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Multidisciplinary
SCIENTIFIC JOURNAL
OF MARITIME RESEARCH

University of Rijeka
FACULTY OF MARITIME STUDIES

Multidisciplinarni
znanstveni časopis
POMORSTVO

https://doi.org/10.31217/p.36.2.7

Emission footprint of 2019 cruise traffic in the port of Dubrovnik

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ABSTRACT

In this study, the environmental footprint within a designated area is determined by an inventory of air pollutants (including toxic and greenhouse gases) emissions generated. The designated area of concern is the port of Dubrovnik, a well-known cruise ship destination, where a major source of pollutant emissions is the diesel engines of the ships operating in the port. This research was undertaken for the port of Dubrovnik in connection with the development of the national strategy and the need for determining the inventory of air pollutants. It was conducted for the last pre – COVID- 19 year, 2019. In this paper, after a short introduction, the basic data of the port of Dubrovnik and the marine traffic (predominantly cruisers) in 2019 are provided, obtained from publicly available data. Next, the emission estimate methodology based on a bottom-up approach is described. The inventory analysis was undertaken from the port boundary to the PWD (pier/wharf/dock) and back. The basic equations for evaluation during cruising, maneuvering, and hoteling are given along with the corresponding data. The aggregated results are presented in the form of tables and column charts. These results show that the generation of CO2 highly dominates. Regarding the pollution analyzed NOx dominates. The results of this study could be of interest for later studies on environmental pollution in the region of Dubrovnik-Neretva County and the Croatian coast.

ARTICLE INFO

Review article
Received 4 April 2022
Accepted 9 November 2022

Key words:
Emission footprint
Atmospheric pollution
Emission inventory
Port traffic
Bottom-up emission assessment

1 Introduction

Dubrovnik is one of best known touristic regions in Croatia. It has rich cultural heritage having its roots in the medieval city of Ragusa. It is also well known by its original and well preserved medieval city walls that encircle the old city with many museums and churches. It is visited by many cruisers over the years, which deliver many thousands of tourists per year. The inventory of their effects on the environment is much needed.

The problem of pollution generated by the cruisers visiting Dubrovnik attracted attention from the beginning of the cruise vessels visits. There were many warning in the local and national wide media. This was also subject of intensive research by H. Caric [3, 4]. He undertook investigations that take into account all major environment impacts: solid waste, air pollution, waste waters, hazardous waste, and eco-toxic metal emissions. He based cruise impact calculation for Dubrovnik using Croatian Bureau of Statistic numbers of passengers and cruise calls for 2009 and scaling it down by assuming that 85% Croatian tourism takes places in Dubrovnik [4]. The daily pollution is calculated in kg or liters per cruise guest [3]. To calculate the annual CO_2 emission in 2009 an estimate of the route of the typical cruiser was made as well. Also per capita values (in average cars and local persons) are estimated for Dubrovnik 'peak days', i.e. five cruisers with 12500 guests.

In this paper a different approach was used. The novelty of the approach is that instead of 'general numbers' the local accurate numbers of cruise vessels, time of stay, installed power, etc., which were obtained from the Port of Dubrovnik Authorities [5]. This asks for lot of pre and post processing work to obtain the wished results. The emissions of pollutants that occur within the Port of Dubrovnik region will be quantified. The sources of the emissions are the ships' diesel engines operating in the port. The pollutants that are the subject of the study are greenhouse gases (GHG) and toxic atmospheric pollutants. These include:

- Carbon Dioxide (CO_2),
- Oxides of Sulfur (SO_x),
- Oxides of Nitrogen (NO_x),
- Volatile Organic Compounds (VOCs),
- Particulate Matter (PM).

The emissions are estimated using a similar methodology as used in the papers dealing with other ports in Croatia: Rijeka [13], Zadar [7], Split [17] and Sibenik [9]. In this way the results obtained are comparable and can help in preparation of the nation-wide emission inventory [14].

The paper is organized as follows. In Sect. 2 the basic data of the port of Dubrovnik and the marine traffic (predominantly cruisers) in 2019 are provided based on publicly available data. Next, in Sect. 3 the methodology for emission estimate used in this paper is overviewed. The methodology is based on a bottom-up approach and is applied from the port boundary and back. The basic equations for evaluation during cruising, maneuvering, and hoteling are given along with the corresponding data. The result and discussion are given in Sect. 4. The aggregated result data are presented in the form of tables and a column charts. These results show that the generation of CO_2 highly dominates. Regarding the pollutions analyzed NO_x dominates. The conclusion of the study and plans for further studies are given in Sect. 5.

2 Cruise Traffic in the Port of Dubrovnik

A general view of the port of Dubrovnik is shown in Figure **1**. It is situated on the eastern Adriatic coast of southern Croatia. The port is located in the district of Gruz, about 3.0 km from the old town, [10].

Before the war for the independence of Croatia in 1991, the Dubrovnik port contained facilities for passengers, timber storage, and a refrigerated plant. These facilities were heavily damaged during the war; thus, in 2009, a big investment was made to renovate and expand the port. Now, it is specialized as a cruise port and can receive mega- and middle-sized ships.

Fig. 1 General view of the port of Dubrovnik, [10]

Table 1 Operational coast, [11]

Pier	Length (m)	Depth/Draught (m)
4 – 6	210	2.0 – 4.0
7 – 9	305	5.0 – 6.5
10 – 11	615	11.0
12	220	11.0 – 11.5
Kantafig	40	11.0
Batahovina I	220	8.50

The port is approached from the southwest through the Velika Vrata (the Large Gate), the south entrance is through Kolocep channel and north of Isle Daksa, at latitude 42°40´ N and longitude 18°04´ E, which lies between peninsula Lapad and the north mainland coast. The operational coast of the port is shown in Table **1**.

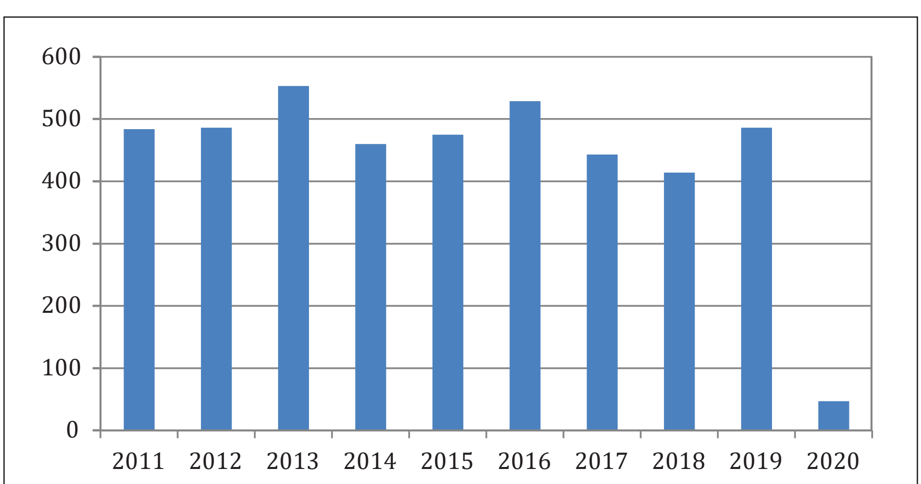

Fig. 2 Cruise calls over years 2011. to 2020, [12]

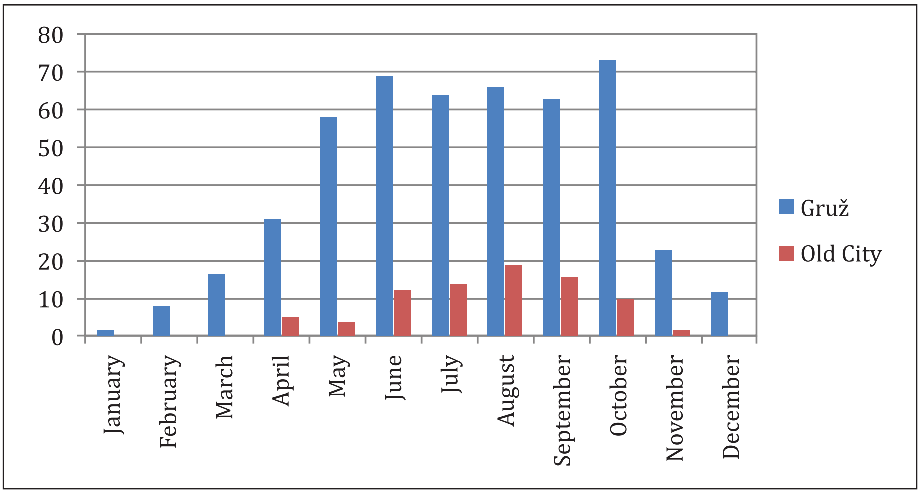

Fig. 3 Cruise calls in 2019 by months, [12]

Table 2 Marine traffic in the port of Dubrovnik in 2019, adopted from [5], [17]

Vessels types	Number of ships	Number of calls	Passengers traffic	Total engine power (MW)
Passenger ships[a]	78	562	813 720	2415

[a] Including the calls to Old Town port.

The marine traffic in the port of Dubrovnik in the last decade was very intensive and dominated by cruise ships. Figure **2** shows cruiser traffic over years 2011 until end of 2020, [12].

The average number of calls per year, counting only pre – COVID- 19 years (2011 – 2019), was 481.1. In 2020 there was a significant drop in the number of calls due to COVID – 19 lock – downs. We use 2019 as the reference pre- COVID – 19 year for calculations. A summary of the vessel calls made in 2019 is given in Figure **3,** [12].

The specifications of all ships that visited the port of Dubrovnik in 2019 and the length of their stay at the port where taken from a document published by Dubrovnik Port Authority, [5]. To complete the data, Scheepvaartwest data base [17] was consulted for the installed main and auxiliary power plants of the ships that visited the port of Dubrovnik; the summary is shown in Table **2**.

The table shows that 78 cruise/passenger ships visited the port in 2019 making total of 562 calls. The passenger vessel traffic dominates with nearly a million cruise ship passengers visiting Dubrovnik during the year. The third column gives the total installed power in of all ships visited.

The exhaust emission inventory analyzed in this paper covers the Dubrovnik aquatorium from Isle Daksa, where the ships enter into the region, to Cape Kantafig at the entrance to the port of Gruz, the port of Gruz bay and the anchorage at the Old City. The distance between lighthouse at Isle Dakse and Cape Kantafig is 1.639 km = 0.885 nm, and form Gruz to the Old City is about 3 km. Reduced speed zone (RSZ) is 4 nm/h from Cape Kantafig to Cape Sipka, and beyond that point 6 nm/h until Isle Daksa.

3 Emission Estimating Methodology

3.1 The top-down and bottom-up methodologies

The two most frequently used methods for estimating ships' exhaust gas emissions are the analyses and inventories. The first is known as a top – down method, which is based on the emissions calculated for a total area that are then transferred to different areas by downscaling. This approach can be used for global purposes, but for regional purposes, this approach can be inaccurate, [2].

The second approach is usually known as a bottom-up method. This approach improves the accuracy of the emissions calculated. It is based on the accurate calculation of the emissions from all individual sources of a specific area, which are aggregated to obtain the emissions from the total area, [6]. A combination of the bottom-up and top-down methodology can be used as well.

In this report the bottom-up approach was used for the emissions resulting from business operations and employee activities at the "pilot" site location. The consideration of greenhouse gas emissions at a given location does not extend to the activities of vendors, visitors, or other parties.

The data used in this analysis can be described as follows:

- Ship movement data, which includes the distance travelled and duration of movement.
- Ship movement type, propulsion type, type of fuel used, main-engine(s) power plant, auxiliary-engines power plant.

Table 3 Vessel movements within MEPA areas, adopted from [1]

	Description
Call	A call is one entrance and one exit from the MEPA area.
Shift	A shift is a vessel movement within the MEPA area. Shifts are contained in calls.
Cruise (hr/call)	Time at service speed.
Reduced Speed Zone (hr/call)	Time in the MEPA area at a speed less than cruise and higher than maneuvering.
Maneuver (hr/call)	Time in the MEPA area between the breakwater and the PWD (pier/wharf/dock).
Hoteling (hr/call)	Hoteling is the time at PWD or anchorage when the vessel is operating auxiliary engines only or is cold ironing.

Table 4 Fuel assumptions inventory Sulfur contents, [20]

Fuel	Assumed Sulfur content		
	2007	2010-2020	
		non-SECA	SECA
Marine Gas Oil (MGO)	0.2%	0.1%	0.1%
Marine Diesel Oil (MDO)	1.5%	1.5%	1.5%
Residual Oil (RO)	2.7%	2.7%	n/a (fuel to be switched over)

- The ship's time staying in a port and activities such as hoteling and embarkation/disembarkation.

The vessel movements within the MEPA (Marine Exchange/Port Authority) area are shown in Table **3**.

The total estimated emissions contain the emissions resulting from the various activities that have impacts on the fuel consumption, and the emission quantity. Weather conditions may also have an impact on the emissions [15].

The ship emissions mainly come from main engines (MEs) and auxiliary engines (AEs). Total emissions are calculated as a sum of emissions while at cruising, maneuvering, and hoteling for each ship's call and each type of emission [1, 6, 8, 18, 19, 20]:

$$E_{trip} = E_{cruising} + E_{maneuvring} + E_{hotelling} \quad (1)$$

The terms on the right-hand side of equation (1) are described by the following equations:

$$E_i = T_i \cdot (ME \cdot LF_{ME,i} \cdot EF_i + AE \cdot LF_{AE,i} \cdot EF_i) \quad (2)$$

where

i denotes the kind of the trip, i.e. *cruising*, *maneuvering* or *hoteling*,

T_i (h) is the average time at each kind of the trip,

ME (kW) is the installed main-engine power,

$LF_{ME,i}$ (%) is the main-engine average load factor for cruising, maneuvering or hoteling,

AE (kW) is the installed auxiliary-engine power,

$LF_{AE,i}$ (%) is the auxiliary-engine load factor for cruising, maneuvering or hoteling,

EF_i (g/kWh) is the emission factor assigned to each vessel for cruising, maneuvering or hoteling.

In (2) the cruising time is approximated by

$$T_{cruising} = \frac{D\ [nm]}{v\ [nm/h]}\,[h] \quad (3)$$

where D is the estimated distance traveled into and out of the port, and *v* is the average ship's speed. Taking into account the Reduced Speed Zone in the port described at end of Sect. 2, the assumed mean cruising time for all ships visiting the port is $T_{cruising}$ = 0.4 h. Time of the cruising to the Old City's anchorage was included into the maneuvering time. According to study [21] maneuvering times of large passenger ships in the port of Dubrovnik is about 0.5 h.

3.2 Engine characteristics and fuel types

Emission factors as well as exhaust emissions are highly dependent on the fuel type and its specifications. These days, the main fuel commonly used for a ship propulsion is Residual Oil (RO), also referred to as Heavy Fuel Oil (HFO), while Marine Diesel oil (MDO) and Marine Gas Oil (MGO) are commonly used for auxiliary power plants (Diesel generators). According to Lloyd's MIU available data, 95% of engines worldwide use Marine Diesel Oil as a main combustion fuel, [20].

It is also recognized that one of the main assumptions made for fuel types is that ships are required to meet fuel Sulfur content requirements by switching over from RO to MDO. A summary of these assumptions is given in Table **4**, [20].

3.3 Load factor

The load factor represents a percentage of the vessel's total propulsion or auxiliary power. At service or cruise speed, the main engine load factor is about 80% [18, 19]. During the maneuvering, the main engine load factor changes and is assumed to be approximately 20%. Finally at hoteling, the main engine load factor is very low and is assumed to be 0%.

Table 5 Auxiliary engine load factors assumptions, [1, 19]

Ship type	Cruise	RSZ	Maneuver	Hotel
Auto Carrier	0.15	0.30	0.45	0.26
Bulk carrier	0.17	0.27	0.45	0.10
Container ship	0.13	0.25	0.28	0.19
Cruise ship	0.80	0.80	0.80	0.64
General cargo	0.17	0.27	0.45	0.22
Miscellaneous	0.17	0.27	0.45	0.22
OG Tug	0.17	0.27	0.45	0.22
RORO	0.15	0.30	0.45	0.26
Reefer	0.20	0.34	0.67	0.32
Tanker	0.24	0.28	0.33	0.26

Table 6 Estimated average vessel AE/ME ratio, [18]

Ship categories	AE/ME ratio
Bulk carriers	0.30
Container	0.25
General Cargo	0.23
Ro- Ro Cargo	0.24
Fishing	0.39
Other	0.35

Several studies have shown that auxiliary engines are on all of the time, with the largest loads occurring during hoteling (except when cold ironing). Based on interviews conducted with ship staff and pilots during its vessel boarding programs, the auxiliary engine load factors obtained are shown in Table **5,** [1, 19]. Auxiliary engines load factors should be used in conjunction with the total auxiliary power. Auxiliary engine power data are often missing from MEPA records. Table **6** shows estimated average auxiliary engine (AE) power, which is compared with main engine (ME) propulsion power, [18].

The cruise ships usually use different engine configurations, which depends on power plant mode requirements, such as sea mode, maneuvering mode, and port mode.

3.4 Emission Factor

The emission factors for the ship engines are the weakest link. In most cases, the power generated is only estimated, leading to inaccuracies in the overall emission factors. The most recent study of emission factors was performed by Whall et al [20], and these factors are generally accepted as the most accurate currently available set. Tables **7** to **9** below list the main- and auxiliary-engines' emission factors, depending on the engines and fuel types and the types of the activity. The following engine type designations are used: SSD – Slow Speed Diesel engine, MSD – Medium Speed Diesel engine, MHSD – Medium High Speed Diesel engine, HSD – High Speed Diesel engine, GT – Gas Turbine, ST – Steam Turbine.

Table 7 Main-engine emission factors (g/kWh) for sailing at sea, [20]

Engine type	Fuel type	NO_x(Pre-2000 engine)	NO_x(Post-2000 engine)	SO_2	CO_2	VOC	PM
SSD	MGO	17.0	14.1	0.7	588	0.6	0.3
SSD	MDO	17.0	14.1	5.6	588	0.6	0.3
SSD	RO	18.1	15.0	10.5	620	0.6	1.7
MSD	MGO	13.2	11.0	0.8	645	0.5	0.3
MSD	MDO	13.2	11.0	6.2	645	0.5	0.4
MSD	RO	14.0	11.6	11.5	677	0.5	0.8
HSD	MGO	12.0	10.0	0.8	645	0.2	0.3
HSD	MDO	12.0	10.0	6.2	645	0.2	0.4
HSD	RO	12.7	10.5	11.5	677	0.2	0.8
GT	MGO	5.7	4.7	1.2	922	0.1	0.0
GT	MDO	5.7	4.7	8.7	922	0.1	0.0
GT	RO	6.1	5.1	16.5	970	0.1	0.1
ST	MGO	2.0	1.7	1.2	922	0.1	0.3
ST	MDO	2.0	1.7	8.7	922	0.1	0.4
ST	RO	2.1	1.7	16.5	970	0.1	0.8

Table 8 Main-engine emission factors (g/kWh) for maneuvering and at berth, [20]

Engine type	Fuel type	NO_x (Pre-2000 engine)	NO_x (Post-2000 engine)	SO_2	CO_2	VOC	PM
SSD	MGO	13.6	11.3	0.8	647	1.8	0.9
SSD	MDO	13.6	11.3	6.2	647	1.8	1.2
SSD	RO	14.5	12.0	11.6	682	1.8	2.4
MSD	MGO	10.6	8.8	0.9	710	1.5	0.9
MSD	MDO	10.6	8.8	6.8	710	1.5	1.2
MSD	RO	11.2	9.3	12.7	745	1.5	2.4
GT	MGO	2.9	2.4	1.3	1014	0.5	0.5
GT	MDO	2.9	2.4	9.6	1014	0.5	0.7
GT	RO	3.1	2.6	18.1	1067	0.5	1.5
ST	MGO	1.6	1.3	1.3	1014	0.3	1.2
ST	MDO	1.6	1.3	9.6	1014	0.3	1.2
ST	RO	1.7	1.4	18.1	1067	0.3	2.4

Table 9 Auxiliary-engines emission factors (g/kWh), [20]

Engine type	Fuel type	NO_x (Pre-2000 engine)	NO_x (Post-2000 engine)	SO_2	CO_2	VOC	PM
MHSD	MGO	13.9	11.5	0.9	690	0.4	0.3
MHSD	MDO	13.9	11.5	6.5	690	0.4	0.4
MHSD	RO	14.7	12.2	0.4	0.8	0.4	0.8

3.5 Aggregation of the Results

In a detailed inventory, the emissions for each mode (cruise, reduced speed zone, maneuvering, and hoteling with and without cold ironing) during a call are calculated using the ship's type, actual speed, engine power, load factor, time-in mode, and emission factors for both main and auxiliary power plants. Data are then summarized for the complete year of the calls.

4 The Results and Discussion

The inventory analysis for the port of Dubrovnik was undertaken using port traffic data for 2019. The data was pre-processed to put them in a proper form, and then post-processed. The bottom-up approach was applied for every vessel movement from the port boundary to PWD and back, also accounting for cruise services from the port boundary to the breakwater. It was calculated for every ship's call, separately for each of three basic activities: cruising, maneuvering, and hoteling. The total estimated emissions per each ship's trip is found by summing the results of all activities as given by (1), where the emissions while cruising, maneuvering, and hoteling are evaluated using (2). The total emissions analyzed during the entire year are calculated. Finally, the total emissions of all the ships visiting the ports in 2019 were calculated by summing up the results for every vessel going in and out of the port of Dubrovnik in 2019. The results, which were originally expressed in grams (g), are converted to tons (t).

Most modern passenger ships use diesel electric propulsions, which all behave similarly as the auxiliary engines in the sense that they are on all the time. Their load factor changes depending on the type of activity (see Table **5**).

The parameters appearing in (1-2) are used as described in Sec. 3, Tables **4 – 9**. The hoteling time was calculated for every ship separately based on the duration of its stay in the port. Calculation was performed by a spreadsheet calculator using data from [5].

Table **10** gives a summary of the marine emissions in the port of Dubrovnik during the complete 2019 year, the

Table 10 Annual inventory of marine traffic emissions in the port of Dubrovnik for 2019

	CO_2 [t]	NO_x [t]	SO_x [t]	VOC [t]	PM [t]
Cruising	3826.32	63.91	36.11	2.29	2.23
Maneuvering	4470.52	74.00	42.13	2.77	2.73
Hoteling	67091.95	1118.20	632.03	38.89	38.89
Total	75388.79	1256.11	710.27	43.95	43.85

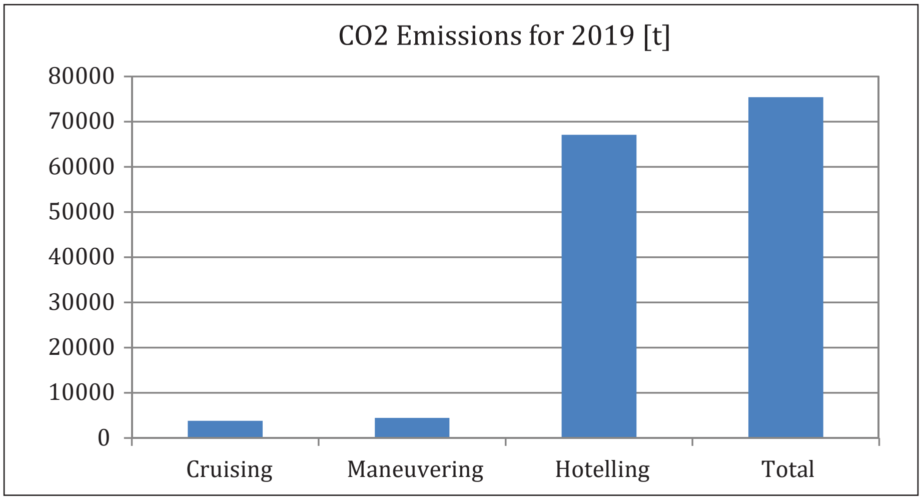

Fig. 4 CO2 emissions during different phases of ships activities

Source: authors

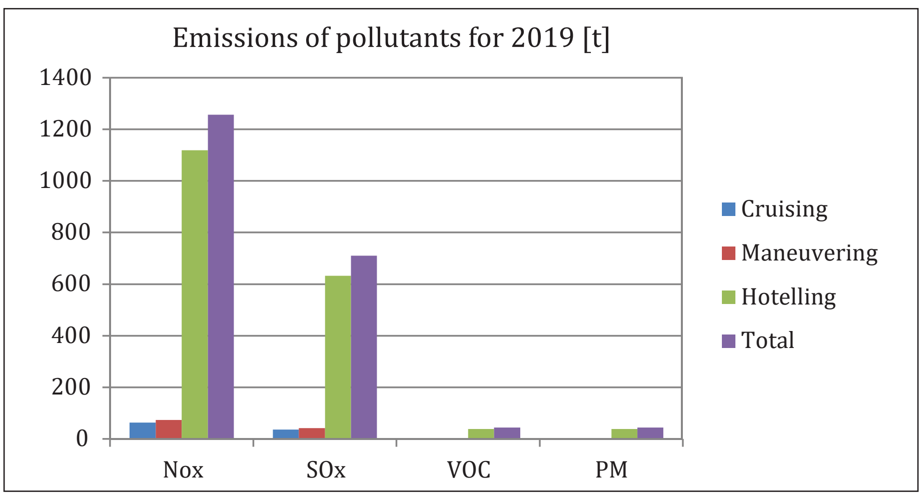

Fig. 5 Emissions of the pollutants during different phases of ships activities

Source: authors

last year before the COVID – 19 pandemic that radically reduced the port traffic. The data are given in tons during every basic activity and the total for the pollutants of concern.

Figure 4 shows the emission of CO_2 during different activities in the port. Similarly, Figure 5 shows the emissions of the pollutants for the same period. At the end Figure 6 shows the total emissions of carbon dioxide and the pollutants during 2019 year. The figures are generated using data in Table 10.

As can be seen from Figures 4 and 5 the emissions during the hoteling phase highly dominate, which is to be expected of the cruise ships in a touristic port. Their stay in the port is much longer than time used to sail in and maneuver inside the port. Comparing the GHG (CO2) and atmospheric pollutant emissions, the first highly dominates, with NOx leading among the pollutants (Figure 5).

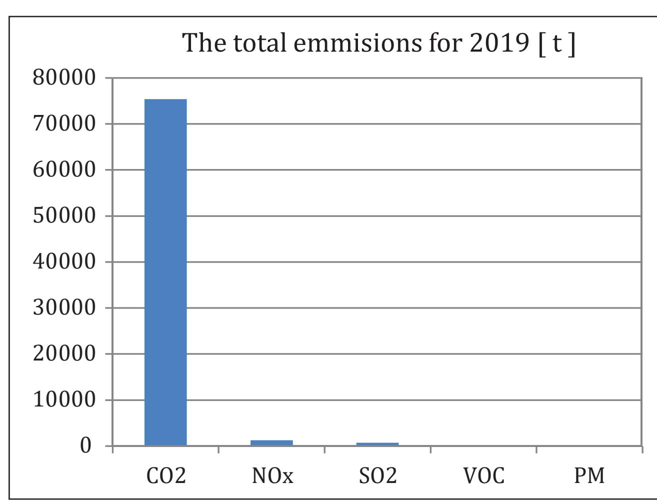

Fig. 6 The total **e**missions in the port of Dubrovnik for 2019

Source: authors

5 Conclusion

The research reported in this paper was undertaken to determine the inventory of air pollutants for the port of Dubrovnik based on official data. It was applied to the port region from Isle Daksa, where the ships enter the region, to Cape Kantafig at the entrance of Gruz port, the port of Gruz bay and the anchorage at the Old City. Thus, it completely covers the maritime region around the City.

The inventory of the air pollutants was conducted by applying the bottom-up method. It is based on the accurate calculation of the emissions from all individual sources in the area of the concern and aggregating the results. This approach improves the accuracy of the emissions calculated at the local level. The following emissions were obtained:

- CO_2 75 389 [t]
- NO_x 1 256 [t]
- SO_x 710 [t]
- VOCs 44 [t]
- PM 44 [t]

The impact of the local weather conditions on the emissions was not taken into account. In the father investigations this effect will be tried to include as well.

After the results obtained in terms of quantities of the pollutions generated, one of the points that can be risen is: What will happened with the generated emissions? Are they hanging over the city or spread out over the surrounding area? How winds blowing over the area during a year affects this. It would be of much interest to analyze the effects of the directions and intensities of the winds blowing over the area during a year (wind rose) on the dispersion of the generated pollutions over a wider area around Dubrovnik. What concentrations of the pollutions we can expect in different location throughout the Dubrovnik region? How they corresponds to the measured values? The simulations of these effects would be welcome. It is planned to include some or most of these subjects in the next researches.

Acknowledgments

We wish to express our thanks to colleagues at the Dubrovnik Port Authority for their help and support; without it this research would be impossible to accomplish.

Funding: The research presented in this paper was not funded from outside sources.

Author's participations: R.R.: Concept, methodology, overview and final improvement. D.D.: Research, analysis of the references, collecting and processing data, writing the paper.

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