI} = \frac{0.093}{1.45} = 0.064 \quad (4)$$

Value of CR is less than 0.1 means the decisions made by ship owner is acceptable. Pairwise comparison matrices and priority vectors for the remaining system decision alternatives criterion are presented in Table 7 and Table 8 respectively.

Table 7 Pairwise comparison matrix[C] for footprint

		j									
		B	F	H	K	M	N	Q	R	S	{*W*}
	B	1	1/5	1/4	1/5	1/7	1/4	1/3	1	1/2	0.029
	F	5	1	3	2	1/2	3	2	5	4	0.189
	H	4	1/3	1	1/3	1/4	1	1/2	4	3	0.082
	K	5	1/2	3	1	1/3	3	2	5	4	0.159
i	M	7	2	4	3	1	3	2	7	5	0.266
	N	4	1/3	1	1/3	1/3	1	1/2	4	3	0.085
	Q	3	1/2	2	1/2	1/2	2	1	5	4	0.122
	R	1	1/5	1/4	1/5	1/7	1/4	5	1	1/2	0.027
	S	2	1/4	1/3	1/4	1/5	1/3	1/4	2	1	0.042

λ =9.380; *CI*=0.047; *RI*=1.45; *CR*=0.033<0.1 OK

Table 8 Pairwise comparison matrix[C] for units

		j									
		B	F	H	K	M	N	Q	R	S	{*W*}
	B	1	3	7	6	5	5	9	7	5	0.358
	F	1/3	1	5	4	3	2	7	5	3	0.190
	H	1/7	1/5	1	1/2	1/3	1/4	3	1	1/2	0.039
	K	1/6	1/4	2	1	1/2	1/3	4	1	1/2	0.053
i	M	1/5	1/3	3	2	1	1/2	5	3	1	0.088
	N	1/5	1/2	4	3	2	1	6	4	2	0.130
	Q	1/9	1/7	1/3	1/4	1/5	1/6	1	1/3	1/5	0.020
	R	1/7	1/5	1	1	1/3	1/4	3	1	1/2	0.042
	S	1/5	1/3	2	2	1	1/2	5	2	1	0.079

λ =9.335; *CI*=0.042; *RI*=1.45; *CR*=0.029<0.1 OK

Similarly, the same procedures are applied for the three criteria pairwise comparison matrix and priority vector as shown in Table 9.

When all pairwise comparison matrices and priority vectors were tabulated, synthesis the three criteria and each system decision alternatives criterion's priority vectors to form an overall priority matrix as shown in Table 10.

Table 9 Pairwise comparison matrix[C] for three criteria

		j			
		Power Requirement	Footprint	Units	{*W*}
	Power Requirement	1	1/3	3	0.260
i	Footprint	3	1	5	0.633
	Units	1/3	1/5	1	0.106

λ =3.039; *CI*=0.019; *RI*=0.58; *CR*=0.033<0.1 OK

Table 10 Overall priority matrix for suitable ballast water treatment system

	Power Requirement (0.260)	Footprint (0.633)	Units (0.106)	Overall Priority
B	0.040	0.029	0.358	0.067
F	0.125	0.189	0.190	0.172
H	0.020	0.082	0.039	0.061
K	0.162	0.159	0.053	0.148
M	0.294	0.266	0.088	0.254
N	0.063	0.085	0.130	0.084
Q	0.046	0.122	0.020	0.091
R	0.046	0.027	0.042	0.034
S	0.204	0.042	0.079	0.088

Overall priority of Manufacturer B= (0.040x0.260) + (0.029x0.633) + (0.358x0.106) = 0.067

3. RESULTS AND DISCUSSION

Different ballast water treatment systems were being ranked according to their over priorities. In the descending ranking, Manufacturer M was ranked the top followed by F, K, Q, S, N, B, H and R. This indicates Manufacturer M's ballast water treatment system is the most favourable according to the ship owner's requirements.

The analysis shows that system M, F and K are all F+EC system type and were ranked the top three in overall priority matrix presented in Table 1 and Table 10. With this result, it is possible to assume that this system type displays the capability to support a moderate to high range capacity vessels. Where vessel in the illustration shows a 4000m3/h ballast pump capacity, which is deemed to be a high mid-range capacity.

Where lifecycle cost is concerned, F+UV system type displays a constant lower curve-points throughout as seen in Figures 2(a) to 2(d). However, in this illustration they were ranked at the bottom three because of their high power consumption rate and the footprint did not meet the requirements. Regardless of their lowest rankings, they still achieved the top units sold and installed among others. Which supposed that most owners would likely prefer a trusted system, as two out of three USCG type approval systems are from F+UV system type apparent in Table 1.

Putting actual facts aside, market data analysis will vary due to it has to be continuously updated, to achieve an accurate comparison. With that being said, there is something that will not change which a buyer should take note on, the characteristics of the system type. F+UV system type is the most environmental and user-friendly method, and it does not admit or discharge any harmful substances or by-products in operation. On the contrary, as shown in Table 1, F+CHEM and F+EC system types are operating using active elements, chances of corrosion in tanks may occur. These systems require extra storages for necessary chemicals, and it will produce harmful by-products which many safety measures have to be carefully considered. In short, fixed system characteristics should play a part in the decision making.

Nevertheless, taking into account the world's maritime fleet, vessels of varying design and construction, operational purposes and size, it is unconvincing that a single best available solution will meet the stringent requirements. With this sets of market data, this could be a one-pit stop to feed ship owners with information about the global market trends and knowledge of different types of ballast water treatment system. Saving their time and effort on researching all over to comply with the regulations, where time now is the critical competence in this new convention era.

In light of this, it is important to note that not all market data of the treatment systems are obtained and are up to date. To say that, the result produced by the analysis are only accurate to a certain extent. With this, a better critical analysis with more in-depth data sources would be required.

In this current analysis, the market data have covered the essential criteria of different types of the treatment system. Contrarily, it would be significant to carry out more in-depth research on the treatment systems for a more solid conclusion.

4. CONCLUSIONS

Results from this critical analysis have shown that market data could only be accurate to a certain extent, due to the global trends and system data have to be continuously updated. Knowing this, there could potentially be some fixed data to be found which could allow more constant data to be compared.

In addition to the above, F+EC system type are mainly more efficient for higher capacity vessels. It operates at low power consumption compared to others. Knowing this, it also has several disadvantages, regarding in requiring extra storages and producing of harmful by-products. Although F+UV system type consumes higher power, it was found to be the most favourable to ship owners due to it is very reliable and environmentally friendly.

There is still more to explore, and it serves as the basis for future research. Future research would require an in-depth study of treatment system application on the different kinds of vessel, and their advantages and disadvantages.

A refined critical analysis of ballast water treatment system should be carried out. This time, factors such as the pros and cons, the entire footprint inclusive of piping and storages of each method are to be included in the criteria comparison matrix. It would allow the owners to think carefully and to see a more unobstructed view if their desired ballast water treatment is appropriate for their vessel's operation.

Lastly, to arrive at a more likely conclusion on which the results are accurate, a cross-reference with an expert's perception can be implemented.

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Estimating Marine Fouling Speed Loss with ISO 19030: Pros and Cons of the Standard

ABSTRACT

Since shipping activities have a significant impact on the environment, a crucial issue for the maritime industry is to develop technologies able to increase the ship efficiency, by reducing fuel consumption and unnecessary maintenance operations. For example, to prevent or reduce the marine fouling phenomenon affecting the ship consumption, costly drydockings for cleaning the hull and the propeller are needed and must be scheduled based on a speed loss estimation.

In this work, the ISO 19030, which is usually considered the de-facto standard for dealing with this task, is used for estimating the speed loss due to marine fouling on real-world data coming from two Handymax chemical/product tankers. Results have been evaluated adopting two different tests in order to verify the ISO 19030 capabilities, thus clearly showing its defects.

INTRODUCTION

As awareness of climate change increases, sustainable shipping is recognized as one of the biggest challenges of the 21st century, both for its contribution to carbon dioxide (CO_2) emissions and to other pollutants [1]. Since international maritime transport represents approximately 90% of global trade, thus contributing to approximately 2.7% of the global anthropogenic CO_2 emissions [2], ship energy systems needs to become more energy efficient [3]. In recent years, however, the International Maritime Organization (IMO) is aiming at reducing Greenhouse Gases (GHG) emissions from shipping by 50%, and working towards phasing out them entirely by the end of the century [4]. Therefore, developing new technologies able to both improve the design of the ships and to maintain their efficiency becomes a crucial issue [5].

In this work, much attention was focused on the problem of keeping the ship as much efficient as possible by estimating the degradation state of its components, with the consequent performance loss and fuel consumption increase [6]. Broadly speaking, as far as propulsion systems are concerned, there are mainly three macro-components in a ship that can degrade: the main engine, the hull, and the propeller [7]. Apart from the ordinary regular maintenance, the main engine degrades very slowly in time and related effects are only noticeable after years of operations [8]. The hull and the propeller, instead, are subject to marine fouling, that increases the frictional resistance of the parts moving through the water and, hence, decreases their efficiency [7]. The effects of marine fouling can be clearly observed after just a few months of operations [9].

Marine fouling, or simply biofouling, is defined as the undesirable accumulation of microorganisms, algae, and animals on artificial surfaces immersed in seawater [10,11]. On the hull, the presence of fouling increases the roughness of the surface, hence increasing frictional resistance [12,13]. On the propeller, the presence of fouling increases the roughness of the blade surface, thus requiring more power to maintain the same speed [14,15]. Currently, shipping companies try to mitigate the problem of hull and propeller fouling by applying anti-fouling paints on the submerged surfaces and by regularly cleaning the hull [16]. Despite their effectiveness, antifouling paints can be expensive and can be harmful to the marine environment [17]. Moreover, the hull and the propeller are cleaned on the occasion of other dry-docking maintenance events, but this practice does not ensure optimal scheduling of the cleaning procedures [18]. Over a typical 4–5 years sailing interval, bare hull and propeller performance is estimated to reduce the efficiency of the entire world fleet by 9–12% [19]. This also comes because of the difficulty of identifying the actual contribution of fouling to the decrease in ship performance, and shipping companies have called for the establishment of a transparent and reliable standard for measuring hull and propeller performance [19]. A reliable and effective planning of these activities should take into account the speed loss caused by the fouling, to find the optimal balance between efficiency and costs. For this reason, an accurate estimation of the speed loss caused by fouling is needed [20,21]. However, providing a quantitative estimation of the speed loss associated with the fouling phenomenon is a challenging task [22,23]. The latter depends on many factors, such as the speed and the draft of the ship, the sea state, the wind speed and direction, etc. Furthermore, the accumulation of marine organisms on the hull is faster when a vessel is frequently in the harbour, stationary, or in high-temperature tropical waters [24].

The ISO standard approach for estimating the speed loss can be carried out by applying the standard ISO 19030 [25] proposed by the International Organization for Standardization (ISO). The ISO 19030 prescribes methods for measuring changes in hull and propeller performance, and it defines a set of relevant performance indicators for their maintenance, repair, and retrofit activities. Specifically, the ISO 19030 suggests comparing the measured performances with the ones obtained during sea trials in particular operating points. This comparison provides an indicator of the hull and propeller efficiency. A continuous monitoring of the efficiency provides a reliable estimation of the changes in the performances. Despite its simplicity and effectiveness, the ISO 19030 presents some limitations. The procedure requires filtering out operating points that are outside the prescribed boundaries, thus limiting the ability of the method to monitor the ship over a wide set of operating conditions [26]. Moreover, some corrections are needed to cope with the environmental disturbances (i.e. winds, waves, and currents). Unfortunately, these corrections require the use of complex fluid dynamics models or additional sea trials. Some attempts have been made to address the ISO 19030 limitations. [27] uses measurements of the propeller performance as efficiency indicators; however, this procedure requires the exclusion of many operating points to eliminate the effects of current, ship motions, rudder, and transients, with techniques similar to the ones reported in the ISO 19030 and with all their inconveniences. [28] proposes an operational approach for obtaining an accurate fuel consumption and speed curve, parametrised for the major influence factors, such as ship's draft and displacement, waves forces and directions, hull and propeller roughness. The proposed approach, similarly to the ISO 19030 procedure, relies on simplified corrections for environmental disturbances, draught, and speed. This applies also for the work proposed by [29], whose method is based on a correction of measured data based on a physical model of the influence of wind and waves on ship performance.

In this work, an evaluation of the extimation of Marine Fouling caused Speed Loss obtained by ISO 19030 is performed, by adopting a collection of data from the on-board monitoring system sensors of two Handymax chemical/product tankers. The evaluation has been carried out adopting two different techniques. Firstly, the drift of the Speed Loss estimated by the ISO 19030 is computed adopting a robust linear regressor. Secondly, the changes in time of the distribution of the drift has been studied adopting Kolmogorov-Smirnov test. These tests have been considered since a good estimation of the speed loss should follow a linear trend in time, which suddenly changes as soon as a major hull and propeller cleaning is performed to reduce the fouling effect of performaces. Results will show that the ISO 19030 is incapable of underlining this trend in time, thus being a limited approach for the speed loss estimation due to fouling.

MAIN CHARACTERISTICS OF THE VESSELS

This section presents the two Handymax chemical/product tankers exploited, their data logging systems, and the available data adopted in the paper for comparing the proposed method and the ISO 19030, as far as the estimate of the speed loss caused by the marine fouling is concerned. In this paper, operational data available from two Handymax chemical/product tankers are used, respectively referred as Vessel 1 (V1) and Vessel 2 (V2). A conceptual representation of the propulsion system of the two vessels is shown in Figure 1, while their main features are presented in Table 1.

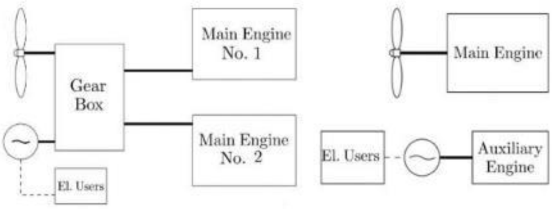

Figure 1: *Conceptual representation of the propulsion systems of V1(left) and V2 (right).*

V1 is equipped with two main engines (MaK 8M32C four-stroke Diesel engines) and designed for operation at 600 rpm. The engines are connected to a gearbox that distributes the power between the controllable pitch propeller for propulsion and a shaft generator. Auxiliary power can also be generated by two auxiliary engines rated 682 kW each. V2 is equipped with one main engine (MAN B & W 6S50MC slow speed, two-stroke engine) and designed for operation at 120 rpm. In this case, the auxiliary power is generated by three Diesel-generators rated 1176 kW each.

Table 1. Main features of V1 and V2 case studies.

Ship Feature	V1	
	Value	Unit
Deadweight	46764	[t]
Design speed	15	[knots]
Draft (summer SW)	12.18	[m]
Length between perpendicular	176.75	[m]
Breadth moulded	32.18	[m]
Main engines installed power	3840×2	[kW]
Shaft generator power	3200	[kW]
Fuel consumption	34.7	[mt/day]
	V2	
	Value	Unit
Deadweight	46067	[t]
Design speed	15.5	[knots]
Draft (summer SW)	12.2	[m]
Length between perpendicular	176.83	[m]
Breadth moulded	32.20	[m]
Main engines installed power	8200	[kW]
Fuel consumption	31.8	[mt/day]

For both V1 and V2, each main engine is equipped with an exhaust gas boiler, which can be integrated with two auxiliary oil-fired boilers. The two vessels are equipped with the same data logging system, used by the company for both on board monitoring and land-based performance control. Table 2 summarises the available measurements from the continuous monitoring system. The original frequency of data acquisition by the monitoring system is equal to 1 point every 15 seconds. In order to provide easier data handling, the raw data are sent to the provider server, where they are processed to collect a set of 15 minutes averages.

Table 2. Data collected from logging system of the two vessels.

Variable name	Unit
Timestamp	[t]
Latitude	[°]
Longitude	[°]
Main engines fuel consumption Auxiliary	[kg/h]
engines power output	[kg/h]
Shaft generator power	[kg/h]
Propeller shaft power	[kW]
Propeller speed	[rpm]
Ship draft (fore)	[m]
Ship draft (aft)	[m]
Draft port	[m]
Draft starboard	[m]
Relative wind speed	[m/s]
Relative wind direction	[°]
GPS heading	[°]
Speed over ground	[knots]
Speed through water	[knots]
Sea depth	[m]
Seawater temperature	[°C]
CPP set point	[°]
Fuel density	[kg/m³]
Fuel temperature	[°C]
Ambient pressure	[bar]
Shaft torque	[kNm]
Rudder angle	[°]
Acceleration x-direction	[m/s²]
Acceleration y-direction	[m/s2]
Acceleration z-direction	[m/s²]
Roll	[°]
Pitch	[°]
Yaw	[°]

In this paper, the latter dataset was used for the application of the proposed method. The available data of the two vessels have been collected in the time slots for V1, between the 21/03/2012 17:45:00 and the 03/10/2014 14:15:00, and for V2 between 01/05/2014 00:15:00 and 26/08/2016 14:15:00. Note that the data are characterized by many missing points due to failure in the data logging system, or maintenance, or stops of the vessels. The two ships mainly operate according to a variable schedule, as far as both the time spent at sea and ports visited are concerned. According to the market requirements, they operate over a wide range of routes (different operational and environmental conditions), thus making it hard to detect a small variation in ship performances. Thus, the two datasets can be considered good candidates for the validation of the ISO 19030, being the collected data strongly affected by changes in operational and weather conditions.

At last, Table 3 reports the recorded relevant maintenance events of the two vessels.

Table 3. Maintenance events for V1 and V2

V1	
Date	Event
21/03/2012	Vessel delivery
29/10/2012	Propeller cleaning
30/03/2013	Hull cleaning
01/08/2013	Loss of the LOG speed measurement
17/07/2014	Change from fixed-speed to variable-speed operations
V2	
Date	Event
19/04/2014	Propeller polishing
20/12/2014	Hull cleaning
28/08/2015	Hull cleaning and Propeller polishing
28/11/2015	Dry-docking

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ISO 19030 PROCEDURE

In order to check the effectiveness of the proposed method, the procedure suggested by the ISO 19030 was implemented for monitoring hull and propeller performance [25]. In this section, the application procedure proposed by the ISO 19030 is presented from an operating point of view. More details are available in the reference documents [26]

The application of the ISO 19030 procedure, given the information collected from the data logging system as reported in Table 2, can be summarized in the following steps:

1. Data filtering
2. Correction for environmental factors
3. Calculation of Performance Values (PVs)
4. Calculation of Performance Indicators (PIs)

Step 1 is performed by applying the Chauvenet's criterion [30] to all measured variables, according to which a datum is to be considered an outlier if:

$$erfc\left(\frac{\Delta_i}{\sigma\sqrt{2}}\right)N < 0.5$$

where erfc is the complementary error function [31], Δ_i represents the difference between the i-th datum and the mean value over the dataset, σ is the standard deviation of the variable of interest, and N the size of the dataset. In addition, further filtering was applied considering outliers also points for which:

$$v_v < 8\,[knots],$$
$$|v_w| > 8\left[\frac{m}{s}\right]$$

where v_v and v_w are the speed of vessel and wind respectively. The additional filtering on the ship speed was added in order to avoid numerical errors in the evaluation of the speed loss for low values in the denominator of v_v, while the filter on the wind speed was added to filter out points with bad weather conditions, since the behaviour of the vessel in those conditions is strongly inconstant and unreliable.

Step 2 included the power correction Δ_P based on measurements of wind speed and direction:

$$\Delta_P = \frac{(R_{rw} - R_{0w})v_v^2}{\eta_{0p}} + P_p\left(1 - \frac{\eta_p}{\eta_{0p}}\right)$$

where R_w represents the ship's wind resistance due to relative wind, R_{0w} is the air resistance in no-wind conditions, P_p is the propulsive power, η_p is the actual propulsive efficiency, and η_{0p} is the propulsive efficiency in calm condition. The ship wind resistance R_{rw} is computed as follows:

$$R_{rw} = 1/2\,\rho_a v_w^2 A_{tp} C_w(\psi_w)$$

where ρ_a is the air density, A_{tp} is the transverse projected area, C_w is the wind resistance coefficient, and ψ_w is the wind relative direction. This equation is used for calculating both the actual and the reference wind resistance using the relative wind speed and the relative wind direction in the first case and the ship speed and head wind direction in the second case. The wind resistance coefficient is computed based on [33].

Step 3 involves the calculation of the percentage speed loss based on the corrected propulsion power. The expected speed v_{exp} is computed based on reference, clean-hull data interpolated starting from actual measurements of draft (T) and trim (δ):

$$v_{exp} = f\left(P_p', T, \delta\right)$$

where P_p' is the corrected power for accounting the effect of the draft and trim. This allows to compute the percentage speed loss $SL_{\%}$ as:

$$SL_{\%} = 100\frac{v_m - v_{exp}}{v_{exp}}$$

where v_m is the measured speed.

The speed loss is then used as performance value for the calculation of the different performance indicator in Step 4. The ISO procedure suggests comparing the average value of the speed loss over a given period of time in order to average out uncertainties and statistically not-relevant fluctuations.

ISO 19030 EVALUATION

In this section, the available data described in Section 2 are exploited to make a detailed evaluation of the results obtained through the state-of-art ISO 19030 procedure. In particular, the properties of the speed losses estimated with the two models for both V1 and V2 are compared. As results will show, the ISO 19030 does not allow the identification of clear drift in the performance of the vessel.

Test 1: Drift Estimation

During the first test, the drift in the behaviour of the $SL_{\%}(t)$ between two propeller and/or hull cleaning events was studied, by finding the best linear regressor for the speed loss percentage. Note that the time series computed from the data is characterized by uncertainties and irrelevant statistically fluctuations. For this reason, instead of applying a simple RLS, the robust regression developed in [34] has been used.

The idea of the robust regression applied to this case is quite simple. Firstly the regressor function had to be defined, in this case, a linear regressor in time $g(t) = a\,t + b$ with $a, b \in \mathbb{R}$. Then instead of minimizing the mean square error, the following costs have been minimized.

$$a^*,b^* = \arg\min_{a,b\in R} \sum_{t\in\{t_1,t_2,\cdots\}} \max[\min[a\,t + b - SL_{\%}(t),\hat{\epsilon}],\check{\epsilon}]$$

where $\hat{\epsilon}$ and ϵ are hyperparameters that needs to be tuned. Note that, basically, robust regression exploits a loss function which does not take into account too small or too large errors. Unfortunately, this loss is nonconvex and in [34] a method for facing this issue is proposed. The robust regression allows obtaining results which are not affected by the high number of outliers observed in the time series.

In the following, the analysis of the drift of ISO 19030 estimated percentage speed loss between two consecutive hull and propeller cleaning events is reported in Figure 2 for V1 and V2 respectively.

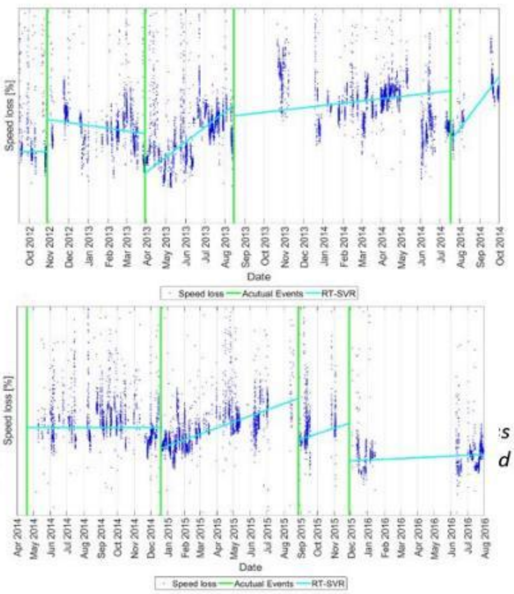

Figure 2. Linear Robust Regression on the Speed Loss Percentages between two consecutive Hull and Propeller Cleaning Events for V1 (up) and V2 (down).

Those results clearly show a poor level of reliability of the prediction achieved by the ISO 19030 model. In both vessels, the linear trend for the speed loss calculated by the ISO 19030 method shows large variations between different maintenance intervals (mainly for V1, but also for V2). Besides, in some intervals between two consecutive hull and propeller cleaning operations, the trend in the estimated percentage speed loss using the ISO 19030 method is negative. These results do not agree with the physical basis of the fouling phenomenon and suggest that, in the case presented in this paper, the application of the ISO can lead to inaccurate results.

Test 2: Changes in Time

In the second test, the automatic identification of changes in time of the distribution of the percentage speed loss was tried, in order to check if those changes were in correspondence to maintenance activities, and testify the quality of the estimated speed loss. For this purpose Kolmogorov–Smirnov test [35] has been adopted. This nonparametric statistical test can be exploited to check if two different data samples of data are derived from the same probability distribution. The Null Hypothesis is that the two samples belong to the same distribution. Then the test tries to quantify the distance between the distributions of the two samples and, if the distance is greater than a specific threshold, the hypothesis is rejected. The distance between the two samples $S^A = SL_{\%}(t-\Delta), \cdots, SL_{\%}(t)$ and $s^B = \{ SL_{\%}(t), \cdots, SL_{\%}(t+\Delta)$, is computed exploiting the empirical cumulative probability distribution $F^j(x)$ of the two different samples, with $j \in \{A, B\}$ which is defined as:

$$F_j(x) = \frac{1}{n}\sum_{i=1}^{n} I_{S_i^j \leq x}$$

where $I_{[-\infty,x]}(S_i^j)$ is the indicator function, equal to 1 if $s_i^j \leq x$ and equal to 0 otherwise. The distance D between $F^A(x)$ and $F^B(x)$ is computed adopting the following metric:

$$D = \sup_{\infty<x<+\infty} \left| F^{A(x)} - F^{B(x)} \right|$$

For the analysis carried out in this paper, the maximum D value tolerable to refuse the hypotheses was set at 95%. The test was applied by comparing subsequent non-overlapping time windows of 30 days, in order to detect a broad variation in the series. It is worth noting that if the test is rejected, then a major change in the distribution of the error has occurred, thus indicating that the state of the vessel has abruptly changed.

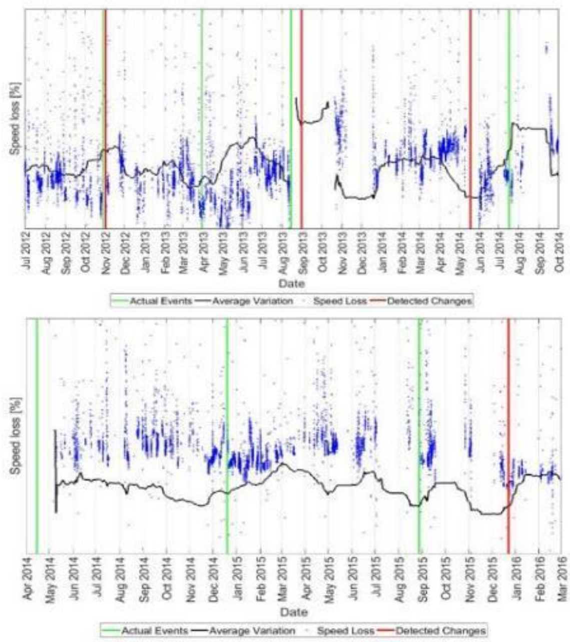

Figure 3. Changes in time of the distribution of the percentage of speed loss estimated with the ISO 19030 *for the V1 (up) and V2 (down).*

In the following, the analysis of the changes in time of the ISO 19030 estimated percentage speed loss distributions is reported in Figure 3, for V1 and V2 respectively.

Those figures testify the poor level of reliability of the ISO 19030 one. In both vessels, there are no statistically meaningful changes in the distribution of the speed losses estimated, and just in a few cases, the Kolmogorov-Smirnov test detects a change in correspondence to an actual hull and propeller cleaning event (see Table 3).

5. CONCLUSIONS

In this work the problem of estimating the speed loss caused by the effect of fouling on the ship hull and propeller is investigated.

Since marine fouling is a phenomenon that strongly affects a ship's regarding powering performance and its effects can be observed after just a few months of operations, the possibility of correctly estimate its impacts can improve the ability of the ship operators to effectively schedule the dry-docking for cleaning the hull and the propeller. For this purpose, the ISO standard method, namely the ISO 19030 standard, using real-world data coming from two Handymax chemical/product tankers has been evaluated adopting several tests in order to assess its capabilities.

Results clearly show that the speed loss calculated by the ISO 19030 does not follow a linear trend in time, and does not suddenly changes as soon as a major hull and propeller cleaning is performed. Thus, this estimation of the vessel speed loss does not provide an accurate picture of the status of the hull and propeller fouling at a specific point in time, due to the poor effectiveness, accuracy and reliability of the ISO 19030. This is shown by both an inaccurate prediction of the loss of performance over time, between cleaning intervals, and by the poor ability of automatically detecting maintenance events tested with the proposed methods, namely robust linear regression and Kolmogorov–Smirnov test.

Given these premises, the ISO standard related to the estimation of marine fouling happens to require an integration with a more precise methodology. This work has been built to assess existing and recommended industry methods for evaluating ship fuel consumption due to fouling. The need for an efficient calculation method for the effect of fouling on ship performance has been highlighted by many actors in shipping, both for economical and for environmental reasons. Given these premises, it appears clear that a modification in the standard is required to determine the effective intervals between maintenance actions, for propeller and hull cleaning, and to estimate ship efficiency. In the future, the authors propose to develop a new method for speed loss due to fouling prediction, able to improve the ISO 19030 standard.

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Overview of Waste Heat Recovery Technologies for Maritime Applications

ABSTRACT

Only 50% of the total energy supplied by the fuels onboard ships is turned into useful power, either for propulsion or electricity generation, the rest of it is lost to the environment as waste heat. To improve the energy efficiency onboard ships to meet IMO's ambitious strategy of reducing 50% of greenhouse gas emissions by 2050, waste heat recovery technologies have been proposed as part of the solution to be installed onboard ships. The Organic Rankine Cycle (ORC) in particular, has been described by several studies as most promising thermodynamic cycle to be able to recover waste heat in the low to medium temperature range from the ship's diesel engines.

This paper will provide an overview of the key waste heat recovery technologies already available in the market as well as those under research and development. Examples of actual maritime applications will be highlighted to give a sense of technology maturity and economics.

1. INTRODUCTION

Increasing decarbonisation and environmental awareness in the maritime industry is changing the energy systems onboard ships. International Maritime Organisation (IMO) is taking steps as the global regulator to implement measures to control Greenhouse Gases (GHG) and other noxious emissions from the marine industry. In an ambitious move, IMO adopted an initial strategy on 13 April 2018 to cut shipping's total greenhouse gases (GHG) by at least 50% from 2008 levels by 2050.

While there is an increased interest in the use of cleaner Liquefied Natural Gas (LNG) due to impending cap of 0.5% sulphur on marine fuels, this is expected to contribute to a reduction of only 20% in GHG emissions from ships (ignoring methane slip). Hence, other measures like energy efficiency will need to be considered holistically to meet the stringent target set by IMO. In this respect, IMO implemented the Energy Efficiency Design Index (EEDI) under MARPOL Annex VI that would encourage shipowners to adopt energy efficient systems onboard their ships.

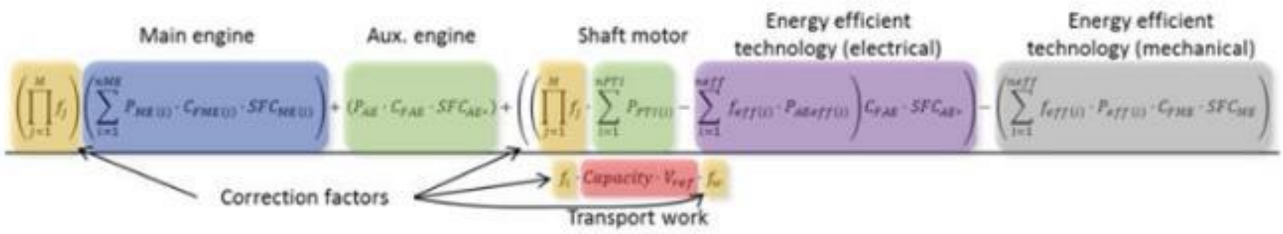

Figure 1 Key components of IMO Energy Efficiency Design Index

Figure 1 shows the main components for EEDI calculation for a ship that measures the environmental cost in terms of grams of CO2 divided by the transport work in ton-miles and take into account the amount of carbon dioxide generated by the diesel engines for propulsion and power generation. A technical file will need to be prepared for each ship detailing the EEDI calculations and it is to be shown that the calculated EEDI is less than the reference EEDI mandated by IMO for each ship type. IMO has also dictated that the reference EEDI be lowered gradually to challenge the industry to provide even more energy efficient designs.

The use of fuel-efficient diesel engines will have a direct impact on lowering the EEDI but the regulation also allows the use of energy efficient technologies like wind propulsion, air lubrication, solar panels and waste heat recovery that help to reduce EEDI with the last two terms in the numerator of1. Figure Of particular interest, waste heat recovery entails reusing thermal energy from exhaust gases of existing diesel engines onboard ships.

It is the objective of this paper to provide an overview of the available waste heat recovery technologies that can be used in maritime applications to reduce its EEDI to achieve the final target of lowering GHG emissions.

2. OVERVIEW OF WASTE HEAT RECOVERY TECHNOLOGIES

Since the first oil crisis in 1973, the efficiency of diesel engines had improved over the years and the fuel efficiency of diesel engines today has reach about 50%. This mean that the other 50% of the fuel's energy is lost as waste heat mainly in the engine exhaust as shown in Figure 2. As it becomes increasing difficult to further improve the fuel efficiency of diesel engines, finding ways to exploit the energy in the waste heat stream becomes extremely important.

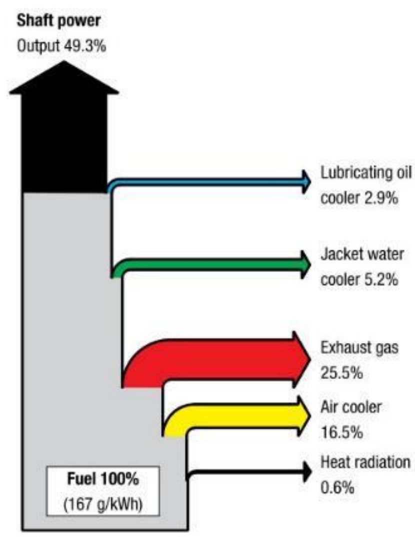

Figure 2 Heat balance diagram for a mAN B&W engine (MAN Diesel & Turbo, 2014)

Currently, it is a common design to recover waste heat energy from diesel engines using a composite boiler to generate steam to provide heat tracing in Heavy Fuel Oil (HFO) tanks and other steam consumers. Other than this application of reusing waste as thermal energy, the interest in converting to other forms of energy like electrical power is only starting to gain traction.

The following sections will describe the various technologies to recover electrical power from waste heat, first those that are already commercially available and those are in the research and development stage.

2.1 Commercially Available Marine Waste Heat Recovery Technologies

2.1.1 Gas Turbine Systems

The waste thermal energy from the engine exhaust gas can be recovered by a gas turbine into kinetic energy. If the kinetic energy is used to power a compressor for the intake air, it is called a turbocharger. Instead if the kinetic energy is used to generate electrical energy by connecting to an alternator, it is called a power turbine generator (PTG). When a separate power turbine is used in addition to a turbocharger, this is known as turbo-compounding.

PTG can be installed in parallel or in series to the turbine of the turbocharger to recover the waste heat energy from the exhaust gas. **Error! Reference source not found.** depicts a PTG offered by an engine maker and shows the two connections on the exhaust gas receiver: one for PTG and the other for exhaust gas bypass with a control valve and orifice.

The PTG consist of a power turbine connected on a common bedplate to the generator that produces electrical power to the main electrical switchboard. The PTG solution could recover about 3-5% of the engine's rated power from the exhaust gas stream.

MAN Diesel and Turbo and ABB are makers who have sold their PTG solutions so far: Reederei Horst Zeppenfeld, owner of four 4700 TEU container vessels had ordered from MAN in 2011 for €4 million; CIMC and MSC had also ordered for their fourteen 8800TEU container vessels from ABB to a total value of $23 million.

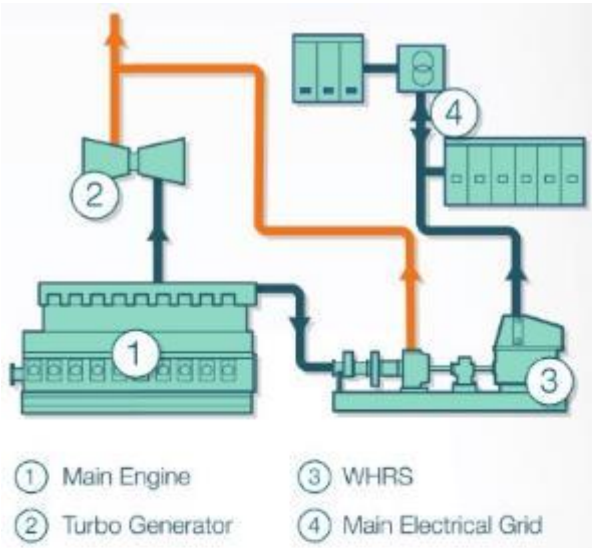

Figure 3 Layout of a Power Turbine Generator (PTG) System (Source: ABB)

2.1.2 Rankine Cycle (RC)

The Rankine Cycle is a classical thermodynamic cycle which converts thermal energy into mechanical work and consists of components like the boiler, turbine, condenser and feed pump. The Temperature-Entropy (T-S) diagram of RC is shown in Figure 4 To recap the various processes of RC: expansion (1 to 2), condensation (2 to

3), pumping (3 to 4) and evaporation (4 to 1).

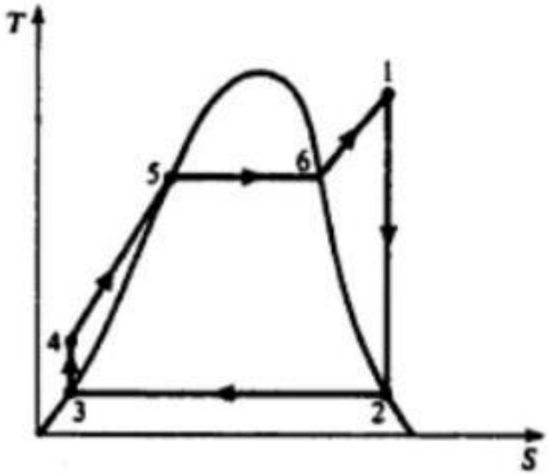

Figure 4 Temperature-entropy diagram for Rankine Cycle

In RC, the choice of working fluid is not fixed and if water has been used as working fluid, it would be known as the Steam Rankine Cycle (SRC) and if other organic fluids had been used, the cycle will be classified as Organic Rankine Cycle (ORC). Both cycles will be described in the following sections.

2.1.3 Steam Rankine Cycle (SRC)

Steam Rankine Cycle had been used in the maritime industry for over a century since the launch of SS Turbinia in 1894. Steam turbine plant had been used for main propulsion and auxiliary power generation widely onboard ships before being replaced by the diesel engines.

When SRC is used for waste heat recovery onboard ships, the waste heat from the turbocharger heats up a boiler which produces steam to drive a turbine coupled with alternator, known as the Steam Turbine Generator (STG). An example of single stage STG layout and example of STG is shown in Figure 5. For higher efficiency, a dual pressure stage SRC can be arranged. Up to 5-8% of the engine rated power can be recovered as electricity with STG depending on main engine size, rating and ambient conditions.

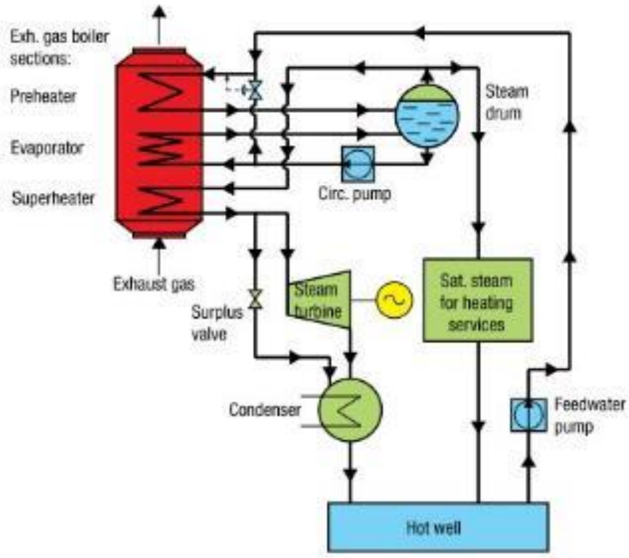

Figure 5 Schematic of Steam Rankine Cycle for Waste Heat Recovery (Source: MAN Diesel & Turbo)

2.1.4 Combined PTG-STG Systems

When the electrical power consumption onboard a ship is very high e.g. a container ship, the PTG and STG can be used in a combined cycle to extract energy from waste heat. Both STG and PTG can be integrated onto a common base skid. The schematic of such a combined system is shown in Figure 6. Using such a system could recover 8-11% of the engine power based on engine size, ratings and ambient conditions.

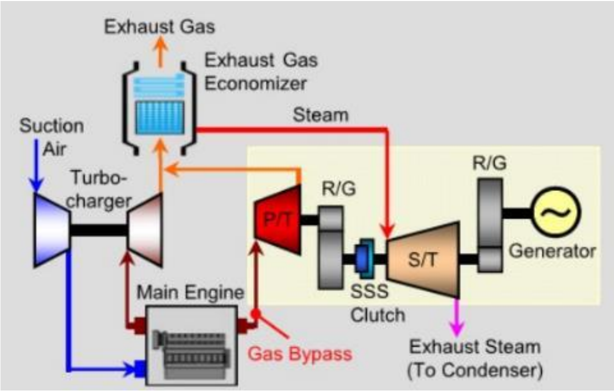

Figure 6 Schematics of a combined PTG-STG Waste Heat Recovery Plant (Source: MHI-MME)

The PTG-STG waste heat recovery system have received very good response from the maritime industry in terms of actual installations. As of end of 2016, Mitsubishi Heavy Industries (2016) reported that there are 108 units of combined PTG-STG units order mainly for the container vessels with generator output from 1700 kW to 7000kW. A list of these projects is given in Table 1. The shipowners who have ordered such system include Maersk, UASC and MOL. Maersk Line, in particular, made a commitment to install waste heat recovery system on all their new ships and till date 78 of their vessels had been fitted which cost them about $10 million on each of their Triple-E container ships.

Table 11 List of ships with PTG-STG installed onboard (Mitsubishi Heavy Industries, 2016)

Kind of Ship	Capacity	Main Engine Type	Contract	Delivered	Gen. Output
Container	8,500 TEU	Wartsila 12RT-flex96C	12	12	6,000 kW
Container	4,500 TEU	MAN B&W 6S80ME-C9	22	22	3,100 kW
Container	7,450 TEU	MAN B&W 9S90ME-C Mk8	16	16	3,700 kW
Container	13,000TEU	MAN B&W 12K98ME-7	9	9	7,000 kW
Container	18,000 TEU	MAN B&W 8S80ME-C9.2(x 2skegs)	20	20	6,000 kW
Ore Carrier	250,000 DWT	MAN B&W 7S80MC-C Mk7	1	1	1,700 kW
Container	15,000 TEU	MAN B&W 9S90ME-C10.2	11	11	2,700 kW
Container	18,800 TEU	MAN B&W 10S90ME-C10.2	6	6	3,000 kW
Container	19,630 TEU	MAN B&W 7G80ME-C9.5(x 2skegs)	11	0	4,600 kW
Total			108	97	

2.1.5 Gap in Existing Waste Heat Recovery System Technology

Virtasalo and Vänskä (2012) estimated that existing waste heat recovery systems will be economical to be installed on vessels especially container ships with installed power above 20MW which are usually fulfilled by large two stroke engines.

MAN Diesel & Turbo (2014) also recommended a rule of thumb:

Combined PTG-STG for main engine power greater than 25MW; PTG or STG with superheat for main engine power less than 25MW; and PTG or Organic Rankine Cycle for main engine power less than 15MW.

The operation of the PTG and STG is also limited by the engine load, for example, the waste heat recovery system will operate only above 40% engine load. This is fine for most cargo vessels when the operation profile is such that it is steaming at high engine loads for most part of the voyage.

The main heat source being explored is mainly the high temperature engine exhaust but other lower temperature heat sources from the engine like the cooling water and lubricating oil has not be fully utilised.

Hence, it is worthwhile to explore other waste heat recovery technologies that can be more suitable for lower power and temperature ranges in the next section.

2.2 Developmental Waste Heat Recovery Technologies

In this section, the main waste heat recovery technologies under intense research and development will be presented with increasing levels of technology readiness.

2.2.1 Thermo-Electric Generation(TEG) System

The Thermo-Electric Generation system relies on the Seeback effect where a voltage difference is produced due to a temperature difference between a pair of dissimilar conductors or semi-conductors in contact with each other. As a result, thermal energy is converted directly to electrical energy.

As seen in Figure 7, the hot and cold fluids can be the exhaust gas and cooling seawater streams respectively. Due to this temperature gradient, a voltage is produced by the electron charge carrier from the hot to the cold junction. The magnitude of the thermoelectric voltage depends on a few factors namely, the temperature difference, properties of the semi-conductor material, and the external load resistance.

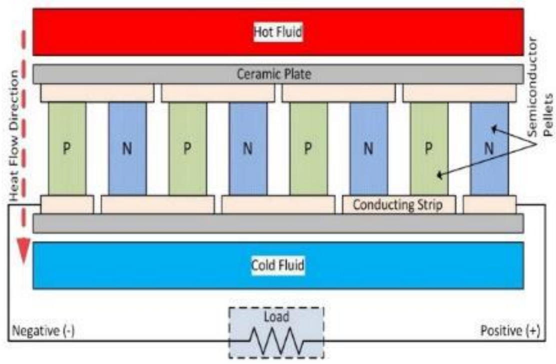

Figure 7 Simple layout of Thermo-Electric System

Based on recent research, the efficiency of TEG ranges from 5-10%. The main advantage is that it has no moving parts and hence require little maintenance. It is modular and hence scalable to meet the required power.

Except for ECOMARINE research project, there is no known installation of TEG onboard a ship. Hence, this technology is still in early stage of development and may need to be combined with other recovery technologies since the efficiency is low.

2.2.2 Kalina Cycle (KC)

The layout of the KC plant is quite similar with RC plant with a few additional components. A simple KC plant as shown in Figure 8 will have a recuperator, separator, mixers and flow control valves in addition to the standard RC plant to offer the possibility to control and vary the ammonia mass fraction. The variation in ammonia mass fraction allows the evaporation and condensation temperatures to be changed.

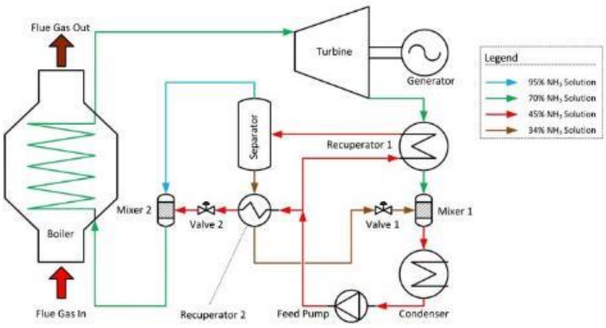

Figure 8 Schematic of simple Kalina cycle plant (Singh and Pedersen, 2016)

The main idea of KC in using the ammonia and water mixture as the working fluid operating is that it allows non-isothermal evaporation and condensation (non-constant temperature) when pressures are held constant. This leads to better efficiency by having a better match with the heat source and sink temperatures as seen in Figure 9 below accomplished by changing the ammonia mass fraction.

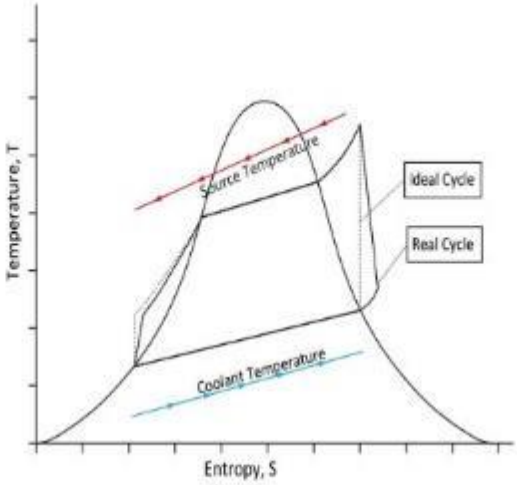

Figure 9 Temperature -Entropy Diagram for Kalina Cycle showing non-isothermal evaporation and condensation (Singh and Pedersen, 2016)

Research literature is optimistic about the use of KC plant as it offers higher efficiencies and could provide 40-50% more power than single pressure RC and 20-24% more power than dual pressure steam system. When compared to Organic Rankine Cycle, it has a performance advantage of about 20-25%.

The main issue preventing quick development is that KC system uses several non-standard components like the separator and its operation is more complex compared to RC plants which the marine crew is very familiar with.

While the performance of KC had been shown in some land-based demonstration projects, actual installation onboard a ship has not been planned yet. Hence, the actual application on ships is still some time away.

2.2.3 Organice Rankine Cycke (ORC)

Coming to the final technology, the ORC is the closest among those under development that can be widely installed on ships based on technology maturity and experience with operations.

The layout of an ORC plant as shown in Figure 10 is very similar to that of an SRC with the same basic components. Instead the ORC uses an organic fluid such as a hydrocarbon or refrigerant in place of water as the working fluid in the SRC. Due to the lower boiling points and heat of vaporisation of these organic fluids, it is possible to exploit the lower temperature heat sources such as waste heat from the cooling water, lubricating oil, etc as well.

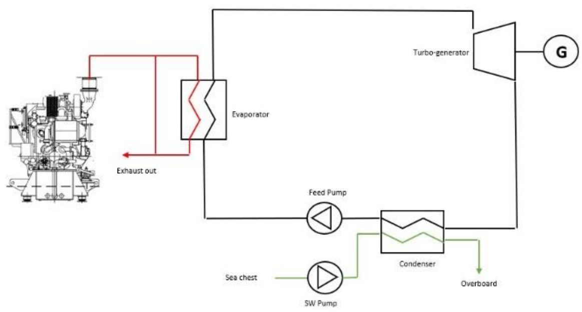

Figure 10 Schematic of an Organic Rankine Cycle Plant

One important advantage that ORC has over SRC is that due to flexibility in choosing working fluids, organic fluids that are considered "dry" or "isentropic" can be used. Dry and isentropic fluids have a positive or vertical slope at the saturated vapour line as shown in Figure 11. When compared with water that is a well. fluid with negative saturated vapour line, ORC do not require substantial superheating and will be able to enter the turbines dry and cause erosion from liquid impingement.

Hence, ORC possesses inherent advantages versus other waste heat recovery technologies due to its similarity to SRC, simplicity and ability to exploit heat from the low to moderate temperature source.

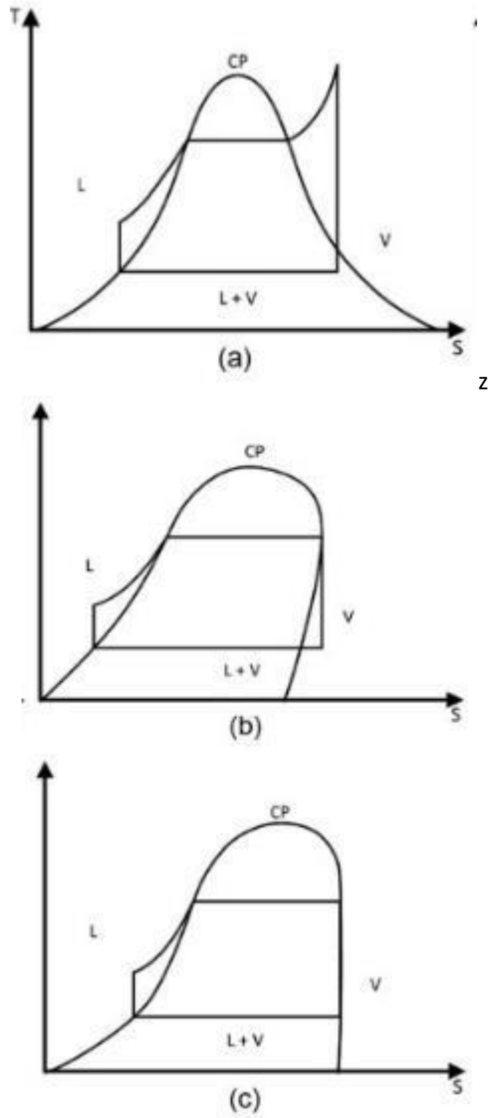

Figure 11 Fluid types: (a) Wet fluid, (b) dry fluid, (c) isentropic fluid (Singh and Pedersen, 2016)

Research base on thermodynamic analysis have generally found that ORC efficiency is between 15 to 20%, and in experiments around half of that was achieved, translating into possible fuel savings improvements of around 10%.

Due to maturity of the technology and economic benefits it could bring, there are several instances of actual installations onboard ships base on an Internet search of news reports and websites as table below:

Table 2 List of reported maritime applications of Organic Rankine Cycle plants

Ship Name (Year)	MV Figaro (2012)	Viking Grace (2015)	Arnold Maersk (2016)	Asahi Maru (2017)	Panerai I & II	Orizzonte (2017)
Vessel type	PCTC	Cruise Ferry	Container	Bulk	Fast ferry	Fishing Vessel
ORC Maker	Opcon	Climeon	Calnetix	Kobe Steel	Orcan Energy	Enogia
Capacity (kW)	500kW	150kW	125kW	125kW	154kW	200kW
Fuel savings	4-6%	Up to 5%	Up to 10-15%	3%	6-9%	unknown
Classification	Lloyd's Register	Lloyd's Register	ClassNK and Lloyd's Register	ClassNK	unknown	unknown

It can be seen from the list that most the generator output is about 150-200kW range and this will be suitable for smaller two stroke and the four stroke diesel engines with fuel savings of 5-10%.

3. CONCLUSIONS

There is a need to improve the energy efficiencies of energy systems onboard ships due to the amount of waste heat generated compared to what is converted into useful energy for propulsion or power generation by diesel engines. Waste heat recovery is a good way to exploit these waste heat that could contribute to around 10% fuel savings that would help to justify the investment costs for these systems.

Some waste heat recovery technologies like the power turbine, steam turbine generators have already been successfully implemented on commercial ships like container vessels. Other technologies have varying level of maturity and among them the Organic Rankine Cycle is the closest to widespread application.

Several ORC installations on ships have been presented with majority of the ORC makers coming from European countries. Further study on the application of the ORC for ships operating in the Southeast Asia region can be interesting to encourage more take-up by shipowners in this technology.

4. ACKNOWLEDGEMENTS

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3D Sea Surface Imaging by Means of X-Band Radar: A Powerful Tool for Oil Spill Detection and for the Prediction of Propagation

ABSTRACT

The use of X-band radar has received an increasing interest over the last few years thanks to the possibility of using it also as a Wave Radar, allowing to measure, with high accuracy and in real time, the waves and the surface current field in a radius up to 10 km. This is achieved by proactive use of the radar clutter in combination with specific mathematical algorithms enabling to measure the parameters describing the sea state, surface currents and seabed shape. A further and new application of this technology is the real time detection and tracking of oil spillages, with the added possibility of predicting the propagation of the spillage over time, providing useful information to coordinate the oil recovery / environmental protection actions. This can be achieved by using X-band radars either by coastal or sea installations, such as oil rigs or others.

INTRODUCTION

The aim of this work is to present an innovative technology, based in the use of marine radars, for the oil spillage detection and for the prediction of its propagation. X-band radars detect the echo of an electromagnetic wave signal from an obstacle or from ships (target). The signals reflected by the sea surface are usually considered background noise (or clutter) and filtered away in order to highlight the target position. Wave radars, applying mathematical algorithms to the clutter signal, can estimate parameters that can describe the sea state, surface currents field. The analysis of the X-band radar data allows, moreover, to detect the presence of oil spills on the sea surface due to the fact that they reflect, differently from the sea, the signal transmitted by the radar. The integration of information about waves, surface currents and oil slicks, allows to predict the propagation of the spill during time using suitable convective models and, therefore , providing useful information to the staff that deals with the recovery. This kind of information can be acquired both on vessels, using the on board radar, and on fixed locations (coastal or offshore platform).

WAVES AND SUPERFICIAL CURRENTS MONITORING

The core of this retrieval strategy is the use of the Normalized Scalar Product approach (Serafino et al 2010) for the surface current and bathymetry join estimation. In particular, the NSP method is founded on the maximization of the normalized scalar product between the amplitude of the radar spectrum, here denoted with $|F_I(\acute{k},\omega)|$, and the following characteristic function:

$$G(\acute{k},\omega,\acute{U},h) = \delta\left(\omega - \sqrt{gktanh(kh)} - \acute{k}\cdot\acute{U}\right)$$

which accounts for the local support of the dispersion relation. In equation (1) k ̅=(k_x,k_y) represents the wave vector (whose magnitude k=2π/λ is the wave number, λ being the wavelength), ω is the angular frequency related to the wave period T by(ω=2π/T), g represents the acceleration due to gravity, h is the bathymetry value and U ̅=(U_x,U_y) is the vector representing the sea surface current. Accordingly, the NSP estimates $\hat{U}$ of the surface currents arise from the following equation:

$$\hat{U} = \underset{\acute{U}}{argmax}\frac{\langle|F_I(\acute{k},\omega)|,G(\acute{k},\omega,\acute{U},h)\rangle}{\sqrt{P_{F_I}+P_G}}$$

where $\langle|F_I(\acute{k},\omega)|,G(\acute{k},\omega,\acute{U},h)\rangle$ denotes the scalar product between the functions $F_I(\cdot)$ and $G(\cdot)G(\cdot)$, having a power equal to $P_{F_I}P_F$ and P_G , respectively.

The knowledge of surface current is a key point in the inversion procedure in order to extract the linear components of the gravity waves from the image spectrum. In fact, an incorrect estimation of these parameters leads to an incorrect spectral filtering with a detrimental effect on the estimation of the sea state parameters in term of wave period, wavelength, wave direction of the dominant waves and significant wave height.

INSTALLATIONS AND RESULTS

The algorithms for the waves estimation and for superficial current field and bathymetry reconstruction, developed in the laboratories of the National Research Council of Italy (CNR) represent the core of the Remocean systems. Remocean company is a spin-off of the CNR that provides systems for navigation and coastal monitoring applications. In the last years Remocean installed and tested their systems on several scenarios and sites, along the coast and onboard vessels, as demonstrated on the several scientific publications listed on the references at the end of this paper. Some example of results are described in the following.

Directional Spectrum Measure

The Remocean System has been used to monitor waves and superficial current field during the removal activities of the Costa Concordia Ship Wreck after its sinking on the coast of the Giglio's Island. Figure 1 shows the scenario.

Fig. 1. *Installation site of the Remocean system indicated by the red circle.*

Fig. 2(a) depicts the directional spectrum obtained by the dataset collected on November 27, 2012 at about 12:00 am (UTC); the directional spectrum exhibits two spectral modes: the dominant one and a secondary mode associated to the sea waves reflected by the Costa Concordia wreck.

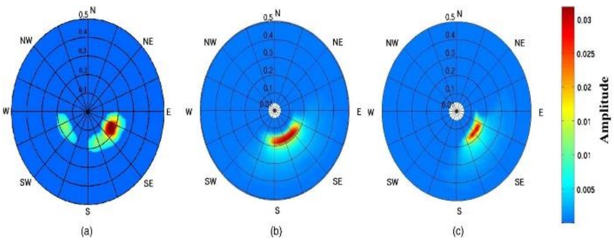

Fig. 2. *Directional spectrum obtained by Remocean system (a) and forecast model [WW3 and SWAN (b) and (c), respectively].*

The outcomes of the Remocean analysis have been compared with the ones of the provided by the WaveWatch III (WW3) and Simulating Wave Nearshore (SWAN) models and do not account the presence for the Costa Concordia wreck. Notice that phase-averaged wave models such as WW3 and SWAN are not able to represent back-scattered waves neither reflected waves.

Superficial Currents Field Measure

To verify the accuracy of the superficial current filed estimation it has been carried out the comparison between the Remocean Wave Radar System and some drifters buoys at Capo Granitola site, which is located in the south-west part of Sicily and washed by the Mediterranean Sea. This area of the Mediterranean Sea has a significant biodiversity and is affected by several complex oceanographic processes. Therefore, the information about the sea state parameters and surface currents is important: to safeguard the biodiversity; to forecast the coastal erosion; to support decisions for the crisis events related to oil spill phenomenon.

The drifters used for the experiment have a truncated-conical shape, with a maximum diameter (at the top) of 0.35 m and height of 0.27 m (see Figure 3). They are equipped with GPS satellite system.

Fig. 3 *Drifter with GPS and radio antenna equipped*

The three trajectories, see figure 4, are similar because the drifters were released in a narrow time range of about 2 hours. The minimum and maximum distances between the drifters and the radar are 1200 m and 2350 m, respectively.

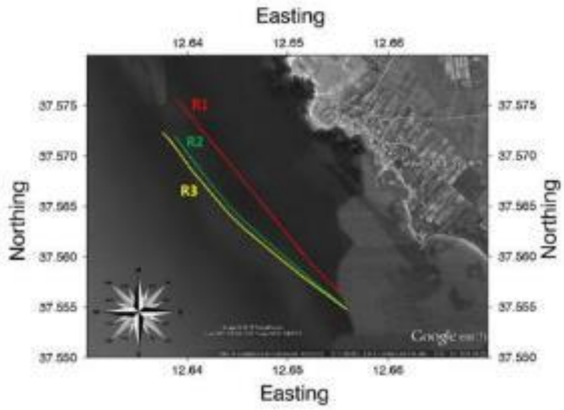

Fig. 4 *Red, green and yellow lines are the trajectories of the release R1, R2, R3, respectively. The drifters moved yet toward North-West*

Figure 5 shows a sample of radar image of the investigated area and the surface current field on a square mesh size of 225 m, estimated by the Remocean System.

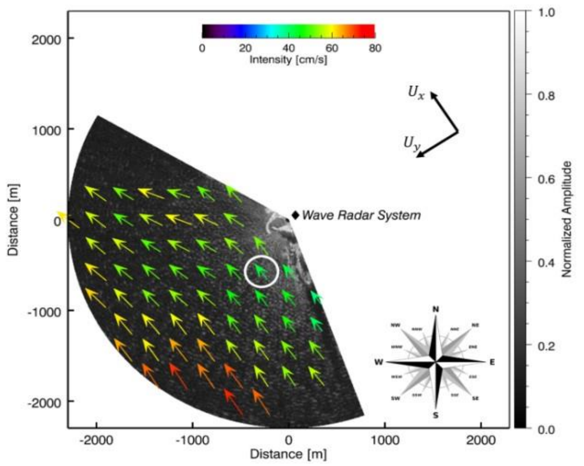

Fig. 5 *Radar image with over plotted the surface current field elaborated during the measurement campaign on May15, 2015 at 13:00.*

The comparison between the measurements has been done at a scale (mesh size equal to 225 m) where the radar estimations are reliable. The results of the comparison of the surface current velocity and direction are shown in Figures 6a and b, respectively.

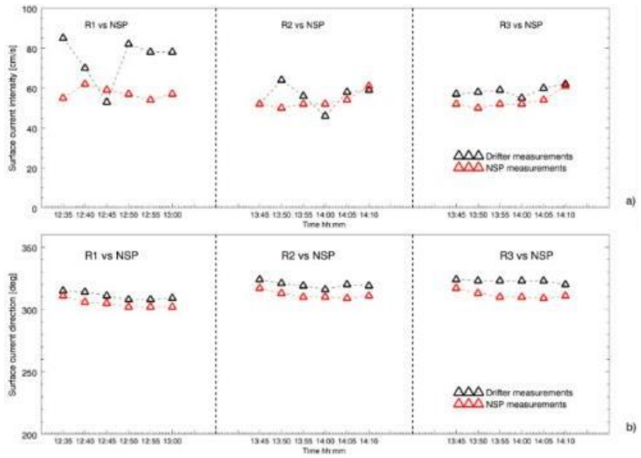

Fig. 6 *Comparison between the measurements of surface current by means wave radar (red triangle) and drifters (black triangle). Panel a) Comparison of the surface current intensity; Panel b) Comparison between surface current directions.*

Wave Elevation Reconstruction

The Remocean Coastal Monitoring System has been used to measure the reflected/refracted waves from the breakwater of the Port of Salerno (Italy). The high accuracy and resolution of the wave elevation estimation provided by the Remocean System allows, in fact, to detect and monitor the phenomena (reflection, diffraction and refraction) due to the interaction between the incident waves and the coastal infrastructures. The breakwater is characterized by two different structure, as detailed in figure 7. the data were acquired by a marine radar installed on board the Caronte & Tourist ferry ship during her call in the Salerno harbour (see Figure 2) on 27 March 2013 from 11:25 a.m. to 12:00 a.m. (UTC). It is worth noting that the whole radar acquisition campaign was carried out in about half an hour, without any interference to the normal operation of the ship, thus proving the effectiveness and the flexibility of the system.

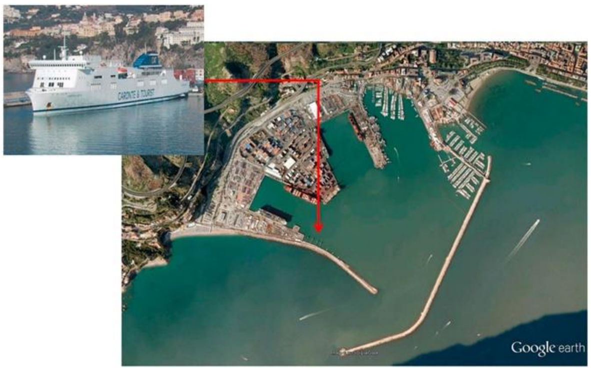

Fig. 7 *A view of Salerno Harbour and its two main jetties. The red arrow denotes the position of the acquisition system installed on the Caronte & Tourist ferry ship.*

A sample image of the collected dataset is shown in Figure 8. In this picture the dashed white lines define the angular sector considered for the reconstruction of the bathymetry and surface currents fields as well as for the retrieval of the sea state parameters, while the white squares identify the subareas (A and B) investigated for the detection of the sea waves reflected by the two jetties of the Salerno harbour.

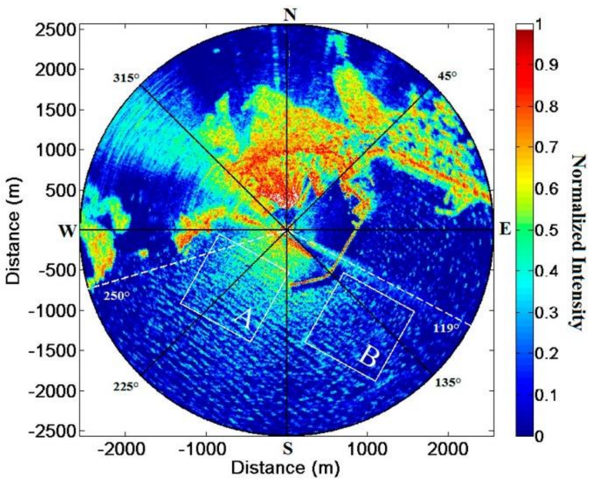

Fig. 8: *A sample image of the raw radar data set.*

Wave field simulation, see figure 9, shows a whole system of reflected waves moves away from the SE facing pier and interferes with the incoming front: an effect obviously caused by reflection. A similar effect caused by the SW facing pier is also visible—less clearly since the wave propagation is nearly perpendicular to the breakwater.

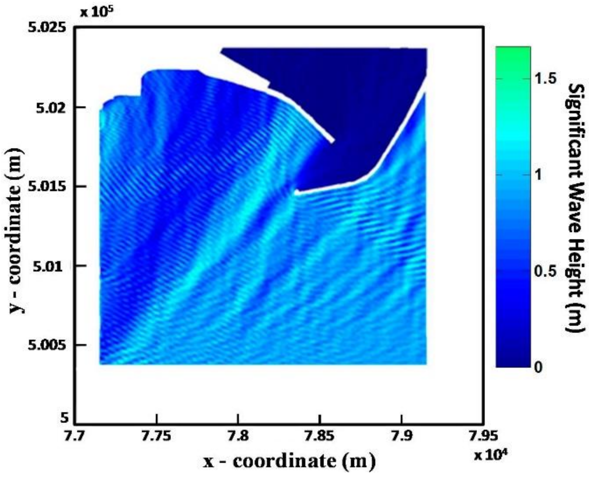

Fig. 9: *Wave field simulation of the Salerno Harbour obtained through the Mild Slope Solver.*

It was found that such effects can be detected by carefully analysing the radar results for two subareas A and B in Figure 3. In both cases two main spectral wave components are clearly visible, related to the incident and to the reflected wave train respectively. The source direction of the dominant wave retrieved by the Remocean system is θ = 214°, thus impacting almost orthogonally to the SW jetty while, according to Snell's law, the reflected wave propagates along the same direction in the opposite way (i.e., its direction of propagation 214°). Both these direct and reflect waves can be observed in Figure 10, which shows a 2D section along the *ki* direction (corresponding to 214°) of the 3D wave spectrum (panel a) and 2D directional spectrum (panel b) relevant to the subarea A.

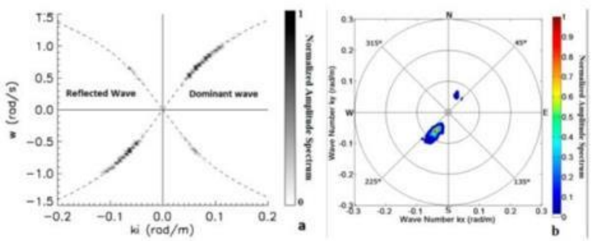

***Fig. 10** (Panel a) 2D section of the 3D wave spectrum relative to the subarea A. The dashed branches are representative of dispersion relation for the incident and reflected waves; (Panel b) 2D directional wave spectrum relative to the subarea A.*

In the picture the increasing (decreasing) dashed line depicts the dispersion relation for the incoming (reflected) wave train: the brighter signal represents the amplitude of the spectral density of the incident wave (coming from 214°), while the weaker signal accounts for the reflected wave (coming from 34°). In principle, the reflection coefficient could be evaluated by taking into account the relevant MTF and by considering the ratio between the spectral power of the incident and reflected wave system. In practise, as the mechanism of the radar detection of reflected is still not fully clarified, there are too many uncertainties so that only a rough estimate can be provided: for the SW breakwater its value is about 0.25, since the reflected wave contributes to the overall sea state with the 20% of the total power.

As for the subarea A, the dominant wave impacts on the SE jetty of Figure 3 with an incidence angle $\theta = 44°$ so that reflected wave propagates along a direction of about 126°; since the two wavefronts do not propagate along the same direction, they cannot be observed in a single $\omega - k$ cut of the 3D wave spectrum, but it is nevertheless still possible to identify the sections of the 3D wave spectrum for subarea B which contain most of the energy of the incident and reflected waves. Figure 11 and 12 show the normalized amplitude spectrum cut along direction ki (left panel), which contains most of the incident wave energy and along the direction kr (right panel), which contains the reflected wave. In this case we found again that the energy reflection coefficient is approximately 0.25, on the basis of the ration between reflected and total sea wave energy. These results are of course purely preliminary and incomplete, since the technique is at its initial stages.

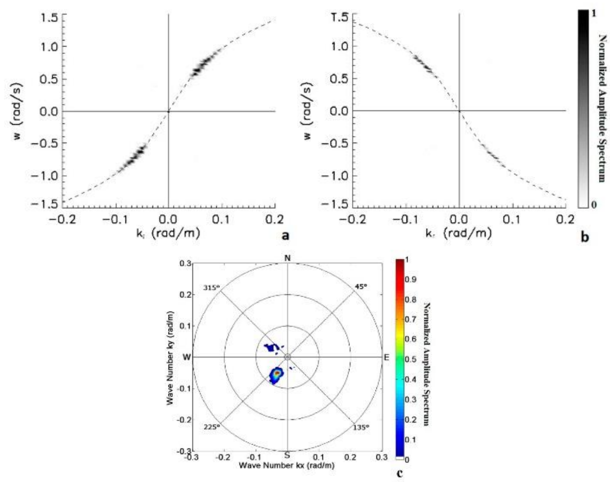

***Fig. 11 and 12** Two cuts of the 3D wave spectrum relative to the subarea B. (Panel a): spectral components representative of the incident wave; (Panel b): spectral components accounting for the reflected wave. The dashed lines represent the theoretical support of the sea waves; (Panel c) 2D directional wave spectrum relative to the subarea B.*

REAL TIME DETECTION OF OIL SPILLAGE

The Remocean System allows, moreover, to detect the presence of oil spills on the sea surface due to the fact that they reflect, differently from the sea, the signal transmitted by the radar. This is due to the fact that the presence of oil on the sea surface flattens the ripples (capillary waves) generated by the wind and that cause the radar backscattering. So the area with oil spill appears in the radar image with a reduced backscattering. The integration of information about waves, surface currents and oil slicks, allows to predict the propagation of the spill during time using suitable convective models and, therefore, providing useful information to the staff that deals with the recovery. This kind of information can be acquired both on vessels, using the on board radar, and on fixed locations (coastal or offshore platform). Figure 13 shows the Integrated User Interface where the system has detected an anomaly that has been investigated as an oil slick area. The systems has already estimated the surface current field around the oil slick and thanks to the use of specific propagation algorithms the system is able to give information about the oil slick propagation (dotted line area).

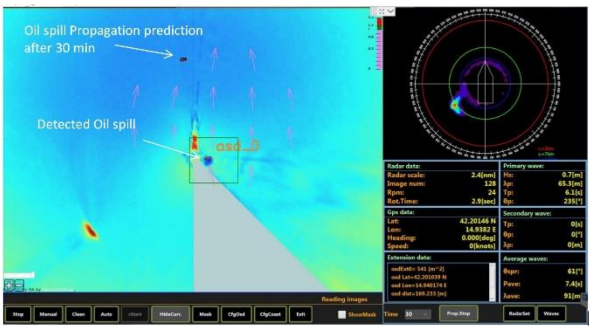

Fig. 13 *the integrated system for oil spill detection and for the prediction of its propagation in time.*

CONCLUSIONS

3D sea surface imaging by means of X-Band radar is a very powerful tool for the direct measurement and interpretation of the conditions of the sea: wave spectra, surface currents and bathymetry can be directly measured and monitored in real time, allowing for harvesting of important information for the safety and for the performance monitoring of ships while underway. Remocean, in addition to pioneering the above, has been able to apply this technique also to the real time detection of oil spillage, and for the prediction of the propagation of the oil patch.

As it has been largely demonstrated in several full scale exercises and documented in scientific publications the accuracy of the output supplied by Remocean 3D sea surface imaging is very high.

This system, as such, is extremely indicated for applications spanning from civil and military scopes as well as for both coastal monitoring and sea monitoring around fixed and mobile installations.

In particular, for ships, the integration of the wave and currents monitoring with propulsion performance monitoring systems is able to greatly increase the accuracy and reliability of the data, removing the biggest uncertainties that currently plague these kind of analysis, and enabling a much deeper insight on the actual propulsion performance and efficiency of the vessel.

In respect to oil spillage the capability of early detection and propagation forecast provides a very innovative and powerful instrument timely to detect the spillage and to support the activities for oil recovery and removal.

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AUTHORS' BIOGRAPHY

Dr. Francesco Serafino spent more than 10 years on Synthetic Aperture Radar (SAR) data processing, Differential SAR Interferometry and Differential SAR Tomography. At the moment his main scientific interest is in the extraction of hydrodynamic parameters from marine radar images sequences, comprising surface current, bathymetry map generation and space-time wave height reconstruction. In September 2010 he founded EMOCEAN S.P.A, a spin-off of the Italian National Centre of Research, CNR, which in 2013 and 2014 was considered among the top 10 Italian startups.

Dr. Giulio Gennaro is a Mechanical Engineer with more than 20 years of very diversified experience: Class Surveyor, Failure Investigator, Engineering Consultant, Technical Director. He is an expert in ship propulsion, asset integrity and in all related to failure investigations of machinery and mechanical components. Lately he has been working on solutions for Shipping 4.0.

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Advanced Predictive / Prescriptive Maintenance System: A Fundamental Tool to Improve Maintenance in Shipping, Increasing Safety and Effectiveness and Reducing Costs

ABSTRACT

As of today Planned Maintenance is by far the most common type of maintenance in shipping, however it has many drawbacks, in particular it doesn't guarantees timely intervention while, at the same time, it generates maintenance jobs that could be postponed or avoided altogether, therefore creating unnecessary scheduled downtime and increased used of resources (spare parts, man hours, ancillary costs...).

Other industries have already move to more effective maintenance practices such as condition based maintenance, predictive maintenance, reliability centred maintenance, prescriptive maintenance… while shipping lags behind.

The application of prescriptive maintenance system to ship level, best if integrated in Remote / On Shore / Virtual Fleet Control Room is the way forward to more effective and cost effective ship management and to safer operation, even more so when considering autonomous or unmanned vessels.

In the present paper the advantages of moving to these more advance maintenance practices will be discussed and an Advanced Predictive / Prescriptive Maintenance System, developed specifically for the shipping industry, will be described.

INTRODUCTION

Maintenance techniques have evolved over time, from simple run to failure maintenance, where a component is run until it fails, and it is substituted, to planned maintenance, where maintenance is scheduled to prevent failure, to predictive maintenance, where the status of the different components and equipment is kept under control in order effectively to schedule and to perform maintenance, to reliability centred maintenance, where a more holistic approach is used in order to perform maintenance with a deeper and wider systemic approach including risk management, to prescriptive maintenance, which aims at diagnosing root causes and then to indicate specific and timely corrective actions.

In particular predictive maintenance, reliability centred maintenance, and prescriptive maintenance represent a subsequent evolution aimed at reducing or eliminating unplanned downtime, maximizing reliability and availability, ensuring compliance of the processes to the required safety and quality standard, and maximizing profitability.

As such, advanced maintenance techniques are a cornerstone of Industry 4.0 and are enjoying an ever wider application onshore, also thanks to the fact that cost of sensors has lowered and that information technology has lead to development of additional techniques and technology such as Internet of Things and Artificial Intelligence that have positive repercussions on maintenance.

Despite the above shipping, in general, is still anchored to planned maintenance, and in some cases to run to failure. As a result, shipping is losing out not only in terms of reliability, availability and safety, but also in profitability.

APMS

APMS, Advanced Predictive Maintenance System, is an hardware & software-based technology fruit of the partnership between AMS, an Engineering Company based in Montecarlo, and Rockwell Automation Inc., one of the most important automation company worldwide.

APMS is an automated Prescriptive and Predictive maintenance system driven by augmented intelligence and populated by customer-based algorithms that process and correlate Condition data with Operation data.

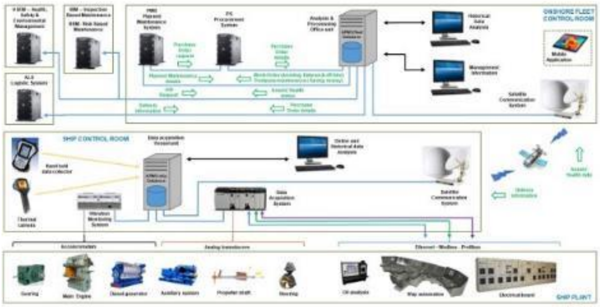

Figure 1. *System Architecture*

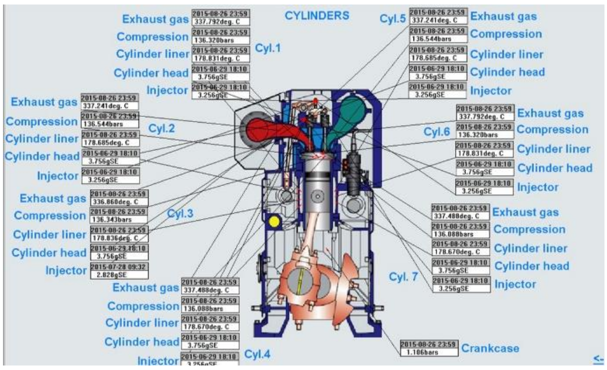

Figure 2. *Cylinder head Operation data*

APMS is designed to monitor and survey rotary as well as alternative machineries such as pumps, compressors, generators, engine motors, fans, conveyors, turbines etc… and it assist field engineers in assessing the health of the machinery and in programming the relevant maintenance activities.

APMS architecture is as follows:

1. Electronics equipment that generates data such as vibration sensors, thermal image cameras and diverse IOT measurement instruments.
2. Data collection equipment (PLC).

3. Predictive technology software that process and correlates Condition & Process data through advanced condition monitoring systems.
4. Prescriptive technology software that generates self and automated diagnosis and prescribe relevant to-do maintenance actions.
5. 24/24 online remote control & access technology with dual server architecture: one server on plant/vessel site and one in remote control Room to monitor all plants/fleet.
6. Integrated Augmented Reality (AR) technology to visualize 3D equipment modelling with interactive online remote technical support and training capabilities.

For complex plants and machinery systems condition data analysis such as vibration monitoring is not sufficient to provide accurate insights needed to identify and to understand the roots causes of abnormal and deviant equipment working conditions.

An integrated system, such as APMS technology, collects not only the data relevant to the condition of the equipment but also all available process data from the automation systems. The simultaneous analysis of condition data with process data allows an effective technical diagnosis and the generation of the "actions to be taken" in order to prevent incurring problems and potential recurrences.

For the Vibrational analysis, the functionality of the system is extended to:

- Monitor the velocity of the vibration in the time domain. *(Fig.3)*.
- *Analyse the vibrational signal in the frequency domain – Spectrum analysis by mean of Fourier transform (Fig.4) and of Wavelet Transform (Fig.5).*

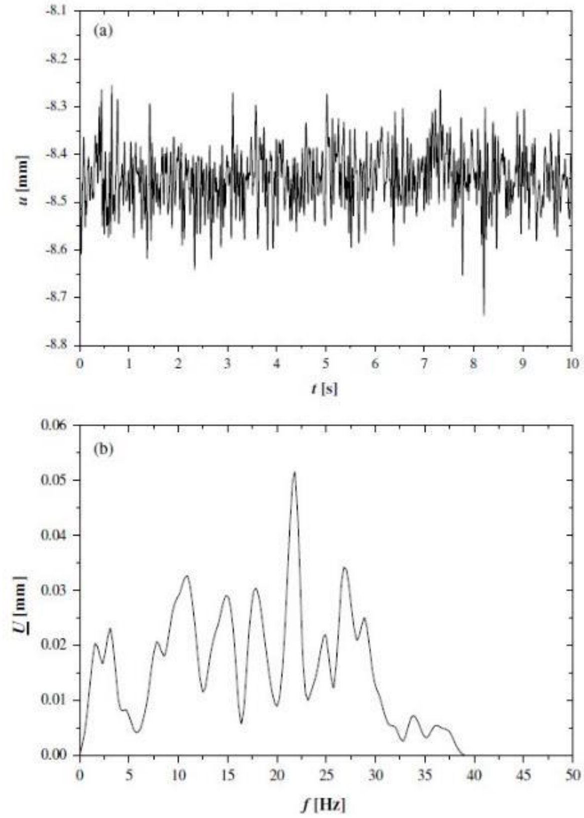

Figure 3. *Vibrations in time and frequency domain*

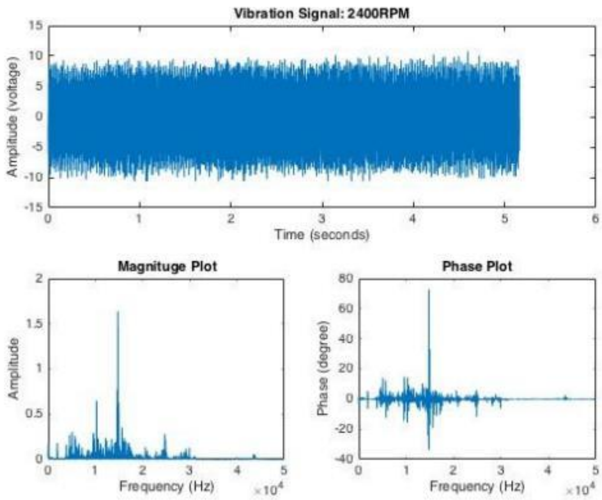

Figure 4. Spectrum analysis with Fourier Transform

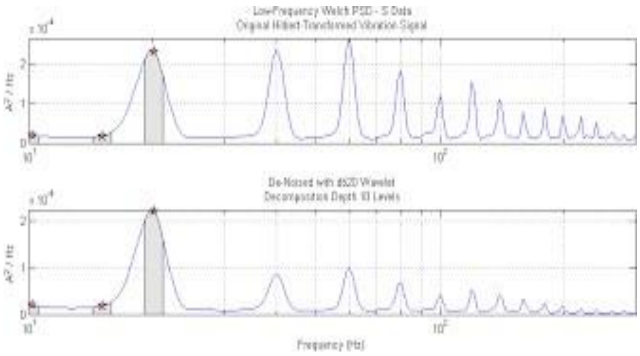

Figure 5. Spectrum analysis with Wavelet Transform

- *Monitoring the Spike Energy for mechanical components (Fig.6).*

Thanks to the above it is possible to define alarm values, alarm types (from a static value, statistical data, trend based etc.) and set up different alarm levels for each alarm.

APMS incorporates a sophisticated rules and algorithms based diagnostic module that allows a fully automated technical diagnosis. When an alarm occurs, APMS runs an analysis by matching, comparing and correlating events and parameters. Once the analysis is finalized and the technical symptoms are duly identified, APMS recognizes the root cause and generates, through automated email notification, prescriptive suggested technical corrective actions to be implemented.

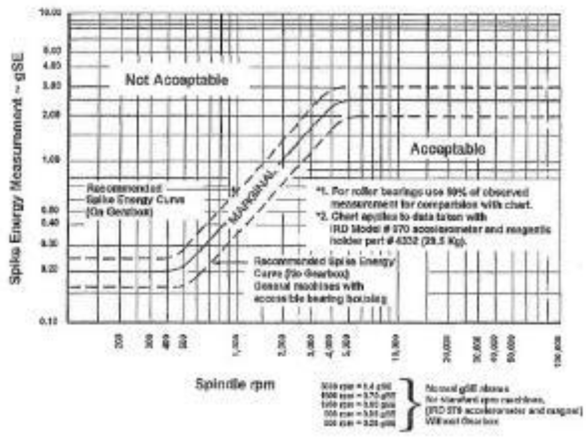

Figure 6. *Spike energy measurement "figure of merit" analysis, see reference [3]*

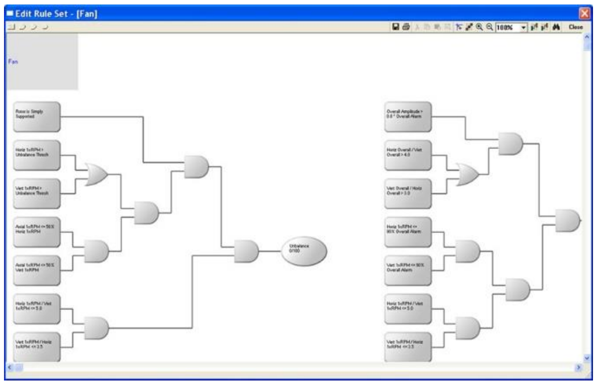

Figure 7. *algorithms based diagnostic*

Finally, through APMS integrated Augmented Reality (AR) technology, onsite field technicians can be assisted and instructed online by remotely located engineers in their corrective maintenance tasks.

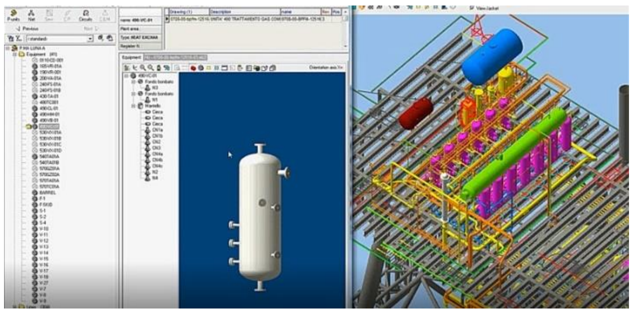

Figure 8. *AR 3D modelling rendering*

APPLICATIONS AND RESULTS

APMS is a cross-industry application which can be tailored to specific industrial sectors such as, but not exclusive to, Oil & Gas, Manufacturing plants, Power generation plants, Marine industry. In its past application the Rockwell predictive and prescriptive technology has shown the capability of reducing unscheduled downtime of at least 50% and of reducing maintenance and spare parts cost of about 25% in average.

A notable application of this technology in the Oil & Gas industry was by CACT, a consortium of China National Offshore Oil Corporation (CNOOC), Agip (Italy), Chevron (USA) and Texaco (USA), CACT Operator's Group was formed to develop hydrocarbon resources off the shores of China in the Pearl River Basin of the South China Sea. Today, CACT produces more than 100,000 barrels of crude oil each day, destined for refineries in China.

CACT was able to reduce unplanned downtime and saved maintenance costs by monitoring critical pumps Condition-based Maintenance Program and eliminated 72% of unscheduled downtime on oil rigs.

Initially, CACT had based their maintenance routine on portable instruments capable of collecting field data, including process variables and vibration information. The portable instruments can measure vibration in units of velocity and acceleration and can also take Spike Energy measurements, which can be used for early detection of surface flaws in rolling element bearings. Temperature and running speed measurements could be acquired as well. Emonitor Software was used to store the data from the portable data collector. However such offline system could not provide the real time pump protection as described in the American Petroleum Institute (API) Standard 670. For such reason CACT decided to implement a new maintenance system API 670 compliant that would provide real-time equipment monitoring and that could help contain their maintenance costs.

CACT decided to install a remotely accessible, condition monitoring system that would incorporate the measurements coming from the existing portable equipment. Through EMonitor Software data is stored and compared against historical data, comprising the one that was originally received from the portable collectors. Via an onboard Ethernet network, the system provides scheduled monitoring of all the pumps on the platform. Measurement parameters include vibration and process variables. On the same network, intelligent modules process critical parameters used to assess the current health — and predict the future health — of the pumps in real-time. The new system is comprised of DIN rail mounted measurement, relays and process modules. This is ideal for critical machinery, as it also includes protection capabilities to safely shutdown a machine before significant damage might occur.

With the new condition monitoring system in place, CACT has eliminated the need for manual data acquisition, and the associated costs. Onshore operators 200 km way from the platform collect, configure and analyse data just as they would on a local server. CACT has reduced their unscheduled downtime from 2.43% to 0.67% — a 72% decrease. In fact, during a five-year period, the maintenance system has protected machinery from catastrophic failures more than 20 times. Thanks to a condition-based maintenance strategy, annual maintenance expenses have also been significantly decreased. In fact, the reduction in service time was so dramatic as to allow CACT to save US $100,000 annually in 3rd party maintenance costs.

APMS is also suited for the marine industry where a typical solution could include modules to monitor critical vibration levels, shaft speed and temperature of the vessel main engines, shaft generators and machinery. Other sensors and data collection can be incorporated into the system to improve surveillance. These enhancements may include online lubricating oil analysis and data logging for historical purposes. An integrated condition monitoring solution can also incorporate additional visual and audible alarm devices such as stack lights, warning beacons and signalling devices. Simply put, the system is designed to help optimize operational readiness – and improve the reliability of the ship and voyage.

One notable application of this technology in the Marine Industry is the by Italian Marine which installed this technology in some of its most important warships such as C550 Cavour, the latest light aircraft carrier and the flagship of the Italian Navy.

The main goal of the Italian Navy was to install a technology that would minimize the risk of technical failure risk and maximize operational availability and reliability when the warship was operating in a NBC (nuclear, biological, chemical) setup.

The system installed on C550 Cavour is composed by 60 fixed and remotely accessible, condition monitoring devices, connected in DeviceNet to a Rockwell data acquisition and analyser which commutate all in Ethernet/IP and, through redundant dedicated channels, to a server located in the O.P.O (Operative Platform Office) on which the EMonitor Software is running. According to the Italian Navy maintenance on the monitored equipment was reduced by 45% while technical failure and emergencies were reduced by 75%.

MARITIME SPECIFIC ADVANTAGES

Advanced predictive and prescriptive maintenance techniques bring about specific advantages to the Maritime Industry, and they do it for a very diversified crowd.

Ship Managers: ship managers can have a remote and in-depth status of the vessels in quasi real time, enabling better communication and synergy between the crew and the office and in particular allowing superintendents to carry out their job more effectively and more timely visits onboard. These techniques also allow easily to comply with higher standards where required, e.g. a predictive / prescriptive maintenance system grants level 4 of Tanker Management and Self Assessment, TMSA.

Classification Societies: class surveyors can inspect the vessels, remotely, in an audit-like fashion, allowing them to spend less time onboard, but in a more effective way.

Charterers: the vetting for vessels to be chartered is a rather complicated matter. Several system are in place to collect information and provide background checks (e.g. port state control reports) to help charterers assess the condition of the ships before chartering them. A system such as APMS goes many steps further by being able to provide charterers with precise and comprehensive information on the actual and the historical status of the vessels they are about to charter.

Insurers: predictive and prescriptive maintenance is a loss prevention tool, as such it reduces the risk incurred by the insurers, as it does for the insurers.

Shipowners: in addition to the economic benefits deriving from lower maintenance costs, higher reliability, availability and efficiency of the vessel the Ship Owners can reap benefits from the activities mentioned in the previous paragraphs, as part of the benefits to the other stakeholder are bound to be passed down to them, but the most important benefit for Shipowners is the fact that the chartering of the vessels is facilitated as it is easy to prove to the Charterers the actual conditions of the vessels.

Finally, the application of predictive and prescriptive maintenance is fully in line with the recent push for digitalization and also for unmanned and autonomous vessels.

CONCLUSIONS

The introduction of predictive and prescriptive maintenance techniques in shipping is a revolution waiting to happen. On shore industries, and in particular aviation, have already applied these techniques with great effect.

Shipping has lagged behind due to its fragmentation, conservatism, opacity, and due to an unbalance in considering CAPEX and OPEX. This situation will change, also thanks to the innovation, to the digitization, and to the need of transparency that the industry itself, as well as the stakeholders, are requesting.

Advances in IT and related fields, such as Industry 4.0, Internet of Things, Machine Learning, Artificial Intelligence, the cheaper cost of communication, also via satellite, all conjure and favor this revolution.

In particular we are already witnessing vessels and fleets being monitored from onshore control centers, the quality of the data available in such rooms is not yet consistent, varying from real time onboard measurements to general data pulled from the www. These fleet control centers will become more and more popular and data pertaining to the actual physical conditions of the assets, duly organized and defragmented, which is exactly what predictive and prescriptive maintenance systems such as APMS do, are an essential and vital component for a modern, timely and effective ship management.

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Prediction of Environmental Forces for Station Keeping: Ships *versus* Semi-Submersibles

ABSTRACT

The dynamic positioning (DP) is a fast-growing technology, which started exactly 50 years back in the USA. In the last two decades, tremendous growth has been noted in DP because of rapid development in both hardware and software associated with dynamic positioning. Dynamic positioning is primarily used in ships; mainly offshore support vessels like AHTSVs, PSVs, AHTs, pipe laying vessels, diving support vessels, etc. due to their operational requirements. However, synonymous with drillships, DP is now being attempted in many deepwater semi-submersibles deploying 6 – 8 thrusters. One of the main design parameters of DP capability for either ships or semi-submersibles is assessing environmental forces quite accurately before selecting the thrusters' power for the ship or the semi-submersible.

Of the three main environmental forces (wave, wind and current), the horizontal wave drift force is quite essential. Calculation of this force is mainly done using 3-D radiation-diffraction theory under potential theory or sometimes empirically using wave drift force coefficients. While this method is entirely accurate in predicting wave drift force for a ship shaped body, the same may not be right for a semi-submersible where the slender column structure, especially in low frequency (long waves), will cause the drift force to be influenced by viscous effects. In irregular waves, it is not only the wave drift force but also the low frequency part also plays an important role. Surprisingly, the viscous effects also influence this low frequency part. A severe design deficiency will result in wave drift force prediction if these viscous effects are not considered for column stabilised semi-submersible type floating structures.

1. INTRODUCTION

Application of dynamic positioning (from now on referred to as DP) is far more rampant nowadays compared to two decades back through its use started almost 50 years back in the USA. DP is now widely used not only in various types of ships, though mainly offshore support vessels, but also for semi-submersibles and even for FPSOs/FSOs. Before going into details of the number of thrusters, their powers and locations, the first task is the accurate prediction of environmental forces. A ship or a semi-submersible is subjected to wave, wind and current forces during operations like dynamic positioning. All these three forces are of steady nature and are of second order, i.e. velocity squared. All possible factors should be analysed carefully in the initial design phase to assure a cost-effective DP ship or semi-submersible.

So, the forces produced by wave, wind and current are of fundamental importance in the design and operation of ships and floating offshore structures especially in the study of dynamic positioning. The scope of this paper is to provide a review of the calculation procedure of environmental design forces due to wave, wind and current for ships and semi-submersibles. While the calculations of wind and current forces seem quite straightforward, the part due to waves (second order mean and slowly varying forces) is not that straightforward though robust calculation methods exist at present due to the availability of many proven computer codes. The mechanisms by which they originate hydrodynamic and aerodynamic forces in the most conventional methods (empirical methods) of force calculations, numerical estimation of steady forces like current and wind forces is hardly possible and as such is beyond the scope of this paper. The traditional methods widely used are the Rules and Regulations of International Classification Societies (Class) like DNV (Det Norske Veritas) [3], Germanischer Lloyds (GL) [7] and American Bureau of Shipping (ABS) [1] and other available literature. These rules treat the current and wind force in the same way as on above water part as well as on underwater part.

The calculations of the above two forces are mainly complicated by the appropriate selection of non-dimensional force coefficients like drag and lift force coefficients, shielding effects, interference effects, etc. It is because of the lack of one adequate single reference source or a specific standard code practice; the author was tempted during his Doctoral research to prepare a mathematical model to develop a computer program followed by [4]. With the pace of time and developments in the design of ships and offshore structures, more sources are available than before leading to a more satisfactory calculation method. As a first approximation, the classic relation for the force is the current / wind pressure acting to an area associated with non-dimensional force coefficients. Consideration of the above indicates immediately that three factors equally bias the generated force.

These are:
(a) Current / Wind characteristics i.e. their design value
(b) Body Geometry i.e. shape, size, orientations, etc.
(c) Force Coefficients

The types of structures considered here are ships and semi-submersibles. For hydrodynamic forces, only buoyant members are considered and not others like risers, tendons, etc. The outcome of a computer program can be used to solve problems like estimation of the powering requirements of DP-type offshore floating structures and also the estimation of the response of offshore floating structures, dynamically positioned in wave, wind and current. Furthermore, the overall hydrodynamic and aerodynamic coefficients may then be used in a non-linear time domain simulation to predict the motions of a moored or dynamically positioned ships or offshore floating structures.

For the steady drift force, generated by waves, for ships or semi-submersibles can now be easily calculated by any 3-D radiation-diffraction software available in the market. However, this drift force calculation is based only on potential theory and as such does not take any account of viscous effects [6] in drift forces for column stabilised semi-submersibles. This is a severe shortcoming in potential theory based drift force calculations. Furthermore, the low-frequency horizontal drift forces are also affected by viscous effects [6]. While environmental forces for wave, wind and current can be calculated separately and added algebraically for a ship, the same may not be entirely true for a semi-submersible. The drift force on a semi-submersible in coexisting field of waves and currents is rather complicated and needs to be treated more carefully. Further details are available in [6]

2. CLASSIFICATION OF GEOMETRY

In case of ships (mono-hull), the whole underwater body (a bluff body) is a sizeable volumetric geometry of somewhat triangular sections in forward and aft end and a more or less rectangular body in the middle. The shape (hull form) is more explained by the introduction of various form coefficients like C_b (block coefficient), C_m (midship area coefficient), C_p (prismatic coefficient), C_w (water plane area coefficient), etc.

For offshore floating platforms like semi-submersibles, there are two major buoyant items - one is the submerged hulls, and the other is the surface piercing vertical columns. Other than these two significant geometries, there are randomly oriented horizontal and inclined circular tubes (bracing) whose main contributions are to the structural reliability and compatibility. Nevertheless, these circular tubes, fortunately, contribute to the increased hydrodynamic viscous damping.

In case of a semi-submersible, the submerged hulls (often called pontoons) can be of circular or rectangular cross-section. Sometimes, cross-sections of a rectangle with semi-circular ends are adopted. There are mostly two numbers of pontoons, and that is why they are called twin-hull semi-submersibles. However, it is possible to have a continuous hull in the form of a square or circular of rectangular cross-section. In case of some early design of semi-submersibles, instead of having two hulls, some submerged floaters (caissons) were used. Their shapes are also cylindrical, spherical, rectangular, etc. having minimum numbers of three of them. Such design comparatively needs more randomly oriented tubes. Surface piercing columns for semi-submersibles can be of either circular or rectangular cross-section.

In case of the above water structures, which are much more varied and complex, it is not possible to make a short classification of the different geometry. The typical structural members for semi-submersibles are mainly production and drilling equipment including flare booms, main deck structures, living quarters and a helideck. Portions of vertical columns and bracing can be categorised for semi-submersibles. For ships of various types, the above water structures differ, but most of the ships have accommodation (mostly forward for those engaged in offshore operations). Generally, bigger offshore support vessels have helidecks. The others vary from drilling derricks on a drill ship to process modules on FPSOs/FSOs.

3. FORCES AND MOMENTS DUE TO CURRENT

For current forces on a ship, there is no comprehensive reference available. However, available data in the public domain can be used to predict the current forces by considering the separate cases of longitudinal and transverse (lateral) currents. For transverse (lateral) currents, the necessary forces can be calculated by considering the ship as an underwater bluff body.

For semi-submersible type structures, the existence of viscosity causes flow separation and give rise to additional hydrodynamic forces. This viscous force in line with flow direction is commonly known as the drag force. They are the most critical importance for structural members with slender dimension and underflow conditions where high fluid particle velocity exists. In addition to the in-line drag force, the wake formation as a consequence of flow separation also gives rise to lift force normal to the flow direction. Lift forces can be of either steady or oscillatory nature. Due to the cross-flow principle, steady lift forces occur for a submerged cylindrical body Hoerner [8]. For a vertical surface piercing column, oscillatory lift forces occur due to the shedding of vortices into the wake. In the calculation method, the steady lift force should be considered as far as practical.

Under the above circumstances, the underwater geometry of a semi-submersible is subject to hydrodynamic forces due to current flow. The basis of the mathematical model would be to compute the forces and moments by sub-dividing the structure into some typical members and summing up the forces and moments due to those individual members. No interference effects would be considered between the forces. OCIMF [10] provides information about wind and currents loads on VLCCs.

Current Force Formulation

Ocean currents may even be quite significant in terms of its values. The characteristic equation is as follows:

$$F_{D,Current} = \frac{1}{2} \rho_w C A_p V_c^2 \qquad (1)$$

C is again a function of both shape and height, i.e. $C = C_s = C_D$ including any effects of shielding, interaction and cross flow velocity. Values of C_s or C_D are available in the literature or can be available by doing wind tunnel tests of various bodies. Effects of "Keel Clearance" are to be included where applicable. Current forces are again a function of direction, i.e. the force needs to be calculated for 0 – 180 degrees.

Evaluation of Input Variables

In the foregoing equations, the two critical variables are noticed - one is the drag coefficient, and the other is the projected area. Depending on the orientation of the individual body (geometry) like horizontal pontoons, floaters, vertical columns and bracing, projected areas vary under different situations. So, they need careful appraisal depending on the incident angle of the flow on the body axis or cross-sectional plane. Similarly, drag coefficients under different circumstances are different for a particular geometry. Some geometry even can have 3-dimensional effects when mostly can be treated as 2-dimensional bodies. Again some bodies are surface piercing and some are entirely submerged. For example, C_D of a column usually equals to 1.20 in the range of low Reynolds Number, but it equals to 0.50 in ABS [1]. All these different hydrodynamic aspects lead the whole exercise to a little extent somewhat perplexed. As the experimental investigation is beyond the scope of this exercise, various published data including Rules Books of different Class would be exploited to an appropriate use of drag coefficients and others.

The selection of design current velocity is equally important. It is quite common to assume a sea surface current of uniformly distribution. In reality, current profiles are different as well as their components. According to GL[7], sea currents are characterised as the followings:

- Near surface currents, i.e. wind/wave generated currents
- Sub-surface currents, i.e. tidal currents and thermo saline currents
- Near shore currents, i.e. wave induced surf currents

The first two components i.e. tidal current and wind generated current are important and where necessary linear superposition of them should be considered. Both GL [7] and DnV [3] provide specific formulation of design current velocity. In the computer program, options would be made for different selection for calculating the current pressure. Step by step description is available in [4].

4. FORCES AND MOMENT DUE TO WIND

Wind forces acting on ships is available in most literature. MacTaggart and Savage [9] describe model tests conducted on a generic frigate model to calculate the wind forces. Van Mannen and Oosanen [11] gave an overview of wind forces on ships. Blendermann [2] gave useful practical formulae for estimating wind forces on ships of various heading angles. OCIMF [10] also gave calculation formulae with the values of air drag coefficients for tankers. Wind-tunnel tests at the design stage can be used to ensure that the vessel meets the operational and class requirements concerning propulsion, manoeuvring, dynamic positioning, mooring, and stability. The thruster units can be dimensioned to handle harbour manoeuvring up to certain wind speed, as dynamic positioning units can be dimensioned to a particular combination of wind and current speeds. To determine the environmental forces that the vessel or the semi-submersible will experience, the above-water part of the model is exposed to a wind profile, which resembles an ocean wind with regards to the velocity distribution and turbulence intensity, while the underwater part is exposed to a uniform wind profile with low turbulence intensity to resemble a current vertical profile.

The similar approach (projected area) for calculating forces due to current for under water applies to above water according to different Classification Societies' Rules with only a difference in height correction (height coefficient) for wind velocity. Various investigators agree that Classification Societies' Rules and Regulations are conservative in calculating the wind forces and moments resulting in overdesign. It appears that the offshore industry shares the same view. Therefore the recent trend is wind tunnel testing of models of semi-submersibles to achieve more accurate determination of the wind forces and moments.

One of the apparent flaws of the Rules of Classification Societies is that it does not deal adequately with an inclined platform and their treatment of angled winds is not well defined, i.e. code recommendations fail to quantify the aerodynamic induced forces in a direction different to the mean wind flow. In short, the centre of action of the wind force is usually taken to coincide with the geometrical centre of the projected area. The wind moment for a particular axis is then calculated as the product of the wind force and the distance to the centre, of action. Such a method is reasonably acceptable when the flow around the body produces a pressure that is in balance, in the vertical direction, so that the lift component becomes negligible. When the body is tilted concerning the main flow direction, the pressure distribution also will be asymmetrical, and as a consequence of it, a lift force will be generated. The fluctuating component results from the buffering action of wind gusts or flow-induced effects. Under such condition, the behaviour of semi-submersibles in the horizontal plane increases their sensitivity to dynamic effects of wind.

Similar to the calculation of current forces and moments, the entire above water structures would be split-up into some standard types of elements so that specific treatment of them becomes convenient. The mean wind velocity on any element is the velocity 'Vw' according to the desired wind velocity. Vertical 'Z' coordinate would be taken as the middle of the projected area or point of application of the force whichever is deemed necessary.

4.1 Wind Force Formulation

Wind Forces are mainly due to a steady flow, but dynamic winds also exist. The characteristic equation is as follows:

$$F_{D,Wind} = \tfrac{1}{2}\, \rho_a\, C\, A_p\, V_w^2 \qquad (2)$$

C is again a function of both shape and height, i.e. $C = C_s \times C_h$ including any effects of shielding, interaction and cross flow velocity. Wind Velocity, V_W, is height dependent. Values of C_s and C_h are accessible in the literature or can be available from wind tunnel tests of various bodies or a complete structure as a whole. Wind profile effects need to be included. Wind forces are again a function of direction, i.e. the force needs to be calculated for 0 – 180 degrees.

4.2 Evaluation of Input Variables

Similar to input variables for current forces and moments, the identical approach be used for forces and moments due to wind. As some principal structures on deck are of lattice type, for the calculation of the projected area to be performed via standard solidification factor. Those principal structures which causes invariably lift forces and thus overturning moments due to lift forces are to be treated accordingly using appropriate lift coefficients.

The well-recognised power law

$$V_{1m} / V_{2m} = (Z_1 / Z_2)^a \qquad (3)$$

is acceptable representation of the wind velocity profile. In the above equation, V_{1m}, V_{2m} are mean wind velocities usually averaged over a period of one hour at heights Z_1 and Z_2 respectively and 'a' is a constant depending upon the roughness of the earth's surface. The value of approximately 1.0 is suggested for vast expanses of open quite water.

Now, if averaged wind speeds are considered, it is common practice to allow for gusts by introducing a gust factor 'G' as given in the following equation:

$$G = V_t / V_m \qquad (4)$$

where V_t is the gust velocity averaged over the gust period 't'. 'G' is smaller for smoother surface profiles and larger with shorter gust periods. Some of the values for 'G' for open level country at the 10 m level are 1.54, 1.425 and 1.35 for 't' equal to 3, 5 and 15 seconds respectively and 1.45 to 1.60 for 't' equal to 3 seconds.

The factor 'G' decreases with height and the variation can be represented by the power law:

$$G_1 / G_2 = (Z_1 / Z_2)^{-b} \qquad (5)$$

where G_1 and G_2 are gust factors at heights Z_1 and Z_2 respectively.

Now multiplying equations (3) and (5) and substituting values by equation (4), the following equation is obtained where Z_2 is made equal to 10m, V_{2m} equal to V_{10m} and introducing the parameter, $\gamma = a - b$

$$V_z = G_{10m} V_{10m} (Z / 10)^{\gamma} \qquad (6)$$

5. CONCLUSIONS ON WIND AND CURRENT FORCES ALONE

- Depending on the design code available in the Rules and Regulations of different Class like ABS, DNV and GL, the developed mathematical model made could be used, for a Computer Program, to calculate the current and wind forces on offshore floating structures like semi-submersibles and tension leg platforms. Besides, other literature and the results of different model tests especially for wind forces would be utilised to achieve the results as accurate as possible.
- Redundancy is bound to be expected in the results, but the aim would be to keep them as few as possible.
- If the force coefficients involving interaction effects and the wind velocity profile are suitably treated, the procedures described for summing up the elemental force is useful for the estimation of the total forces.
- The force coefficients used in the theoretical calculations are not exaggerated; it is the overall geometry which as a whole result in less force due to interference/interaction among different structural members.
- Though enormous criticisms nowadays exist especially for wind loading for offshore structures, due

to the conservative code of practice by Class, unfortunately, so far no alternative code has been either proposed or yet fully established to forego the present state-of-the-art of the Rules and Regulations. It is rather hoped that it is the Class, which would confound their critics with a modified version of Rules and Regulations.

- How far practical would be the model tests results to predict the behaviour of the full-scale structure, when there are questions of scale effects, blockage effects and to some extent employment of dubious techniques while performing the tests. Besides, modelling of the proper boundary layer in the wind tunnel to simulate the actual flow over the sea generated by surface roughness remains as an essential requirement.
- The widely used traditional (empirical) methods would be much more efficient in computation compared to individual model tests. However, essential findings different model tests result can be incorporated where relevant towards a more reliable prediction of computational results.

6. WAVE DRIFT FORCES

Ships, mainly various types of offshore support vessels, mostly work in not so relatively harsh environments except larger offshore supply vessels. FPSOs/FSOs are also placed in an area where the weather condition is rather benign. Semi-submersibles often operate under severe environmental conditions, and the forces and the motions are dominated by an extremely complex environmental loading mainly dominated by wave, wind and current. In general, the wave loading makes up the significant environmental loading including its interaction with currents. The accurate estimate of the excitation forces on these ships and semi-submersibles is essential for both economical and safe design of them.

The wave excitation forces in small amplitude monochromatic long-crested waves are divided into wave frequency (first order) forces, mean and slowly varying wave (potential) drift (second order) forces in an irregular sea state. While the first order force with the wave frequency is linear with the wave height, the mean force being nonlinear is quadratic with the wave height. The slowly varying drift forces occur in irregular waves because of the existence of two waves of different frequencies (beating effect of two wave components), which always implies, the existence of wave excitations at the sum and difference frequencies. The latter frequency may occur at the resonance frequency of the floating structures moored in horizontal motions. If the damping is low (as it is usually in such motions), a highly tuned resonance force is always expected although the low-frequency force is generally small in amount. Accordingly, the motion of a floating structure moored in irregular waves consists of a slowly varying component and a component oscillating at wave frequencies. The spectrum of this time history (forces or motions) has two peaks - one occurs within the wave frequency range, and the other occurs below the lowest frequency (close to the resonance frequency) at which there is any significant energy in the incident waves.

These quadratic wave forces are believed to be due to potential effects and as such treated by linear potential theory like either the conservation of momentum principle (far field approach) or the pressure integration method (near field approach). Such methods have proved to be entirely satisfactory where viscous effects are less prominent like for ships. The theory-based diffraction analysis has the added advantage of allowing for diffraction forces, member interactions with incident waves and interaction between members. On the other hand, the diffraction theory neglects drag forces which ultimately influence mean and low-frequency drift forces especially in massive waves in extreme sea (storm) conditions and thus cannot be disregarded. For semi-submersibles whose columns and pontoons have small ratios of cross-sectional dimension, viscous effects are equally important. Besides the mean forces, the slowly varying drift force is the most critical excitation. Estimating the structure's maximum excursions caused by the resonance motion is now being considered as essential in the design of a mooring system and hence for DP system as well. Apart from the contribution as a wave excitation force due to viscous effects, its presence as hydrodynamic damping is equally important concerning the system damping towards an accurate prediction of the response. Viscous damping is relatively large compared to radiation wave damping in any mode of slow drift motions. The presence of current can further enhance such viscous effects. Current can be expected to have an influence over the whole submerged part of the structure and the free surface. The presence of current has thus several effects, which need to be considered, in the wave excitation force calculations. The drag force on a member is proportional to the square of wave-particle velocities and current even with a low velocity may have a significant effect. This effect is significant for slender members to calculate the forces on such members as it is modified through the velocities.

The importance of viscous effects in the mean and low-frequency drift forces has been in the minds of the hydrodynamicists in a parallel fashion to that of potential effects. While methods of computation concerning potential effects have been well proven, knowledge of viscous effects from its nature and importance has not yet been fully established. An attempt was made [6] to investigate the physical phenomena of viscous effects influencing the horizontal mean and low-frequency drift forces on floating structures like semi-submersibles in a waves-only flow field as well as in a wave-current coexisting flow field.

A semi-submersible consists of two major structures - the submerged underwater hull hereinafter referred to as the pontoons, and the surface piercing vertical columns hereinafter referred to as the columns. Before dealing with viscous effects for a complete semi-submersible, these two structures - the vertical columns and the submerged pontoons need to be treated separately.

6.1 *Waves Only Field*

In [6], it has been shown that the viscous drift forces on a vertical cylinder are given by

$$F_{D0,Wave} = \frac{2}{3\pi} \rho_w \, \omega^2 \, C_{D0} \, D \, \zeta_a^3 \quad (7)$$

The above viscous drift force is due to viscous effects in the splash zone of a vertical cylinder (cylindrical column of a semi-submersible) is found by integrating the unit length force on the cylinder over the splash zone. The viscous mean drift force on the splash zone is thus found to vary with the cube of the wave height, and for particular wave height, it would increase linearly with wave frequency squared.

The value of C_{D0} should not be confused with a drag coefficient value obtained in literature for either steady flow or oscillatory flow. This mean drag coefficient is different from those values and are obtained from experimental results in waves. As a result of experimental investigation, the values of C_{D0}.

In a waves only field for vertical cylinders can be expressed as follows:

$$C_{D0} = c_1(\kappa D) + c_2(\frac{H}{D}) + c_3(\kappa H); \; For \; N_{K-C} < 3 \quad (8)$$

Where c_1 = 1.863, c_2 = 0.433 and c_3 = - 1.373

$$C_{D0} = c_0 + c_1 N_{K-C}; \; For \; 3 \le N_{K-C} < 8 \quad (9)$$

Where c_0 = 1.826 and c_1 = - 0.070

For further details, please see [6]. Similar formulae are available for the values of mean drag coefficients of vertical cylinders and submerged pontoons in [6].

6.2 *Waves and Currents Field*

It has been shown [6] that for a fixed cylinder in waves only, the mean drift force due to viscous effects on the submerged part is zero when the force is averaged over one cycle. In the presence of currents, this is no longer true. Even the presence of a low magnitude of currents can account for the mean drift force due to viscous effects of the combined velocity of waves and currents. As the interaction effects of a wave-current coexisting flow field are also of viscous origin, the nonlinear viscous drag force term of the Morison equation would be exploited again to compute the mean drift force. Though current is assumed to be present up to the mean water level, its presence in the splash zone would also be investigated by considering it as a constant velocity, in addition to the constant crest velocity. In the presence of positive or negative currents, the viscous drag force becomes as follows:

Splash Zone

For $|U| \geq u_a$

$$F_{D0,waves\pm currents} = \frac{1}{2}\rho_w C_{D0} D \zeta_a u_a^2 \left(\frac{u_a}{U}\right) \quad (10)$$

For $|U| \leq u_a$

$$F_{D0,waves\pm currents} = \frac{1}{2\pi}\rho_w C_{D0} D \zeta_a u_a^2 (d_1 + d_2 + d_3) \quad (11)$$

Where,

$$d_1 = \frac{1}{6}(\sin 3\Theta + 9\sin\Theta)$$

$$d_2 = \left(\frac{U}{u_a}\right)(2\Theta + \sin 2\Theta - \pi); \quad \Theta = \cos^{-1}\left(\frac{U}{u_a}\right)$$

$$d_3 = 2\left(\frac{U}{u_a}\right)^2 \sin\Theta$$

Submerged Zone

For $|U| \geq u_a$

$$F_{D0,waves\pm currents} = \frac{1}{2}\rho_w C_{D0} D \zeta_a u_a^2 \left(\frac{u_a}{U}\right) \quad (12)$$

For $|U| \leq u_a$

$$F_{D0,waves\pm currents} = \frac{1}{2\pi}\rho_w C_{D0} D u_a^2 (d_1 + d_2 + d_3) \quad (13)$$

Where,

$$d_1 = \frac{1}{2}(2\Theta + \sin 2\Theta - \pi)$$

$$d_2 = 4\left(\frac{U}{u_a}\right)\sin\Theta; \quad \Theta = \cos^{-1}\left(\frac{U}{u_a}\right)$$

$$d_3 = \left(\frac{U}{u_a}\right)^2 (2\Theta - \pi)$$

Further details about the above are available in [6]. The above derivations are for a fixed cylinder but the same can be developed for a floating cylinder and a number of cylinders like those on a floating semi-submersible based on their position with respect to semi-submersible reference axes.

Similar equations could also be developed for the submerged pontoons of a semi-submersible [6].

7. CONCLUDING REMARKS ON STEADY(MEAN) WAVE DRIFT FORCES

In the above theoretical analysis, the contributions have been evaluated of viscous effects in a waves-only flow field and a wave- current coexisting flow field (wave-current interaction effects) to the mean drift force for floating structures like semi-submersibles. From the results presented [6], the following conclusions were drawn:

- Due to the splash zone nonlinearity, the mean drift force due to drag effects has been found be proportional to wave height cubed. Its effectiveness is further enhanced with the increase of wave height.
- A linear superposition method, to consider a wave-current interaction, is not an appropriate approach because the presence of a small amount of current leads to a substantial increase of viscous drift force even for the submerged zone of a cylinder. Interaction effects seem to modify the force on the splash zone as well.
- Prediction of viscous mean drift forces in a waves-only flow field based on the idea of subtracting the force due to currents only from that in a wave-current coexisting

flow field shows much deviation from the present method which includes the splash zone (free surface zone) force.

- For a floating cylinder, the relative velocity and the relative surface elevation concept considering their combined amplitude and phase seems to be sufficient to deal with the terms derived for a floating cylinder.
- Great uncertainties still lie ahead with respect to the value of the mean drag coefficient. Though many published test results are available in the existing literature, they are not suitable for direct application for such a mean force computation problem. Additional treatment is always necessary before they can be applied.

8. EXPERIMENTAL VALIDATION AND DISCUSSION

Experiments were conducted using the small and large diameter cylinders in waves only field and waves and currents field. Some results are shown here. Further details are available in [6].

Figure 1 shows a small cylinder (*H/D* larger) in a waves only field. The measured mean forces are much higher than the mean drift force (potential effects only) claiming that the difference is due to viscous effects. Figure 3 and Figure 4, on the other hand, show the similar experimental results through using the large diameter cylinder at two different testing facilities. The noticeable thing is clear that due to large diameter (*κD* larger), the viscous effects are less dominant for similar wave heights.

Figure 6 shows three curves (theoretical ratio of viscous to potential mean drift force) equal to 5, 1 and 1/5 representing 80% viscous, viscous equal to potential and 80% potential respectively. At *H/D*>1 and very low values of diffraction parameter, the force is dominated mainly by viscous effects, which is also, indicated by the experimental results. Around the line (R_{ft}=1), both viscous and potential drfit forces are equally important. Experimental results from the small diameter cylinder, as well as the large diameter cylinder, show the trends with a few discrepancies.

Figure 2 shows that results of a cylinder in waves and currents. It indicates that the mean drift force in waves and currents is much more than in waves only. Figure 5 shows the results of a semi in currents only. The calculations show a very close result to the experimental results showing that the mathematical model developed in [6] is quite accurate. Figure 7 and Figure 8 again show the calculation of mean drift forces in waves and currents on a semi-submersible in head seas and beam seas respectively. Calculating the forces in waves and currents for two separate zones: splash and submerged zone provide more accurate results when compared to measured results.

9. CONCLUDING REAMRKS ON EXPERIMENTAL VALIDATION

In this experimental validation [6], contributions of viscous effects in a waves-only flow field and a wave-current coexisting flow field (wave-current interaction effects) to the horizontal mean drift force have been investigated.

- Due to the splash zone nonlinearity, the mean drift force due to viscous effects has been found to exist even in a waves-only flow field.
- The constantly submerged zone, which is not influenced by viscous effects in a waves-only flow field, emerges as another critical zone of the viscous mean drift force in the presence of a wave-current coexisting flow field.
- Prediction of viscous mean drift forces in a waves-only flow field based on the idea of subtracting the force due to currents only from that in a wave-current coexisting flow field shows considerable deviations from that measured in a waves-only flow field. So, treatment of the viscous mean drift force for different flow fields has to remain independent.
- Uncertainties in the choice of the values of the mean drag coefficient can be eliminated through systematic experimental investigations when hydrodynamic parameters are carefully chosen to treat those.
- In the absence of any tremendous numerical techniques, the present 2-D method along with experimental data should be sufficient enough to predict the viscous contributions towards the mean drift force originating from the surface piercing columns of a semi-submersible or even a tension leg platform.

10. DISCUSSION AND CONCLUSIONS

The calculation of the environmental forces on a dynamically positioned ship or a dynamically positioned semi-submersible is not necessarily the same.

Wave (potential) drift force computations based on 3-D potential theory, is not adequate for predicting the drift forces on a slender body floating structure like a semi-submersible in a sea state. In longer waves, diffraction effects are reduced, and viscous effects become comparatively dominant.

Systematic model tests in regular waves with major structural components (vertical columns and submerged pontoons) of a semi-submersible established the fact that the splash zone (the free surface zone) of the vertical columns is the primary source of viscous contributions in the horizontal mean drift force in waves only.

In case of the submerged structures like the constantly submerged zone of a vertical column or a completely submerged pontoon in waves only, the experimental investigations show similar trends in the mean drift forces as predicted by the present 3-D computational technique. However, in the presence of currents with waves, an additional source is established for a further contribution of viscous effects for the constantly submerged structures.

For a ship or a ship-shaped body, the

$$F_{Total\,Drift,\,Environment} = F_{P0,Wave,Potential} + F_{D,Current} + F_{D,Wind} \quad (14)$$

following may be used.

In fact, in the wave drift forces increases with a forward velocity.

For a column-stabilized semi-submersible, for calculation of the total environmental forces, the following may be used:

Option 1:

$$F_{Total\,Drift,Environment} = \left(F_{P0,Wave,Potential} + F_{D0,Wave,Viscous}\right) + \\ + F_{D,Current} + F_{D,Wind} \qquad (15)$$

Option 2:

$$F_{Total\,Drift,Environment} = \\ = \left(F_{P0,Wave,Potential} + \delta F_{P0,CorrectionforCurrent}\right) + \\ + \left(F_{D0,Wave+Current,SpalshZones} + F_{D0,Wave+Current,Submerged\,Zones}\right) + \\ + F_{D,Wind} \qquad (16)$$

Due to the limitations of the size of the paper, the author could not explain much about slowly varying forces in connection with DP in an irregular seaway. The mechanism of such forces on DP is yet to be investigated. It should be borne in mind that even the slowly varying force is affected by viscous effects like the way it does the steady drift force.

One more item needs attention is that all calculations are done for a single body. In offshore activities, many ships go near to a semi-submersible, i.e. it is then a scenario of multi-bodies and both bodies are subject to horizontal excursions due to environmental forces. This is an area that could be further looked into for future research.

In connection with the environmental forces for Dynamic Positioning,

- The calculation of all horizontal forces on a ship is summative, i.e. wave, wind and current – all could be considered collinear, and their forces can be added together to get the total environmental (wave, wind and current) forces. The wave drift forces can be calculated using any standard 3-D potential theory based software.
- In the case of a semi-submersible, the above may not be accurate due to the presence of viscous effects. As a result of this, the wave drift force has to be corrected for viscous effects.
- Further, for a semi-submersible, it is not recommended that the wave drift forces and current forces are calculated separately and added together. It is more appropriate to calculate the drift force in waves and currents for the splash zone as well as for the submerged zone. Even the drift forces due to potential effects get affected due to the presence of currents.
- Whether the slowly varying (low frequency or difference frequency) force is to be accounted for DP, is a question for further research. As the slowly varying force and its motions are different from the first order force and its motions, both experimental and numerical study need to be taken in hand by the interested researchers.

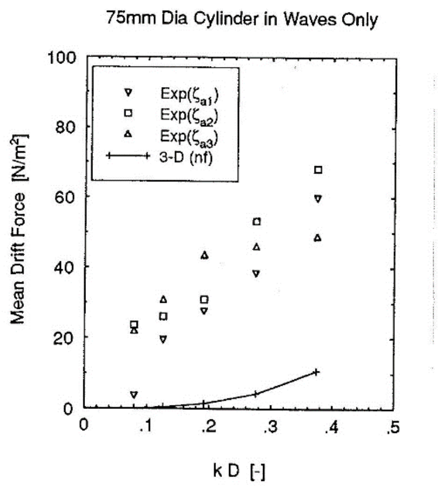

Figure 1 A Vertical Cylinder in Waves Only

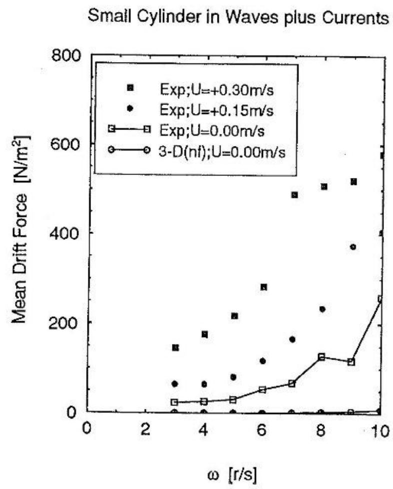

Figure 2 A Vertical Cylinder in Waves and Currents

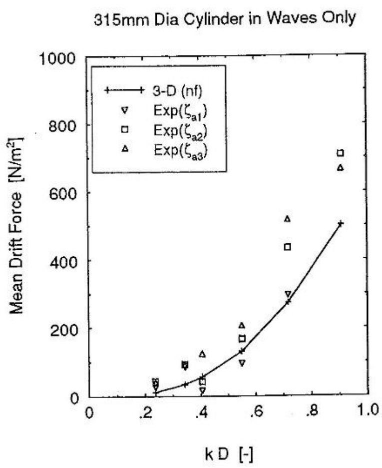

Figure 3 A Large Cylinder in Waves Only at MARIN

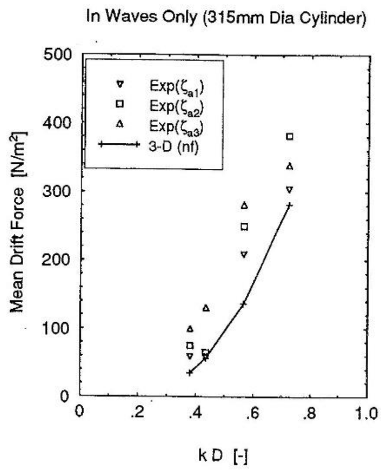

Figure 4 A Large Cylinder in Waves Only at DUT

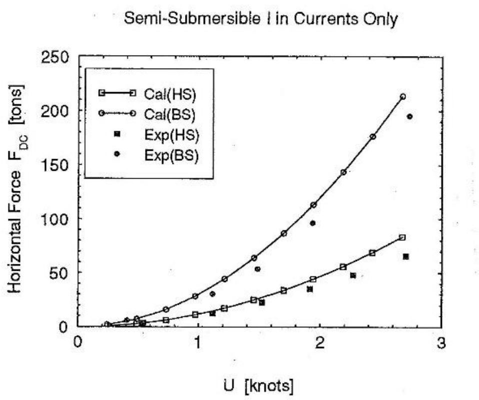

Figure 5 A Semi-Submersible in Currents

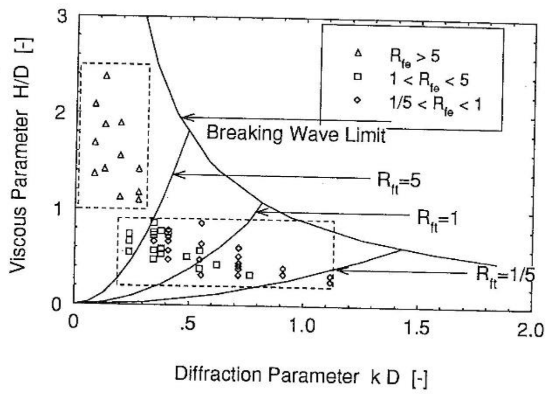

Figure 6 Potential vs. Viscous Effects for the Splash Zones of both Cylinders in Waves Only

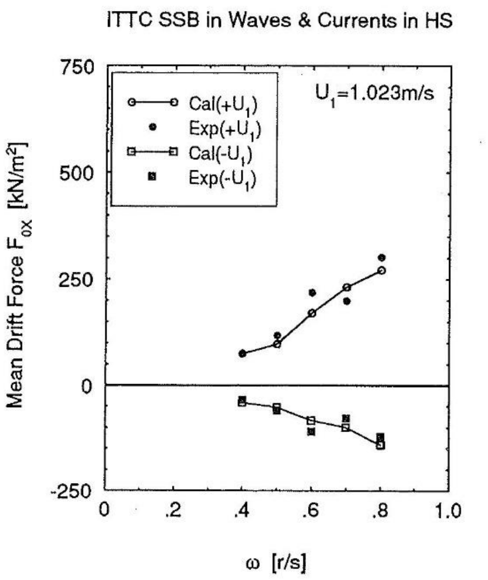

Figure 7 A Semi-Submersible in Waves and Currents in Head Seas

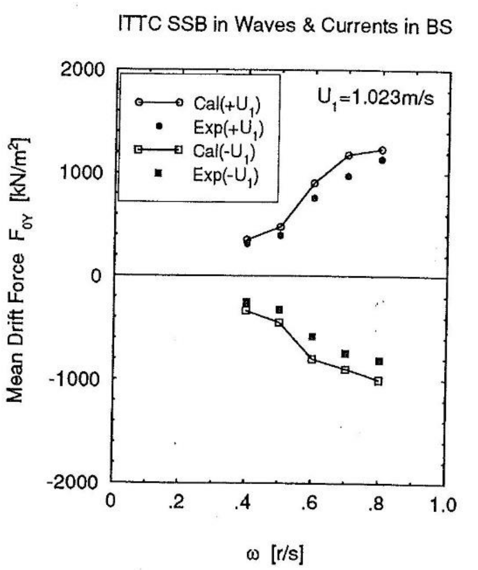

Figure 8 A Semi-Submersible in Waves and Currents in Beam Seas

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The Need for Ethical Hacking in the Maritime Industry

ABSTRACT

The recent cyber attacks on shipping companies and ports had caused considerable losses financially as well as in reputation for those organizations affected. Going forward, the number of cyber attacks is more likely to increase and also likely to get much worse. The maritime industry is considered too slow in gearing up to face cyber risks. This article will provide an overview of a cyber security management framework that a shipping company can adopt; the possible types of cyber attacks and the counter-measures that can be taken; and also discuss why it is useful for shipping companies to carry out ethical hacking (penetration testing).

1. INTRODUCTION

On 20 September 2018, the Port of Barcelona announced that it had fallen victim to a cyber attack and warned that its operations could be subject to delay while officials resolved the situation. Less than a week later on 25 September 2018, the Port of San Diego also declared that it suffered a cyber attack though ships have been able to enter and leave as normal (Johnson, 2018).

The 'notPetya' ransomware cyber attack on Maersk Line and its related AP Moller container terminals in June 2017 cost the group between US$200 to 300 million (Dixon, 2018). Just one month later in July 2017, another well-known shipping group BW was targeted by hackers. A BW Group spokesperson confirmed that there was unauthorised access and actions had been taken to rectify the matter. The spokesperson did not provide further information on any financial or data loss due to the unauthorised external access (Wainwright, 2017).

Figure 1: *'notPetya' Ransomware*

Cyber attacks in the maritime industry are not new as going back to the last few years, an organised gang hacked computers in the Port of Antwerp for two years to carry out smuggling of drugs and guns before the crime was discovered in 2013. It was also reported that the Global Positioning Satellite (GPS) signals to ships in the Port of Incheon had been blocked by a neighbouring country. According to Bray, known attacks were few and hard to find but actual incidents could have been under-reported due to fears on the part of owners and operators of alarming investors, regulators and underwriters (Bray, 2015).

Einarsson and Maltho also believed that cyber crimes were under-reported probably due to the victims not wanting to attract other hackers, having no knowledge of the attack, or being unable to stop the attack. They also cited an attack that caused a floating oil platform to tilt to one side, as well as the use of hackers by Somali pirates to infiltrate shipping company's cyber systems to identify vessels passing through the Gulf of Aden with valuable cargoes and minimal onboard security which led to the hijacking of at least one vessel (Einarsson and Maltho, 2016).

There were also unconfirmed reports of GPS interference, which is also known as GPS spoofing, near Jeddah Port, Saudi Arabia on October 15th and 18th, 2018 received by the Maritime Administration (MARAD) of the United States Department of Transportation. According to MARAD, this interference has resulted in either inaccurate positions or no position and vessels were advised to exercise caution when transiting this area (MARAD, 2018).

Going forward, the number of cyber attacks is more likely to increase as Graham of CNBC has reported that the "number of devastating cyber attacks is surging and it's likely to get much worse" (Graham, 2017). This sentiment is also echoed by MacAskill of the Guardian, who reported that "UK businesses face growing threat from cyber-attacks" (MacAskill, 2018). Based on the above reports and cyber attacks, one would have thought that the maritime industry would be well prepared for future attacks but according to Philp Roche, a partner of Norton Rose Fulbright, "the shipping industry is too slow in gearing up to face the cyber risk and deal with the forthcoming regulatory changes around cyber" (Safety4Sea, 2018).

Similar findings from an inaugural Maritime Cybersecurity Survey carried out by US law firm Jones Walker revealed that most maritime businesses in the US were ill prepared against a significant attack, with only 45% using encrypted data. Further, 20% had undergone a data security systems audit in the past year and only a third conducted annual testing. While all large companies reported regular cybersecurity training for employees, only 11% of small firms and 57% of medium-sized ones offered such guidance (Juliano, 2018).

This article provides an overview of a cyber security management framework; the possible types of cyber attacks and the counter-measures that can be taken; and discusses why it is useful for shipping companies to carry out ethical hacking (penetration testing). It is organised into five main sections: Introduction; Overview of a Cyber Security Management Framework; Types of Cyber Attacks and Their Counter-Measures; Ethical Hacking, and Concluding Remarks and Recommendations.

2. OVERVIEW OF A CYBER SECURITY MANAGEMENT FRAMEWORK

2.1 National Institute of Standards and Technology (NIST) Cybersecurity Framework

The National Institute of Standards and Technology (NIST) is an agency of the United States Department of Commerce. NIST works with the private sector, other government agencies, and universities to develop and apply the technology, measurements and standards needed for new and improved products and services (NIST, 2009).

In February 2014, the NIST issued version 1.0 of its Cybersecurity Framework. It has been revised in April 2018 to version 1.1. The Framework is a risk-based approach to managing cybersecurity risk, and is composed of three parts: the Framework Core, the Framework Implementation Tiers, and the Framework Profiles. The Framework Core consists of five concurrent and continuous functions: Identify, Protect, Detect, Respond, and Recover. When considered together, these functions provide a high-level, strategic view of the lifecycle of an organization's management of cybersecurity risk. The Framework Implementation Tiers are used by an organization to clarify for itself and its partners how it views cybersecurity risk and the degree of sophistication of its management approach. A Framework Profile is a list of outcomes that an organization has chosen from the categories and subcategories, based on its needs and risk assessments (NIST, 2018a).

Figure 2: *NIST Cybersecurity Framework Source: (NIST, 2018b)*

2.2 International Maritime Organization (IMO) Guidelines on Maritime Cyber Risk Management

The Facilitation Committee and the Maritime Safety Committee of the IMO approved the Guidelines on Maritime Cyber Risk Management on 5 July 2017 after having considered the urgent need to raise awareness on cyber risk threats and vulnerabilities. The Guidelines provided high-level recommendations on Maritime Cyber Risk Management to safeguard shipping from current and emerging cyber threats and vulnerabilities. The Guidelines also included the following functional elements that are based on NIST's Framework Core:

1. Identify: Define personnel roles and responsibilities for cyber risk management and identify the systems, assets, data and capabilities that, when disrupted, pose risks to ship operations.
2. Protect: Implement risk control processes and measures, and contingency planning to protect against a cyber-event and ensure continuity of shipping operations.

3. Detect: Develop and implement activities necessary to detect a cyber-event in a timely manner.
4. Respond: Develop and implement activities and plans to provide resilience and to restore systems necessary for shipping operations or services impaired due to a cyber-event.
5. Recover: Identify measures to back-up and restore cyber systems necessary for shipping operations impacted by a cyber-event (IMO, 2017a).

2.3 The Guidelines on Cyber Security Onboard Ships

The second edition of The Guidelines on Cyber Security Onboard Ships was released in July 2017 shortly after the IMO's Guidelines on Cyber Risk Management were adopted. The updated edition was supported by BIMCO, CLIA, ICS, Intercargo, Intertanko, OCIMF and IUMI. It was also aligned with the IMO guidelines and provided practical recommendations on maritime cyber risk management covering both cyber security and cyber safety. The NIST framework was also used during the development of these guidelines. The development, understanding and awareness of key aspects of cyber security and safety found in the guidelines are highlighted in Figure 3 below (Safety4Sea, 2017, BIMCO, 2017).

2.4 Code of Practice - Cyber Security for Ships

This Code of Practice (CoP) was published by Institution of Engineering and Technology (IET), United Kingdom (UK) and commissioned by the Department for Transport (DOT), UK. According to the CoP, it should be read by board members of organisations with one or more ships, insurers, ships' senior officers and those responsible for the day-to-day operation of maritime information technology (IT), operational technology (OT) and communications systems. The CoP does not set out specific technical or construction standards for ship systems, but instead provides a management framework that can be used to reduce the risk of cyber incidents that could affect the safety or security of the ship, its crew, passengers or cargo. In the CoP, there is also a reference to the cyber security assessment (CSA) and relationship of this CSA to the ship security assessment (SSA) and ship security plan (SSP) that are required by the International Ship and Port Facility Security (ISPS) Code is illustrated in Figure 4 below (IET, 2017).

Figure 3: *Cyber security approach as set out in the guidelines Source: (BIMCO, 2017)*

2.5 Remarks on Cyber Security Management Framework

From the abovementioned NIST Cybersecurity Framework, its related guidelines and the IET's CoP, it could be confusing as to which framework a shipping company should adopt for its cybersecurity.

IET's CoP considers cybersecurity related to a vessel's ship security assessment (SSA) and ship security plan (SSP). Any amendment to the SSP will require the approval of the Recognised Security Organisation (RSO) under the ISPS Code and this may not be practical if new types of cyber risks are discovered on a frequent basis.

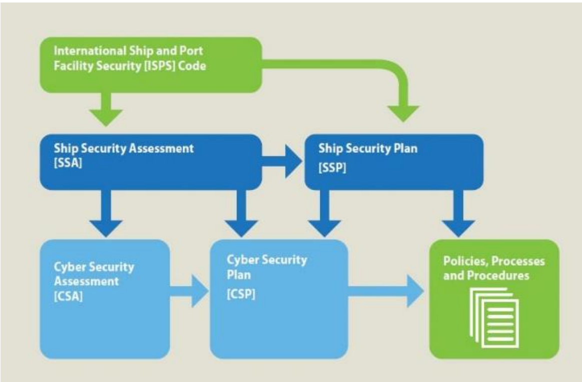

Figure 4: *Relationship of the CSA and CSP to other documents Source: (IET, 2017)*

Although it can be strongly argued that cybersecurity should be part of an overall ship's security plan however, the IMO has decided that cybersecurity will become part of the International Safety Management (ISM) code from 2021 and has encouraged flag and port states to address cyber risks "no later than the first annual verification of the company's document of compliance after 1 January 2021" (IMO, 2017b).

With this upcoming change to the ISM Code and the Oil Companies International Marine Forum's (OCIMF) Tanker Management and Self-Assessment (TMSA) version 3 that already came into effect on 1 January 2018 and which requires tanker operators who are subscribed to the Ship Inspection Reporting Programme (SIRE) programme, to incorporate cyber risk security policies and procedures within the company/vessel's operating procedures, the need for cyber risks to be addressed by senior management in a top-down approach such as the IMO and BIMCO guidelines will increase significantly.

3. TYPES OF CYBER ATTACKS AND THEIR COUNTER-MEASURES

3.1 Footprinting (Reconnaissance)

Footprinting is the process of collecting as much information as possible about a target network; the purpose is for the hacker to identify ways to intrude into the network and is first step of any attack.
There are many methodologies in footprinting and these include through Search Engines, Website, Email, Network, and Social Engineering. A brief description of each methodology as is as follows:

1. *Search Engines*

   Attackers use search engines to extract information about a target such as technology platform, employee details etc which helps in performing social engineering and other types of advanced system attacks. Search engine caches and internet archives may also provide sensitive information that has been removed from the web.

2. *Website*

   Website footprinting refers to monitoring and analyzing the target's website for information. From the website, the attacker may be able to find out what are the software used and its version, the operating system used, sub-directories and parameters, scripting platform etc. An attacker can also use an application such as Website Informer to view the Webpage header to find out the web server in use and its version, last modified information, connection status and content-type etc. An attacker can also use Web spiders to perform automated searches on the website and collect specific information such as employee names and email addresses, and use the collected information to perform further footprinting and social engineering attacks.

3. *Email*

   From the header of an email, an attacker can collect information such as the address from which the message was sent, the Sender's IP address, the Sender's mail server, authentication system used by Sender's mail server, and Sender's full name. Using email tracking tools such as Email Lookup, Trace Email etc, and the attacker can even find out the physical location of the email server. This information again will allow the attacker to make use of it later during social engineering attacks.

4. Network

   Network footprinting such as network range information assists an attacker to create a map of the target network. The range of IP addresses can be found by using ARIN Whois database search tool as well as from the Regional Internet Registry. An attacker can also conduct traceroute to extract information about the network such as network topology, trusted routers and firewall locations.

5. *Social Engineering*

   Social Engineering is an art of exploiting human behaviour to extract confidential information such as userid, password and even credit card details. A social engineer will prey on a person who is unaware of his/her valuable information and who is careless about protecting it. Some of the social engineering techniques include eavesdropping, shoulder surfing, and impersonation.

Footprinting countermeasures include:

a) Restricting employees to access social networking sites from the network inside the organization.
b) Configuring the web server to avoid information leakage.
c) Educating employees to use pseudonyms on blogs and forums.
d) Limiting the amount of information published on website.
e) Educating employees about various social engineering tricks and risks.

3.2 Scanning of Networks

Network scanning refers to a set of procedures for identifying hosts, ports and services in a network. It is one of the components of reconnaissance an attacker uses to create a profile of the target. The objectives of network scanning include discovering the operating systems and system architecture; the live hosts, their IP addresses and open ports; the services running on the live hosts; and their vulnerabilities. Some of the possible tools used by an attacker include Nmap Zenmap and NetScan Tools.

Countermeasures for Port Scanning include:

a) Configuring the Firewall and Intrusion Detection System (IDS) rules to detect and block probes.
b) Running the port scanning tools against hosts on the network to determine whether the Firewall properly detects the port scanning activity.
c) Ensuring that router, IDS, and Firewall firmware are updated to their latest releases.
d) Using custom rule set to lock down the network and block unwanted ports at the Firewall.
e) Ensuring that the anti-scanning and anti-spoofing rules are configured.

3.3 Network Enumeration

Network enumeration is a process that involves gathering information about a network such as the hosts, connected devices, along with usernames, group information and related data. Using protocols like Internet Control Message Protocol (ICMP) and Simple Network Management Protocol (SNMP), network enumeration offers a better view of the network for the attacker.

During the enumeration phase, the attacker creates active connections to the system and performs directed queries to gain more information about the target. The attacker uses extracted information to identify system attack points and perform password attacks to gain unauthorised access to information system resources. These enumeration techniques are conducted in an Intranet environment, meaning that the attacker has already gotten into the organisation's private network through a gateway and firewall.

Countermeasures for Enumeration include:

a) Removing the SNMP agent or turning off the SNMP service. SNMP is a popular protocol for network management.
b) Disabling the Domain Name System (DNS) zone transfers to untrusted hosts. DNS is a hierarchical decentralized naming system for computers, services, or other resources connected to the Internet or a private network.
c) Making sure that the private hosts and their IP addresses are not published into DNS zone files of public DNS server.
d) Configuring Simple Mail Transfer Protocol (SMTP) server to ignore email messages to unknown recipients and not including sensitive mail server and local host information in mail responses. SMTP is an Internet standard for electronic mail (email) transmission.

e) Using Secure Sockets Layer (SSL) technology to encrypt Lightweight Directory Access Protocol (LDAP) traffic. SSL is a standard security protocol for establishing encrypted links between a web server and a browser in an online communication. The LDAP is an open, vendor-neutral, industry standard application protocol for accessing and maintaining distributed directory information services over an Internet Protocol (IP) network.
f) Disabling Server Message Block (SMB) protocol on Web and DNS servers. SMB is a network protocol used by Windows-based computers that allows systems within the same network to share files. It allows computers connected to the same network or domain to access files from other local computers as easily as if they were on the computer's local hard drive.

3.4 System Hacking

After completing the stages of footprinting, scanning and enumeration, the attacker is now ready to embark on the next stage of system hacking. At this stage, the attacker's goals are to bypass the access controls to gain access into the system; acquire the rights of a system administrator; create and maintain remote access to the system; hide the attacker's malicious activities and data theft; and hide the evidence of the compromise of the system. Some of the techniques or tools used include password cracking, Trojans, spywares, keyloggers, Rootkits, steganography, and clearing of logs.

Countermeasures for System Hacking include:

a) Enabling information security audit to monitor and track password attacks; not allowing the same password during password change; not allowing passwords that can be found in dictionary; setting frequent password change policy; and not using any systems' default passwords.
b) Restricting the interactive logon privileges; using encryption technique to protect sensitive data; implementing multi-factor authentication and authorization; and patching the system regularly.
c) Using pop-up blocker to defend against keyloggers; installing and keeping anti-spyware and antivirus program up to date; installing professional firewall software and anti-keylogging software; recognizing phishing emails and deleting them; and not clicking on hyperlinks in doubtful emails that could point to malicious websites.
d) Avoiding using any computer system which is not totally under your control to defend against any Spyware; adjusting browser security settings to medium or higher for Internet zone; and installing professional firewall software with outbound protection.
e) Using an integrity-based detection to compare a snapshot of the file system, boot records, or memory with a known trusted baseline in detecting rootkits; performing kernel memory dump analysis to determine the presence of rootkits; reinstalling the operating system from a trusted source if rootkit is detected; and updating and

patching operating systems and applications regularly.

4. ETHICAL HACKING

4.1 What is Ethical Hacking?

Ethical hacking, also known as penetration testing (Pen Test), is an act of penetrating into system or network to find out threats, vulnerabilities in those systems which a malicious attacker may find and exploit causing loss of data, financial loss or other major damages. Ethical hackers may use the same methods and tools used by the malicious hackers but with the permission of the authorized person for the purpose of improving the security and defending the systems from attacks by malicious users (Greycampus, 2018).

A security audit only checks whether an organisation is following a set of standard security policies and procedures while a vulnerability assessment focuses on discovering the vulnerabilities in the system but provides no indication if the vulnerabilities can be exploited . Pen Test is a methodological approach to security assessment that encompasses the security audit and vulnerability assessment and demonstrates if the vulnerabilities in the system can be successfully exploited by attackers. Figure 5 below shows a shipboard vulnerability spot-checking of most critical IT/OT systems using Pen Test.

Figure 5: Vulnerability spot-checking of most critical IT/OT systems using Pen Test (Rossi,Einarsson and Perez, 2018)

4.2 How a Pen Test may be conducted?

1) Pen Test Service Agreement

Before a Pen Test is to be carried out, there has to be an agreement for such a service between the client and the Pen Tester. The agreement will include for example:

a) That the client has the legal right to the designated computer system for the Pen Test
b) That the Pen Tester will not divulge any information about the client's network it received as a result of the Pen Test.
c) The conditions of the Pen Test such as the IP addresses, if it is a white box testing. Unlike black box testing, which the client gives the tester no information about the systems, so that the tester has to start by using footprinting techniques to try and find out about them; in white box testing,

the client shares in-depth knowledge of the internals of the systems that are being tested. That understanding is used to simulate attacks that directly assess how secure the systems actually are (Gargiullo, 2017).

d) A network diagram to be provided in the Pen Test report.

2) Network Diagram of the System that has been Pen Tested

Figure 6 below shows a sample Network Diagram of the System that is being Pen Tested. The Pen Tester has been given permission to get into the network of the client and carried out a Pen-Test specifically on the workstation with the IP address of 192.168.1.16.

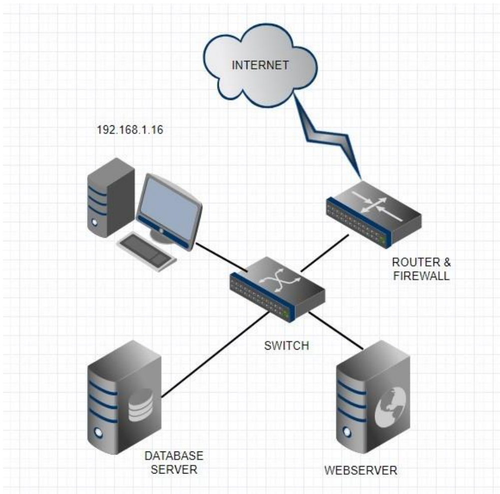

Figure 6: *A Sample Network Diagram of the System that is being Pen Tested*

3) Scanning for Open Ports

After gaining access to the specific workstation, the Pen Tester could use a tool such as NMAP Zenmap to scan for open ports on the workstation. Figure 7 below shows the results of NMAP Zenmap carried out on the selected workstation. It can be seen from the results that there are 3 open ports, namely 135/tcp, 139/tcp and 145/tcp out of 1000 ports.

Remote Procedure Call (RPC) allows a program running on one computer to execute code on a remote system and Microsoft operating systems use RPC on port 135/tcp. There has been several serious security issues linked to Microsoft's RPC services, including denial of service (DoS) issues, arbitrary code execution and privilege escalation.

NetBIOS is a protocol used for File and Print Sharing under Windows. NETBIOS Session Service uses port 139/tcp and there are a number of vulnerabilities associated with leaving this port open. The following trojans/backdoors use this port: Chode, God Message worm, Msinit, Netlog, Network, Qaz, W32.HLLW.Moega, and W32.Reidana.A.

UAAC protocol uses port 145/tcp and although there is not much vulnerability associated with this port but leaving it open could allow a worm such as W32.spybot to exploit.


```
Starting Nmap 6.46 ( http://nmap.org ) at 2017-10-04 22:54 China Standard Time
NSE: Loaded 118 scripts for scanning.
NSE: Script Pre-scanning.
Initiating ARP Ping Scan at 22:55
Scanning 192.168.1.16 [1 port]
Completed ARP Ping Scan at 22:55, 0.13s elapsed (1 total hosts)
Initiating Parallel DNS resolution of 1 host. at 22:55
Completed Parallel DNS resolution of 1 host. at 22:55, 0.03s elapsed
Initiating SYN Stealth Scan at 22:55
Scanning 192.168.1.16 [1000 ports]
Discovered open port 135/tcp on 192.168.1.16
Discovered open port 139/tcp on 192.168.1.16
Discovered open port 445/tcp on 192.168.1.16
Completed SYN Stealth Scan at 22:55, 1.20s elapsed (1000 total ports)
Initiating Service scan at 22:55
Scanning 3 services on 192.168.1.16
Completed Service scan at 22:55, 6.08s elapsed (3 services on 1 host)
Initiating OS detection (try #1) against 192.168.1.16
NSE: Script scanning 192.168.1.16.
Initiating NSE at 22:55
Completed NSE at 22:55, 22.09s elapsed
Nmap scan report for 192.168.1.16
Host is up (0.00s latency).
Not shown: 997 closed ports
PORT    STATE SERVICE      VERSION
135/tcp open  msrpc        Microsoft Windows RPC
139/tcp open  netbios-ssn
445/tcp open  microsoft-ds Microsoft Windows XP microsoft-ds
MAC Address: 00:0C:29:C6:30:02 (VMware)
Device type: general purpose
Running: Microsoft Windows XP|2003
OS CPE: cpe:/o:microsoft:windows_xp cpe:/o:microsoft:windows_server_2003
OS details: Microsoft Windows XP SP2 or SP3, or Windows Server 2003
Network Distance: 1 hop
TCP Sequence Prediction: Difficulty=258 (Good luck!)
IP ID Sequence Generation: Incremental
Service Info: OS: Windows; CPE: cpe:/o:microsoft:windows

Host script results:
| nbstat: NetBIOS name: HACKER, NetBIOS user: <unknown>, NetBIOS MAC: 00:0c:29:c6:30:02
| Names:
|   HACKER<00>          Flags: <unique><active>
|   HACKER<20>          Flags: <unique><active>
|   BELLY-VMW<00>       Flags: <group><active>
|_  BELLY-VMW<1e>       Flags: <group><active>
| smb-os-discovery:
|   OS: Windows XP (Windows 2000 LAN Manager)
|   OS CPE: cpe:/o:microsoft:windows_xp::-
|   Computer name: HACKER
|   NetBIOS computer name: HACKER
|   Workgroup: BELLY-VMW
```

Figure 7: Results of NMAP Zenmap carried out on selected workstation

4) Scanning for Vulnerabilities

Next, the Pen Tester could use Nessus to carry out the scanning of vulnerabilities on the workstation. Figure 8 shows the results of Nessus scan carried out on selected workstation. The results of the Nessus Scan are 5 Critical Vulnerabilities and 1 High Risk Vulnerability. Based on the vulnerabilities found, the Pen Tester will then recommend to the client in his report what actions can be taken to improve on the security of the system.

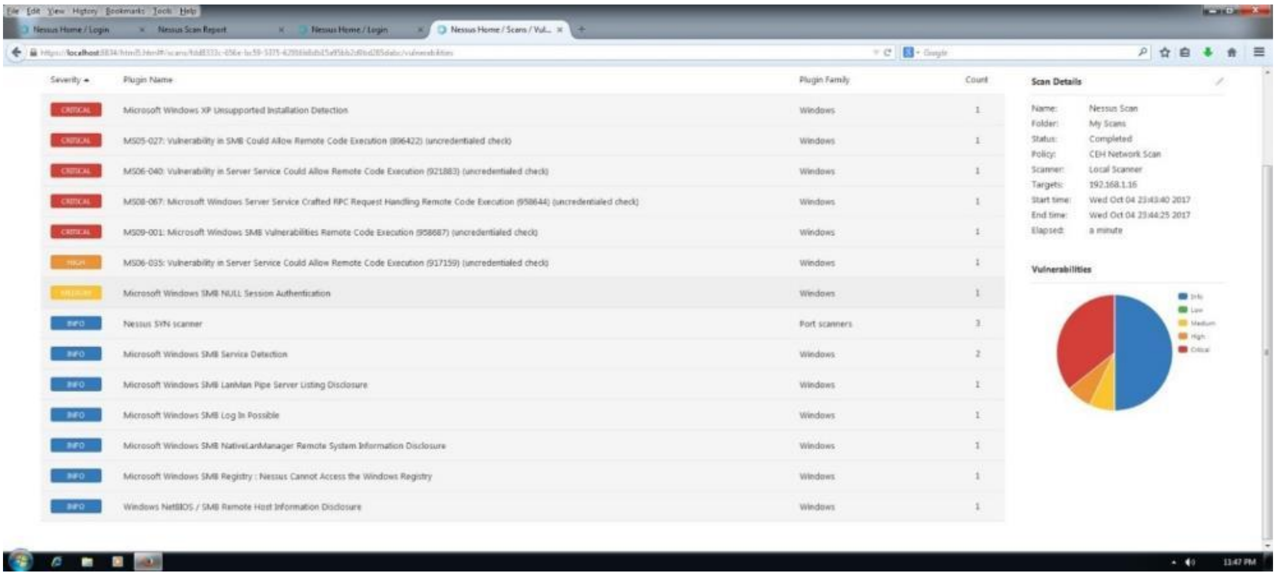

***Figure 8**: Results of Nessus scan carried out on selected workstation*

4.3 Remarks on Pen Test

The above example Pen Test is not comprehensive of an actual test carried out by qualified cyber security experts but it is just to give the reader an idea of what Pen Test can do to improve the security of the network or systems by fixing the vulnerabilities found during testing. Although Pen Test is unlikely to be common among shipping companies for now but it has been reported that bigger shipping companies such as Great Eastern Shipping has commissioned an independent cyber security organization to carry out an ethical hacking exercise of its on-board computer systems to assess their vulnerability (Bera, 2018).

5. CONCLUDING REMARKS AND RECOMMENDATIONS

The following can be concluded from the above findings of this article:

- The number of cyber attacks is more likely to increase and also likely to get much worse and that the maritime industry is considered too slow in gearing up to face cyber risks.
- There are cyber security management frameworks that a shipping company can adopt to incorporate cyber risk security policies and procedures within the company/vessel's operating procedures and the need for cyber risks to be addressed by senior management will increase significantly, especially with the amendment in the ISM Code coming into force.
- Ethical hacking would be useful for shipping companies in improving the security and defending the systems from attacks by malicious users by using the same methods and tools to discover the vulnerabilities of the system.
- A security audit only checks whether an organization is following a set of standard security policies and procedures while a vulnerability assessment focuses on discovering the vulnerabilities in the system but provides no indication if the vulnerabilities can be exploited. Ethical hacking is a methodological approach to security assessment that encompasses the security audit and vulnerability assessment and demonstrates if the vulnerabilities in the system can be successfully exploited by attackers.

This article, therefore, has explained why ethical hacking would be useful to shipping companies in improving the security and defending the systems from attacks by malicious users by using the same methods and tools to discover the vulnerabilities of the system. It is recommended that further research be carried out by shipping companies themselves before embarking on any penetration testing of their networks, be it in the offices or on board their vessels as the author has barely scratched the surface of cyber attacks and security. The intention of the author is only to provide an introduction of ethical hacking to the readers and why it could be useful for shipping companies to prevent a serious cyber security incident from taking place.

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Machine Learning to Avoid Ship Collision – Agent-based Model

Abstract

The safety of sea traffic is a primary concern for various transportation means. Ship collision avoidance is regulated by the Convention on the International Regulations for Preventing Collisions at Sea, 1972 (COLREGs) under open sea areas. Hence, a general overview of the COLREGs and its implementation challenges, i.e. regulatory failures and violations, under autonomous ships are also discussed with the possible solutions as the main contribution of this study.

The Automatic Identification System (AIS) tracks vessel movement by means of electronic exchange of navigation data between vessels, with onboard transceiver, terrestrial and/or satellite base stations. The gathered data contains a wealth of information useful for maritime safety, security and efficiency. The AIS data sources and relevant aspects of navigation by International Maritime Organization (IMO) are utilized for collision avoidance. By implementing Agent Based Model, simulations were performed to evaluate the probability of conflict along with a cost associated to a specific trajectory. This work provides two main contributions: (1) recognition of AIS data, (2) development of a simulation via Agent Based Model to emulate vessels dynamics. Thereafter, case study for the tankers in Singapore Strait is carried out to illustrate the capability of the coding and the simulation.

Keywords
Machine Learning; Agent Based Model; Collision avoidance.

1. INTRODUCTION

Ocean navigation risk has been a hot subject in maritime industry as the fact that it is coupled with transport safety, shipping efficiency, distribution reliability and the prevention of loss. The intelligent guidance in maritime transportation is still underdeveloped when compared with the land and air transportation systems.

To avoid collision between vessels, all vessels should follow the same law of the sea. The current law of the sea was formulated by the International Maritime Organization (IMO) in 1972 by the Convention on the International Regulations for Preventing Collisions at Sea (COLREGs). However, the reported data of the maritime collisions presented [2] showing that 56% of major maritime collisions involve violation of the COLREGs rules and regulations. The detailed description of the COLREGs rule and regulations and their interpretation for autonomous ocean navigation with respect to the collision avoidance are presented [1] .Real-time and historical AIS data contains potentially useful markers for the early identification of anomalous activities or vessels and collision risk. There are also challenges in extracting knowledge from AIS data arising from the volume of the data, incompleteness, noise, rogue/dark vessels etc [4]. Significant work has been done in the maritime intelligent technology community on extracting valuable information from AIS data. All above mentioned systems and devices depend significantly on data obtained from the Automatic Identification System (AIS) whose main transmitted data are summarized in Table 1.

Table 1: AIS data

STATIC DATA	Ship NAME Ship LENGTH Ship BREADTH Ship TYPE
DYNAMIC DATA	Ship POSITION LONGITUDE Ship POSITION -LATITUDE Ship SPEED over GROUND Ship COURSE over GROUND

ın the current work, the procedure is to learn the behavioral model of ship captain from historical AIS data in order to construct a collision avoidance system able to suggest safe maneuvering strategies to the pilot in order to guarantee low conflict probability while keeping the distance from the intended path as low as possible. The system is meant to be installed on board of each vessel, thus implementing a distributed control. This objective has also been predicted by Enmei Tu for the safety of vessels [4].

1.1. Work Background

Grounding in the numerous developed technologies for enhancing data exchange, the more general paradigm of e-navigation has started to acquire increasing attention at national, regional and global level as a strategy for enhancing information sharing for improving navigation safety and environmental efficiency. Specifically, e-navigation is a Strategy developed by the International Maritime Organization (IMO), a UN specialized agency, to bring about increased safety of navigation in commercial shipping through better organization of data on ships and on shore, and better data exchange and communication between ships and the ship and shore. Despite the important effort exerted by the authority in the direction of improving navigation safety, the number of conflicts is still high due to the tremendous traffic intensity. As highlighted in several works [3],there is a rising trend in the number of shipping incidents and accidents. It is found that the average number of conflicts occurring at the Singapore Strait is about 2000 per month. The collision between two bulk carriers in the Singapore Strait on Feb 10, 2014 which was the third collision in 13 days resulting in a total of 680 metric tons of fuel being spilled [3]. This has motivated the development of several studies on traffic safety for maritime navigation. The development of navigational decision support systems is a recent topic in the maritime sector. In Norway, a reference group was set up to gather information on known issues of safety at sea and new challenges that could be related to a forecast increase in petroleum and shipping activities in the High North. Subsequently, several follow-up works on safety at sea in high north waters were launched: (1) MARSAFENORTH (Maritime Safety Management in the High North), and (2) BARENTS Secretariat Project. Other works concerning e-navigation and the so called S-Mode have been proposed. S-Mode refers to the standardized display for an integrated information collection increasing the effectiveness of the available technologies to the bridge team. An example is the Baltic Sea Safety project (BaSSy) at Chalmers University, Sweden. S-Mode is a proposal to balance the need for standardization with the need to promote innovation in the development and manufacture of navigation systems. Nevertheless, the representation of the behavioral model for ship captains still represents an open research field. It can be argued how a behavioral model is at the basis for safety characterization as well as effective collision avoidance.

In 2008, Statheros et al. [2] give an overview of computational intelligence techniques that are used in collision avoidance in ocean navigation. Liu and Liu (2006) used Case-Based Reasoning to illustrate learning of collision avoidance techniques in ocean navigation using previous recorded data of collision situations. Furthermore, an intelligent anti-collision algorithm for different collision conditions is designed and tested on the computer based simulation platform by Yang et al. (2007). Zhuo and Hearn (2008) presented a study of two vessel collision avoidance in ocean navigation using a self learning neuro-fuzzy network based online and offline training scheme.

A fuzzy logic approach for collision avoidance conditions with the integration of a virtual force field is proposed by Lee et al. Similarly, automatic collision avoidance facilities for ship system using a fuzzy logic based controller is proposed by Hasegawa. Benjamin et al. propose behavior based controls formulated with interval programming for collision avoidance of maritime transportation. The collision avoidance behavior is illustrated in accordance with the Coast Guard Collision Regulations. Benjamin and Curcio present the decision making process of ocean navigation based on an interval programming model for a multi-objective decision making algorithm.

A machine learning algorithm has been developed to learn patters of mariners from AIS data, thus enabling the design of an agent based simulation model. In fact, historical data provide information on real situations and, in this sense, they maybe more reflective than the same information gathered from training simulators;

An agent based simulation model

is created which makes use of the statistical information generated by the machine learning phase to reproduce the dynamics and the interactions of the different vessels. As a result of these improvements, for the first time in maritime CA, our method makes use of agent based modeling (ABM) as the basis to a meta-model based CA procedure. Using the ABM gives more precision that using stochastic processes (as it is done in the literature for CA), this is due to the fact that we are allowed to perform a bottom up study of the vessel behavior instead of assuming a specific statistical structure describing it (e.g., Markov processes, random walks). The use of simulation is a key aspect already in the work of [4] as it gives the possibility to look ahead in the time horizon to estimate the non-observable future system states.

2.1. Simulation with Case Study

The simulation work in this paper can be summarized in the next three points:

1. A new systematic approach to learn the behavior of vessel captains in crowded waters;

An agent based simulation model which embeds the statistical learning models and reproduces the dynamic interaction between vessels;

A new collision avoidance strategy generation engine which uses Agent Based Simulation as the basis of a decision support system which improves safety. Concerning the first and second contributions, we define new criteria which enable the clustering of historical trajectories. Being a bottom-up, data-driven, approach, it can applied to learn behavior in real-environments in an automated way, i.e., without any human intervention or behavioral assumption. Indeed, the use of patterns and Agent Based Model based on the analysis of the minimum distance between vessels, led to reflect the real behavior in a specific region. Related to the last point, we show how to incorporate the learned behavioral model into the agent based simulator and we use the Singapore strait as a real implementation example. Concerning the Collision Avoidance part, we enable a *real-time* application, by proposing a framework, which incorporates the simulator with the real time AIS updates. Specifically, to enable safe navigation, the CA approach leverages on the simulator and uses a meta-model based algorithm to determine the safest and most efficient strategy, where the efficiency is characterized through the dissimilarity from the original intended path of the pilot. In this regard, a new multi-objective optimization criterion for safe trajectory is developed for the solution of this optimization problem [5].

In order to implement the proposed approach, we will refer in this manuscript to data coming from the west sector of the Singapore Strait (Figure1). In 1998, the IMO enforced the Mandatory Ship Reporting System in the Straits of Malacca and Singapore (STRAITREP) which divided the Straits into 9 reporting sectors.

Among the 9 sectors, sectors 7 to 9 are controlled by Singapore Vessel Traffic Service (VTS) under the Maritime and Port Authority of Singapore (MPA).

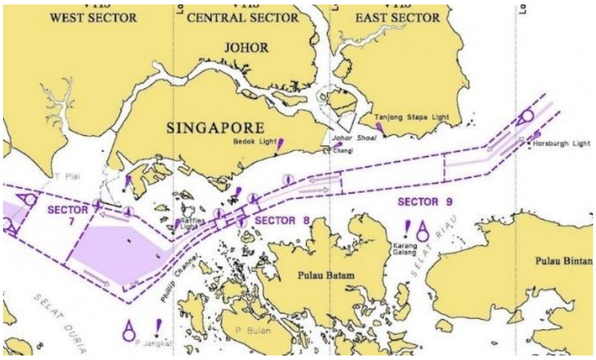

Figure 1: *The Singapore Strait [5]*

In order to present the proposed approach, the remainder of the paper is structured as follows: section 2 presents the main approaches in the literature as well as the main software available to mariners as support in collision avoidance tasks. Subsequently, section3detailed the proposed simulation based approach. In particular, section3.1details the construction of the Agent Based Model, while section3.4presents the multi-objective meta-model based collision avoidance procedure. The results for the methodology are shown over historical sample paths in the Singapore Strait in section5. Finally, section6closes the paper presenting directions for future development.

2.2. Collision avoidance at sea

Ship domain is the smallest safety region around a ship that allows navigator to take a timely action to avoid any potential collision. Any violation of the ship domain is interpreted as a threat to navigational safety and may cause a collision. So the definition of ship domain is not only very important for collision detection, but also is a collision risk assessment method. Actually, it has been recognized that limited work has been done to apply them for active inference and analysis as well as generation of maneuvers in intense traffic areas. In particular, the authors highlight how the introduction of AIS has replaced the previous scarcity of ship traffic and maneuver data with an overabundance. Whereas one previously had to construct limited shore based measurement systems with limited lifespan or rely on data from a selected set of vessels with logging equipment, AIS provides a continuous stream of information of the position and speed all AIS enabled vessels in range. The system provides position and speed updates on predefined intervals depending on vessel speed and maneuver situation with a sample rate varying from 3 seconds for high speed or turning vessels to 15 min for ships at anchor.

2.3 Behavioral Modeling and Collision Avoidance

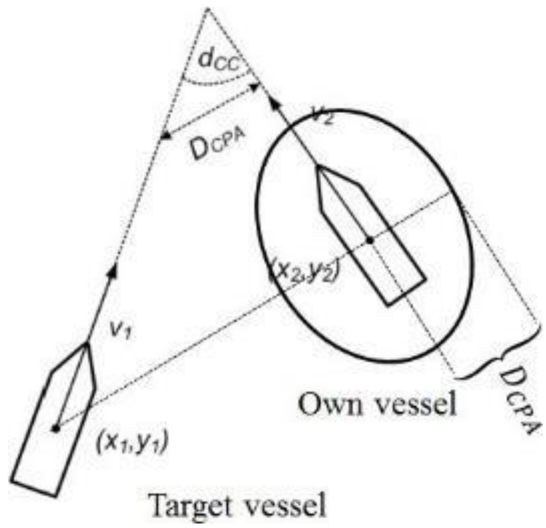

Figure 2: *Ship Domain (elliptical shape) and Conflict Definition*

Traffic simulation for road traffic has received a remarkable attention. In general, the problem becomes considerably more difficult when, as in the case of concern in this work, obstacles are dynamic. When moving objects are present in the environment it becomes necessary to predict their behavior.

2.4. Agent Based Model

It is believed that this approach can also satisfy the respective milestones, appropriately. An agent can be defined as a system located in a specific environment, therefore it interacts with the environment by intelligent decisions and actions to satisfy its design objectives[3]. However, other similar and/or different agents can also be located within the same environment, where these agents should interact. Therefore, various cooperative and non-cooperative interactions among these agents are expected in this same environment. However, each agent may have its own design objectives, therefore adequate intelligent to fully or partially satisfy the same should be facilitated. If individual design objectives cannot be achieved (i.e. unsatisfactory) in this environment, adequate compromising strategies to satisfy appropriate group objectives should be considered. Such situations can be categorized as a cooperative multi-agent learning approach with machine learning approaches (i.e. reinforcement learning). Therefore, adequate system intelligence in each agent should be facilitated to handle rather complex interactions among agents in the environment. It is expected that autonomous ships will be agent based systems, therefore various cooperative and non-cooperative interactions among vessels in open sea areas and traffic lanes are expected In general, such intelligent agent should have the following basic properties [3]:

- **Autonomy**: Each agent should operate by its own actions and/or internal states without the direct inference of humans or others.
- **Social-ability**: Each agent should interact with other agents (i.e. including humans) by appropriate agent-communication language.
- **Reactivity**: Each agent should not only interact with the environment but also respond to a timely fashion for the respective environmental changes and challenges.
- **Pro-activeness**: Each agent should not only interact with the environment but also take appropriate initiatives to exhibit goal-oriented behavior to satisfy its design objectives.

One should note that these properties should also be a part of future autonomous vessels. Therefore, the interactions among vessels and ocean environmental conditions can be facilitated by agent based systems. However, vessels and ship systems should have adequate ship intelligence and decision support facilities to support these agent functionalities and that can overcome the respective challenges in autonomous ship navigation.

2.5. Simulation procedure

Concerning conflict detection and resolution, currently the main available technologies are: (1) Vessel Traffic Service, (2) ECDIS for chart display, (3) AIS data, (4) ARPA for vessels tracking in encounter situations. VTS is a shore service implemented by a "Competent Authority to improve the safety and efficiency of vessel traffic and to protect the environment". It is a service that operates through VTS centers, from which VTS operators (VTSOs) inform and assist the vessel traffic in a designated area, a VTS area. VTS is normally offered in sensitive sea areas or in areas with a high traffic density and it is regulated on an international level by a legal framework of IMO guidelines and regulations, but it is implemented through national maritime administrations and organized on a local level by VTS managers and supervisors. The IMO recognizes three services a VTS center can offer: information service (INS), traffic organization service (TOS), and navigational advice and assistance (NAS). Within information service (INS), VTS operators provide general information to the vessels in the area, which can be identified as state information of the area.

This work is a first proposal to (1) provide a data-driven instead of a rule-driven behavioral model to simulate vessels, and (2) show how to effectively integrate such a model into a stochastic search procedure that can suggest avoidance maneuvering in real time. In such a setting, the development of the simulation model represents a contribution with respect to the current literature as it gives the possibility to model the ship captains as agents in the simulation. In order to meet these advancements, the proposed methodology articulates into the following main components:

- Data gathering and trajectory tracking for off-line learning of motion patterns;
- Machine learning algorithms for patterns characterization;
- Agent Based Model development for the emulation of vessels behavior;
- Design of an efficient optimization procedure to identify good maneuvering strategies.

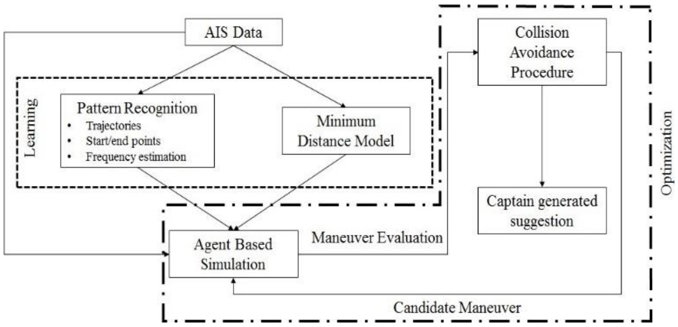

Figure 3: *Trajectory Learning and Optimization Methodology [5]*

The overall approach is represented in Figure3. The AIS data transmitted by the vessels at an certain frequency, were collected and adopted for the purpose of learning off-line the vessels behavior. Such a behavior was subsequently adopted to design an agent based simulation model, which could emulate the path of vessels moving in congested sea waters.

The ABM is the input to the Collision Avoidance Procedure that generates candidate maneuvers that are subsequently evaluated by the simulator and improved again by the optimization module.

The procedure recurs until a satisfactory solution is reached or the available time for providing the avoidance strategy is expired (in terms of number of ABM simulation replications that can be performed).

2.6 AIS Sample Data description

AIS technology is the most developed technology in the maritime environment and it has substantially enhanced navigation safety [5]. It is based on the VHF radio signal and it has been made mandatory by the International Maritime Organization's (IMO) Safety of Life at Sea (SOLAS) convention. The messages are broadcast on two VHF channels, AIS1 and AIS2, respectively 161.975 MHz and 162.025 MHz. The transponders emit on only one channel at any given time, and a message is emitted on one and only one channel. A message is encoded in Non-Return-to-Zero Inverted (NRZI) and emitted by Gaussian-Filtered Minimum Shift Keying (GMSK) at a rate of 9600 bps. The system divides the time in frames, one frame equals one minute. The clock is synchronized against the Coordinated Universal Time (UTC), typically enabled by a GPS signal, and a new frame starts at a new minute of the UTC. One frame is further divided into 2250 slots. This means that at a rate of 9600 bps, one slot is 256 bits long.

An AIS message must report the following information: the ships identity as its Maritime Mobile Service Identity (MMSI) number, ship type, position coordinates, course, speed, draft and timestamp of the message. Due to the mandatory reporting of AIS messages, we base our collision avoidance procedure on this technology. To the knowledge of the authors, this is one of the pioneering studies on the use of AIS data for behavioral learning and real time collision avoidance.

2.7 Vessel Spatial Trajectory Interpolation

In the scope of performing clustering over spatial trajectories and therefore identifying the main patterns (as prescribed by the learning algorithm in Figure 3), we needed to create connected trajectories from AIS point observations. We need to interpolate coordinates (*x*, *y*) located at constant distance. This can be non-trivial for circular trajectories. In case the distance between the two points selected on the grid is larger than one unit grid distance, grid points in between are added in a pattern of diagonal traversal. As a result, with a very dense grid, the augmentation will be close to the observed shape of the observed trajectory.

2.8 Modeling of the interactions between vessels

After the cluster centroid / protocol trajectory has been assigned to each of the endpoints, the vessel behavior can be potentially simulated. However, the geographical patterns are not enough for an accurate representation of the actual vessel movement. Indeed, each vessel will be able to change the assigned pattern.

In particular, the probability distribution of the different identified patterns was estimated by the frequency of the trajectories within each cluster. While the simulation is running, the distance of the vessel from its starting point and the current pattern are used to compute the likelihood that a vessel will take on a certain protocol trajectory pattern as shown in Vasquez and Fraichard [4]. Once a vessel is assigned to a pattern, also the speed profile will be assigned following the procedure in the previous section.

Besides the speed, the interaction of close vessels needs to be modeled to make the dynamics of the vessels movement more realistic. In particular, different vessels have to keep a safety distance between each other to ensure no collision. To reproduce this behavior, the minimum distance between vessels has to be analyzed as a function of the vessel speed and type. In order to do so, we developed an algorithm for extracting the minimum distance between vessels pairs and used such minimum distance in order to control the relative motion of the vessels in the agent based simulation model. The procedure is formalized in Algorithm 1.

Algorithm 1: Minimum Distance Computation Algorithm

```
Load Cleaned Vessel Data Points in the set A with related timestamps τi;
Sort the data according to the time stamp ;
t = minA τi, T = maxA τi, set the time widow T = 30j;
while t < T do
    for i = 1, ___ |A| : ti < t + T do
        for j = 1, ___ |A| : ti < t + T, i f=j do
            Store relative speed |vi − vj|;
            record the distance d(xi, xj);
        end
    end
    Advance time widow t ← t + T;
end
```

3 . SUMMARY

we have illustrated our bottom-up data driven approach for pilot behavioral learning based on the following steps:

1.Data Collection and cleaning for trajectory input construction;
2.End points identification for entry/exit points as well as transition points between multiple trajectory patterns;
3.Application of hierarchical clustering for spatial pattern recognition;
4.Velocity interpolation for the trajectories within the same pattern;
5.Analysis of the minimum distance for the vessels in the training set.

We highlight that the proposed procedure is robust and general. In the current implementation,

we do not use specific domain knowledge as well or dynamic models to explain vessels motion. Nevertheless, it is worthy that having good dynamic models would enrich and improve the precision of the proposed simulator without impact on the overall framework for real-time avoidance. As a result, the proposed learning approach could be potentially applied to any case where sensor data are available in an amount such to construct reliable learning models. This is true for almost all traffic systems and the amount of information from road as well as sir traffic is increasing, thus fostering approaches like the one we propose in this paper.

Table 4: Summary Results: number of detected conflicts

	D_1	M_1	M_2	C_1	C_2	C_3	C_4	C_5
Mean w/o CA	0.16	0.34	0.38	0.82	1.1	1.82	2.62	3.92
Std Error	0.51	0.59	0.6	1.02	0.93	1.21	1.66	2.32
Mean with CA	0	0	0	0	0.04	0.02	0.08	0.08
Std Error	0	0	0	0	0.2	0.14	0.34	0.27

cases with the collision avoidance procedure and without it, it is clear that while the proposed approach is not able to avoid all potential conflicts, it does manage to ensure most collisions are avoided consistently; as the surrounding area becomes more congested, the number of unavoidable conflicts increases. Even so, the data show that the collision avoidance procedure is capable of avoiding at least 95% of the potential conflicts when in place, thereby demonstrating the high potential in terms of guiding ship captains through 7 congested waterways such as that in the straits of Singapore.

4 CONCLUSIONS

Agent based model is customized to simulate the ship collision avoidance efficiently. The consideration of stochasticity of vessels behaviors and the optimization of trajectories based on a preset trajectory are two of the main contributions of this paper. This paper demonstrates that this approach allows for more complex dynamics models which account for environmental factors as well as other hardware constraints of the vessels (acceleration and turning limits) to be used, providing a more accurate prediction of the future to evaluate candidate trajectories. Specifically, we test the approach over the Singapore Strait case to show the reduction in conflicts derived from the use of the proposed algorithm. As for the Agent based Model, more complex synchronization mechanisms can be considered also taking into account COLREGs.

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Naval Architecture and Marine Engineering, Going Beyond Building Ships and Oil Rigs

Crisis the Root of Innovation

Although Archimedes discovered the principle of buoyancy about 2300 years ago, naval architecture did not appear as a formal field of study in universities until the mid-nineteen centuries. The preoccupation with most university courses was and still is on ships as a mode for transporting cargoes and passengers.

This changed when oil prices rocketed four folds in six months after the oil crisis. Naval architects, marine engineers, step out to help push boundaries to meet the challenges of extreme weather conditions to drill and process oil and gas.

The world is in crisis of a different kind: the high and rising concentration of carbon dioxide in the atmosphere and ocean. The danger with this crisis is its positive feedback, and deceptive character and may be irreversible if not addressed at its early phase.

The polar ice caps are melting at an unprecedented rate. With less ice cover at the poles, less solar heat is reflected, and the oceans gets warmer. Rising sea levels will lay waste to many low-lying coastal and riverine areas in the world where food is grown.

Naval architects and marine engineers are well equipped to rise to the challenge to prevent a catastrophic warming of the planet. They should lead an evolution where man is less reliant on land for his survival towards one where he live in harmony with the oceans.

Planet Earth's First Anthropogenic Crisis

For more than 5000 years civilisation progressed at a pace at which man's activities did no harm to the environment. The planet was able to heal itself. There was equilibrium in the dynamics of life. There was time for regeneration.

That changed when he discovered coal and then oil and gas. Suddenly the pace of change hastened like never before. Two hundred years is like a millisecond in astronomical time scale. In that millisecond this beautiful planet is at serious risk of an irreversible process which could undo four billion years' worth of evolution. The ocean and the atmosphere have become so toxic so fast that the planet is in danger of not being able to recover.

What is crippling the self-regenerating capacity of the planet? Carbon dioxide. It is responsible for global warming and the acidification of oceans; the two processes are linked in a positive feedback loop; the intensity of one increases the intensity of the other in a vicious cycle.

Acidification of Oceans

Global annual mean CO_2 concentration has increased by more than 45% since the start of the Industrial Revolution, from 280 ppm during the 10,000 years up to the mid-18th century to 410 ppm as of mid-2018. This amount is not noticeable because carbon dioxide forms a very small percentage (0.04%) of the composition of the air we breathe.

However, the increased CO_2 concentration in the atmosphere has affected the pH value of the ocean's water. The pH of seawater was for 300 million years stable at a value of 8.2. It has dropped to 8.1 representing a 25% increase in the water's acidity level. (Note the pH index is logarithmic.)

The impact on marine life is serious: Planktons are under pressure due to the higher acidity. "Scientists believe that phytoplankton contribute between 50 to 85 percent of the oxygen in Earth's atmosphere." Zooplanktons which feed on phytoplanktons are food and nutrients to large creatures at the base of the food chain which in turn feed marine creatures higher up all the way to fish and mammals including whales and dolphins.

The higher acidity in the ocean are also damaging shell fish, crustaceans and corals. Carbonic acid is bad news if you need calcium to form bones or shells. The poor formation of ear bones of whales and dolphins results in defective echolocation capability which impairs their ability to navigate and search for food.

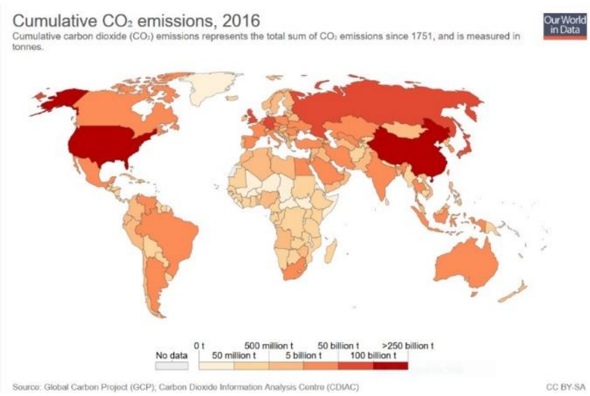
With phytoplanktons under threat the oceans capacity to remove CO_2 is compromised. The greenhouse gas concentration in the atmosphere increases leading to rising temperatures and the melting of more of the polar ice caps causing sea levels to rise.

Global temperature rise also melts the permafrost which could trigger the release of deadly bacteria lying dormant in the tundra region.

Planet Earth has gone through 4.5 billion years of evolution. On that time scale the evolution of man is hardly a millisecond. In that millisecond, man has disturbed the equilibrium of life so fast it has no time to recover. Our grandchildren and their grandchildren will suffer for the wanton way we have discharged carbon dioxide in the past two hundred years. Earth will not be teeming with life like it was before the industrial revolution. Many marine biosystems will perish.

Carbon Free Energy

Naval architects and marine engineers play a huge part in the production of oil and gas. Without them the additional supply of offshore fossil fuels, the world's GDP would have not made the same progress as it did.



However, the pendulum has swung the other way. We need to curb the emission of CO2 into the atmosphere and the oceans. The cost to the environment is too serious to gloss over.

Naval architects of the future need to join forces with climatologists and marine biologists find ways to fight CO2 emission into the atmosphere.

The new generation of naval architects and marine engineers should be equipped with the skill sets to redress the damage that their forebears were partly responsible for.

IMO is struggling to set limits to carbon emission in the shipping industry. In early 2018 IMO declares its target of halving carbon emission from global shipping by 2050. Well and good if it can but it is not enough.

The ocean is home to many potential sources of renewable energy: wind, tidal currents, waves, solar and OTEC (Ocean Thermal Energy Conversion.) They are all carbon free energy necessary to reduce the warming of the world.

Naval architects and marine engineers can and should play a key role to explore and exploit these embryonic energy alternatives. Their traditional training in the analysis of intact and damage stability is key to the development of offshore floating wind turbines, floating solar farms or marine bio-sequestration system for the absorption of carbon dioxide from the combustion of fossil fuels. They cannot stand idly by as others less well equipped than they struggle to moor structures in the sea and cope with the forces on such structures due to wind, waves and currents. They have been down that road before in designing offshore oil and gas rigs.

Floating Out Greenhouse Gas Emitting Industries

Power stations, refineries and petrochemical plants are usually sited onshore near large water bodies because they need vast quantities of cooling water. Most take fuels and deliver their products with tankers and need loading and unloading jetties.

Now that we know more about the behaviour of large floating platforms, it is timely to promote the advantage of building these facilities in the sea rather than on land.

Out at sea they will not compete for land used for agriculture, housing, recreation. There is yeat an important reason. A floating power plant or refinery can easily be connected to a floating marine bio-sequestration system mentioned above. These are large structures and would be too costly to erectly on land because of their large footprint. The system essentially uses algae to absorb CO2 and convert it by photosynthesis into oxygen as well as several nutraceutical products.

A floating refinery located in 30 meters of water would be able to receive larger tankers Berthing facilities can also be floating. There is no need for piled structures which are costly at depths exceeding 15 meters. There would be no need to carry out maintenance dredging of the channels and the quayside.

Floating concrete platforms can be designed for twice of three times the life span of the plants on which they are erected.

The fact that these offshore structures may be relocated as well as repurposed is attractive to financiers. Loans may be raised using them as collateral. They are a lot safer for equity holders and financial institution than an immovable equivalent on shore in a foreign country.

Floating petrochemical plants are no different from many hydrocarbon floating plants such as FPSO, FLNG, FSRU plants which are tried and tested in severe marine environment.

Tank farms may be sited offshore too. Hydrocarbon storage tanks floating in the sea are much safer than tanks on land. Oil spills are more easily contained. The pressure exerted by the liquid inside on the walls of the containment are counterbalanced by seawater pressure outside reducing stresses in the shell. The chances of a fire spreading and melting adjacent tanks as has happened on land tank farms are unlikely due to the fact that the fire will not spread to combustible liquids below the water line. Floating storage tanks have performed well for a few decades in Japan. NUS is engaged in studying the feasibility of prototyping one under a government grant.

Floating Ports

Singapore is one of the world's leading port. However, 85% of the container boxes unloaded in Singapore are transhipped to another port.

It makes good sense to have the port at the edge of the state's maritime boundary, rather than for the ship to steam all the way into Tuas. All the boxes could be offloaded offshore and the 15% of the boxes destined for inland may be transferred to smaller ports on shore around the island. This would take a substantial trans-island container traffic off the road.

Phase 1 of a mega port for a final capacity of 65 million TEUs is now under construction. I urge the authorities not to proceed with Phase 2 and 3 as planned. Instead build a floating port. This could be located at the inner side of our territorial limits with capacity to handle all transhipment cargo. The floating port can be built incrementally rather easily as these structures need not be built on site. They may be constructed in China or Korea outfitted with cranes and substations and other paraphernalia prior to delivery to Singapore. Disruption to ongoing shipping activities will be minimal. Mooring and activating the port will be a matter of months as all systems can be tested prior to delivery in Singapore.

Illustrated here is the 700-foot long Valdez floating container port commissioned in 1982 and still in service. It was built in Seattle and towed to Valdez.

The US is also considering a floating transhipment port near Louisiana to tranship boxes to and from Panamax vessels. The design envisages a 906-ha port for both dry and liquid cargo. The Mississippi River will link this port to ports along the river in the Midwest. Currently boxes are trucked from the western or eastern seaboard ports. By barging instead of trucking the pressure on freeways is reduced and so is the greenhouse gas emissions.

For Singapore the relocation of ports offshore will free up large swathes of sea space that are now unusable except for shipping. The sea space freed up could be used for living working and playing.

Floating Shipyards

All mariners are familiar with floating docks. Some of these docks are of enormous sizes, The Royal Dock 5 in DSME is 432m long, 85.6m wide, and a capacity of 130,000dwt. Floating cranes have higher capacities than goliath cranes and can cover a larger production area.

The floating shipyard illustrated below is based on a scaled drawing. It is 35 hectares in area and has impressive berth of 4000 meters on 12 sides. Blocks of up to 3000 tons may be lifted or dropped anywhere all around the shipyard, a feature not attainable with land-based shipyards. The four "arms" of the shipyard may be rigidly or flexibly connected.

Floating Runway

Singapore's northern neighbour is unhappy that aircrafts landing at Seletar Airport are flying too low over Malaysian airspace.

Malaysia's unhappiness over encroachment of airspace can be resolved by having a floating airport in the Straits of Singapore

The illustration here is Japan's 1000-m long floating runway an example of naval architecture applied in a new situation. The runway was built in a shipyard.

In the benign waters in Singapore landing and taking off on a floating runway will be no more difficult than a normal one.

Floating Reservoirs, Parks and Condos

In land scarce Singapore there is a lot of good reasons to use floating recreation facilities. These facilities such as nature parks, golf courses, water parks are necessary for urban living. While neighbourhood parks should be with walking distance from residents, large parks and golf course can be located offshore if there is a severe need to find space for housing.

The 2300 mm of annual precipitation in this country is more than sufficient for the entire population. However, due to insufficient water storage capacity on land about half of it ends up in the sea. To increase water storage capacity new reservoirs can be built on large floats. Water catchment areas in Singapore island can be linked by pipes to the floating ones via reservoirs along the coastline to take the runoffs during a storm.

Each reservoir could be the centrepiece lagoon of an upmarket real estate similar to the illustration shown here. Floating condominiums with 99-year lease may be developed for sale by the private sector.

Floating Bridges

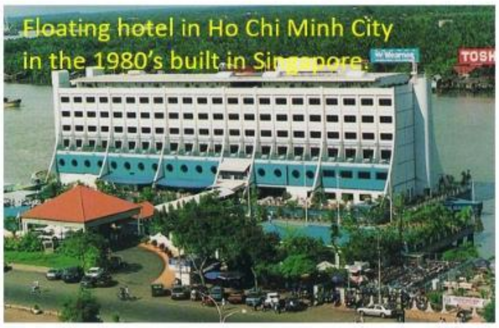
It used to be that bridges are built on piers with foundation in the seabed. Floating bridges are far more economical where calm waters prevail. Examples include the pontoon bridge (length 2350 m) across the Lake Washington in Seattle (illustrated here) and the rotatable Osaka Yumemai Bridge in Japan.

Submerged highways may soon be a feature across Norwegian fjords. Floating bridges are subject to forces of buoyancy as well as to waves and currents. They have the tendency to heave, pitch, roll and yaw. How to minimise them are issues which naval architects are better equipped to address than normal bridge engineers.

Examples of Floating Structures in Service

Other examples of floating structures in service are illustrated here to facilitate the understanding of this solutions for non-ship structures

Other examples of how knowledge of naval architecture may be applied to a variety of structures other than vessels for transporting cargoes



Building the Capability in Our Academia

The capability to design and build offshore structures including semi-submersibles, spars, floatels, and process plants such as FPSO, FSRU, FLNG are present in Singapore in a network comprising shipyards, naval architect consultants, and classification societies. So are engineers for the design of on-board waste water treatment systems, freshwater generators and power generation systems in a marine environment.

That capability hitherto is confined to steel structures with compact foot prints. We need to develop a capability to design, construct, integrate, connect and moor structures with large foot prints.

We also need to be able to execute all these with material other than steel as the platform to support the structure above it. Steel is not necessarily the best material for the platform as it is it is subject to corrosion. It is an excellent material for the structure above water because it is lighter and may be built in larger blocks on ground and lifted with floating cranes for erection. Also, being lighter the entire floating structure has a better response to environmental forces.

Marine engineering and naval architectural courses are offered in a number of polytechnics and universities. It is timely to restructure the course curriculum to include other aspects of very large floating non-ship shape structures that could have formed by simple geometrical shapes by being rigidly or non-rigidly connected. The dynamic response of these non-slender structures to waves, and wind in shallow and deep waters could be worthy of postgraduate research.

Additionally, students should be taught methods of connecting modular elements of rectangular, hexagonal and triangular shapes either rigidly or flexibly to form larger platforms of hundreds of hectares in size. MARIN (Maritime Research Institute Netherlands) is currently testing a 3sq.km floating city.

TCOMS the deep-water research facility at the NUS would be useful to support the development of such capability. The capability of the shipyards in the understanding the dynamics of offshore structures should be exploited to cover floating structures of other geometry. (A 1000-meter high tower erected on a flat circular platform as proposed by the Japanese. A floating theatre complex such as the one in the Han River in Seoul offers many challenges for naval architects and marine engineers. For instance, how would to predict the motion of the theatre and how to moor it to keep any of the six motions of a floating body within the comfort levels of a very discerning audience? Would the list be noticeably pronounced if the entire audience make their way to exit the theatre in an emergency?

Construction material such as high strength fibre reinforced concrete and high-density polypropylene which are corrosion free should be studied. Natural renewable material should be also considered such as bamboo, teak and cane. These are appropriate material for the platform on which may be erected any structure that is erected on land; houses, theatres, stadiums, offices, logistic bases, process plants etc.

Experts in this field may be invited to temporarily staff our universities and polytechnics from institutions and research facilities from Norway (SINTEF), Netherlands (TU Delft), Japan (Nihon University, Department of Oceanic Engineering and Architecture), and South Korea (KIOST, Korea Institute of Ocean Science and technology). In the consultancy and contracting space EDB may find it interesting to contact organisations such as BergerABAM and Ciudad FCC. These firms have experience designing, making and delivering these structures. They could be the catalyst serving the same purpose that IHI, MHI, Bethlehem and Levingston did in the 1970s when

Singapore was eager to develop a ship building and repairing capability.

Applying the Capability Worldwide

Singapore has the greatest need for VLFS (Very Large Floating Structure) on a per capita basis. This is because we are fast running out of land. One million more people need to be housed by 2030 according to official estimates. Ours is already the mostly densely populated city in the world. The 99-year lease for HDB apartments is a ticking time bomb. Hundreds of thousands now living in houses built in the 1960s need to give up the homes well be the 99-year term so that their houses may be demolished, and the land be rebuilt with higher density home clusters.

With structures that are not permanently fixed on the ground, it would be easy to tap into the private sector to fund their construction, especially with the high AAA credit rating that Singapore is well known for.

Apart from serving our national needs, the expertise that we nurture, and build can also serve us well to build exportable hotels, parks, apartments, wind farms, ports, desalination plants, vertical vegetable farms, and many more for a global market. Just as we have done with oil rigs and floatels. The Singapore brand is there for us to exploit.

Here is anecdote worth recalling: In 1986 a shipyard in Singapore launched a 200-room 5-star floating hotel. It serves for a time at the Great Barrier Reef, Australia. Shortly after there was a desperate need to find high end hotel rooms in Ho Chi Minh City as the market economy there gain traction. The hotel was towed to the city and was fetching room rates at US$200 per night when the best hotel in Singapore at that time the Shangri-La Hotel was charging about 30% less. It could command that kind of rate partly because of its Singapore brand. The hotel was managed by Singapore hotelier and staff. Mr and Mrs Lee Kuan Yew were among its hallowed guests.

I believe there is still a market for such ventures in the remote islands of the Pacific and Indian Oceans such as Fiji, Tahiti, Maldives and Mauritius. With the Singapore brand to support it, it would be worthwhile for a team to seek out opportunities.

As mentioned before, floating structures are relocatable assets with minimal exposure to country risk. It is therefore a viable collateral for financiers. The asset may be Singapore flagged, meaning that the laws of Singapore apply to anyone on board.

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AUTHOR'S BIOGRAPHY

Lim is an advocate of floating solutions to address climate change as well as to protect marine life by addressing issues related to the acidification of oceans and land reclamation.

His years' experience in the construction of quays and graving docks for shipyards leads him to question the rationale of reclaiming land for activities that require deep waterfronts and to ask the obvious question: why not build these as floating facilities instead.

He has published papers on the floating structures internationally as well as locally.

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Durability Design of Floating Concrete Platforms

ABSTRACT

Concrete is the cheapest construction material and the second most consumed man-maid product after drinking water, which is easily cast to any shape. Concrete technology has evolved very rapidly in recent years and continues to improve with new advancement in construction and materials technology. Early concrete platforms dated to more than 100 years ago with primitive design mixes, materials and construction technique. Since then, many concrete platform constructed some with poor quality and some with very reasonable performance. However, generally the concrete platforms were more durable when compared to steel structures but slower to construct. In past 30 years, there is a new wave of concrete platforms riding on advancement of concrete and construction technology. The owners of concrete platforms now demand for durability design of 100 years or more. The construction time is also significantly reduced. As stationary platform, concrete platforms are more durable, less expensive, safer, and more stable and require less maintenance compared to steel platforms. However, structural and durability design as well as construction experience is critical for successful execution. The concrete mix, construction joints, concrete cover and design stresses are essential to design durable concrete platforms. In this paper, durability design of floating concrete platforms is discussed.

KEYWORDS

Floating concrete platforms, concrete technology, durability

INTRODUCTION:

Concrete is the cheapest construction material and the second most consumed man-maid product after drinking water, which is easily cast to any shape. Concrete technology has evolved very rapidly in recent years and continues to improve with new advancement in construction and materials technology.

The corrosion of reinforcement in concrete is the main cause of deterioration and progressive collapse of concrete structures (Mehta P.K., 1986). The parameters affecting corrosion rate are 1) the critical chloride content (which depends on type of reinforcement materials and alkalinity of concrete), 2) concrete cover and permeability of concrete, 3) presence of water, 4) presence of oxygen, 5) Environmental factors such as temperature, 6) cracks in the concrete and 7) corrosion cell formation (Markeset G. and Myrdal R., 2008). Construction quality has important influence on some of the parameters and needs to be addressed separately from intended design.

Concrete has been widely used in construction of ports, jetties and costal structures due to its proven performance against rapid deterioration. Early concrete platforms dated to more than 100 years ago with primitive design mixes, materials and construction technique. Since then, many concrete platform constructed some with poor quality and some with very reasonable performance. However, generally the concrete platforms were more durable when compared to steel structures but slower to construct. In past 30 years, there is a new wave of concrete platforms riding on advancement of concrete and construction technology. The owners of concrete platforms now demand for durability design of 100 years or more. The construction time is also significantly reduced. As stationary platform, concrete platforms are more durable, less expensive, safer, and more stable and require less maintenance compared to steel platforms. However, structural and durability design as well as construction experience is critical for successful execution.

Despite number of concrete platforms and concrete structures in marine environment, there is still large variation in quality and design requirement of newly built structures. Some are designed and constructed with careful consideration of important parameters while others are constructed with no or little consideration about durability in marine environment. Beside parameters affecting corrosion rate, construction joints, construction technique, constriction sequence, design concepts and stresses are essential to design a durable concrete platform.

In this paper, some of these parameters and their effect of durability of concrete has been discussed.

Parameters affecting durability of concrete

Cementitious Materials and Concrete mix design

Cementitious materials and concrete mix design, controls permeability and strength of concrete. Water to cementitious ratio (w/c) is probably the most important parameter (Zivica V., 2003) followed by selection of type of cementitious materials (Ground Granulated Blast-furnace Slag (GGBS), or Silica fume (SF) replacement). The w/c ratio required for full hydration of cementitious materials is about 0.22 to 0.25 (Pang X, 2015). The excess water acts as capillary pores providing a path for chloride ion ingress to rebar location.

The main hydration products of Ordinary Portland Cement (OPC) is Calcium hydroxide and Calcium Silicate Hydrate. The main contribution of GGBS as SF as partial replacement of OPC is to consume Calcium hydroxide from OPC reaction and to produce more Calcium Silicate Hydrate. With this, the pore structure of concrete is more refined and chance of drying shrinkage is reduced.

The secondary reactions of GGBS and

SF are important; however, if initial w/c ratio is high, this refinement of microstructure is localize and will have little effect on total permeable pores. Our in-house studies showed that an OPC based mix with w/c=0.35 has much better water absorption coefficient due to capillary action (BS EN 772-11:2011) than a concrete mix with 10% SF replacement with w/c=0.45.

The specification of mix design is another important consideration. Most specifications are combination of performance based and prescriptive requirements that does not yield to a good outcome. For example, some specification calls for Grade 40 MPa concrete with w/c <0.4 and 7% SF. However, in order to achieve Grade 40 MPa with SF, a w/c as high as 0.55 is sufficient which has a poor durability performance yet will achieve the required strength. Therefore, specifying a good mix design with proper tools for quality control is very important.

With low w/c ratio, effect of GGBS/ SF replacement is more pronounced resulting in significantly denser concrete with much lower permeability.

Cracks in concrete:

Concrete is brittle in nature and is prone to cracking. The main types of cracks are plastic shrinkage crack, drying shrinkage crack and constraints cracks. These cracks have detrimental effect of concrete durability (Shaikh, F.U.A., 2018) and often designers do not have any specification or precaution to limit or eliminate these cracks. The plastic shrinkage cracks are deep cracks often to first layer of reinforcement or sometime through the concrete section happens in first few hours of casting when concrete is in plastic status. When rate of evaporation is more than 1 kgm2/h, plastic shrinkage crack has high chance of occurring (Ghourchian S. et al, 2017) and often designers neglect to define concreting condition and protection requirement to prevent plastic shrinkage cracks. Drying shrinkage cracks are also common and can be mitigated by proper additives (Nagy N. et al, 2013) or selection of aggregate type. Figure 1 shows drying shrinkage cracks on Grade 40 MPa concrete with granite aggregate compared to Grade 40 MPa lightweight concrete after three month of casting. Two modules are identical and cast in a same time. Constraints cracks happens when part of concrete is cast against old concrete or joint, which cannot move/ shrink and therefore it will crack. Construction sequence is very important factor to prevent or minimize the constraint cracking. Figure 2 shows restraint cracking on fresh concrete cast in-between two precast members.

***Figure 1:** Drying shrinkage crack on normal Grade 40 MPa concrete with granite aggregates (Top), No Crack on Grade 40 MPa light weight concrete (Bottom)*

Figure 2: *Restraint cracking on fresh concrete cast in-between two precast members*

Concrete cover:

Concrete cover is one the important factors often not appropriately considered by designers. If concrete cover is too little or two much, both have negative effect on concrete durability. A thick layer of unreinforced concrete is easily cracked with small tension.

According to ACI 318-14, concrete cover in reinforced concrete is the least distance between the surface of embedded reinforcement and the outer surface of the concrete. This is cover to main reinforcement and link reinforcement is ignored. Also most designers ignore that reinforcement is threaded and not smooth. Threads for 20 mm nominal reinforcement is 3 mm and for 12 mm reinforcement is 2 mm. Also there is always gap of 1-2 mm between link and main reinforcement. Let's assume main reinforcement is 20 mm and link reinforcement is 12 mm, designer is proposing 30 mm cover. The actual executed cover to surface of link reinforcement is 30-1.5 (half of T20 thread)- 2 mm (gap between main reinforcement and link reinforcement) – 14 (link reinforcement and its thread) = 12.5mm. For marine concrete structures, cover to link reinforcement for durability is very important.

In addition, the accuracy of reinforcement placing follows normal distribution. A typical standard deviation (SD) of about 5 mm is observed. It means 99% of reinforcements have at least design cover minus 2×SD. For the case above with 30 mm cover, 1% of link reinforcements will have less than 12.5 mm-10 mm=2.5 mm of cover. This is unacceptable in marine environment. Optimum cover of 55 to 60 mm from surface of main reinforcement should be considered to factor in all the parameters.

Design Concept:

Concrete structures are often designed to ultimate limit state (ULS) which involves excessive cracking and deformation in concrete section. This is not acceptable for marine environment. Marine structures should be designed to limit state of cracking. This limit can be increased by post tensioning and addition of fibers to achieve strength hardening with limited crack propagation.

Design of floating concrete dry-dock:

The author was part of a team to build a large floating concrete dry-dock of 138×46 meters and lifting capacity of 9500 tons in Batam Indonesia. For this platform, a Grade 85 MPa concrete with superior performance was proposed. According to specification, durability of concrete shall be measured according to ASTM C1202 for its ability to resist chloride ion penetration using the accelerated test. In Rapid chloride permeability (RCP) test, the total charge (Coulombs) passes through concrete in 6 hours of testing shall be less that the limit specified in following Table. Alternatively, concrete shall be tested according to NT Built 492 for Rapid chloride migration or for its Electrical resistivity, using four points Wenner Probe as described in ACI 222. Either of limits presented in following table shall be considered.

RCP according to ASTM C1202	Rapid chloride migration test (NT Built 492)	Electrical resistivity using 4 points Wenner Probe as specified by ACI 222
Bellow 300 coulombs	$D < 0.4 \times 10^{-12}$	>160 kΩ.cm

Figure 3 shows Wenner probe reading of 186.6 kΩ.cm beyond the limit specified in the above table.

Figure 3:*Wenner Probe reading to measure concrete mix durability*

For success of this project, many considerations and small details had to be considered. This includes, large slab casting at night (to minimize plastic shrinkage crack), two step quality control which includes retempering of concrete to ensure all ready mix trucks having slump of 650 +/-50 mm, and special considerations for curing and to ensure no cold-joint when there are long delays in concrete arrivals. Many lessons were learned and correction were made during this construction.

The structural framing of this platform is closely spaced honeycomb system, which slabs and main walls are post-tensioned. Post tensioning and close spacing of cells will make this platform work under compression for most loadings, which will reduce cracking. Use of flat slab and avoiding sharp corners will minimize anode-cathode formation, which is important consideration in structural design and well as durability design.

CONCLUSIONS

In summary, there are many factors from concrete mix design, structural design, construction sequence and construction quality affecting achieved quality of concrete platform and most of these parameters are often ignored or unplanned when designers or builders are not familiar with construction in marine environment. It is important to differentiate between design of concrete in Marine environment and design of normal concrete buildings.

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Dr Sabet is Managing Director of Global Engineering Creators Pte Ltd. He is concrete technology specialist with more than 15 years of experience in concrete related research and practice. Dr Sabet actively participate in design and construction of floating concrete platforms. He was part of a team to build a large concrete dry-dock (138×46 meters) for ship-repair. Dr Sabet has more than 50 keynote presentations and publications in relevant journals and conferences. Dr Sabet is President of Singapore Concrete Institute and 2nd Vice President of Society of Floating Solutions Singapore.

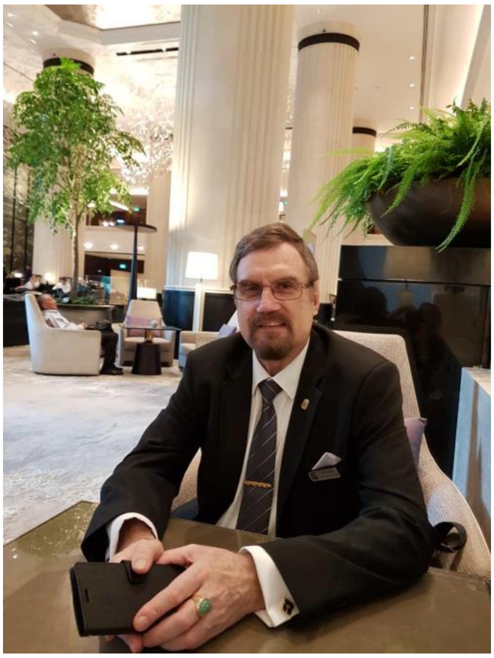
Editor's Note

For year 2019, we have chosen the theme **"TIME FOR A NEW MARITIME ERA"** for SNAMES 38th Annual Journal. The maritime industry is undergoing globally transformation with increasing digitalization, vessel cyber security, new era of autonomous, hybrid and eco vessels. The climate change and the stricter environmental regulation for using newer, safer and cleaner energy is the next technological advance and challenge in maritime industry.

In the era of increasing sea-borne trade and world-wide awareness of global warming, when the international shipping today contributes approximately 12 % of global sulphur emissions, it has been put into place to be reduced these emissions globally. Furthermore IMO, the body responsible for the safety and environmental performance related to the shipping sector has taken decision for the reduction of Sulphur in marine fuel oil with effect 1st January 2020. This is another challenge to maritime industry.

We sincerely hope that trough the various technical papers published in 38th Annual Journal all readers, professional and business leaders to be inspired and meet the new challenges in the new maritime era in an industry.

In a process of preparing the Annual Journal we were very pleased to receive the papers which are written by accomplished professionals and academics. The publication committee would like to express our sincere gratitude to all authors for their contribution and submission their excellent technical



papers for the 38th SNAMES Annual Journal.

On behalf of the SNAMES I would like to thank you to our Publication Committee Members - **Dr Iris Jiyeon Kim and Dr Giulio Gennaro** who have worked hardly for completion of this Journal. I would like to thank you to all authors for their participation to 38th Annual Journal, to our partners supported the Journal and SNAMES over the years. We look forward to our partners continual strong support and our members in our activities.

I would like to thank you to all SNAMES Council Members who have worked hard and closely, put and combined efforts to make every activity and event successful.

I wish you and your organization fair wind and success in the new maritime era.

Sincerely

Ivan Stoytchev
Chairman
Publication Committee

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