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Analysis and measurement of SOx, CO2, PM and NOx emissions in Port auxiliary vessels.

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Analysis and measurement of SOx, CO_2, PM and NOx emissions in Port auxiliary vessels.

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Abstract:

The objective of this paper is to provide an estimation of air emissions (CO_2, NOx, SOx and PM) released by port assistant vessels at port level. The methodology is based on the "full bottom-up" approach and starts by assessing the fuel consumed by each tug ship during its individual port exercises (movements during docking and undocking of merchant vessels). The scenario selected for the analysis and measurements is one of the most significant Port of the Mediterranean Sea, where seven auxiliary vessels were monitored for 407 calls. The analysis also gathers real-time data from the Automatic ship Identification System (AIS), tug ship particulars from IHS Sea-web database (www.maritime.ihs.com) and emission factors established by the International Maritime Organization (IMO). The research findings show that the key indicators are inventory emissions per dock, types of towed vessels and docking and undocking manoeuvres.

This paper also presents an action protocol for the assessment of the inventory of emissions produced by the main engines of tug ships operating inside ports, which can be extrapolated to other ports operating with tug ships of the same technical characteristics. Evaluating, therefore, the amounts emitted of nitrogen oxides, sulphur oxides, carbon dioxide and particulate matter.

Keywords. Air pollution. Ships emissions. Tug ship. Emission inventories. Port-level.

1. INTRODUCTION

Since 70% of the ships' emissions happen within 400 km of land, the emissions that are released to the atmosphere have a significant environmental impact on the local communities (Eyring et al. 2005).

Moreover, the urban character of some ports and their populated surroundings are the focus of the negative effects of exhaust pollutants due to the associated local impacts on human health. Thus, the need to control air pollution at ports is widely acknowledged as an active policy issued by various authoritative port associations (IAPH 2007 and ESPO 2003) as an answer of main regulations (IMO 2017, EC 2015, EPA 2016, etc.).

The control of emissions not only goes with a proper assessment of the impacts of a growing shipping activity but also with mitigation strategies. Emission inventories (ICF 2006) would help the policy makers to develop effective systems in order to control ships' emissions in port (Tzannatos 2010).

Noting all the features above, there are currently no studies of the SOx, CO_2, PM and NOx emissions caused by different working regimes of power, because engine manufacturers have not measured these emissions across the range of operating power, from 0% to 100% load engine.

There's likewise and issue with ports located within urban areas. These cities have the biggest problems caused by pollution emitted from the ports, from the factories that lie within them, from merchant and non-merchant ships constantly docking and undocking and from other auxiliary port vessels working continuously throughout the year

These pollutants emitted inside the port can be transported to the city, through the wind and other weather factors and they can also be carried by the particular terrain of each territory, causing environmental and health problems for the resident population.

In such a context, the goal of this paper is to develop accurate emission inventories (CO_2, SOx, NOx and PM) and emission indicators for ports where ship tug's activities are notorious.

1.1 Objectives

The goal is to establish the amount of nitrogen oxides, sulphur oxides, carbon dioxide and particulate matter that are emitted by the tug ship manoeuvres performed during docking, undocking and removing of merchant ships, considering the power developed by it and setting, therefore, a relationship between the power developed by the tug ship during the performance of those manoeuvres and the emissions of NOx, SOx, CO_2 and PM emitted while on it.

The International Maritime Organization (IMO) established the amount of exhaust emissions caused by marine engines using emission models, based on actual emission factors adopted from measurements performed on board engines or theoretical factors deduced from the respective equations of chemical reactions, combined with the actual fuel consumption (based on international maritime statistics of fuel sales). In this study, several factors of NOx, SOx, CO_2 and PM, provided by different organizations according to the power and according to the fuel consumption, have been used. By surveying different operations performed by the tug ships in the port and its duration while measuring the power used in each manoeuvre, the NOx, SOx, CO_2 and PM emission values are found and analysed. Considering the total number of manoeuvres that tug ships carry in a year (2018) it is possible to find the total of emissions for each power emitted, over a year, by the tugs inside the port.

Therefore, it will be determined which power range produces more emissions for these type of ships that work with a large variation of propulsive power. In addition, the total of pollutant emissions per hour of work of the tug ships for the different type of vessels towed will be calculated according to the different docking terminals of these and ways to reduce or significantly mitigate nitrogen oxides, sulphur oxides, carbon dioxide and particulate matter emissions as well as the harmful effects these marine engines cause on the environment and on the health of the population, especially in the port-city area.

1.2 Assessment protocol

This paper also presents an action protocol for the assessment of the inventory of emissions produced by the main engines of tug ships operating inside ports.

From the initial stage, we have posed the following working hypotheses:

1. The tug ships built after January 2000 but before January 2011, thus belonging to the Tier I group (IMO regulation MARPOL Annex VI 2010*)*. The choosing of this group as a reference for the assessments is set, as they form the major share of the tug ships in the considered Mediterranean Port, 1 tug ship of the year 2005, 1 of 2007, 1 of 2008, 3 of 2009 and 2 of 2016 operate. That is, of the 8 tug ships that operate in that port, 6 tug ships are TIER I and only 2 tug ships are TIER III. Additionally, using this group as being the most pollutant one among the three Tiers group, we will obtain the maximum possible NOx pollution, compared with engines complying Tier II or Tier III.
2. The tug ships have two main engines of 2400kW (each one) to 1000 rpm. The fuel used in tug's normal service is Marine Diesel Oil (MDO) type B with 0.1% of sulphur.
3. The main engines on board the tug ships have been chosen, avoiding the auxiliary ones and generators. Because of their small size and to the fact that in hoteling mode (when the tug ship is docked waiting to be called for a towing service by the harbour maritime traffic control), the tug ship is plugged to the port electrical shore-connection.
4. A port in the Mediterranean basin is chosen for the study. A classification of the main berthing docks of merchant ships requiring towing service have been included, grouping them according to the freight type of the ships. Up to 6951 merchant towing services have been carried out in 41 different berths or cargo terminals.
5. The main characteristics of the Mediterranean port are the following: 1,109.2 hectares (ha) of land area, 23,183 km of wharves and berths, 30 ramps to Roll-on/Roll-off ships (RO RO ramps), 203,304 m^2 of covered warehousing and 5,023,964 m^2 of open

warehousing, 38 wharf cranes of which 27 are container cranes.

Several international container terminals, with an area of more than 3,000 metres of berthing line, up to 16 meters depth for all sort of ships (super-post-panamax) and 17 container cranes.

Several cruise terminals with the following characteristics: one with a berthing line of 1,379 metres without limitation of ship length and 11 meters of draught, and the other with a berthing line of 281 meters (N), 350 meters (S) and 160 meters (E), ship length: 169 meters (N), 253 meters (S), 205 meters (E), and draught: 7.3 meters (N), 8 meters (S), 8 meters (E).

Several ferry terminals, 2 specialised terminals with daily connections to Balearic Islands: Mallorca, Menorca and Eivissa.

One multipurpose terminal for multipurpose ships with handling of containers, vehicles, RO RO cargo and conventional cargo.

Several vehicle terminals with two specialised terminal leaders in vehicle traffic in the Mediterranean. The main characteristics are 5 rail cargo tracks, 5 RO RO ramps and several vertical areas with a capacity for 24,000 units, 1,200 linear metres of berthing space and new areas underway for the distribution of cars.

Several bulk terminals with more than 17 metres of draught adapted for new generation vessels, warehouses with a capacity of more than 75,000 m^3 and segregated tanks for all kind of products, direct connection by rail, road and oil pipeline.

6. The cargo terminals have been grouped into 3 different docks of container ships, because there is the highest demand for towing services, 1 RO RO ship dock, 1 LNG ship dock, 1 Ferry ship dock, 1 cargo ship dock (Bulk), 1 Cruise ship dock, 1 VLCC ship dock, 1 car vessel dock, 1 chemical tanker dock and 1 dock for other type of ships.

7. Up to 407 towing manoeuvres have been analysed, counting the time and required power to the tug ship (Maximum Continuous Rate) in each manoeuvre. This information is obtained from the orders given by the harbour pilot, keeping in mind the time required at each range of developed power.

8. For every merchant vessel arrival, the tug ships’ fuel consumption (based on the power consumed) and their corresponding emissions will be estimated for: (a) from the call of maritime traffic controller (start main engines’ tug ship in tug ships’ dock base) to the arrival of the towing vessel, (b) from the arrival to the towing vessel to the start the towing manoeuvre, (c) from the start of the towing manoeuvre to the end of the towing manoeuvre, (d) from the end of the towing manoeuvre to the arrival to the tug ships’ dock base.

9. In the incoming manoeuvring, the normal point to start towing is in the Landfall Buoy (the first mark or buoy seen by an observer approaching the harbour from the open sea) and in the outgoing manoeuvring the normal point to finish towing is also in the same point, Landfall Buoy.

The present paper proposes a methodology based on the full bottom-up approach and begins by evaluating the fuel consumed by each tug ship based on its individual port-activities (manoeuvring), disregarding hoteling as the harbour tugs have a shore-connection during that time. With this individual fuel consumption we can calculate the pollutants emitted by each tug ship in each manoeuvre (incoming and outgoing manoeuvres). Once these pollutions emitted by each tug ship have been calculated, we can evaluate the total annual pollution of all the tug ships in this Mediterranean port.

2. MATERIAL AND METHOD

The first step in the emissions evaluation is the estimation of the fuel consumed by the tug ship according to its manoeuvres. The specific fuel consumption (measured in g/kWh) is, therefore, an important contribution to it. Once fuel consumption is obtained, it is possible to use emission factors to estimate the emission of the different pollutants analysed.

Furthermore, an extensive study has been conducted of the engine power provided by the tug ship when required manoeuvres in docking, undocking or removal of merchant ships in the Inner Harbour.

The methodology used comprised the following steps:

1. Collection of data from the IHS Sea-web database (particulars of tug ships and their main engines (www.maritime.ihs.com)), real-time data from the Automatic Ship Identification System (AIS) and characteristic curves of tug ship main engines (speed-load, power, specific fuel consumption, fuel rack index, etc.).
2. Collection of the number of manoeuvres performed by the port tugs during the year 2018, the time used to perform them (from AIS) and the number of tugs used in each towing manoeuvre.
3. From each main engine characteristic curves and depending on the power required by the harbour pilot, we can first obtain the engine fuel rack index (in mm) on the main engines injection pumps and with this, we obtain the specific fuel consumption (SFC, in g/kWh), in the characteristic curves of the main engines, at every power range (% MCR, in kW) supplied by the tug ship in each towing manoeuvre. These characteristic curves that are obtained in the main engines technical manuals relate the engine power, the specific fuel consumption, the engine fuel rack and the engine speed.
4. With the data obtained during the exhaustive analysis of the 407 analysed towing manoeuvres on board the tug ship, we can obtain the percentage of time required in each of them (% t) based on each power range developed by the tug ship (% maximum continuous rating (MCR)) depending on the orders given by the harbour pilot.
5. These power-time rates are extrapolated and applied to all towing manoeuvres of the year 2018.

6. Knowing the duration of each manoeuvre and the docking / undocking terminal of the towed merchant ship, we can calculate the fuel consumption of the tug ship in each performed manoeuvre:

$$C_P = \sum_{ij} \left(P_{B_{ij}} t_{ij} \right) c_e \tag{1}$$

   Where C_P is the amount of fuel consumed by the tug ship main engines during the towing manoeuvre of the vessel. The tug ship travelled distance is i, counted since it receives the call from the maritime traffic controller and starts its main engines to carry out the towing service, until the end of the towing manoeuvre and up to its docking base again.

   The stage of tug ship activity is j (manoeuvres of entry or exit of towed merchant ships); t_{ij} is the time elapsed when carrying out the towing maneuver inside the port (h); c_e is the specific fuel consumption of the main engines (g/kWh) and $P_{B_{ij}}$ is the power developed by the tug ship (kW) during the manoeuver, which is calculated by extrapolating the time percentages of the tug ship's working range during the 407 towing manoeuvres analysed on board, based on the orders given by the harbour pilot of the towed merchant ship.

7. By knowing the SFC (g/kWh), obtained from the characteristic curves of the main engines through the fuel rack index of fuel injection pumps in those main engines, with the power supplied in each of the tug's operating ranges (% MCR in kW) during each manoeuvre and applying the emission factors (EF), we can calculate the partial CO_2 emissions, SOx, PM and NOx at every power range (g emissions/h).
8. Then, knowing the time of each manoeuvre, we can assess the pollution emitted by the tug ship at each incoming / outgoing manoeuvre and at each docking / undocking terminal.
9. Adding the total towing manoeuvres in the port during the year 2018 we can calculate the total annual pollution emitted by the tug ships in that port. In addition, the pollution emitted in the port incoming manoeuvres and the pollution emitted in the port outgoing manoeuvres are split. It can also be established which types of towing manoeuvres are the ones that pollute the most and least, depending on the type of towed merchant ship and the duration of each manoeuvre, establishing polluting emissions per hour of operation of its main tug ship engines.

The 407 analysed towing manoeuvres sum up to 29725 effective minutes and can be broken down according to the power supplied by the towing vessel (table 1 and figure 2).

MCR	18% MCR	34% MCR	54% MCR	81% MCR	100% MCR
Tugs' Manoeuvres Hours	12429	11978	4125	146	1048

Table 1 Minutes worked according to the power developed by the harbour tug operations

There's been computed a total of 12429 minutes at 18% power, 11978 minutes at 34% power, 4125 minutes at 54% power, 146 minutes at 81% power and 1048 minutes at 100% power.

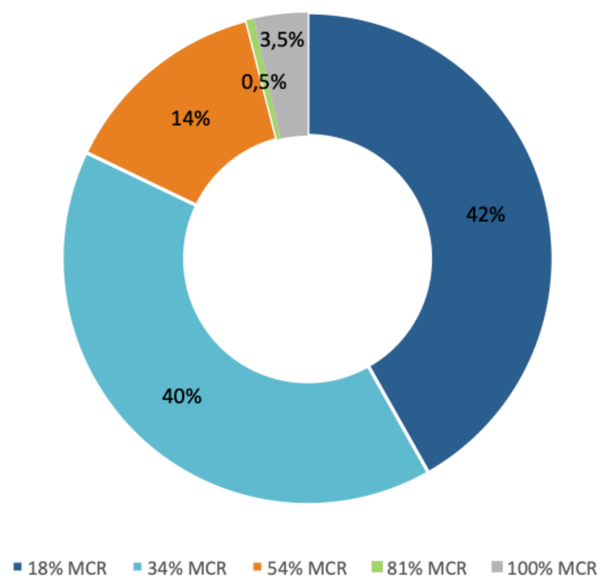

Fig. 1 Percentage in minutes of the power developed by the tugs' main engines during manoeuvres

Type of Fuel	EF CO_2	EF SOx	EF PM
LSFO (HFO -1.5% S)	3.114 g CO_2/g fuel	0.030 g SOx /g fuel	0.00426 g PM /g fuel
MDO/MGO (0.1% S)	3.206 g CO_2/g fuel	0.002 g SOx /g fuel	0.00097 g PM /g fuel

Table 2 Emission Factor (EF) CO_2, SOx, PM. Data source IMO regulation
Low Sulphur Fuel Oil (**LSFO**), Heavy Fuel Oil (**HFO**), Marine Diesel Oil (**MDO**)/Marine Gasoil (**MGO**), Sulphur (**S**)

Tier	Year of Ship Construction	EF Limits NOx (g NOx/kWh)		
		n<130 rpm	n=130-1,999 rpm	n≥2,000 rpm
Nº Tier	Pre-2000	18.1 for HFO 17.0 for MGO/MDO	14 for HFO 13 for MGO/MDO	12.7 for HFO 12.0 for MGO/MDO
I	1 January 2000	17.0	$45 \cdot n^{(-0.2)}$	9.8
II	1 January 2011	14.4	$44 \cdot n^{(-0.23)}$	7.7
III	1 January 2016	3.4	$9 \cdot n^{(-0.2)}$	2.0

Table 3 Emission Factor (EF) NOx. Data source IMO regulation MARPOL Annex VI

The figure 2 shows the methodological framework considered in this paper, in which step 1, 2 and 4 is related to the input data model and the other steps 3, 5, 6, 7, 8, and 9 are methodological aspects that are described in Section 2.

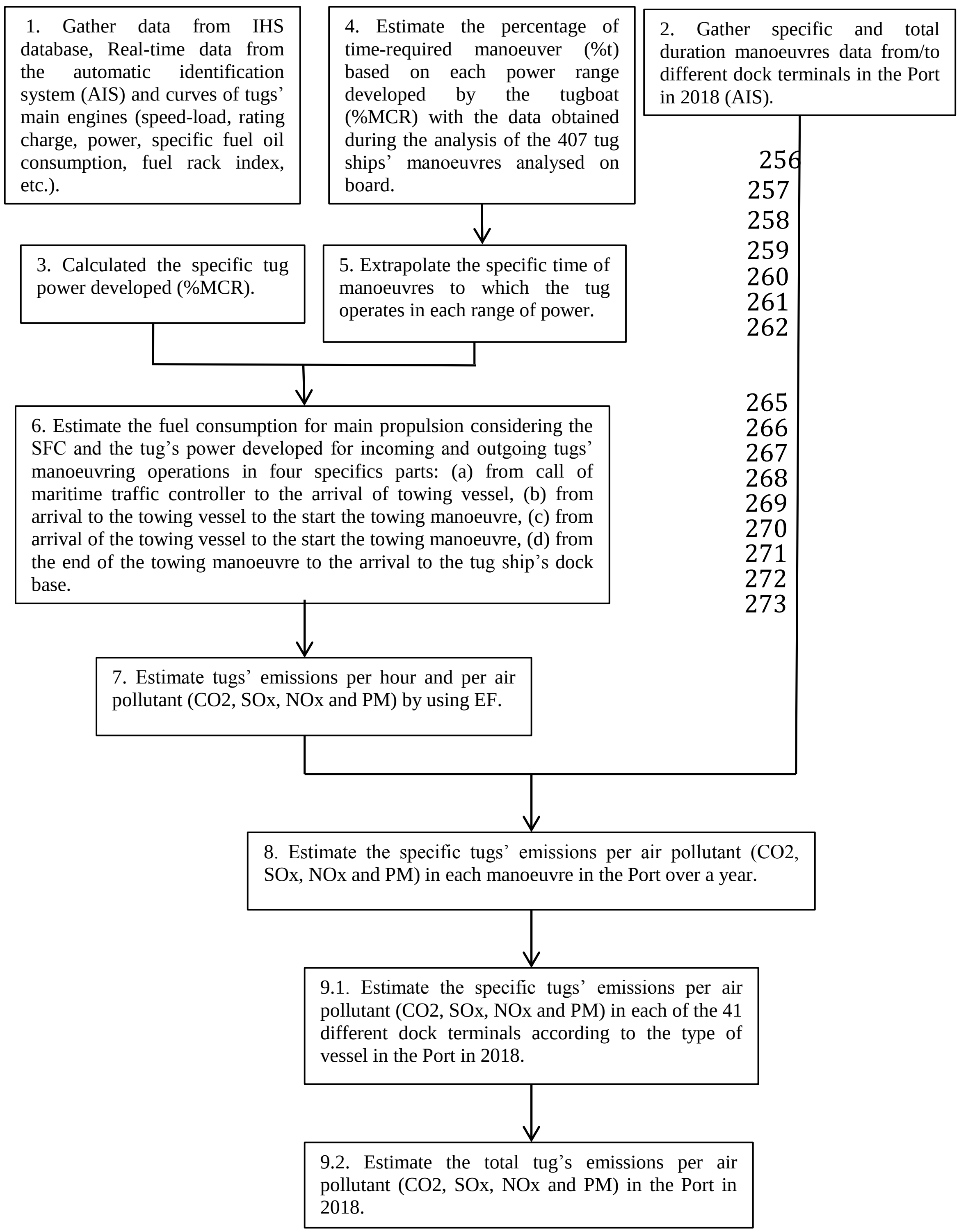

Fig. 2 Methodological framework

3. RESULT

3.1 Data samples

The data sample for this study ranges 7 tug ships that were monitored during 2018. According to the statistics of the Mediterranean Port, those 7 tug ships accounted for more than 11341 calls which represent 6951 towing services of which 6071 were incoming tug services and 5270 were outgoing tug ship services. These towing services have towed 6951 commercial vessels of 9038 number of calls vessels that have entered in the Mediterranean Port (container ships, cargo ships, car carrier ships, LNG ships, bulk carrier ships, chemical ships, etc.).

In the year 2018 there was a total of 6951 vessel services in 41 different berths or cargo terminals in the Mediterranean Port, 3530 incoming services, and 3421 outgoing services. Of all these services, 11341 tug ships were used, 6071 were incoming tug services, and 5270 were outgoing tug services.

In the incoming tug ship services, the average time was 1.7 hours for each tug ship manoeuvre and a total effective tug time of 10509.6 hours.

In the outgoing tug ship services, the average time was 1.5 hours for each tug ship manoeuvre and a total effective tug time of 6821.8 hours.

The total annual tug ship services time was the 17331.4 hours, in which the tug ships' main engines are on, emitting greenhouse gas emissions (GHG) inside the port-city.
In the next table (table 4) you can see the total number and type of merchant vessel towed by the tug ships that provide the towing service in that Mediterranean port during the year analysed. It must be borne in mind that, for the preparation of this table, the number of incoming manoeuvres and outgoing manoeuvres counted to obtain the total manoeuvres. As an example, it is seen that for the type of LNG ships, in that year, 156 towing manoeuvres were carried out, of which 78 were incoming manoeuvres and 78 were outgoing manoeuvres.

On the other hand, the towing services used for each type of towed merchant vessels are counted, that is, the total number of tug ships used to perform these services, considering both, the entry and exit of those merchant vessels.

Continuing with the previous example of LNG vessels, it can be observed that a total of 509 tug ships have been used to perform the towing services of those 156 towed LNG vessels (293 tug ships in the incoming manoeuvres and 216 tug ships in the outgoing manoeuvres). By dividing the total number of tug ships used to perform those docking and undocking manoeuvres, with the total number of towing manoeuvres, the number of tug ships used in each towing manoeuvres for that type of ship can be obtained (3.8 tug ships used in each incoming manoeuvres and 2.8 tug ships in each outgoing manoeuvres).

Tugs' Emission inventory	Services towing			Tug ships numbers			Tug ships number per manoeuvre		Manoeuvres Duration (h)					
Berthing dock / Terminal	**I**	**O**	**T**	**I**	**O**	**T**	**I**	**O**	**I***	**O***	**Ti**	**To**	**Ti ME On**	**To ME On**
Others - Container Ship	142	124	266	152	138	290	1.1	1.2	1.4	1.0	194.8	129.0	209.5	144.9
Sth. Dock - Container Ship	631	592	1262	1125	926	2051	1.5	1.4	1.6	1.1	1041.4	686.3	1863.4	1078.4
Prt. Dock - Container Ship	1068	1071	2139	1848	1768	3616	1.7	1.7	1.8	1.5	1904.2	1582.8	3294.9	2612.8
Prp. Dock - Container Ship	72	75	147	111	111	222	1.5	1.5	1.5	1.2	110.1	88.4	169.7	130.8
Chemical Carrier	670	659	1442	977	753	1730	1.5	1.2	1.7	1.1	1110.2	722.6	1622.1	823.6
Car Carrier	421	405	826	758	735	1493	1.5	1.5	1.7	1.3	692.6	543.5	1247.6	987.3
VLCC Oil Tanker	125	125	250	290	192	482	2.3	1.5	1.9	1.1	236.9	139.9	549.5	214.9
Cruise	28	24	52	39	32	71	1.4	1.3	1.5	1.2	42.0	29.0	59.6	38.9
Bulk Carrier	112	113	225	206	188	394	1.9	1.7	1.8	1.3	194.9	139.5	363.5	234.8
Ferries	35	23	58	38	24	62	1.1	1.0	1.3	1.0	47.3	24.5	51.6	25.7
LNG	78	78	156	293	216	509	3.8	2.8	2.4	1.5	187.8	114.5	705.4	317.2
Container RO RO	53	38	91	60	47	107	1.2	1.3	1.4	1.2	79.7	43.3	89.5	53.7
Others	95	94	37	174	140	314	1.5	1.5	1.7	1.3	153.1	106.2	283.3	158.8
Total	**3530**	**3421**	**6951**	**6071**	**5270**	**11341**	**1.7**	**1.5**	**1.7**	**1.2**	**6043**	**4344.1**	**10509.6**	**6821.8**

Table 4 Services towing, tug ships numbers used, tug ships number per manoeuvre and manoeuvres duration in Mediterranean Port in the year 2018

Incoming manoeuvres (**I**), Outgoing manoeuvres (**O**), Total manoeuvres (**T**), Time Incoming manoeuvres (**Ti**), Time Outgoing manoeuvres (**To**), Average time Incoming manoeuvres (**I***), Average time Outgoing manoeuvres (**O***), Total hours of running engine in Incoming manoeuvres (**Ti ME On**), Total hours of running engine in Outgoing manoeuvres (**To ME On**).

3.2 Annual inventory at port-level

The total GHG (CO_2) and air pollutant emissions (NOx, SOx and PM) for 7 tug ships during 2018 in the Mediterranean Port (about 11314 vessel calls and 41 different docking terminals) are estimated in this section.

The next graphics (table 5, figure 3, figure 4 and figure 5) show the yearly emission inventory (CO_2, SOx, PM and NOx) within the Mediterranean Port considering the incoming and outgoing tug services.

Tugs' Emission inventory 2018		**t CO2**			**t SOx**			**t PM**			**t NOx**		
In Manoeuvres		**I**	**O**	**T**	**I**	**O**	**T**	**I**	**O**	**T**	**I**	**O**	**T**
Tugs' Power MCR	**10%**	2637.6	1712.1	**4349.7**	1.6	1.1	**2.7**	0.8	0.5	**1.3**	45.0	29.1	**74.1**
	34%	4500.4	2921.2	**7421.6**	2.8	1.8	**4.6**	1.4	0.9	**2.3**	77.1	49.0	**126.1**
	54%	2255.1	1463.8	**3718.9**	1.4	0.9	**2.3**	0.7	0.4	**1.1**	40.8	25.9	**66.7**
	81%	123.4	80.1	**203.5**	0.1	0.05	**0.15**	0.04	0.02	**0.06**	2.3	1.5	**3.8**
	100%	1254.1	814.1	**2068.2**	0.8	0.5	**1.3**	0.4	0.2	**0.6**	22.9	14.5	**37.4**
Total	**t/year**	10770.6	6991.3	**17761.9**	6.7	4.4	**11.1**	3.3	2.1	**5.4**	188.1	120.0	**308.1**
	kg/h	-	-	**1024.8**	-	-	**0.6**	-	-	**0.3**	-	-	**17.8**

Table 5 Tugs' emission inventory in tons of CO_2, SOx, PM and NOx emissions from tug ships depending on the type of manoeuvres in Mediterranean Port in the year 2018

The highest annual emission of polluting gases is the one corresponding to carbon dioxide with an annual total of 17761.9 tons of CO_2 followed by nitrogen oxides with 308.1 tons of NOx per year, sulphur oxides with 11.1 tons of SOx per year and finally the least polluted emission is the one corresponding to particulate matter with an annual total of 5.4 tons of PM.

On the other hand, if we analyse the emissions per hour, we observe that the highest pollutant is the carbon dioxide with an emission of 1024.8 kg of CO_2 per hour, followed by the nitrogen oxides with 17.8 kg of NOx per hour, the sulphur oxides with 0.6 kg of SOx per hour and finally the particulate matter with 0.3 kg of PM per hour.

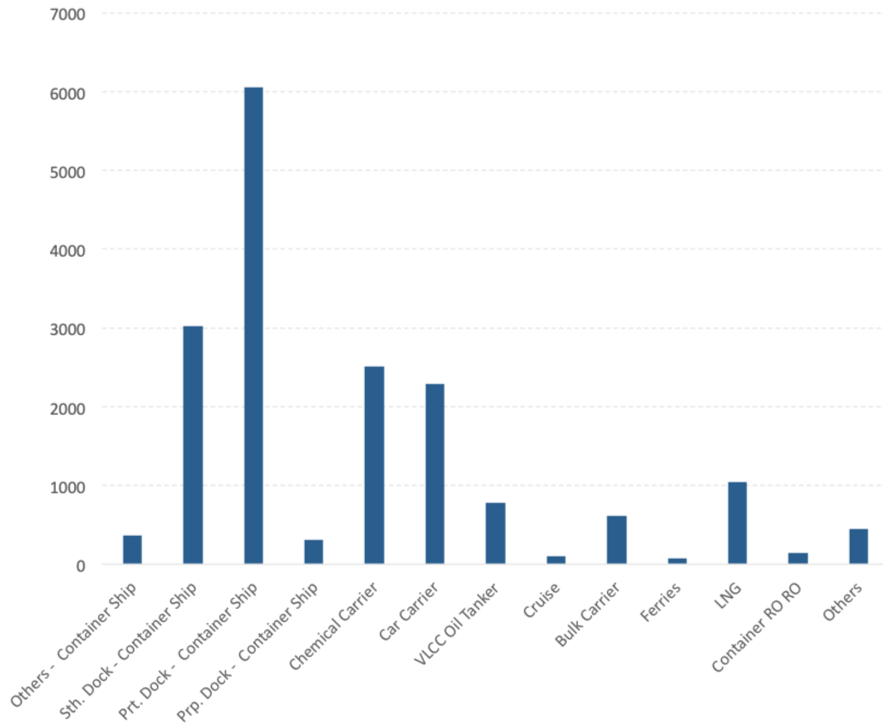

Fig. 3 Total emission inventory of CO_2 in incoming and outgoing manoeuvres (in tons)

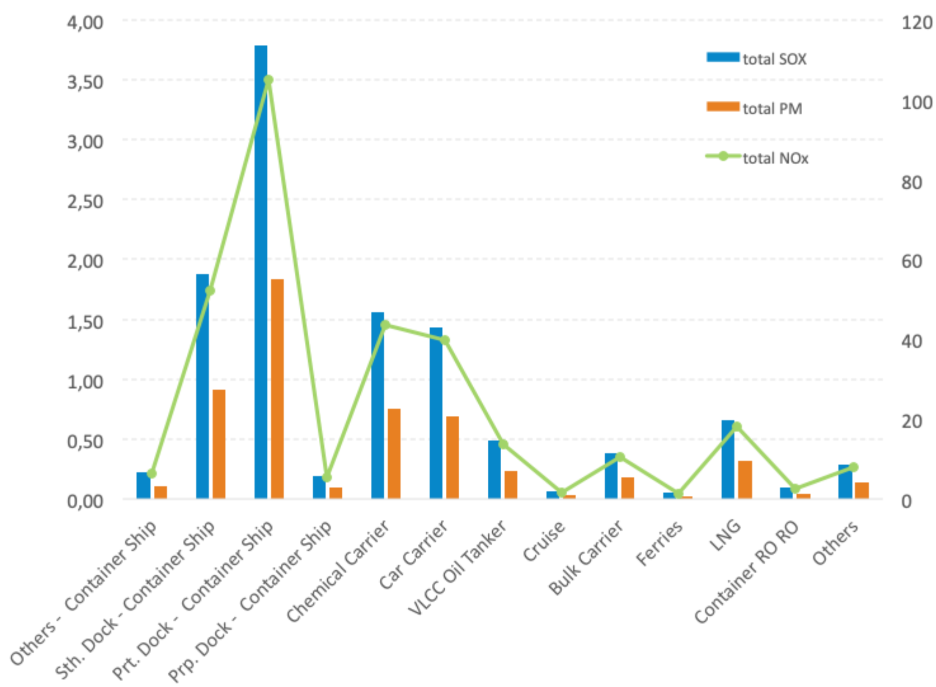

Fig. 4 Total emission inventory of SOx, PM and NOx in incoming and outgoing manoeuvres (in tons)

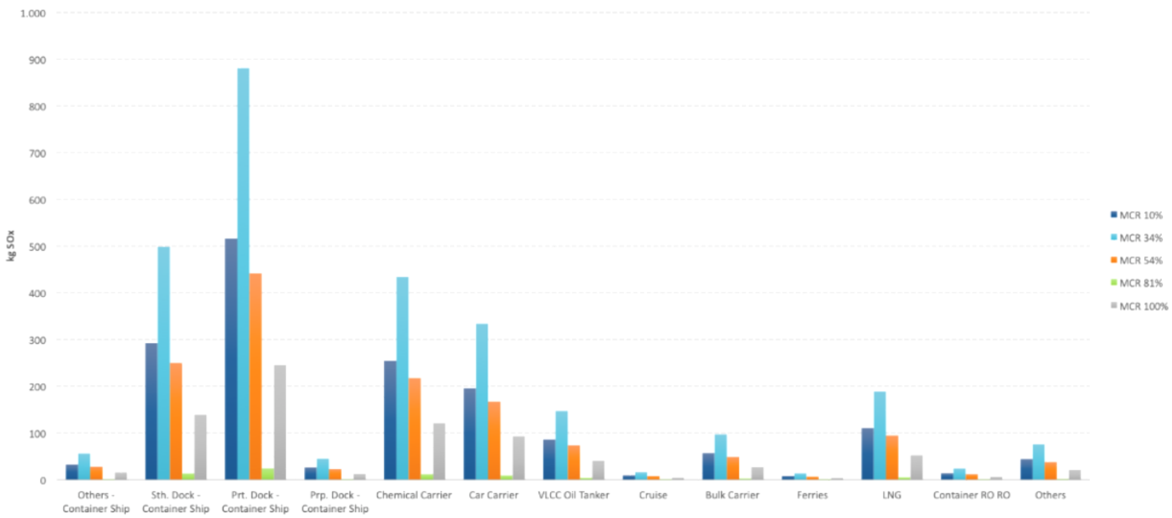

Fig. 5 Example of Tug ships' SOx emissions in the incoming Manoeuvres, across the range of tug ship's operating power (in kg SOx)

4. RESULTS AND DISCUSSION

No studies have been found analyzing the pollution emitted by these specific tug ships or methods used to calculated these pollution emissions in harbour areas near urban areas. The only studies found analyze the global general ship emissions inside and outside the harbour.

This paper evaluates SOx, CO_2, PM and NOx contamination emitted by port auxiliary vessels, explicitly by tug ships, because of its particular working specifics; not only tug ships require discontinuous large propulsion power changes, they also have some distinctive technical attributes which sets them apart from other auxiliary vessels, such as large tonnage and high propulsive force.

The total tugs' emissions in the year 2018 were 17761.9 tons of CO_2**,** 11.1 tons of SOx, 5.4 tons of PM and 308.1 tons of NOx, with a total annual tug's service time of 17331.33 hours. The average of 1024 kg CO_2 per hour, 0.6 kg of SOx per hour, 0.3 kg PM per hour and 17.8 kg of NOx per hour.

The maximum pollutant emissions are produced during towing manoeuvres to/from the following dock terminals. First to Prt. Dock, followed by Sth. Dock, both referring container ships. Next are the Chemical Dock, Car carrier Dock, LNG Dock, VLCC Dock and Bulk Carrier Dock.

This is mainly due to the fact that in this type of berthing dock or for this type of merchant vessels, a greater number of tug ships are used to perform the towing services, being the duration of the towing manoeuvres longer compared to others types of towed merchant ships as the number of towing services provided is greater.

Prt. dock is the dock where more pollution is emitted because there are a greater number of tugs used in incoming and outgoing manoeuvres (1848 and 1768 respectively), more merchant ships towed to/from the docks or cargo terminal (1068 and 1071 respectively) and more hours used in every incoming or outgoing manoeuvre in which the main engines have been on all the time (1904.2 and 1582.8 respectively).

Sth. dock is the second dock where more pollution is emitted because there are a large number of tugs used in incoming and outgoing manoeuvres (1125 and 926 respectively), 1041.4 and 686.3 hours have been used respectively in each incoming or outgoing manoeuvre in which the main engines have been on all the time, but nevertheless is the third in merchant vessels towed to/from this dock or cargo terminal (631 and 592 respectively).

Chemical dock is the third dock where more pollution is emitted because there are a large number of tugs used in incoming and outgoing manoeuvres (977 and 753 respectively), 1110.2 and 772.6 hours have been used respectively in each incoming or outgoing manoeuvre in which the main engines have been on all the time, but instead it is the second in number of merchant vessels towed to/from this dock or cargo terminal (670 and 659 respectively).

Car carrier dock is the fourth dock where more pollution is emitted because there are a large number of tugs used in incoming and outgoing manoeuvres (758 and 735 respectively), 692.6 and 543.5 hours have been used respectively in each incoming or outgoing manoeuvre in which the main engines have been on all the time and 421 and 405 merchant ships have been towed to / from this dock or cargo terminal.

LNG dock is the fifth dock where more pollution is emitted because a greater number of tug ships are used per manoeuvre (3.8 in the incoming and 2.8 in the outgoing manoeuvres) and also for the longer duration of their manoeuvres (2.4 hours in the incoming manoeuvres and 1.5 hours in the outgoing manoeuvres).

The VLCC dock is the sixth dock where more pollution is emitted mainly due to the number of tugs used in the entry manoeuvres (2.3 tug ships per incoming manoeuvres). Being the second largest number after the LNG ships.

The bulk carrier is the seventh dock where more pollution is emitted because the second largest number of tugs per manoeuvre is used (1.9 tugs in the incoming manoeuvres and 1.7 tug ships in outgoing manoeuvres).

The highest pollution emitted by the tug ships is produced at 18% MCR (42% pollution emitted), followed by the produced at 34% MCR (40% pollution emitted), at 54% MCR(14% pollution emitted), at 81% MCR (0.5% pollution emitted) and finally at 100% MCR(3.5% pollution emitted).

5. CONCLUSIONS

Considering these results obtained, pollution caused by the emission of nitrogen oxides, sulphur oxides, carbon dioxide and particulate matter by tug ships in the harbour areas, can be easily reduced by:

Towing's Optimization: 42 per cent of the total time of the operations, the tug ships remain on stand-by (the ship just waits to be required for any work). Regarding the annual statistics of every tug ship, those emissions produced during this power range could be reduced by more than two-thirds. Furthermore, on minimal power (18% Maximum Continuous Rate) the emission of those nitrogen oxides, sulphur oxides, carbon dioxide and particulate matter can also be reduced in half, it could be done by using only one of the two main engines every tug ship has (in standby mode, without both main engines there isn't a reduction in the safety of the tug ship though). This reduction could be possible improving the logistics and the planning of the different manoeuvres.

Speed Reduction favours emission reduction: Nitrogen oxide, sulphur oxide, carbon dioxide and particulate matter emissions are proportional to the speed of the ship. Reducing the speed also reduces the fuel consumption by 25 per cent.

Reduction of maximum propulsion power in harbour tug ships: With the experience, it can be verified and confirmed that smaller tug ships are sufficient for the different port manoeuvres. Only 3.5 per cent of the total time they are required to give maximum power and only 0.5 per cent of total manoeuvring time, main engines have a Maximum Continuous Rate of 81%.

With the experience of the Tug ships Masters, it is confirmed that not as much propulsion power is needed during the manoeuvres of incoming and outgoing of merchant vessels and so smaller tug boats could perform just as efficiently as bigger ones, having the latter the advantage of polluting less than the former.

Implementing these measures would significantly reduce the harmful effects of the pollutants emitted from the engines, benefiting the health of the population, especially in port-cities.

From a technical point of view, the purpose of reducing SOx, CO_2, PM and NOx emissions should be specially considered in areas where ports are located within cities with a high density of population.

There's a need though, to keep researching and improving engine designs and technologies to make them more efficient and less polluting. A list of improvements could be:

- Optimization of indoor and outdoor lighting using LED technology, which would result in a reduction of fuel consumption by the auxiliary engines of the tug ship.
- Different designing of the power transmission.
- Optimizing the design of the hulls and superstructures.
- Cylinder lubrication.
- Energy recovering from the propeller using: Propeller nozzle, hull coatings, coaxial contra-rotating propeller (CCRP), integrated unit with rudder and propeller, blade wheel or wheel freewheeling Grim, pre-swirl devices.
- Reduce the friction in pumps and pipes.
- Optimize coolers, nozzles, turbochargers, ventilation systems of the ship as well as update the current models or use different propulsion technologies.
- Using or switching different fuels: Using diesel fuel with low sulphur content, and then, switching it to a very low sulphur fuel (ULSD), or the use of lower fuel-cycle as Biofuels, Liquified Natural Gas (LNG), Liquified petroleum gas (LPG), Propane ethanol blended with diesel fuel, E-diesel, Oxygenated diesel or Synthetic diesel.
- Fuel modifications, including fuel-water emulsion and the use of fuel with low nitrogen content.
- Reducing the temperature of exhaust gasses using air humidification or exhaust gasses cleaners such as Scrubbers (Scrubber Technology).
- For the reduction of NOx emissions, the use of CRS (Catalytic Reduction System).
- Modifying the combustion process by advancing the fuel injection or the compression rate.
- Some other technologies are being researched as well, to name a few: The cleaner of NOx, NOx absorption traps, Diesel Oxidation Catalysts (DOC), Catalysed filters Wire Mesh (CWMF), and Diesel Particulate Filter (DPF).

All these results can be extrapolated to other ports operating with tug ships of the same technical characteristics. Evaluating, therefore, the amounts emitted of nitrogen oxides, sulphur oxides, carbon dioxide and particulate matter in these.

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The data that support the findings of this study are available on request from the corresponding author JCMG*.

The data are not publicly available due to maritime companies and Port Authority restrictions e.g., “them containing information that could compromise research participant privacy/consent”.

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