Towards an indicator of copper emissions from ships in Swedish waters

A case study on two ships types operating in Swedish waters

Bachelor thesis for Marine Engineering Program
Bachelor thesis for Shipping and Logistics Program

JOHN NORDQVIST
MARTIN SJÖBERG

DEPARTMENT OF MECHANICS AND MARITIME SCIENCES

CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden, 2021

Towards an indicator of copper emissions from ships in Swedish waters

A case study on two ships types operating in Swedish waters

Bachelor thesis for Marine Engineering Program
Bachelor thesis for Shipping and Logistics Program

JOHN NORDQVIST
MARTIN SJÖBERG

Department of Mechanics and Maritime Sciences
Division for Maritime Studies
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden, 2021

Towards an indicator of copper emissions from ships in Swedish waters
A case study on two ships types operating in Swedish waters

JOHN NORDQVIST
MARTIN SJÖBERG

Department of Mechanics and Maritime Sciences
Chalmers University of Technology
SE-412 96 Göteborg
Sweden
Telephone: + 46 (0)31-772 1000

Department of Mechanics and Maritime Sciences
Chalmers University of Technology
Göteborg, Sweden, 2021

PREFACE

This report has been written in the spring of 2021 at Chalmers University of Technology. Under the program of Marine Engineering and Shipping and Logistics. The joint knowledge of the shipping industry will give a wider perspective in the investigation of this subject. We would like to thank our mentor Ida-Maja Hassellöv for the support and guidance given in the working process.

Towards an indicator of copper emissions from ships in Swedish waters
A case study on two ships types operating in Swedish waters

JOHN NORDQVIST
MARTIN SJÖBERG

Department of Mechanics and Maritime Sciences
Chalmers University of Technology

SAMMANDRAG

Miljömålsberedningen har gett Trafikanalys ett förslag på ett uppdrag, att följa upp en utvärdera sjöfartens inverkan på den marina miljön. Idag är det få och enda indikatorer som finns på luftutsläpp. Studien har fokuserat på kopparutsläpp som en indikator och vilka källor på fartyget som släpper ut koppar. Kongsberg-simulatorn har använts för att simulera två olika typer av fartyg, en färja och oljetankfartyg. Den data som kom genom simuleringen gav underlag om volymen vatten som de olika källorna producerar. Resultatet från de två fartygen kan vara utgångspunkten för vidare forskning och utveckling av indikatorer relaterade till vattenutsläpp. Det kan ge mer förståelse över hur den marina miljön påverkas av sjöfarten.

Towards an indicator of copper emissions from ships in Swedish waters
A case study on two ships types operating in Swedish waters

JOHN NORDQVIST
MARTIN SJÖBERG

Department of Mechanics and Maritime Sciences
Chalmers University of Technology

ABSTRACT

The Swedish Cross-Party Committee on Environmental Objectives has proposed Traffic analysis to follow up and evaluate the impact from shipping on the marine environment. Today there are only few indicators in use, and only for air emissions. This study has focused on copper emissions as an indicator and what sources on the ship that releases copper. The Kongsberg engine simulator has been used to simulate two different types of ships, ferry and a very large crude carrier (VLCC). To determine the volume of water that the different sources produce. The result from the two ships can be the starting point in further research and development of indicators related to water emission. That can give more understanding of the impact on the marine environment caused by the shipping industry.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS AND TERMINOLOGY

CO_2	Carbon dioxide
C_u	Copper
EU	European Union
BRF	Biocidal Product Regelation
NO_x	Nitrogen oxide
SO_x	Sulfur oxide
BONUS	Science for a Better Future of the Baltic Sea
SHEBA	Sustainable Shipping and environment of the Baltic sea region
VLCC	Very large crude carrier
IMO	International Maritime Organization
MARPOL	International Convention for the prevention of pollution from ships
AIS	Automatic identification system

1. INTRODUCTION

A ship can be seen as an industry or, especially for cruise ships, a small city with its associated emissions. Many of these emissions are harmful to the marine environment and contribute to climate change and pollution of the seas. Emissions of nutrients present in greywater (wastewater from cleaning and laundry and galley) combined with black water (sewage) and food waste contributes to eutrophication of the seas. Other emissions include smokes, propeller shaft lubricants, bilge water, antifouling paint, residues from tank cleaning and noise all contributes to degradation of the marine environment. A literature review from Sustainable Shipping and environment of the Baltic sea region SHEBA (Moldanová, 2018)(*Havet Och Människan. SOU 2020: Delbetänkande Från Miljömålsberedningen (M 2010:04).*, n.d.)provides an estimate that a ship has at least 147 different chemicals onboard many of these with unknown effect on the marine environment. Furthermore studies have shown that copper is the biggest contributor to pollutant from shipping (Moldanová, 2018).

In 2020, the Swedish Cross-Party Committee on Environmental (Miljömålsberedningen) published their interim report “Sea and man” (Miljömålsberedningen 2020, 2020)with suggestions of laws to protect the waters around Sweden. A whole chapter is dedicated to marine traffics impact on the marine environment and it is said that there are few indicators for the ship related emissions and discharges to the marine environment, and it is suggested that indicators should be developed. In this paper it will be studied how an indicator for copper can be developed, how much a copper a ship releases with the help of computer simulations, how agencies can gather information and use it to get in their assessment of the environmental status in Sweden’s economic zone. Copper and zinc are used as an antifouling agent on ships hulls. The paint releases copper and zinc to create a toxic environment for unwanted species such as barnacles. This comes with the drawback that the copper can also affect non targeted species not directly affecting the ship. Studies have shown that the larva of blue shell mussels (*Mytilus edulis)* can be affected negatively by small amount of copper in the water (Zitoun et al., 2019), kelp is affected negatively during reproduction stages (Andersson S & Kautsky L, 1996), and even small amounts of copper in water can make it hard for salmon to navigate to its breeding grounds(Scannell, 2009).

1.1 Background

In 2018 the Swedish Cross-Party Committee on Environmental Objectives was commissioned by the Swedish government to propose a strategy that will improve the work to conserve and sustainably use of the marine environment. The strategy was released in January of 2021 and in the report, it is pointed at a shortage of indicators and criteria to assess the impact on the marine environment from shipping. The government agency Transport Analysis that has the responsibility to provide decision-makers with relevant policy advice in the transportation sphere (*About Transport Analysis*, n.d.). The Swedish Cross-Party Committee on Environmental Objectives proposal was sent to Traffic analysis and other governing agencies and organizations working with task regarding the marine environment. Traffic analysis will release a statement of their opinion in May 2021.

Transport Analysis collects data from 28 authorities and calculate and put together and publish the official statistic (*Om Vår Statistik*, n.d.). It was stated in the “Sea and mankind” that several recent investigations have been done regarding marine environmental data. The conclusion was there are flaws in the organization and handling of the data. Swedish Cross-Party Committee on Environmental Objectives has perceived from different agency’s that this flaws still exist and need to be solved.(Miljömålsberedningen 2020, 2020; Volym, n.d.)There are several agencies in Sweden committed to maintaining the health of Swedish waters.

The Swedish Meteorological and Hydrological Institute (SMHI) are experts on meteorology, climatology, hydrology and oceanography. They do observation, forecasting, and collect data to analyze (*About SMHI | SMHI*, n.d.) Swedish Agency for Marine and Water Management has the responsibility to protect, restore and ensure sustainable use of the ocean (*About SwAM - Swedish Agency for Marine and Water Management*, n.d.) Swedish Environmental Protection Agency is responsible for environmental issues concerning hazardous substances. This agency carries out assignments related to environment given from the government (*About the Swedish Environmental Protection Agency - Swedish Environmental Protection Agency*, n.d.). The geological survey of Sweden is the expert agency of issues related to soil, bedrock, the seabed, ground water and monitoring pollutants in sediments. and the seabed (*About SGU*, n.d.)

The Swedish Transport Agency has the overall responsibility to drawing up regulations and look after companies, authorities, organizations, and citizens abide them (*About Us - Transportstyrelsen*, n.d.) The Swedish Maritime Administration works in the transport sector and is responsible for marine safety and availability (*About SMA - Sjofartsverket*, n.d.) Swedish Transport Administration mission are to create modern, effective and a sustainable transportation system (*About Us - Trafikverket*, n.d.).

1.2 Aim of the study

The aim with this study is to identify which type of pressures and impacts of shipping on the marine environment that should be included in regular assessments. To link emissions to ship operation, a case study on the possible development of an indicator for copper emissions from ships will be investigated. To assess how much copper a ship releases and how one can measure it. This thesis is primarily based on review of scientific papers and two case studies in Kongsberg simulator at Chalmers University of Technology and a interview with Traffic analysis.

1.3 Research questions

- Which type of pressures of shipping on the marine environment should be included in regular assessments?
- How indicators can be developed to describe copper emissions from ships?
- How can indicators be developed to generate outputs that are useful for both the transportation sector and marine management?

1.4 Delimitations

No emissions from leisure crafts, fishing vessels., industries or other land-based emissions have been taken in consideration in this study. The Geographical limitations are set to the Baltic sea and Kattegat.

2. THEORY

To get a good understanding of emissions and discharges of ship it is of most importance to have the knowledge of how different waste streams produced onboard and what operational emissions a ship have. It is also important what the potential effect these waste streams can have on the marine environment.

2.1 Liquid waste streams and atmospheric emissions from ships

A ship has many kinds of emission and discharge sources. While exhaust fumes and cooling water is constantly put out in the environment while the ships engines are running, discharges like grey- and black-water, cleaned bilge water is pumped overboard sporadically either when the tanks are full or when the situation allows them to be pumped overboard like when the ships is at harbor and the port has facilities to take care of the ships waste (Jalkanen et al., 2020).

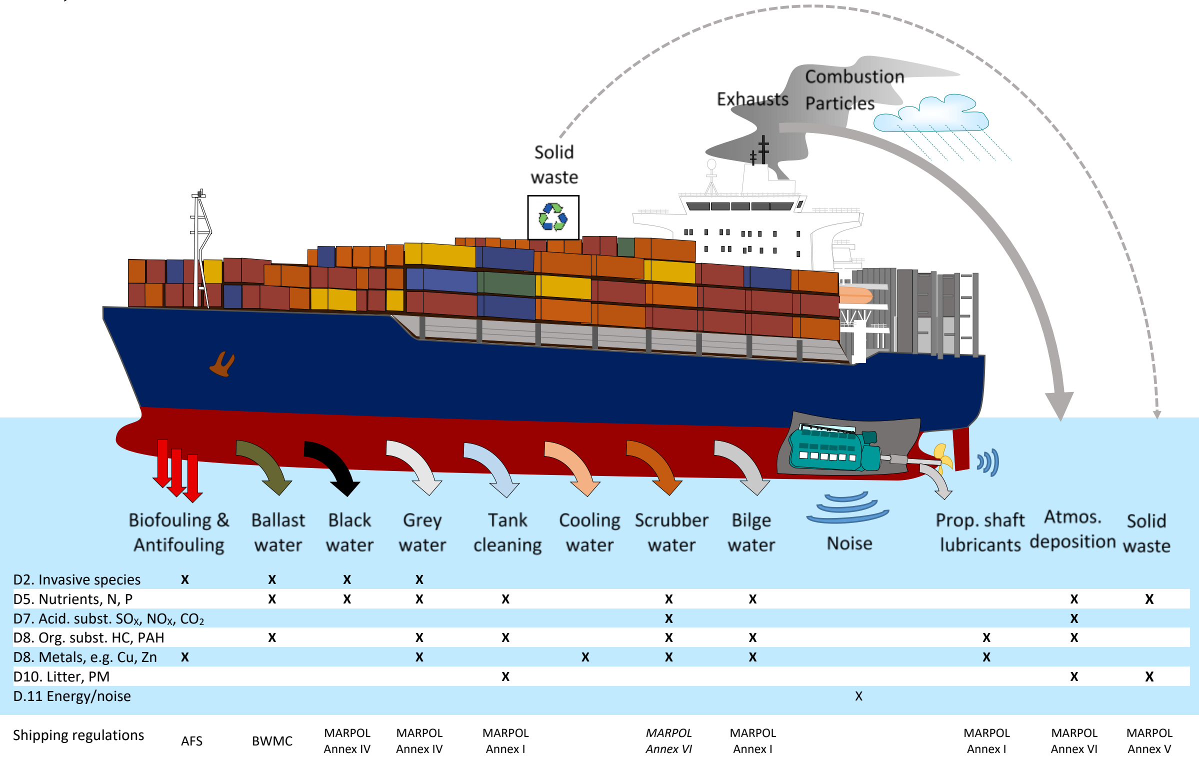

Figure 1 Ship emission and discharges. I-M Hassellöv, reprinted with permission.

2.1.1 Scrubber water

Since January 1 2015 ships travelling in Sulfur Controlled Areas (SECA) is not allowed to have nor more than 0.1% mass per mass (m/m) sulfur content in its fuel. There are currently four SECA: The North American control are which includes most of the United States of Americas coast and Canadas eastern and western coast, the United States Caribbean Sea Emission control area, the Baltic Sea which includes the Gulf of Bothnia, the Gulf of Finland, and the entrance to the Baltic Sea and finally the North Sea which includes the English Channel and Skagerrak. Furthermore, there are global regulations for sulfur emissions which from January 1 2020 are set to 0.5% m/m in the fuel (*MARPOL annex VI*).

To comply with these rules and to save money, a ship can be installed with a so-called scrubber. A scrubber washes out the sulfur from the exhaust fumes with a fine water spray. The scrubber water can then be stored onboard and pumped ashore later or be pumped directly overboard meaning that shipping companies can still use high sulfur heavy fuel oil compared to the low sulfur fuel oil which is more expensive.
It has been have shown that there can be a considerable amount of copper in scrubber water (Turner et al., 2017) and is not entirely known how scrubber water contains copper, but some suggestions are that copper is introduced to the water through combustion of fuel, combustion of lubrication oil, it could come from the pipes or from the scrubber system itself and the impressed current cathodic protection system in the sea chest (Turner et al., 2017).

2.1.2 Antifouling

Antifouling is used to prevent growth on the hulls on the ships or water pipes which can reduce the ships maneuverability, increase fuel consumption, and reduce cooling capacity. Copper is the most common biocide on ships today, not only on hulls as antifouling paint but also as additives put in cooling water even though it is more common to use an impressed current system which releases far less copper to the cooling water compared to additives and can adjust its release rate according to the situation (Hassellöv et al., 2019)

When used as an antifouling agent on hulls, small amounts of copper leaches off and creates a toxic environment for marine life, thus prevents growth of barnacles and other subaquatic organisms. This is an environmental compromise since growth on the hull will lead to high water resistance which in turn leads to a higher fuel consumption and worsen maneuverability. There is also the risk that invasive species take up residence on the hull and is introduced to new environments. If these invasive species thrive in their new environment, it can be catastrophic as native species who often do not have any natural protection. Once an invasive species is established it is almost impossible to eradicate them (Hassellöv et al., 2019) An alternative to painting the hull is to clean it, with brushes or pressure washer. It is very important to take care of the waste from the cleaning to reduce the risk of distribution of invasive species (Hassellöv et al., 2019). A good example of a non-native species being introduced to new environments, is the Signal crayfish *(Pacifastacus leniusculus)* introduction to Swedish rivers and lakes in the 1960s. Signal crayfish was introduced to help with the declining of the European crayfish (*Astacus astacus)* which were affected by the crayfish plague. What was not know was that the Signal crayfish was both immune to crayfish plague and would transfer the disease to the European crayfish which caused a great decrease of the European crayfish population in Sweden leading to its current red listed status (Bohman et al., 2006)

2.1.3 Cooling water

Seawater provides the water in the cooling system and it is used to exchange the heat from the propulsion plant and the auxiliary system. The releases to the environment can contain of dissolved materials from the cooling system and bottom sediment (Epa & of Water, 1999a). The ship can regulate the amount of copper or zinc they release into the cooling water that will prevent growth in the cooling systems pipes (Hassellöv et al., 2019). The amount of copper in the cooling water according to United States Environmental protection agency is 34,4 micro gram per liter (Epa & of Water, 1999b)

2.1.4 Grey and black water

The black water contains wastewater from toilets and medical facilities. Black water can contain pathogens (viruses, bacteria), nutrients and organic matters. It can also contain heavy metals and residues from pharmaceuticals. The black water is more concentrated on ships than sewage water produced on land, this because it uses less water is used when flushing. Black water only be released out in the water under special conditions regulated by the laws in the specific country the ship is travelling in. Grey water is produced from showers, dishwashers, and laundry. The grey water can contain of heavy metals, bacteria, suspended solids, oil, and food particles. The ship can discharge the grey water if it does not contain of any components that are regulated in MARPOL annex IV. It is recommended that ships use treatment plants for gray water as well (Andersson et al., n.d.) The grey and black water are associated with passenger travel and the passenger ships produce considerable amount of grey and black water that can be a threat to the marine environment if discharged at sea.
The grey and black water can be held in separate tanks on the ship but in some cases only one tank is used for the two types of water. The Marpol annex IV was accepted in 2005 by The Maritime Organization (IMO), and it contains of regulations regarding the sewage discharge from ships. Equipment and system for control of sewage discharge. It applied to ship over 400 gross tonnage and are certified to carry more than 15 people onboard. Governments are obligated to provide reception facilities to handle waste such as bilge, sludge for example in port and terminals (*Prevention of Pollution by Sewage from Ships*, n.d.). In 2011 the Baltic oceans introduced as a special area and new requirements for passenger ships operating in special areas was added in MARPOL annex IV. If the ship uses an approved treatment plant and meet the regulations in annex IV 9.2.1: the effluent can neither produce visible floating solids nor cause discoloration of the surrounding water. No minimum distance is required for discharging black and grey water (Andersson et al., n.d.). The average emission from copper in the grey water is 267 micro gram per liter (Sweden, n.d.)

2.1.5 Ballast water

Ballast water is used to stabilize the vessel. When ballast water is pumped outside one coast foreign species can get in the ballast tanks and when the water is unloaded at port or outside the coast the species will be released into a new. The water in the tank is very low on oxygen due to no sunlight which means that the most durable species that will survive. It´s likely that these durable species have a good chance to establish in the new environment. The Ballast convention was adopted in 2004 (Andersson et al., n.d.) but it was entered in to force in September of 2017 (*Implementing the Ballast Water Management Convention*, n.d.). The purpose with the convention is to prevent, minimize and ultimately eliminate transfer of harmful aquatic organisms and pathogens. The ships must establish ship-specific ballast water management plan and regulations are stated in the annex of the convention (Andersson et al., n.d.).

2.1.6 Bilge water

Bilge water is oil and detergent water from the engine and auxiliary room. It can contain of grease, hydrocarbons, hydraulic fluids, oil additives and heavy metals (Andersson et al., n.d.). It´s collected and stored in tanks on the vessel. The vessel can have a system onboard that separate the oil from the water or pump it ashore when at port. If bilge water is cleaned, the cleaned water can according to MARPOL annex IV get released in the ocean if it´s done more than 12 nautical miles from the land and if is less the 15 ppm of oil in the water. There is no regulation regarding the release of heavy metal in the bilge water. In a case study by EPA to reduce the metals in the bilge water, it was shown that bilge water could contain about 5 microgram copper per liter bilge water (Rincón & la Motta, 2014)

2.1.7 Operational oil spills

The propeller shaft bearings are needed to prevent water to enter the ship and keep the axis straight. The bearings are regularly lubricated with special oil but sometimes engine and transmission oil are used. Overtime the bearings wear down and seals hardening then the bearing start to leak. It is estimated that a ship can leak between two and six liters of oil per day. There are two alternatives that are more environmentally friendly then conventional bearings, non-minerals oil and water lubrication. The non-minerals oil is supposed to be non-toxic and easier for the marine environment to decompose (Andersson et al., n.d.)

2.1.8 Solid waste

The target of MARPOL is to reduce and eliminate the discharge of solid waste into the ocean. Almost every type of solid waste is prohibited to discharge, and garbage is recommended to be discharged in ports. The exception that can be discharged into the ocean is food waste, and cargo residues contained in the wash water and animal carcasses (Andersson et al., n.d.)

2.1.9 Noise

Propulsion of a ship create noise and vibrations. The noise comes from the propeller shaft and the engine. The sound can disturb the communication for fish and mammals like seals and wales (Hassellöv et al., 2019)

2.1.10 Atmospheric emission

A large amount of the emission into the air is going to have an impact on the ocean. Sulfur oxide is one of the by-products when the fuel is combusted. The sulfuric oxide will react with water and make sulfuric acid. Before January of 2020 a fuel could contain 3,5% sulfur by weight. After January 2020 fuel must have under 0,5 % of sulfur content by weight. This means that the ships need to use fuel with less sulfur or clean the exhaust gases with the help of a scrubber or with an selective catalytic reduction system (Hassellöv et al., 2019).

2.2 Copper emissions from ships

Copper is a vital element for all life but too high of a concentration of copper in the environment, be it either marine or land, can be toxic for marine life. According to the literature study (Scannell, 2009) copper affects the breeding habits of many marine living creatures.

2.2.1 Environmental impact

Copper from anti fouling also affects non-targeted organisms. It is not known what impact copper has on the marine ecosystem, but studies have shown that high levels of copper in freshwater environments have an negative impact on the ability of fish to reproduce and grow (Vardy et al., 2014). Furthermore, copper has a negative impact on the blue mussel (*Mytilus edulis*) in the larva stage (Andersson S & Kautsky L, 1996)

2.2.2 Measuring copper discharges

It is estimated that in 2012, ships released about 301 tons of copper into the Baltic sea, which represents approximately one-third of all copper emissions into the Baltic sea (Moldanová, 2018)

There are several methods to measure copper emissions from anti fouling paint and many of these methods are done in laboratory environments or with calculations. One method is the Ship Traffic Emissions Assessment Model (STEAM) method which not only shows copper discharges but all the emissions and discharges a ship produces (Jalkanen et al., 2020).

The method that is considered most reliable of measuring copper emissions from antifouling paint is the dome method developed by the US navy. Originally the method was used to measure organotin but now it is mainly used to measure copper released from antifouling pint. A dome is placed on the hull by a diver and is secured through vacuum suction. Water is drawn from inside the dome and that water is then tested for its desired compounds. Due to its high cost this method confined to the US navy (Valkirs et al., 2003)

Recently a new method to measure released copper from antifouling paint has been developed, a handheld X-Ray Fluorescence spectrometer (XRF) device that can measure the release rate of copper and zinc while in the field (Ytreberg et al., 2017) This could potentially be useful when calculating the total release rate of copper from ships.

Copper is released at different rates based on the salinity of the water (Lagerström et al., 2018)and water temperature (Valkirs et al., 2003), furthermore a ships speed and wetted area need to be taken into consideration if a more accurate estimation is desired (Hassellöv et al., 2019)(Jalkanen et al., 2020).

Practical methods such as the dome method and the XRF- method are used for collecting raw data that then is used by methods such as STEAM to help show the total impact. The XRF-method and the Dome method is used to collect raw used in calculation methods such as STEAM to get a picture over copper discharges from ships.

Most studies that have been conducted focus mainly on copper releases of copper from the ships hull. Not emissions from scrubber-water, stern tube oil, bilge water or cooling water with the exception is the STEAM method.

2.3 Marine traffic in Sweden

Ships use a system called Automatic Identification system (AIS). In 2018 it was 7840 merchant ships that has a IMO number traveling in Swedish waters according to the AIS system. (Hassellöv et al., 2019) Ships arrived 80 600 times to Swedish ports. 71 500 of the ships started from a foreign port. The types of ships in this data were general cargo, tankers, and passenger ships. (Sjötrafik 2019 170 miljoner, n.d).

2.4 Environmental indicators and marine traffic indicators

Indicators are often shown as number with or without a unit (Andersson et al., n.d.). In assessments of environmental and sustainability, indicators has been defined as “simple measures, most often quantitative that represent a state of economic, social and/or environmental development in a define area” (p. 499)(Ness et al., 2006). Environmental indicators can consist of biological, chemical, or physical indicator. That are used to measure environmental pressure and conditions (Andersson et al., n.d.).

Indicators within the Swedish environmental goals can be used to spot changes in factors that can be significant in the follow-up. These indicators can display if the progress of environmental goals is on the right track and progressing at a good pace. The data collected from the indicators can also be used as support for new laws and regulations from decision makers. The indicators data is based on regional and national samplings, emission statistic and surveys.

The indicators for the shipping industry in Sweden are few and focused to air emissions mainly emissions of CO_2, SO_x and NO_x.The estimate CO_2, SO_x and NO_x emission is based on the amount of bunker that are bunkered in Sweden and not what is released from the ships as emissions (Trafikanalys, n.d.). SMHI and the Swedish energy have created a model that calculate the greenhouse gases from ships. They use the data from AIS system onboard to track the ships movement. The model calculates travel distance with the characteristics of the ship, size, engine, and type. To predict the amount of greenhouse gases that has been created through burning of bunker(*SMHIs Metod Shipair Visar Utsläppsstatistik Från Sjöfart | SMHI*, n.d.).

3. MATERIALS AND METHODS

Information was collected from Chalmers Library discovery system (EDS). For laws regarding pollution IMOs MARPOL convention was used. Information from agencies was collected from their corresponding web pages and reports they published. In addition, two case studies were carried out in the engine room simulator at Chalmers University of Technology. Two model ships were used, one VLCC and one ferry. For each ship, the routes Gothenburg – Frederikshavn and Stockholm – Helsinki was simulated.

3.1 Simulation and model ship characteristics

Kongsberg Engine room simulator was used for the case studies developed by Kongsberg in Norway. Kongsberg develops engine room control systems and simulators engine room for training of different operations regarding shipping. For understanding the working theory behind the ships different systems, the manual of the simulated ship was used. (Halvorsen, 2010; Hermanson & Kluken, 2005).

When measuring the total release rate of copper from a ship a model ship was used and from that model the individual sources was measured. These sources where:

- Antifouling paint
- Cooling water
- Scrubber water
- Bilge water
- Grey water
- Black water

Furthermore, the copper discharger per MWh was compared to see if there was any correlation between the ships hull size, engine effect and number of crew and passengers onboard.

Two different ships where simulated, one passenger ferry and one VLCC. The ships were chosen because of their different characteristics (**Table 1**). The ferry had much more people onboard, had a higher speed and more effect on its engines compared to the VLCC, whilst the VLCC had much larger surface area of the hull. Both ships used high sulfur heavy fuel oil as fuel to also simulate the copper discharges from the scrubber systems. After the emissions from the individual sources was calculated, they were added to calculate the total release rate from the ship.

Table 1 *Ship measurements and coefficients*

	VLCC	Ferry
Cb	0,885	0,635
Cm (0,95–0,98)	0,97	0,97
Width(m)	46	24
Draft(m)	18,4	5,23
Length(Ft)	1000,65	524

Length (m)	305	160
Speed in Knots	13	19
K	1,09	1,05
Daily copper release rate Baltic sea µg/cm^2/d	7,507	7,507
Daily copper release rate Kattegat µg/cm^2/d	15,507	15,507
Wetted area m^2	23 472	4590
Number of passengers and crew	20	400
Main Engine (MW)	18 MW	2*10,93 MW
Auxiliary Engine (MW)	2*0,9 MW	2*0,6 MW

The coefficient K used in calculations of the wetted hull area of the ship under speed was dependent on the speed of the ship, so a lower K was used for the VLCC and a higher K was used for the passenger ferry. According to (Ivče, Bakota Mario, et al., 2020) the main frame Coefficient (C_m) is between 0.95-0.98 so the middle value of 0.97 was used since the C_m was not defined in the particulars of the ships.

3.2 Route scenarios

Two one-way travel simulations were done, Gothenburg to Frederikshavn and Stockholm to Helsinki. The distance from Gothenburg to Frederikshavn is 50 nautical miles (figure 2) and it would take three hours with ferry and four hours with the VLCC. The distance from Stockholm to Helsinki is 237 nautical miles (figure 3) and it would take 36 hours with ferry and 53 hours with the VLCC.
The speed for passenger ship was set to 19 knots for the ferry and 13 knots for VLCC. The speed was decided by looking at time schedules and taking the mean speed for a trip.

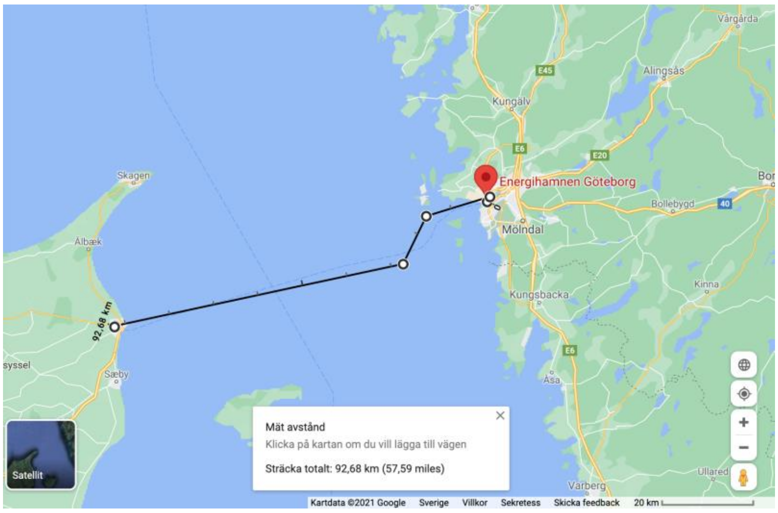

Figure 2 Route between Gothenburg -Frederikshavn (Google Maps, n.d.)

Figure 3 Route Stockholm-Helsinki (Google Maps, n.d.)

3.3 Operational procedures and emission/discharge -factors of onboard operational systems

The copper content of the individual copper sources was taken from research papers while the volume of the discharge sources was taken in the simulator. The area of the hull on the different ships were done by calculations.
Copper from stern tube oil was excluded as a so low amount is expected to leak and therefor a miniscule of copper is expected to leak.

When all the different copper emissions have been calculated they are all added together to get an indicator of a ships copper emissions. This can be used either as an hourly rate or for the whole trip or for any other desired timeframe.

3.3.1 Anti fouling paint

To determine how much of the antifouling paint is affected, the wetted area of the ship must be known. An approximation of the wetted surface area under movement can be done by using the formula mentioned in (Ivče, Bakota, et al., 2020)

$$A = L(2D + W)\left[c_m(0.53 + 0.63c_b) - 0.36(c_m - 0.5) - 0.0013\left(\frac{L}{D}\right)\right]^{0.5} \qquad (1)$$

Were:
c_m is the main frame coefficient for the specific ship. c_b is the bloc coefficient of the ship
W is the width
D is the draft
L is the length

The bloc coefficient can be calculated with the Alexander formula (Ivče, Bakota Mario, et al., 2020):

$$c_b = K - 0.5\frac{V_k}{\sqrt{L_f}} \qquad (2)$$

Where K is a coefficient ranging from 1.03 for fast vessels to 1.12 for slower vessels. For both ships K was decided to be:

1.09 for the passenger ship
1.05 for the VLCC

When the wetted hull was calculated the area was multiplied with the release rate of copper in different waters. For the simulated trips between Stockholm and Helsinki which went in the Baltic sea the release rate was set to 7.507 µg/cm^2/day and for the simulated trip between Gothenburg and Frederikshavn which went in Kattegat, the release rate was set to 15,507 µg/cm^2/day (Jalkanen et al., 2020)

3.3.2 Bilge water

The bilge water cleaning system working method was by using a tank with bafflers, as the oily water passes through the bafflers coalescers attract the oil in the oily water which then floats up to the surface of the tank meanwhile the cleaned water is pumped out at the bottom of the tank. It was assumed that there was no leaking from machinery due to good maintenance of the onboard systems and no cleaning or major maintenance was done during the trip so there were very little accumulation of bilge water in the bilge wells.

The bilge water separator was activated and the mean release rate of the clean bilgewater was calculated. Depending on where the ship is located pumping bilgewater into the sea is forbidden and it is never allowed under normal circumstances to pump bilge water overboard with an oil content over 15 ppm so that needed to be taken into consideration when doing the calculations.

3.3.3 Grey- and Black Water

On both simulated ships the sewage treatment plant contains three steps before the sewage can be pumped overboard. First blackwater is collected in an aeration tank where the sewage is broken down by bacteria and the gas produced as a byproduct is vented out in the atmosphere. The sewage is then pumped over ta a settling tank where the water and sludge are separated. The sludge is then pumped back to the aeration tank whilst the water is pumped to a chlorination tank where the sewage is disinfected and sterilized. Before pumping overboard, the water is treated a second time by UV-radiation. The greywater is not treated the bacteria and is pumped directly into the chlorination tank.
. The mean discharge rate was used and compared to copper contents of grey and black water. For the simulation, a mean value for blackwater and graywater production per person/day onboard was used. The mean value for blackwater person/day was 31 l per person and day and for greywater 221 l per person and day (Nelleson et al., 2019). The amount of copper in grey water was 267 µg (Ytreberg, Eriksson, et al., 2019). The amount of grey and blackwater delivered to the tank was set by opening a valve. The ferry was estimated to be fully loaded with passengers which was about 400 people and the crew of the VLCC was estimated to be 20 people. To get the desired amount produced the total amount of grey and blackwater produced, was calculated by:

$$\dot{V} = \frac{P * V_p}{24} \quad (3)$$

Were:
P is the amount of people onboard.
V_p is the blackwater or greywater produced per passenger/ day in liter.

When the total volume of both waters produced is known the inlet valve from the suction system is open to the desired amount to be produced.

3.3.4 Scrubber

None of the ships had a scrubber system simulated but according to (Ytreberg, Hassellöv, et al., 2019) an open loop scrubber system contains about 260 µg/L which was used as a reference in the calculations and produces 45 m^3 scrubber wash water per MWh.

Both ships had one of their auxiliary engines running which added an extra 0,6 MW to the ferry's and 0,9 MW to the VLCCs, power consumption.

3.3.5 Copper content in waste streams

The different amounts of copper content in waste streams were collected from different research reports done in the field and from reports based on calculations.

Table 2 *Copper content of individual discharge sources*

Blige water (µg/l)	5 (Rincón & la Motta, 2014)
Grey water (µg/l)	267(Ytreberg, Eriksson, et al., 2019)
Black water (µg/l)	267 (Epa & of Water, 1999b)
Cooling water (µg/l)	34,4 (Epa & of Water, 1999b)
Antifouling leaching rate Baltic sea (g/cm^2/day)	7,507(Jalkanen et al., 2020)
Antifouling leaching rate Kattegat (g/cm^2/day)	15,507(Jalkanen et al., 2020)
Scrubber water µg/l	260(Ytreberg, Hassellöv, et al., 2019)

3.4 HELCOM maps

HELCOM maps track ships with AIS and collect the data in a database. The density of the map is based on 1x1 km cells. The value in the cells representing the total amount of trips that has crossed the cell. A trip is defined as movement between two ports (*Helcom Map And Data Service*, n.d.). The ships traveling often on specific routes that creates a line from starting port to arrival port. Cells was chosen across the line to cover the width, then one by one was investigated and added together to determine the total amount of trips.

3.5 Interview with Traffic Analysis

Björn Olsson works at Traffic Analysis at the department of policy instruments and external analysis. His focus areas are maritime competitiveness, maritime support, and policy issues as well as issues related to infrastructure planning and economics. A short interview over e-mail was done asking questions regarding the task the Swedish Cross-Party Committee on Environmental Objectives commissioned Traffic Analysis. The questions asked was such:

We have read that Traffic Analysis has been proposed by the Environmental Objectives committee to be commissioned to regularly follow up and evaluate the effects of shipping's overall impact on the marine environment and its ecosystem.

- How do you view that type of assignment?
- How do you set up work for it when you get a new assignment like this?
- Do you get any directives on which emissions you should look at, for example SO_x, NO_x? Or do you produce data that you think is relevant?
- How does the workflow work to produce a new indicator? Something that traffic analysis produces. Or do they come from the various authorities?
- Do you think that in advance the information in the data that you will receive will benefit or disadvantage shipping? For example, that the impact on the environment in certain areas is worse than previously thought.

4 RESULTS

There are many waste streams from a ship and in this report have focused on copper emission into the marine environment. water. The different waste stream that can contain copper and be released from ships are grey and black water, cooling water, bilge water, scrubber water and the antifouling paint.

Most of the research of copper waste streams from ships is focused on the copper release from anti fouling. this seems like a good focus area since our simulations showed that the two single biggest contributors copper discharge from ships were the antifouling on hulls and in cooling water. The hull contributed to almost 60% on the VLCC and 46% on the ferry. Cooling water is also big contributor, 39,6% of the VLCCs copper discharge came from cooling and the ferry's contribution was 51%.

4.1 Result from simulation

Even though the ferry had higher discharge rates of the other sources they were relatively small compared to the ships hull and cooling water discharges, shown in (**Table 2)**.

The VLCC had by far the largest waste stream of copper of the two ships mainly to its large, wetted area and to the amount of cooling water produced even if the release rate of the antifouling paint and the content of copper in the cooling water was relatively low (**Table 1**)

What is also relevant is the speed the ship is travelling in, as a ship travelling in higher speeds most often have bigger effect on its engines and thus need more cooling, furthermore a ship travelling at a higher speed has a higher wetted surface area compared to if it was going at lower a speed.

Table 3 *Emission of copper from ships per trip all units are in grams.*

	Time perTrip in hours	Bilge water	Grey water	Black water	Scrubber water	Anti Fouling Paint	Cooling water	Total	Copper per MWh
Passenger Ferry	3,0	0,02	2,8	0,4	788,3	89	37,9	918,5	13,6
Passenger Ferry	36,0	0,19	33,8	5,0	9460,2	516,9	454,5	10 471	12,9
Tanker	4,0	0,05	0,13	0,03	884,5	606,6	190,4	1681,8	22,2
Tanker	54,0	0,69	1,8	0,4	11 720	3891,2	2570,9	18 185	17,8

When calculating the release of copper from bilge water, grey water black water and cooling water the total volume of each individual discharge sources was multiplied with the estimated copper content of each category. The copper content of scrubber water was calculated by multiplying total effect with running time with how much scrubber water a scrubber produces per MWh. This number was then multiplied with the copper content in scrubber water.

To get the release rate of copper from the hulls the total area of the hull was calculated with the help of the formula:

$$A = L(2D + W)\left[c_m(0.53 + 0.63c_b) - 0.36(c_m - 0.5) - 0.0013(\frac{L}{D})\right]^{0.5}$$

And by multiplying the release rater of copper with regards of which body of water the ships were travelling in.

4.2 Copper discharge per MWh (Cu/MWh)

The Cu/MWh was noticeably lower for the longer trips. Since the longer trips went in the Baltic Sea which has a lower salinity compared to Kattegat, the calculations were redone with a 54-hour trip in water with the same salinity as in Kattegat to exclude that the salinity of the sea water was the cause for the lower values, and still the Cu/MWh was lower. The reason for the lower Cu/MWh for the longer trips was that the copper discharges were constant and not dependent of the running hours of the ship.

4.3 Yearly cooper release from passenger vessel

Using the AIS data from passenger ship to get the total amount of trips a passenger ship did in a year on the simulated routes. It was 3406 trips between the Gothenburg and Frederikshavn and 1508 trips between Stockholm and Helsinki. The route between Gothenburg and Frederikshavn was more frequently used and releases 445,74 kg copper per year. Route between Stockholm – Helsinki is a longer trip and releases 1339,25 kg copper per year **(Table 4).**

Table 4 *Yearly copper discharges from passenger ferry*

Passenger ship		
Route	**Gothenburg – Frederikshavn**	**Stockholm - Helsinki**
Nautical miles	50	237
Total trips/year	3406	1508
copper release g /trip	918,5	9460,3
Yearly copper release in kg	3128	14866

4.4 Traffic analysis

The answers from Björn Olsson at Traffic Analysis indicates that it´s only a proposal they have got from the Swedish Cross-Party Committee on Environmental Objectives. They have looked at the proposal over the spring and will release a statement about their opinion at latest 23 of May. Regarding other question he will return with answer when it´s decided if they got the task or not.

5 DISCUSSION

We did two simulated trips with two different types of ships. The ships size has a big impact on the antifouling paint, engine size on the bilge and cooling water and passenger ships have more grey and black water due to more people onboard. Furthermore, the salinity of the water was a big factor in the release rate of copper from the hulls where the release rate was more than doubled in Kattegat compared to the Baltic sea.

During the simulation it was observed that different copper emissions varied greatly between different ships and different routes, for example, emissions of copper from black water was very low in the VLCC compared to the passenger ferry due to much fewer people onboard while the copper emissions from the hull of the VLCC was much larger due to its larger hull area. The two single largest copper emissions were leaching from anti fouling paint and cooling water even though they did not have the highest concentration of copper of the waste streams. This is due to the vast area of the ship's hull and to the large amount of cooling water produced onboard of the ships.

One drawback of using a simulator to calculate copper emission is that even though a lot is stimulated many numbers were static which is not the case in the real world, during hard weather a ship engine change its speed for short times due to the rocking of the boat, this will lead to a higher fuel consumption and more copper dischargers from the scrubber.
No leakage like oils or water from machinery, due to worn down packings was simulated, and it was assumed there were very light accumulation in the bilge wells during the simulation, this was done because it is hard to know how much leakage there is in an engine room. Accumulation in the bilge wells can differ from day to day, higher levels of bilge water is expected during cleaning, major repairs of machinery or during maintenance.
Different rates of leakage or malfunctions can be set in the parameters of the machinery and therefore obtain a more accurate bilge accumulation and production. This was not done since the copper contribution from the bilge wells were very low. During the simulation, a constant speed of the ship was held which in reality is not the case since a ships speed changes when entering and exiting port or while traveling in the archipelago.

It was known that a VLCC very seldom travels the routes simulated, the reason it was used was because of the limitation of the different engine room simulators as there were no. It would be much preferable simulating a product tank ships, smaller cargo ship or a bulk ship.

The most complicated part of the calculations was the release rates from the antifouling on the hull. Release rates differ depending on water temperature and salinity. This is especially relevant for us since one simulation was in the Baltic sea, which is brackish. Also, the speed of the ship must be taken in consideration when doing calculations. Mainly because the ships wetted area changes at different speeds. Using the equation

$$c_b = K - 0.5\frac{V_k}{\sqrt{L_f}}$$

One can se that when the ship is travelling at lower speeds the wetted area increases, for example the difference of the wetted area when the VLCC is travelling 13 knots and when it is still is 1648 m^2.

The simulations were done where the ship did its discharge control at the bare minimum of what the law dictates. Many ports have sludge, bilge and sewage management included in the harbor fee so that ships do not need to clean and pump those liquids overboard. If only direct copper waste streams into the ocean is studied and it is assumed that the sludge, bilge and sewage is pumped ashore these discharges can be ignored. If one also wants to include the impact of copper on the environment, then the discharges should be taken in the calculations.

With this information of the copper release from ships into the water, there can be a starting point for further development of indicators that can be used in the shipping industry. What we can see today are that the existent indicators are focused on the amount of bunkering in Sweden and not the actual emission from the ship. This method can give a more precise picture of emission from ships because every ship that travels in Swedish water do not bunker in Sweden.

6. CONCLUSION

The waste streams from ships are a known subject but lacks indicators to produce relevant data that can be used to support decisions in environmental and transportation questions. The few indicators that exist today from the shipping industry are air emission as CO_2, NO_x and SO_x. The indicators to understand and develop strategy to reduce the emission into the water are nonexistent, furthermore different ship types have different volume of discharges and emissions and therefore a general indicator that includes all ship types can be misleading. Indicators over emissions and discharges that include more ship-types would give a more detailed picture of shipping's impact on the marine environment. Time will tell if Traffic Analysis gets the task to include indicator in their assessment of the marine environment.

6.1 Recommendations for further research

Perform studies on ship because in the simulator we got constant numbers. In real cases it can be many different variables speed, size, engine, and people onboard.

Regarding the lower CU/MWh for the longer trips raises the question if further research is needed to compare copper discharges from shipping and truck transportation to compare at which distance shipping is a better alternative regarding copper discharges.

Follow up the proposal from the Swedish Cross-Party Committee on Environmental Objectives and the response from affected agency's

REFERENCES

About SGU. (n.d.). Retrieved April 15, 2021, from https://www.sgu.se/en/about-sgu/

About SMA - Sjofartsverket. (n.d.). Retrieved February 24, 2021, from https://www.sjofartsverket.se/en/About-us/About-SMA/

About SMHI | SMHI. (n.d.). Retrieved February 24, 2021, from https://www.smhi.se/en/about-smhi

About SwAM - Swedish Agency for Marine and Water Management. (n.d.). Retrieved May 11, 2021, from https://www.havochvatten.se/en/our-organization/about-swam.html

About the Swedish Environmental Protection Agency - Swedish Environmental Protection Agency. (n.d.). Retrieved February 24, 2021, from http://www.swedishepa.se/About-us/

About Transport Analysis. (n.d.). Retrieved February 24, 2021, from https://www.trafa.se/en/about-transport-analysis/

About us - Trafikverket. (n.d.). Retrieved May 14, 2021, from https://www.trafikverket.se/en/startpage/about-us

About us - Transportstyrelsen. (n.d.). Retrieved February 24, 2021, from https://www.transportstyrelsen.se/en/About-us/

Andersson, K., Brynolf, S., Lindgren, J. F., & Wilewska-Bien Editors, M. (n.d.). *Shipping and the Environment Improving Environmental Performance in Marine Transportation*.

Andersson S, & Kautsky L. (1996). Copper effects on reproductive stages of Baltic Sea Fucus vesiculosus. *Marine Biology*, *125*, 171–176.

Bohman, P., Nordwall, F., & Edsman, L. (2006). The effect of the large-scale introduction of signal crayfish on the spread of crayfish plague in Sweden. *Handbook of Environmental Chemistry, Volume 5: Water Pollution*, *380–381*, 1291–1302. https://doi.org/10.1051/kmae:2006026

Epa, U., & of Water, O. (1999a). *Appendix A: Seawater Cooling Overboard Discharge NOD, Phase I Uniform National Discharge Standards for Vessels of the Armed Forces, Technical Development Document*.

Epa, U., & of Water, O. (1999b). *Appendix A: Seawater Cooling Overboard Discharge NOD, Phase I Uniform National Discharge Standards for Vessels of the Armed Forces, Technical Development Document*.

Halvorsen, L. P. (2010). *ERS M22 10 PC4-Ferry Operator's Manual Part 3 Machinery & Operation*.

Hassellöv, I.-M., Larsson, K., & Sundblad, E.-L. (2019). *Effekter på havsmiljön av att flytta över godstransporter från vägtrafik till sjöfart havsmiljöinstitutets rapport nr 2019:5*. www.havsmiljoinstitutet.se

Havet och människan. SOU 2020 : Delbetänkande från Miljömålsberedningen (M 2010:04). (n.d.).

Helcom Map And Data Service. (n.d.). Retrieved May 5, 2021, from https://maps.helcom.fi/website/mapservice/

Hermanson, A., & Kluken, H. (2005). *ERS MAN B&W 5L90MC-L11 Machinery & Operation MC90-V*.

Implementing the Ballast Water Management Convention. (n.d.). Retrieved May 12, 2021, from https://www.imo.org/en/MediaCentre/HotTopics/Pages/Implementing-the-BWM-Convention.aspx

Ivče, R., Bakota, M., Kos, S., & Brči´c, D. B. (2020). Advanced Numerical Method for Determining the Wetted Area of Container Ships for Increased Estimation Accuracy of Copper Biocide Emissions. *Marine Science and Engineering*. https://doi.org/10.3390/jmse8110848

Ivče, R., Bakota Mario, Kos Serdjo, & Brčić David. (2020). Advanced Numerical Method for Determining the Wetted Area of Container Ships for Increased Estimation Accuracy of Copper Biocide Emissions _ Enhanced Reader. *Journal of Marine Science and Enginerring*.

Jalkanen, J.-P., Johansson, L., Wilewska-Bien, M., Granhag, L., Ytreberg, E., Eriksson, K. M., Yngsell, D., Hassellöv, I.-M., Magnusson, K., Raudsepp, U., Maljutenko, I., Styhre, L., Winnes, H., & Moldanova, J. (2020). Modeling of discharges from Baltic Sea shipping. *Ocean Science Discussions*, 1–54. https://doi.org/10.5194/os-2020-99

Lagerström, M., Lindgren, J. F., Holmqvist, A., Dahlström, M., & Ytreberg, E. (2018). In situ release rates of Cu and Zn from commercial antifouling paints at different salinities. *Marine Pollution Bulletin*, *127*, 289–296. https://doi.org/10.1016/j.marpolbul.2017.12.027

Miljömålsberedningen 2020. (2020). *Havet och människan*.

Moldanová, J. (2018). *BONUS SHEBA Project title: Sustainable Shipping and Environment of the Baltic Sea region*. www.sheba-project.eu/deliverables/index.php.en.

Nelleson, T., Broeg, katja, Dorgeloh, D., Joswig, M., & Heitmüller, S. (2019). *A Technical Guidance for the Handling of Wastewater in Ports of the Baltic Sea Special Area under MARPOL Annex IV helcom.fi*. www.helcom.fi

Ness, B., Urbel-Piirsalu, E., Anderberg, S., & Olsson, L. (2006). *Categorising tools for sustainability assessment*. https://doi.org/10.1016/j.ecolecon.2006.07.023

Om vår statistik. (n.d.). Retrieved May 11, 2021, from https://www.trafa.se/sidor/statistik/

Prevention of Pollution by Sewage from Ships. (n.d.). Retrieved May 4, 2021, from https://www.imo.org/en/OurWork/Environment/Pages/Sewage-Default.aspx

Rincón, G. J., & la Motta, E. J. (2014). Simultaneous removal of oil and grease, and heavy metals from artificial bilge water using electro-coagulation/flotation. *Journal of Environmental Management*, *144*, 42–50. https://doi.org/10.1016/j.jenvman.2014.05.004

Scannell, P. W. (2009). *Effects of Copper on Aquatic Species: A review of the literature*.

SMHIs metod Shipair visar utsläppsstatistik från sjöfart | SMHI. (n.d.). Retrieved May 14, 2021, from https://www.smhi.se/nyhetsarkiv/smhis-metod-shipair-visar-utslappsstatistik-fran-sjofart-1.147353

Sweden. (n.d.). *Chemicals and nutrients in grey water from ships*.

Trafikanalys. (n.d.). *Rapport 2020:5 Uppföljning av de transportpolitiska målen 2020*. Retrieved May 4, 2021, from www.trafa.se

Turner, D. R., Hassellöv, I. M., Ytreberg, E., & Rutgersson, A. (2017). Shipping and the environment: Smokestack emissions, scrubbers and unregulated oceanic consequences. *Elementa*, *5*. https://doi.org/10.1525/elementa.167

Valkirs, A. O., Seligman, P. F., Haslbeck, E., & Caso, J. S. (2003). Measurement of copper release rates from antifouling paint under laboratory and in situ conditions: Implications for loading estimation to marine water bodies. *Marine Pollution Bulletin*, *46*(6), 763–779. https://doi.org/10.1016/S0025-326X(03)00044-4

Vardy, D. W., Santore, R., Ryan, A., Giesy, J. P., & Hecker, M. (2014). Acute toxicity of copper, lead, cadmium, and zinc to early life stages of white sturgeon (Acipenser transmontanus) in laboratory and Columbia River water. *Environmental Science and Pollution Research*, *21*(13), 8176–8187. https://doi.org/10.1007/s11356-014-2754-6

Volym. (n.d.). *Havet och människan, Volym 2, SOU 2020:83*. Retrieved February 24, 2021, from www.nj.se/offentligapublikationer

Ytreberg, E., Eriksson, M., Maljutenko, I., Jalkanen, J.-P., Johansson, L., & Granhag, L. (2019). *Chemicals and nutrients in grey water from ships*.

Ytreberg, E., Hassellöv, I. M., Nylund, A. T., Hedblom, M., Al-Handal, A. Y., & Wulff, A. (2019). Effects of scrubber washwater discharge on microplankton in the Baltic Sea.

Marine Pollution Bulletin, *145*, 316–324. https://doi.org/10.1016/j.marpolbul.2019.05.023

Ytreberg, E., Lagerström, M., Holmqvist, A., Eklund, B., Elwing, H., Dahlström, M., Dahl, P., & Dahlström, M. (2017). A novel XRF method to measure environmental release of copper and zinc from antifouling paints. *Environmental Pollution*, *225*, 490–496. https://doi.org/10.1016/j.envpol.2017.03.014

Zitoun, R., Clearwater, S. J., Hassler, C., Thompson, K. J., Albert, A., & Sander, S. G. (2019). Copper toxicity to blue mussel embryos (Mytilus galloprovincialis): The effect of natural dissolved organic matter on copper toxicity in estuarine waters. *Science of the Total Environment*, *653*, 300–314. https://doi.org/10.1016/j.scitotenv.2018.10.263

APPENDIX

Calculations for wetted area and copper emissions from hull:

VLCC:

Length	305 m (1000,65 ft)
Width	46 m (18,4 ft)
Measured draft	18,4 m (28,4 ft)
Speed	24 km/h (13 knots)
K	estimated to 1,09
Cm (0,95-0,98)	estimated to 0,97
Daily copper leach rate per in the Baltic sea(dcrb)	3,8 µg/cm^2/day
Daily copper emission rate in Kattegat (dcrk)	15,507 µg/cm^2/day
Trip time Stockholm-Helsinki (t_{SH})	53 h
Trip time Gothenburg-Frederikshavn (t_{GF})	4 h

Bloc coefficient Cb:

$c_b = K - 0.5\frac{V_k}{\sqrt{L_f}} = 1{,}09 - 0.5\frac{13}{\sqrt{1000.65}}$ ≈ 0.885 (Ivče, Bakota, et al., 2020)

Wetted area:

$$A = L(2D + W)\left[c_m(0.53 + 0.63c_b) - 0.36(c_m - 0.5) - \ 0.0013(\frac{L}{D)}\right]^{0.5} = 305(2 * 5.23 + 24) * \left[0{,}97(0{,}53 + 0{,}63 * 0.885) - 0.36(0.97 - 0{,}0013(\frac{305}{24})\right]^{0{,}5} \approx 23472m^2$$

Copper emissions from hull per trip:

$$Copper\ release\ per\ trip\ in\ grams = \frac{dcrx*t_x*wetted\ area(cm^2)}{24} \tag{3}$$

$$Stockholm - Helsinki = \frac{7{,}507*10^{-6}*53*23472*10^4}{24} \approx 3891{,}24$$

$$Gothenburg - Fredrikshavn = \frac{15{,}507*10^{-6}*4*23472*10^4}{24} \approx 606{,}64\ g$$

Copper emissions from bilge water per trip($\boldsymbol{Cu_{bilge/trip}}$):

Bilge water l/h($\dot{m}_{bilge}$)	2565 l/h
Amount copper in bilge water (Cu_{bilge})	5 µg/l
Trip time Stockholm-Helsinki (t_{SH})	54 h
Trip time Gothenburg-Frederikshavn (t_{GF})	4 h

$$Cu_{bilge/trip} = Cu_{bilge} * t_x * \dot{m}_{bilge} \tag{4}$$

$$Cu_{SH} = Cu_{bilge} * t_{SH} * \dot{m}_{bilge} = 5 * 10^{-6} * 54 * 2565 \approx 0{,}693\ g$$

$$Cu_{GF} = Cu_{bilge} * t_{GF} * \dot{m}_{bilge} = 5 * 10^{-6} * 4 * 2565 \approx 0{,}051\ g$$

Copper emissions grey water per trip ($\boldsymbol{Cu_{grey/trip}}$)

Greywater ($\dot{m}_{grey}$)	26 l/h
Amount copper in grey water (Cu_{grey})	267 µg/l
Trip time Stockholm-Helsinki (t_{SH})	54 h
Trip time Gothenburg-Frederikshavn (t_{GF})	4 h

$$Cu_{grey/trip} = Cu_{grey} * t_x * \dot{m}_{grey} \tag{5}$$

$$Cu_{SH} = Cu_{grey} * t_{SH} * \dot{m}_{bilge} = 267 * 10^{-6} * 54 * 26 \approx 0{,}03\ g$$

$$Cu_{GF} = Cu_{grey} * t_{GF} * \dot{m}_{bilge} = 267 * 10^{-6} * 4 * 26 \approx 0{,}37\ g$$

Copper emissions black water trip ($\boldsymbol{Cu_{black/trip}}$):

Greywater ($\dot{m}_{black}$)	26 l/h
Amount copper in grey water (Cu_{black})	267 µg/l
Trip time Stockholm-Helsinki (t_{SH})	54 h
Trip time Gothenburg-Frederikshavn (t_{GF})	4 h

$$Cu_{black} = Cu_{black} * t_x * \dot{m}_{black} \tag{6}$$

$$Cu_{SH} = Cu_{black} * t_{SH} * \dot{m}_{black} = 267 * 10^{-6} * 54 * 26 \approx 0{,}03\ g$$

$$Cu_{GF} = Cu_{black} * t_{GF} * \dot{m}_{black} = 267 * 10^{-6} * 4 * 26 \approx 0{,}37\ g$$

Copper emissions scrubber water trip $\boldsymbol{Cu_{scrubber/trip}}$

Scrubber water produced per MWh (${m^3}_{MWh}$)	$45 m^3/MWh$
Amount copper in scrubber water ($Cu_{scrubber}$)	260 µg/l
Trip time Stockholm-Helsinki (t_{SH})	53 h

Trip time Gothenburg-Frederikshavn (t_{GF})	4 h
Main engine effect (E_{ME})	18 MW
Auxiliary engine effect (E_{aux})	0,9 MW

$$Cu_{scrubber/rip} = m^3{}_{MWh} * t_x * (E_{ME} + ME_{aux}) * Cu_{scrubber}$$
(7)

Stockholm-Helsinki = $45 * 10000 * 54 * (18 + 0,9) * 260 * 10^{-6} \approx 11\,720\ g$
Gothenburg – Frederikshavn = $45 * 10000 * 4 * (18 + 0,9) * 260 * 10^{-6} \approx 884,5\ g$

Copper emissions cooling water trip Cu_{tot}

Cooling water produced(V_{cw})	1384000 l/h
Amount copper in cooling water (Cu_{cw})	34.4 µg/l
Trip time Stockholm-Helsinki (t_{SH})	54 h
Trip time Gothenburg-Frederikshavn (t_{GF})	4 h

$$Cu_{cwtot} = Cu_{cw} * t_x * V_{cw} \quad (8)$$

Stockholm − Helsinki = $34,4 * 10^{-6} * 1384000 * 54 \approx 2570,9\ g$
Gothenburg – Frederikshavn = $34,4 * 10^{-6} * 4 * 138400 \approx 190,44\ g$

Total emissions

$$Cutot = Cu_{hull} + Cu_{bilge} + Cu_{grey} + Cu_{black} + Cu_{scrubber} + Cu_{cooling} \quad (9)$$

Stockholm-Helsinki

$$Cutot_{SH} = 3891,24 + 0,693 + 0,37 + 0,32 + 11,62 + 11\,720 \approx 18\,226\ g$$

Total emissions Gothenburg-Frederikshavn

$$Cutot_{GF} = 606,64 + 0,051 + 0,13 + 0,03 + 0,842 + 884,5 \approx 1681\ g$$

Ferry

Length	160 m (524 ft)
Width	24 m (18,4 ft)
Measured draft	5,23 m (28,4 ft)
Speed	29,6 km/h (19 knots
K	estimated to 1,05
Cm (0,95-0,98)	estimated to 0,97
Daily copper leach rate per in the Baltic sea(dcrb)	3,8 µg/cm^2/day
Daily copper emission rate in Kattegat (dcrk)	15,507 µg/cm^2/day
Trip time Stockholm-Helsinki (t_{SH})	36 h
Trip time Gothenburg-Frederikshavn (t_{GF})	3 h
Bloc coefficient Cb:	

$$Cb = K - 0{,}5\left(\frac{Speed\ in\ knots}{\sqrt{Lenght\ in\ feet}}\right)=1{,}05 - 0{,}5\left(\frac{19}{\sqrt{524}}\right) \approx 0{,}635 \tag{10}$$

Wetted area:

$$A = L(2D + W)\left[c_m(0.53 + 0.63c_b) - 0.36(c_m - 0.5) - 0.0013\left(\frac{L}{D}\right)\right]^{0.5}$$
$$= 160(2 * 5.23 + 24) * \left[0{,}97(0{,}53 + 0{,}63 * 0.635) - 0.36(0.97 - 0{,}5) - 0{,}0013\left(\frac{160}{24}\right)\right]^{0{,}5} \approx 4590m^2$$

Copper emissions from hull per trip:

$$Copper\ release\ per\ trip\ in\ grams = \frac{dcr * t_x * wetted\ area(cm^2)}{24}$$

Stockholm-Helsinki= $\frac{7{,}507*10^{-6}*27*4590*10^4}{24} \approx 387{,}68\ g$

Gothenburg-Frederikshavn = $\frac{15{,}507*10^{-6}*4*4590*10^4}{24} \approx 88{,}98\ g$

Copper emissions from bilge water per trip($Cu_{bilge/trip}$):

Bilge water ($\dot{m}_{bilge}$)	1055 l/h
Amount copper in bilge water (Cu_{bilge})	5 µg/l
Trip time Stockholm-Helsinki (t_{SH})	36 h
Trip time Gothenburg-Frederikshavn (t_{GF})	3 h

$Cu_{bilge/trip} = Cu_{bilge} * t_x * \dot{m}_{bilge}$
$Cu_{SH} = Cu_{bilge} * t_{SH} * \dot{m}_{bilge} = 5 * 10^{-6} * 36 * 1055 \approx 0{,}19\ g$
$Cu_{GF} = Cu_{bilge} * t_{GF} * \dot{m}_{bilge} = 5 * 10^{-6} * 4 * 1055 \approx 0{,}016\ g$

Copper emissions grey water per trip ($Cu_{grey/trip}$)

Greywater l/h ($\dot{m}_{grey}$)	3520 l/h
Amount copper in grey water (Cu_{grey})	267 µg/l
Trip time Stockholm-Helsinki (t_{SH})	36 h
Trip time Gothenburg-Frederikshavn (t_{GF})	3 h

$$Cu_{grey/trip} = Cu_{grey} * t_x * \dot{m}_{grey}$$

$Cu_{SH} = Cu_{grey} * t_{SH} * \dot{m}_{bilge} = 267 * 10^{-6} * 36 * 3520 \approx 33{,}83\ g$
$Cu_{GF} = Cu_{grey} * t_{GF} * \dot{m}_{bilge} = 267 * 10^{-6} * 3 * 3520 \approx 2{,}82 g$

Copper emissions black water trip ($Cu_{black/trip}$):

Greywater ($\dot{m}_{black}$)	520 l/h
Amount copper in grey water (Cu_{black})	267 µg/l
Trip time Stockholm-Helsinki (t_{SH})	36 h
Trip time Gothenburg-Frederikshavn (t_{GF})	3 h

$$Cu_{black} = Cu_{black} * t_x * \dot{m}_{black}$$

$Cu_{SH} = Cu_{black} * t_{SH} * \dot{m}_{black} = 267 * 10^{-6} * 36 * 520 \approx 5\ g$
$Cu_{GF} = Cu_{black} * t_{GF} * \dot{m}_{black} = 267 * 10^{-6} * 3 * 52 \approx 0{,}42\ g$

Copper emissions scrubber water trip $Cu_{scrubber/rip}$

Scrubber water produced per MWh (${m^3}_{MWh}$)	$45 m^3/MWh$
Amount copper in scrubber water ($Cu_{scrubber}$)	0.26 µg/l
Trip time Stockholm-Helsinki (t_{SH})	36 h
Trip time Gothenburg-Frederikshavn (t_{GF})	3 h
Effect of engine (E)	21,86 MW

$$Cu_{scrubber/rip} = {m^3}_{MWh} * t_x * E * Cu_{scrubber}$$

Copper emissions cooling water trip Cu_{tot}

Cooling water produced ($\dot{m}_{cw}$)	1384000 l/h
Amount copper in cooling water (Cu_{cw})	34.4 µg/l
Trip time Stockholm-Helsinki (t_{SH})	36 h
Trip time Gothenburg-Frederikshavn (t_{GF})	3 h

$$Cu_{cwtot} = Cu_{cw} * t_x * \dot{m}_{cw}$$

$Stockholm - Helsinki$ = $34{,}4 * 10^{-6} * 367000 * 36 * \approx 454{,}49\ g$
Gothenburg – Frederikshavn = $34{,}4 * 10^{-6} * 3 * 367000 \approx 37{,}87\ g$

Copper emissions scrubber water trip $Cu_{scrubber/trip}$

Scrubber water produced per MWh (${m^3}_{MWh}$)	$45 m^3/MWh$
Amount copper in scrubber water ($Cu_{scrubber}$)	260 µg/l
Trip time Stockholm-Helsinki (t_{SH})	36 h
Trip time Gothenburg-Frederikshavn (t_{GF})	3 h
Main engine effect (E_{ME})	21,86 MW
Auxiliary engine effect (E_{aux})	0,6 MW

$Cu_{scrubber/rip} = m^3{}_{MWh} * t_x * (E_{ME} + ME_{aux}) * Cu_{scrubber}$
(7)

Stockholm-Helsinki = $45 * 10000 * 54 * (21{,}86 + 0{,}6) * 260 * 10^{-6} \approx 9460\ g$
Gothenburg – Frederikshavn = $45 * 10000 * 4 * (21{,}86 + 0{,}6) * 260 * 10^{-6} \approx 788\ g$

Total copper emissions

$Cutot = Cu_{hull} + Cu_{bilge} + Cu_{grey} + Cu_{black} + Cu_{scrubber} + Cu_{cooling}$

Stockholm-Helsinki

$Cutot_{SH} = 387{,}68 + 0{,}19 + 33{,}83 + 5{,}0 + 6{,}91 + 9460 \approx 10\ 470\ g$

Gothenburg-Frederikshavn

$Cutot_{GF} = 88{,}98 + 0{,}016 + 2{,}82 + {,}042 + 0{,}77 + 788{,}3 \approx 919\ g$

Copper per MWH

MW_{main} Main engine effect
MW_{aux} Auxiliary engine effect

$$\frac{Cu}{MWh} = \frac{Cutot}{t_x(MW_{Main}+MW_{aux})} \quad (11)$$

VLCC (Stockholm – Helsinki)

$$\frac{Cu}{MWh} = \frac{18\ 226}{54(18+0{,}9)} \approx 17{,}9$$

VLCC (Gothenburg – Frederikshavn)

$$\frac{Cu}{MWh} = \frac{1685}{4(18+0{,}9)} \approx 22{,}3$$

Ferry (Stockholm – Helsinki)

$$\frac{Cu}{MWh} = \frac{10\ 492}{36(21{,}86+0{,}6)} \approx 13$$

Ferry - Gothenburg – Frederikshavn)

$$\frac{Cu}{MWh} = \frac{920}{3(21{,}86+0{,}6)} \approx 13{,}7$$

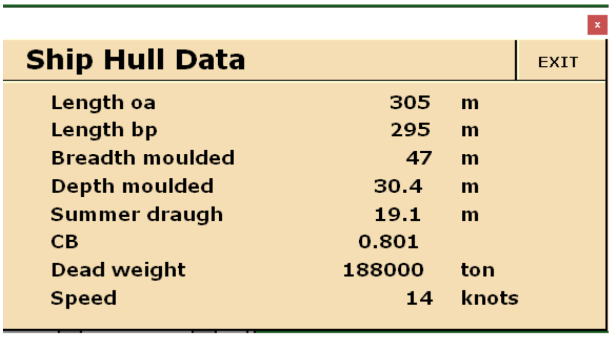

Figure 4 Hull data VLCC

Figure 5 Draft VLCC

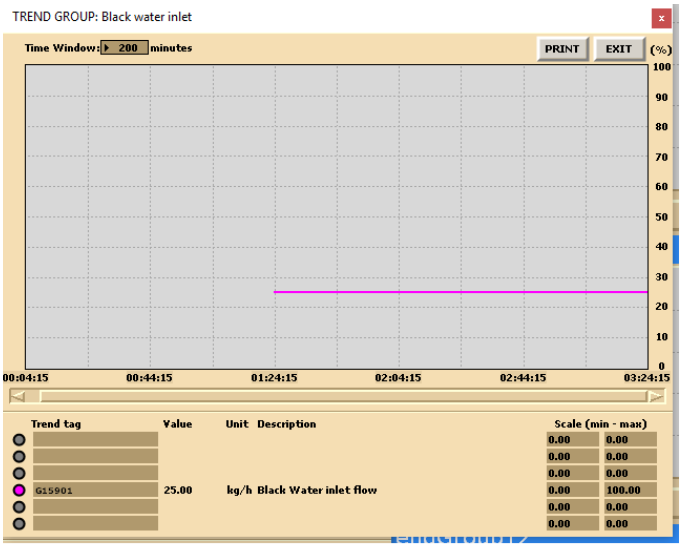

Figure 6 VLCC black water inlet

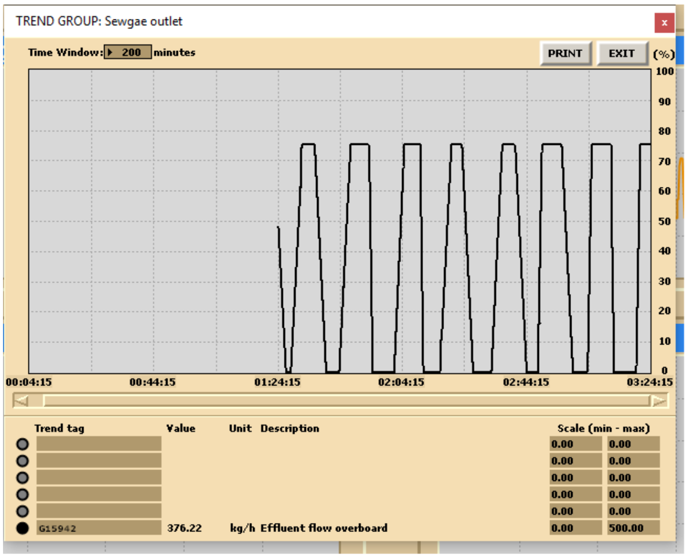

Figure 7 VLCC outlet

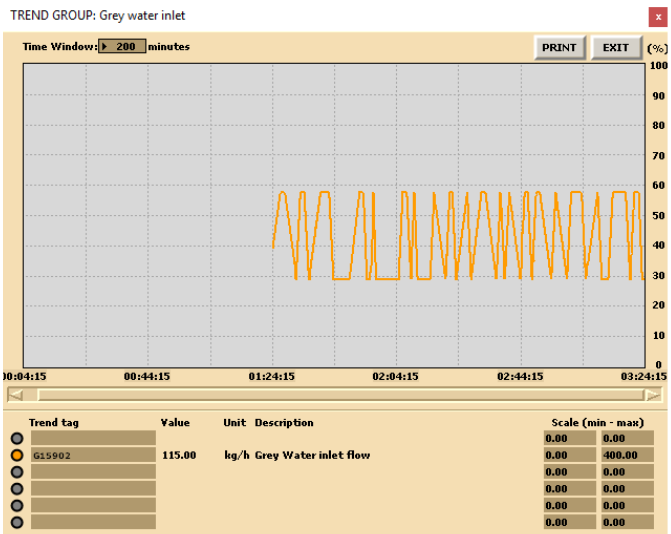

Figure 8 Grey water inlet VLCC

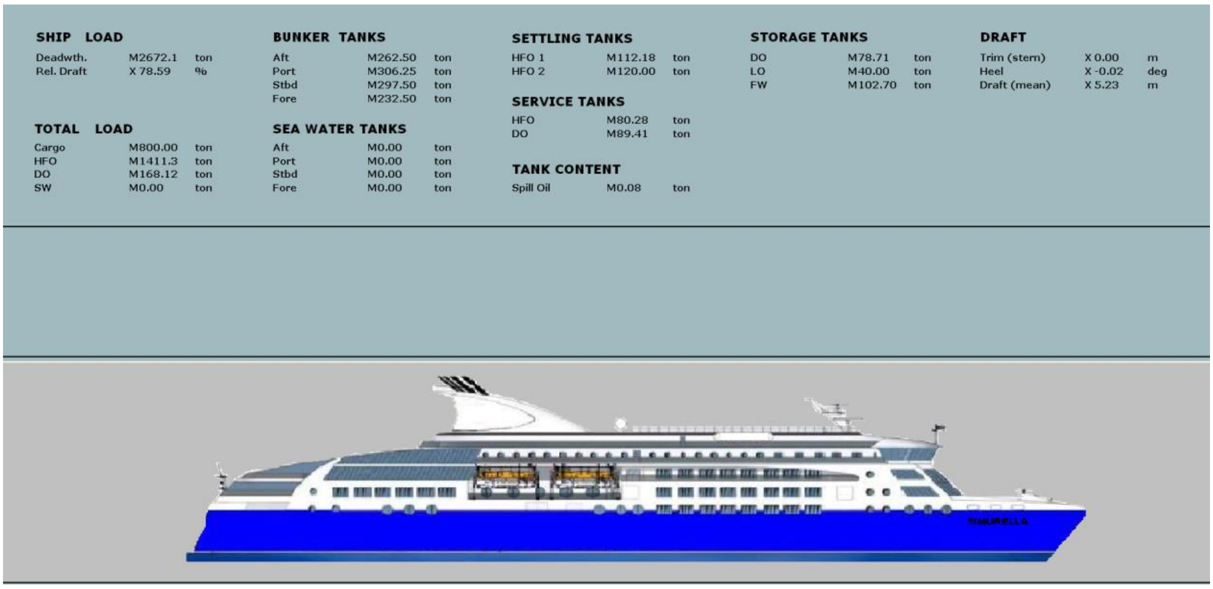

Figure 9 Ferry data

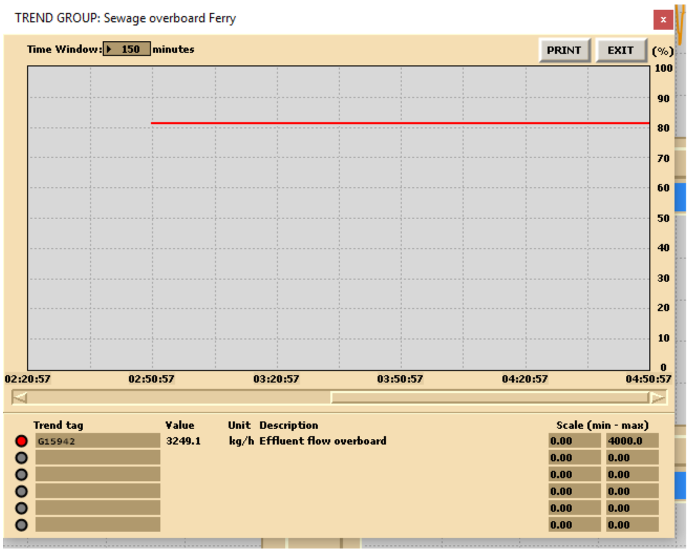

Figure 10 Ferry Sewage overboard

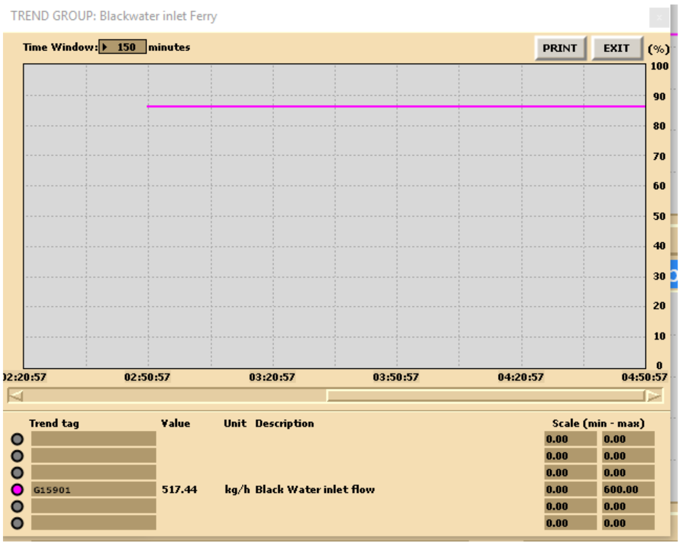

Figure 11 Ferry blackwater inlet

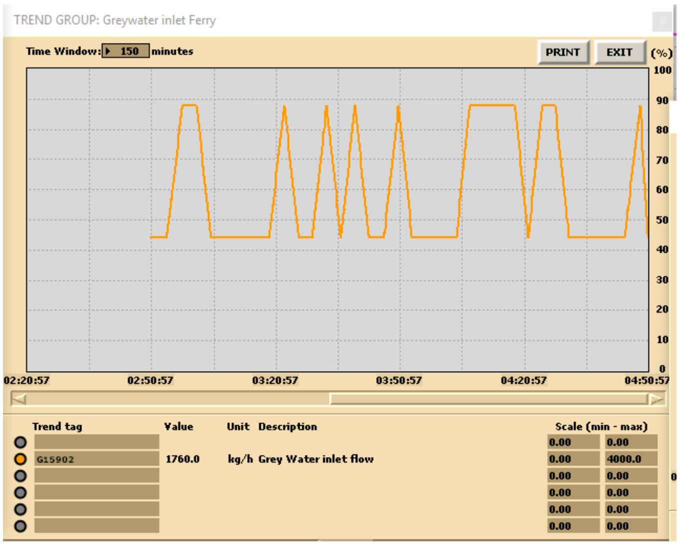

Figure 12 Ferry greywater inlet

DEPARTMENT OF MECHANICS AND MARITIME SCIENCES
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden, 2021
www.chalmers.se

CHALMERS