Strategy Analysis to Control Emissions from Ships at Berth: A System Dynamics Approach

Srikar Prithvi Chinam*, Lewlyn Raj Rodrigues**

Abstract
The contribution of maritime transport to air pollution is significant and necessitates a call for effective strategies to regulate ship emissions. Since most major ports are part of major cities, it is inferred that the emissions from ships at berth are the most harmful due to their proximity to the human population. Effective strategies are required to regulate these emissions in order to reduce risks to human health. This paper proposes a System Dynamics methodology to assess the effectiveness of strategies employed to reduce emissions from ships at berth. Though there is high uncertainty in the estimation of ship emissions, one particular research suggests that a correlation between fuel consumption and gross tonnage of a ship can be established. The inputs from this research were taken to approximate the emissions from ships and the threat to environment was quantified to automatically select the appropriate strategy. Behaviours of various system parameters were studied and the effective range for each strategy was determined based on the port traffic.

Keywords: System Dynamics, Ship Emissions, Strategy Analysis, Air Pollution

Introduction:

In recent years, major port cities are paying higher attention to the in-port ship emissions and their impacts on the coastal communities. Though maritime transport is widely accredited as the most competent with reference to the emissions per cargo tonnage moved, the increasing global trade and port traffic make ships a key contributor to anthropogenic emissions (Corbett and Fischbeck, 1997; Agrawal et al., 2008; Eyring et al., 2010). From increased risk of illness, such as respiratory disease or cancer, to increases in regional smog, degradation of water quality, the impacts of ship emissions have been the primary cause for the blight of local communities and public lands (NRDC, 2004). According to results from continuing scientific research, it was estimated that in the year 2012, premature deaths caused by ship emissions would approximate 87,000 (Corbett et al., 2008).

The major air pollutants from ship emissions at ports that affect human health include particulate matter (PM), sulfur oxides (SOx), nitrogen oxides (NOx), and volatile organic compounds (VOCs) (Eyring et al., 2005). With approximately 1.7 million tons of PM being emitted annually due to ships, and with nearly 70% of these emissions occurring within 400 km of the coast (Endresen et al., 2003; Eyring et al., 2005, 2010), it is vital to discern the risks associated with these emissions. Particulate matter less than or equal to 10 microns in size (PM10) from ship emissions poses special concerns as ambient concentrations of PM10 have been associated with a wide range of health effects such as hospital admissions, asthma and heart attacks. Increment of atmospheric PM concentrations have also been linked to increases in premature cardiopulmonary and lung cancer mortalities to the exposed populations (Pope et al., 2004). Ships being the principal sources of PM10 emissions at harbors, it

*Mr. Srikar Prithvi Chinam, M.S. in Management Science and Engineering, Columbia University in the City of New York, New York, 10027, USA. Email: spc2139@columbia.edu
**Dr. Lewlyn L.R. Rodrigues, Prof. & Head, Humanities & Social Sciences, Manipal Institute of Technology, Manipal, 576104, India. Email: rodrigusr@gmail.com

is important to comprehend and estimate to what extent these emissions can pose a risk to the human population.

Ships at berth are one of the major sources of PM emissions at harbors as the time spent by ships at berth is usually one or more days while the time spent in maneuvering is only a few hours. (Su Song, 2013). Many attempts have been made to accomplish the challenging task of measuring ship emissions during berthing. Numerous studies have been conducted to estimate the magnitude of shipping emissions into the atmosphere (Corbett and Fischbeck, 1997; Corbett and Koehler, 2003; Endresen et al., 2003; Deniz and Durmuşoğlu, 2007; Janhäll, 2007; De Meyer et al., 2008) while other works have attempted to estimate the impacts of ship emissions at local scale on urban areas proximal to harbor sites by means of dispersion modeling and studying the characterization of emissions from ships (Isakson et al., 2001; Saxe and Larsen, 2004; Gariazzo et al., 2007; Lucialli et al., 2007). However, effective measurement of ship emissions must be followed by a set of effective strategies to regulate these emissions. Hence, it is necessary to determine to what extent each of these strategies can be used to control ship emissions.

Literature Review:

A number of methods were used to measure ship emissions. Contini et al., 2011, monitored sampling sites with optical detectors operating at a high temporal resolution to measure PM2.5 and PM10 concentration levels in Venice. Lonati et al., 2010, used the 3-dimensional Calpuff transport and dispersion model to assess the ground level spatial distribution of atmospheric pollutants. Miola et al., 2010, used the Automatic Identification System (AIS) to reduce the uncertainty in the estimation of ship emissions. Hulskotte et al., 2009, conducted a survey of energy consumption and fuel use of seagoing ships and then used the EMS-modeling system (Emission registration and Monitoring of Shipping) to approximate ship emissions.

According to Hulskotte et al., 2009, emissions from ships mainly depend on the Gross Tonnage (GT) of the ship and the kind of fuel used. After conducting a survey consisting of questions such as fuel consumption at different stages of shipping (with most emphasis during berthing), duration of stay at berth, fuel quality, the type of engine, type of ship, GT, year of build, etc., a linear correlation between fuel consumption and GT was established for each type of ship through the EMS system. Special attention was given to container ships as they contribute significantly to total emissions and their transport volumes are rising steeply. However, a non-linear correlation between fuel consumption and GT (as shown in Fig. 1) was suggested as the calculated fuel consumption of small container ships was underestimated while fuel consumption of bigger container ships was overestimated.

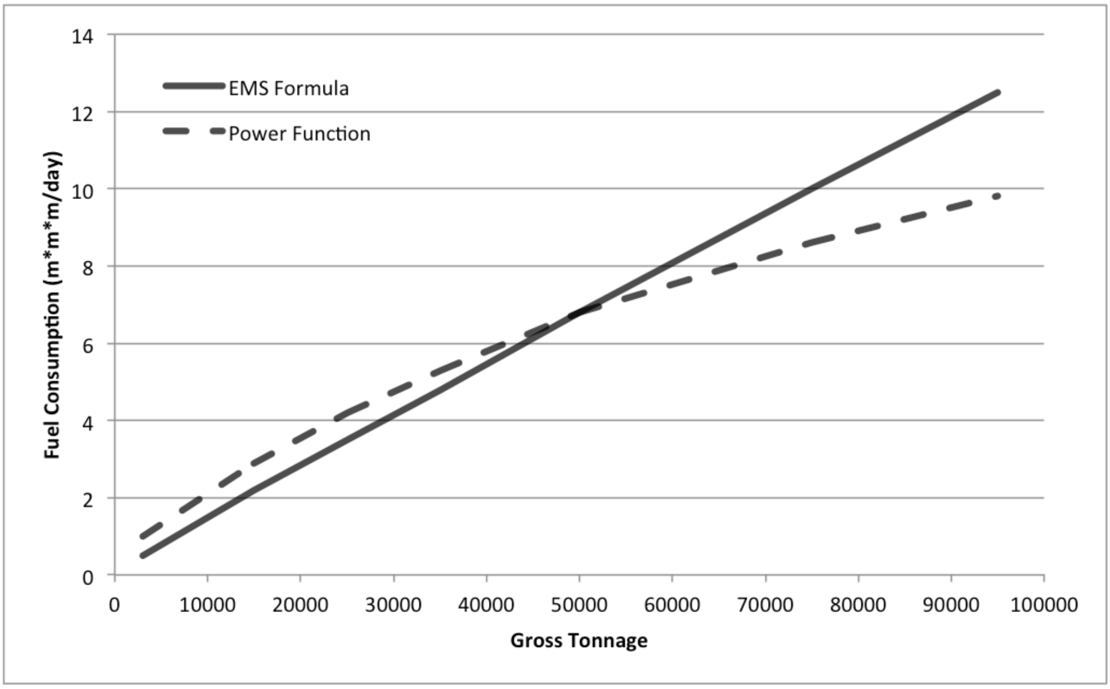

Fig. 1. Graph of fuel consumption of container ships at berth showing calculated fuel consumption (black line) and modeled best fit with a power function (dashed line)

Some ports choose to measure various emissions in the units of ‘tons per year’. Fig. 2 shows the Los Angeles port’s data on the annual PM10 emissions from the year 2005 to 2013. A 7% decrease was observed in the annual PM10 emissions from 2012 to 2013 and an 80% decrease from 2005 to 2013 (The Port of Los Angeles, 2015).

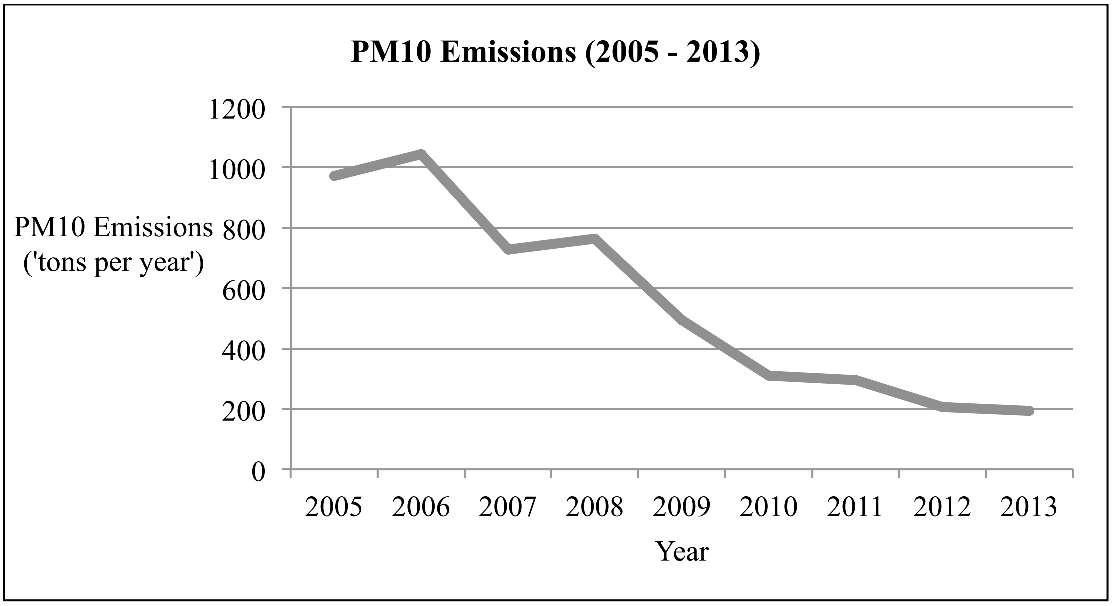

Fig. 2. Annual PM10 emissions in the Port of Los Angeles from year 2005 – 2013

Each port can strategise to regulate the emissions of each harmful pollutant and set targets for the following year. This can depend on the trends of previous years and also the changing regulation. For example, from January 2015, under MARPOL Annex VI for SOx emissions, sulphur limits for fuels used by ships dropped from

1.00% to 0.10%, thus affecting the annual emissions (in tons per year) for several pollutants (International Maritime Organisation, 2015).

Methodology:
The System Dynamics (SD) methodology has been adopted and an attempt is made to understand the complexity behind selection of appropriate strategies to regulate ship emissions. Since the pioneering work of Forrester in Industrial Dynamics, System Dynamics (SD) has been extensively used to study the dynamics of various systems (Forrester, 1961). Computer based simulation is one of the most important and valuable aid for understanding the behavior of systems. Though discrete event simulation is often recommended, potential of SD simulation has become popular in the recent past (Lin et al., 1998). Running "what if" simulations to test policies on SD models aids in the understanding of how systems change over time.

This study deals only with the PM10 emissions from ships, which specially depend on the type of fuel used. Usually, ships use two types of fuels viz., Heavy Fuel Oil (HFO) and Marine Diesel Oil (MDO). The PM10 emissions for each type of fuel were taken from Oonk et al., 2003. This model will be tested for two strategies:

1. The ships at berth use HFO.
2. The ships at berth use MDO.

Though HFO is more contaminating than MDO, ships generally use HFO due to its lesser cost. The port may prefer to use Strategy-2 if the threat to environment escalates due to PM10 emissions. However, since Strategy-2 necessitates ships to use only MDO, the preference for the ships to dock at the nearby ports will rise due to the excess costs associated with MDO. Thus, it is necessary for the port authorities to offer certain discounts to attract ships to use MDO. The discount given can be a certain percentage of the excess cost to be bore by the ships. However, it is important to analyze the capability to generate funds and also the duration to generate these funds before implementing Strategy-2.

The Model:
The model (shown in Fig. 3) can be broadly divided in to three components, viz., the Port System, the Environment Check System, and the Funding System.

Port System:
The number of berths available at the port for ships to dock is a level, which is influenced by the inflow ‘Construction of New Berths’. The inflow, ‘Ships Arriving’ and the outflow, ‘Ships Departing’ determine the number of ships berthed at any time. The ships arriving depends on the number of berths in the port, the time to process each call and the attractiveness of the price offered by the port for each call. The Gross Tonnage of the incoming ships is assumed to be Stochastic Based and a Gaussian Function is utilized for GT variation. The daily fuel consumption is computed through the GT, the number of ships berthed and the density of the fuel used.

Environment Check System:
The daily PM10 emissions are computed through the fuel consumption of the berthed ships and the emission rate for the type of fuel used. Total PM10 emissions are

determined by summing up the daily PM10 emissions. The daily PM10 emissions are averaged out over a certain time to obtain a mean value of the daily PM10 emissions. This mean value is compared with the maximum daily PM10 emissions to determine the ‘Threat to Environment Smooth’, which is smoothed over a specific time. The ‘Threat to Environment Smooth’ is assumed to range over a scale from 0 to 1. Its value nearer to 0 suggests that no danger present for the surrounding environment while its value greater than or equal to 1 suggests high danger to the environment and calls for appropriate measures to be taken. The ‘Threat to Environment Smooth’ is continually compared with ‘Strategy Shift’ and whenever the former rises over the latter, ‘Strategy’ shifts from Strategy-1 to Strategy-2 once and for all. A level named ‘flag’ is used to ensure that ‘Strategy’ remains at Strategy-2 continually as soon as Strategy-2 is chosen over Strategy-1. The change in strategy will be implemented only after a specific time, which is represented by ‘Implementation Delay Time’.

Funding System:
When Strategy-2 is adopted, ships must use MDO and thus an excess cost has to be bore by the arriving ships. ‘% Discount’ determines the percentage of the excess cost that must be given as a discount and the ‘Discount To Be Given’ is estimated. However ‘Discount To Be Given’ is not always the same as the ‘Actual Discount Given’ due to the latter’s dependence on ‘Available Funds’. The ‘Discount To Be Given’ directly influences the ‘Funds Required’, which further influences the contributions from the Government, Agencies and Citizens. These contributions sum up together to increase the ‘Available Funds’ through the inflow ‘Incomings’. The outflow ‘Outgoings’ depends on the discount given to the ships that have used the port services. ‘Attractiveness of Price’ measures the discrepancy between ‘Discount To Be Given’ and ‘Actual Discount Given’.

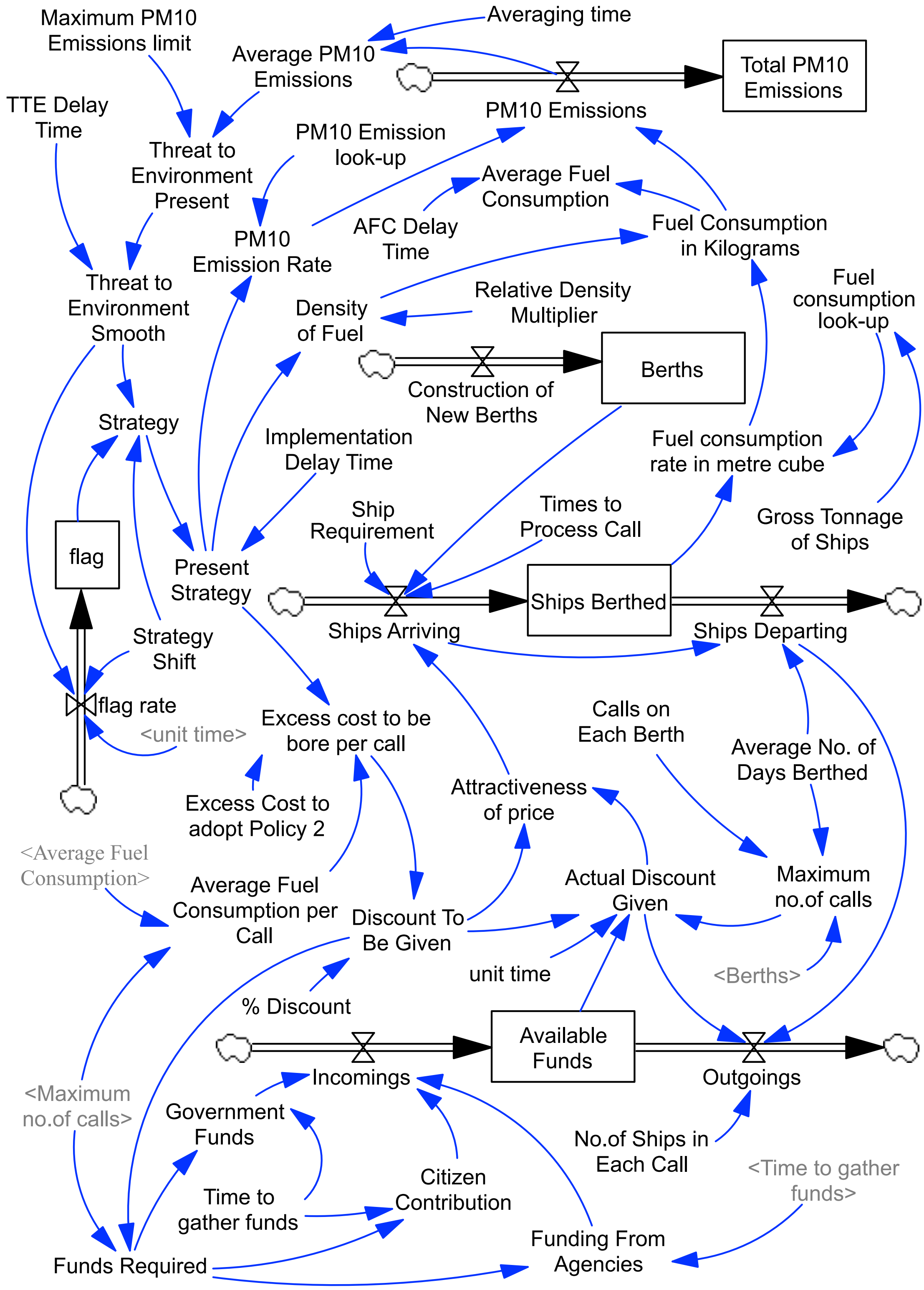

Fig. 3. Stock and Flow Diagram for Strategy Analysis to Control Ship Emissions

Simulation and Analysis:
The model was simulated for 365 days and the dynamic behavior of the model was studied by varying the number of 'Berths'. Four simulations scenarios 1, 2, 3 and 4 have been considered which take the inputs 7, 12, 17 and 25 'Berths' respectively. The 'Strategy Shift' is set at a value 0.75 implying that when 'Threat to Environment' rises over this value, Strategy-2 is preferred over Strategy-1.

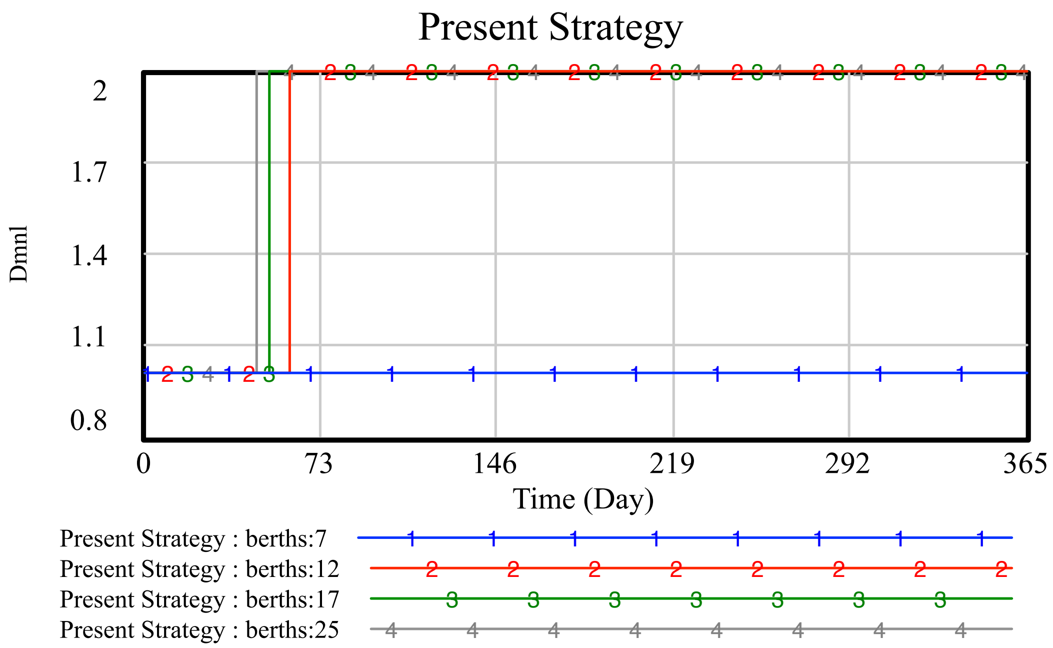

Fig. 4. Behavior of Present Strategy

From Fig. 4, it is observed that the scenarios 2, 3 and 4 adopt Strategy-2 in a few months, whereas scenario-1 continues to adopt Strategy-1, indicating no significant threat to environment for the scenario-1 (The units for 'Present Strategy' is dimensionless, denoted by 'Dmnl').

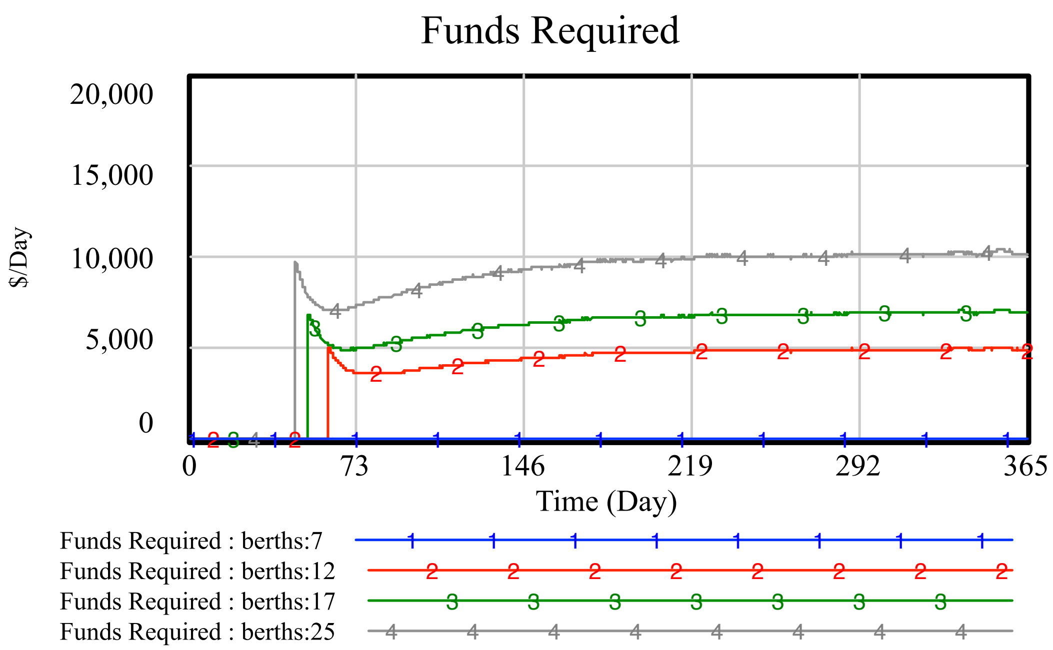

Fig. 5. Behavior of Funds Required

The scenarios 2, 3 and 4 in Fig. 5 increase suddenly, implicating the adoption of Strategy-2. It presents the need to procure sufficient funds, as discounts for ships adopting Strategy-2 must be provided. No funding for scenario-1 is required as it continues to adopt Strategy-1.

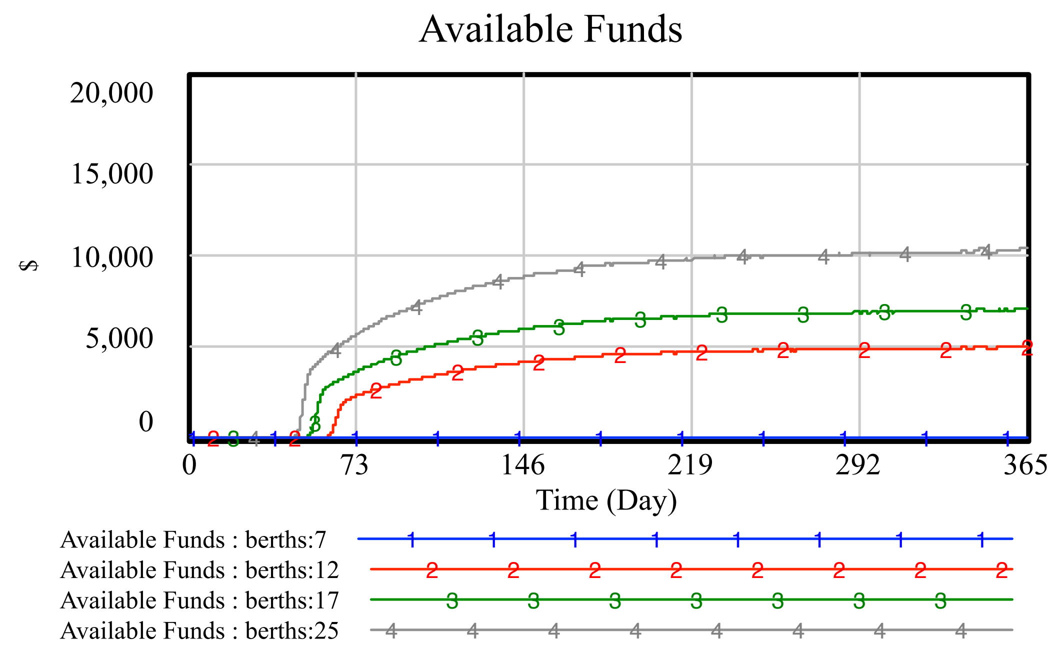

Fig. 6. Behavior of Available Funds

The 'Available Funds' for the scenarios 2, 3 and 4 (shown in Fig. 6) increase less rapidly than 'Funds Required' as certain time is taken to acquire funds.

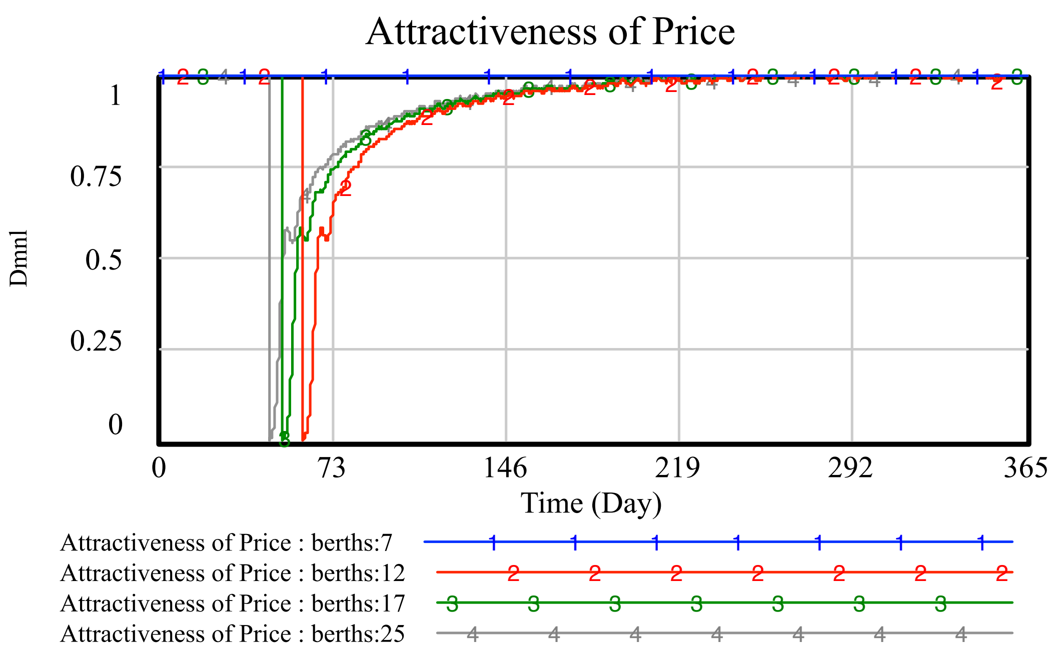

Fig. 7. Behavior of Attractiveness of Price

Since certain time is required to acquire funds, a discrepancy between the discount to be given and discount given is observed. This is made evident through 'Attractiveness of Price' for the scenarios 2, 3 and 4, where a drastic drop and rise are observed consecutively (as shown in Fig. 7), signifying the importance of acquiring initial funds before the implementation of Strategy-2. (The units for 'Attractiveness of Price' is dimensionless, denoted by 'Dmnl')

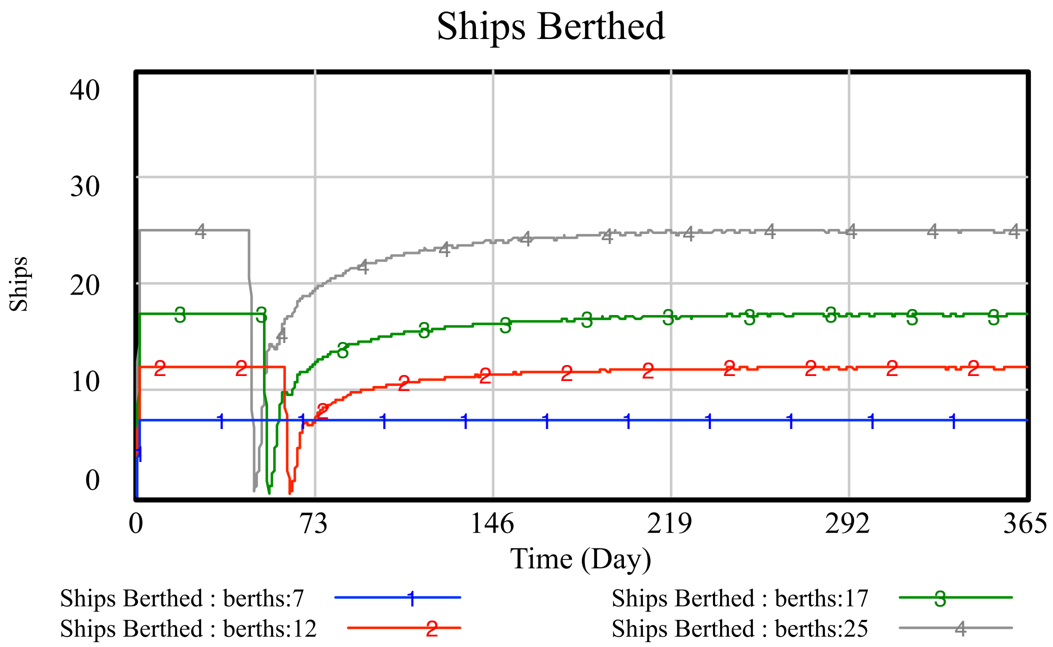

Fig. 8. Behavior of Ships Berthed

Due to the influence of 'Attractiveness of Price' on the 'Ships Berthed' through the rate 'Ships Arrival', 'Ships Berthed' observes (in Fig. 8) a similar pattern as 'Attractiveness of Price', once again signaling the effect of Strategy-2 in the scenarios 2, 3 and 4. Regardless, scenario-1 continues to be stable due to the absence of shift in 'Strategy'.

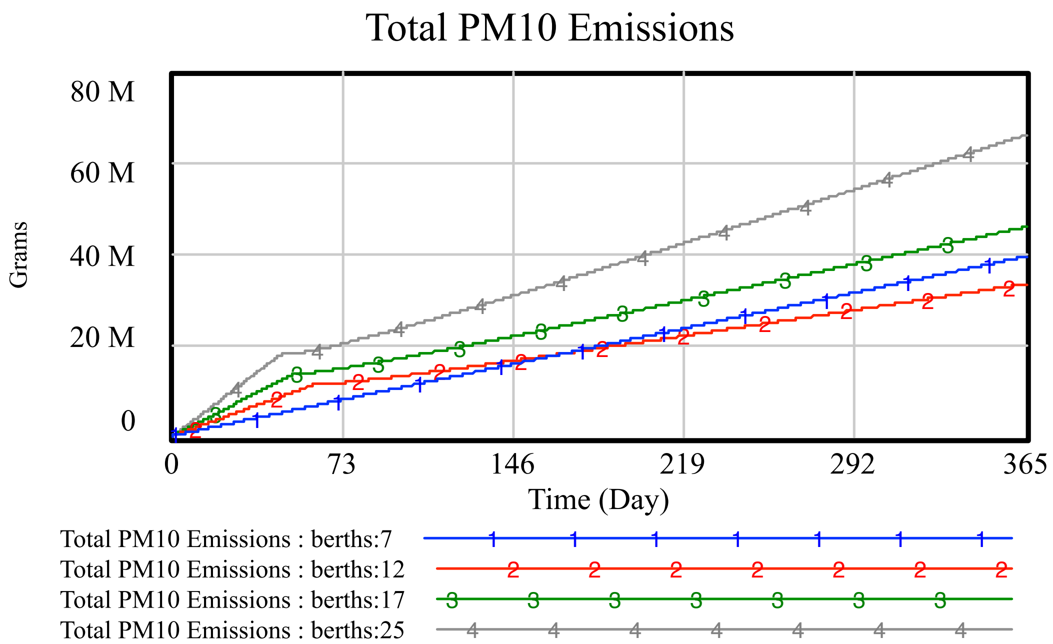

Fig. 9. Behavior of Total PM10 Emissions

The ‘Total PM10 Emissions’ (in Fig. 9) for all the 4 scenarios increases proportionally until scenarios 2, 3 and 4 adopt Strategy-2. Once Strategy-2 is adopted, the rate at which the ‘Total PM10 Emissions’ rises is seen to relatively decrease. Nonetheless, the rate of increase for scenario-1 remains the same as only Strategy-1 is implemented throughout. Eventually, the total PM10 emissions of scenario-1 sum up to be greater than the scenarios 2 and 3. This behavior depicts that adopting Strategy-1 does lead to higher PM10 emissions over a long period of time.

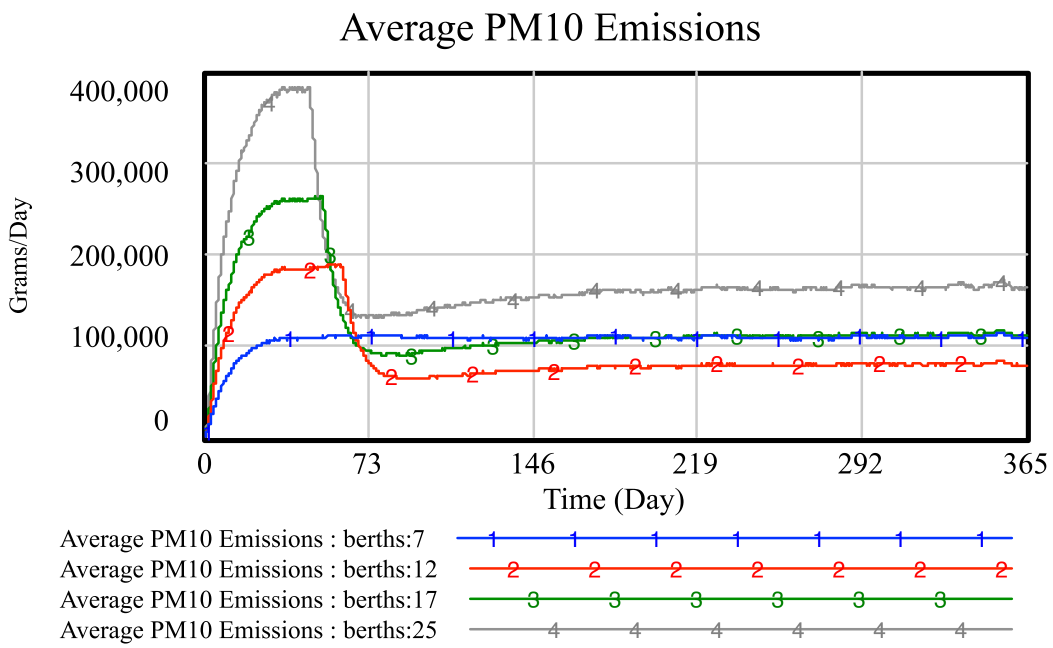

Fig. 10. Behavior of Average PM10 Emissions

It is seen from Fig. 10 that the Average PM10 Emissions initially rise in all the four scenarios proportionally to the assumed number of berths respectively. However, a sudden fall is observed in the scenarios 2, 3 and 4, signaling the effect of a change in ‘Strategy’. The fall shows a remarkable decline in the PM10 emissions, strikingly showing the effectiveness of Strategy-2.

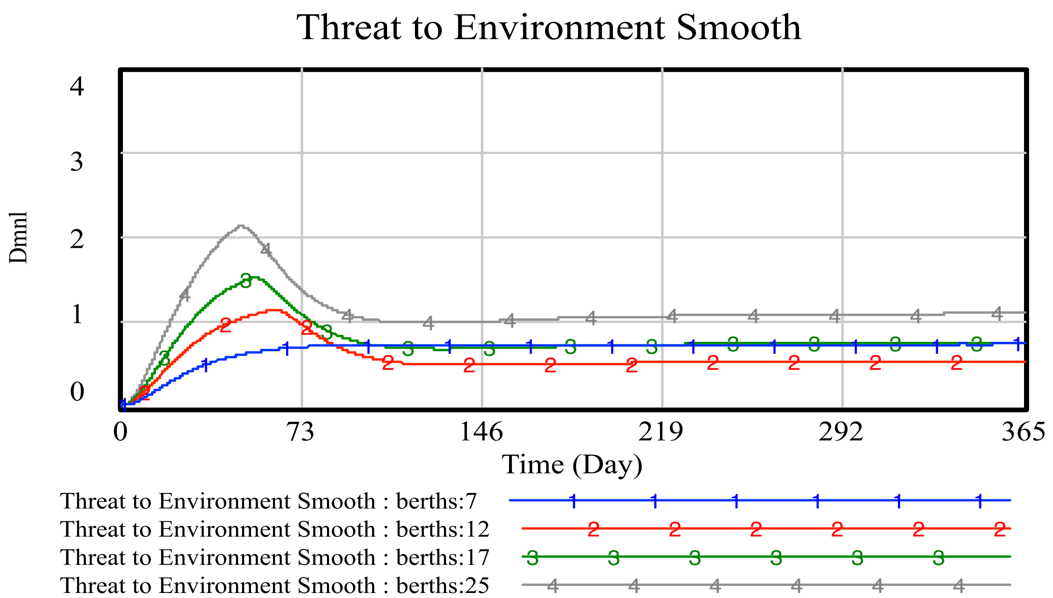

Fig. 11. Behavior of Threat to Environment Smooth

From Fig. 11, it is seen that for the scenarios 2, 3 and 4, 'Threat to Environment Smooth' rises over the value of 'Strategy Shift' (i.e., 0.75) causing a shift in the strategy (from Strategy-1 to Strategy-2) (The units for 'Threat to Environment Smooth' is dimensionless denoted by 'Dmnl'). The shift in strategy affects the 'Threat to Environment Smooth' only after an 'Implementation Delay Time'. These three scenarios then decline to stabilize at a certain value. No shift in strategy is seen for scenario-1 as it stabilizes at a value lesser than the value of 'Strategy Shift'. Scenarios 2 & 3 initially rise over the value of 'Strategy Shift' and then later decline to stabilize on a value lesser that the value of 'Strategy Shift'. Scenario-4 too, like scenarios 2 and 3, initially rises over 'Strategy Shift' and declines to stabilize a certain value. However, this value being greater that 1 indicates an active threat to environment and the need for a better strategy with greater effectiveness to be employed.

Model Validation:

Hulskotte et al., 2009, studied the emission patterns for different types of pollutants released by all kinds of ships that approach the Port of Rotterdam. To test this model, we will consider only the PM10 emissions released from Container Ships. Inputs such as average number of calls made by container ships (6309 Calls in the year 2005; approximately 17.28 Calls/Day), PM10 emissions when HFO and MDO are used, average GT of container ships, relation between GT and fuel consumption for container ships, have been taken from the study. Further, according to the above study, the total PM10 emissions released by container ships was 49 tons in the Port of Rotterdam for the year 2005. This value is used for the validation of the model. When the model was simulated with an input of 17 berths, the 'Total PM10 Emissions' turned out to be approximately 46 tons, thus validating the model.

Inference:

As the number of berths in the port increase, the emissions increase proportionately. Based on the 'Threat to Environment Smooth', a need to shift the 'Strategy' is established. Strategy-2 comes into picture with great effectiveness by reducing emissions to lessen the threat to environment. Further, it is observed that the two strategies implemented are effective only for a certain range of ship traffic. Strategy-1 was found to be effective for one to seven berths under full utilization and Strategy-2 was found to be effective for eight to seventeen berths under full utilization. However, for busy ports with higher number of berths, the effectiveness of Strategy-2 will not suffice and a need for a new strategy with higher effectiveness is required.

The discrepancy between the funds required and the funds available affects the discrepancy between the discount to be given and the discount given, which is conspicuously evident through the behavior of 'Attractiveness of Price'. This finds the need to have sufficient funds before adopting a new strategy.

Conclusion:

With the escalating concern for the safety of our environment and ports being one of the major sources of pollution, it has come to be a global interest to challenge the ways and methods adopted by the ports. It has thus become imperative to analyse the outcomes of the methods employed by the ports. This study demonstrates the capability of System Dynamics as a tool to analyse two strategies with the intent to reduce ship emissions. The research based on modeling and simulation has very successfully proved that employing efficient strategies can immensely reduce ship emissions.

Tremendous reductions were observed in the average emissions per day when a better strategy was employed to replace the existing one. The total emissions were computed to study the overall effects of emissions over long periods of time. An attempt was made to quantify the threat to environment, which was used to scrutinize the feasibility of both the strategies. The extent to which these strategies can be effective was perceived. However, both the strategies were proven effective only for a certain range of ship traffic, suggesting a need to establish a more beneficial strategy. Also, the significance of the funding required to employ a strategy was envisaged and it is suggested to procure the necessary initial funding required before the implementation of new measures.

Future Scope:
A need has been established for a more effective strategy to be employed. Strategies such as the one adopted by the Port of Los Angeles called the Alternative Maritime Power (AMP) may be recommended. According to this program, AMP-equipped ships, instead of running on diesel power while at berth 'plug-in' to shore side electrical power, which forms an alternative power source for oceangoing vessels. A provision can be made in the model to accommodate the needs of this strategy and its effectiveness can be measured.

The present model measures only the PM10 emissions and measures the threat to environment based only on the PM10 emissions. The model may accommodate measurement of other emissions too and the threat to environment may be computed with weights attached to each of these emissions. Further, each source of pollution at the port may be considered and a model incorporating all these sources may be employed for analyzing an overall effective strategy.

References

Agrawal, H., Welch, W.A., Miller, J.W., Cocker, D.R., 2008. Emission measurements from a crude oil tanker at sea. Environ. Sci. Technol. 42, 7098–7103.

Corbett J., Winebrake J., Green E., Eyring V., and Lauer A., 2008. Mitigating Health Impacts of Ship Pollution through Low Sulfur Fuel Options: Initial Comparison of Scenarios.

Corbett, J.J., Fischbeck, P.S., 1997. Emissions from ships. Science 278 (5339), 823–824.

Corbett JJ, Koehler HW. Updated emissions from ocean shipping. J Geophys Res 2003;108 (D20):4650.

De Meyer P, Maes F, Volckaert A. Emissions from international shipping in the Belgian part of the North Sea and the Belgian seaports. Atmos Environ 2008;42:196–206.

Deniz C, Durmuşoğlu Y. Estimating shipping emissions in the region of the Sea of Marmara, Turkey. Sci Total Environ 2007;390:255–61.

Endresen, O., Sorgard, E., Sundet, J.K., Dalsoren, S.B., Isaksen, I.S.A., Berglen, T.F., Gravir, G., 2003. Emission from international sea transportation and environmental impact. J. Geophys. Res. 108, 4560.

Eyring, V., Isaksen, I.S.A., Berntsen, T., Collins, W.J., Corbett, J.J., Endresen, O., Grainger, R.G., Moldanova, J., Schlager, H., Stevenson, D.S., 2010. Transport impacts on atmosphere and climate: shipping. Atmos. Environ. 44, 4735–4771.

Eyring, V., Kohler, H.W., van Aardenne, J., Lauer, A., 2005. Emissions from International shipping: 1. The last 50 years. J. Geophys. Res. 110, D17305.

Forrester, J.W., 1961, Industrial Dynamics, New York: MIT Press and John Wiley & Sons Inc.

Gariazzo C, Papaleo V, Pelliccioni A, Calori G, Radice P, Tinarelli G. Application of a Lagrangian particle model to assess the impact of harbour, industrial and urban activities on air quality in the Taranto area, Italy. Atmos Environ 2007;41:6432–44.

International Maritime Organisation, 2015, Sulphur oxides (SOx) – Regulation 14. Available from: <http://www.imo.org/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Sulphur-oxides-%28SOx%29-—-Regulation-14.aspx>. [18 March 2025].

Isakson J, Persson TA, Selin Lindgren E. Identification and assessment of ship emissions and their effects in the harbour of Göteborg, Sweden. Atmos Environ 2001;35:3659–66.

Janhäll S. Particle emissions from ships. The alliance for global sustainability. Göteborg, Sweden: Chalmers university978-91-976534-3-5; 2007.

Lin, C., Baines, T.S., Kane, J.O., and Link, D., 1998, 'A Generic Methodology That Aids The Application Of System Dynamics To Manufacturing System Modelling,' *IEEE International Conference On Simulation*, No.457, pp. 344-349.

Lucialli P, Ugolini P, Pollini E. Harbour of Ravenna: the contribution of harbour traffic to air quality. Atmos Environ 2007;41:6421–31.

Miola, A., Ciuffo, B., 2010. Estimating air emissions from ships: meta-analysis of modelling approaches and available data sources. Atmos. Environ. 45, 2242–2251.

NRDC, 2004. Chapter 1: Health and Environmental, Effects of Port Pollution, Harboring Pollution – Strategies to Clean Up U.S. Ports.

Oonk, H., Hulskotte, J., Koch, R., Kuipers, G., Ling van, J., 2003. Emission Factors of Seagoing Ships on the Purpose of Yearly Emission Calculation (in Dutch). TNO- report R 2003/438 version 2.

Pope, C. A.; Burnett, R. T.; Thurston, G. D.; Thun, M. J.; Calle, E. E.; Krewski, D.; Godleski, J. J. Cardiovascular mortality and long-term exposure to particulate air pollution: Epidemiological evidence of general pathophysiological pathways of disease. Circulation 2004, *109* (1), 71–77.

Saxe H, Larsen T. Air pollution from ships in three Danish ports. Atmos Environ 2004;38: 4057–67.

Statistics Netherlands, 2007. Data Extraction from CBS Publicatiebestand, pers. Comm. Dick Broekhuizen.

Su Song, 2013. Ship emissions inventory, social cost and eco-efficiency in Shanghai Yangshan port. Atmos. Environ. 82, 288–297.

The Port of Los Angeles, 2015, Inventory of Air Emissions Highlights - 2013, Available at: <http://www.portoflosangeles.org/pdf/2013_Air_Emissions_Inventory_Highlights.pdf>