Sustainability of logistics infrastructures: operational and technological alternatives to reduce the impact on air quality

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Abstract: Modern ports are productive systems characterized by transport-type activities (of goods and people) and by activities typically related to the sectors of industry, construction, commerce and related services. Despite their fundamental role in the economic and social development of the local area, ports also have a negative impact on the environment. This paper analyses the effect on the air quality of a maritime container terminal by assessing the typical activities carried out there. Five scenarios were studied using an EMEP/EEE (2019) bottom-up air pollutant inventory approach and through air quality numerical simulations with the ADMS-5 model. Changes in the layout of where the activities are carried out, the use of cold ironing, and the use of LNG as a fuel are the scenarios compared with the "BASE" condition. The results highlighted the improved air quality due to each solution, demonstrating how the use of alternative fuels or the electrification of the docks reduces pollutants by more than 70-80%. Delocalizing some of the handling was found to have fewer benefits. Economic factors and the engagement of key stakeholders would seem to influence the diffusion of these solutions.

Keywords: Logistics infrastructures; Terminal Container; Air quality; Scenario modelling; Cold ironing; LNG

1.Introduction

Many regions throughout the world have great difficulty in respecting the limits imposed by legislation on air quality, particularly in industrial and urban areas. With the numerous activities they host, ports also have a significant impact on air pollution (Bai et al., 2020; Bermúdez and Aguayo-lorenzo, 2019).

Freight transport is a key sector for the international economy and is constantly increasing thanks to increasing levels of trade on a global scale (C. Chen et al., 2019; UNCTAD, 2018). Over 80% of international merchandise trade - corresponding to 10 billion tons of goods - uses shipping (Bjerkan and Seter, 2019; Carpenter et al., 2018), with a high impact on air quality. As reported by Buber et al. (2020) and J. Chen et al. (2019), shipping is responsible for 13% and 12% of global annual emissions of NOx and SO2, respectively. Approximately 70% of shipping emissions occur within 400 km of land (Mason et al., 2019) and this not only impacts the environment, but also citizens' health. Sofiev et al. (2018), estimated that the impact on citizens' health worldwide was 400,000 premature deaths from lung cancer and cardiovascular disease, and about 14 million cases of childhood asthma every year. These results are also supported by other studies, such as Bilsback et al. (2020); Caiazzo et al. (2013); Contini and Merico (2021).

Emissions of air pollutants from international shipping are regulated by the International Maritime Organization (IMO) through Annex VI of the International Convention for the Prevention of Pollution from Ships (MARPOL) which regulates the sulphur content of marine fuels and emissions of NOx from ship engines. There are also supranational policies (e.g. the European Directive 2016/802 for the reduction in the sulphur content of certain liquid fuels) and national and regional laws. The emissions of sulphur and nitrogen oxides in shipping have wide potential for improvement (Contini and Merico, 2021; Eiof Jonson et al., 2020; Zhang et al., 2019; Zou et al., 2020), thanks to the improvement of technologies, variations in the fuels used and various eco-sustainable solutions that are tested internationally and schematically reported in section 2.

2.Literature review

The impact of anthropogenic atmospheric pollutants on ambient air quality has been studied not only by traditional monitoring with sensors, but also by estimating emissions and using mathematical models to simulate the dispersion of air pollution.

An emission inventory is a database of air pollutants emitted in an area of interest that can be quantified through top-down or bottom-up approaches (Righi et al., 2013). There are several methods for estimating port emissions, which have been developed, for example, by the United States Environmental Protection Agency, International Maritime Organization, STEAM (Ship Traffic Emission Assessment Model), TNO and ENTEC (this is the approach used by the Air Pollutant Emission Inventory Guidebook of the European Emission Agency) (Toscano and Murena, 2019).

Buber et al. (2020) used these approaches to quantify emissions from domestic shipping in the Bay of Izmir (Turkey). J. Chen et al. (2019) estimated maritime traffic within the Pearl River Delta (PRD) region of China, and Ekmekçio et al. (2020) used the ENTEC approach to estimate ship emissions at the port of Istanbul (Turkey). There are also hybrid quantification approaches, which combine top-down methodologies and bottom-up approaches. Fameli et al. (2020) used different methodologies to estimate the impact of transport (land and sea) of two port cities in Greece. His study highlighted how, during the tourist period, maritime traffic increases and emissions in the vicinity of the port area have more impact than those deriving from road transport. Marinello et al. (2020) reviewed emission factors for mobile sources.

There are numerous mathematical models for simulating air pollution, e.g. advanced Gaussian models, Lagrangian particle, puff, and photochemical models. Bai et al. (2020) used the CALPUFF model (puff model) in the port area of Yantian, Shenzhen (China) to analyse how the smokestacks on ships impact pollution levels in the port. Gariazzo et al. (2007) used the 3D Lagrangian particle dispersion model (SPRAY) to assess the impact of harbour, industrial and urban activities on air quality in the Taranto area (Italy). J. Chen et al. (2019) and Shang et al. (2019) used the WRF-Chem model to simulate dispersion and chemical reactions for three different emission scenarios. Liu et al. (2018) and Lang et al. (2017) used the WRF-CMAQ model in different ports in China. Kuzu and Bilgili (2020) exploited an AERMOD Gaussian model to Bandirma Port (Turkey), while Matthias et al. (2016) used the CMAQ chemistry transport model to study the impact of maritime traffic on SO2, NOx and O3 concentrations. Lucialli et al. (2007) applied the ADMS-URBAN model to the port of Ravenna (Italy).

Table 1 reports the alternatives proposed to reduce the impact of ports on air quality.

This paper describes the results of research conducted to assess the pressure of a port terminal on the surrounding area, comparing alternative scenarios that adopt organizational and technological solutions to reduce the impact of transport activities. A mathematical simulation model of the dispersion of pollutants in the atmosphere was used to analyse and compare different scenarios. Our results can be exploited in decision-making in the development and planning of management and technological interventions, as well as in the evaluation of investments in green and sustainable ports.

Table 1: Possible solutions to reduce the air quality impact of terminal container

Type	Measure	Reference
Technological strategies	Lower S fuel	Walker et al. (2018) Gilbert et al. (2020)
	Selective Catalytic Reduction	Ni et al. (2020) Liu et al. (2018)
	Alternative fuels (LNG, gas, electric)	Gilbert et al. (2020) Ni et al. (2020) Helgason et al. (2020)
Operational strategies	Speed reduction	Karoline and Gribkovskaia (2013)
	Cold ironing	Spengler and Tovar (2021)
	Reorganisation of layout activity	Bermúdez and Aguayo-lorenzo (2019)
Market-based strategies	Environmentally fee	Walker et al. (2018) Mjelde et al. (2019)
	Cap and trade system	Walker et al. (2018)

3.Materials and methods

3.1. Domain definition and study scenarios

We analysed a maritime container terminal located in proximity to an urban area (Figure 1). For reasons of confidentiality, we used data representative of port and container handling activities from the literature. Figure 2 reports the emission sources considered in the study.

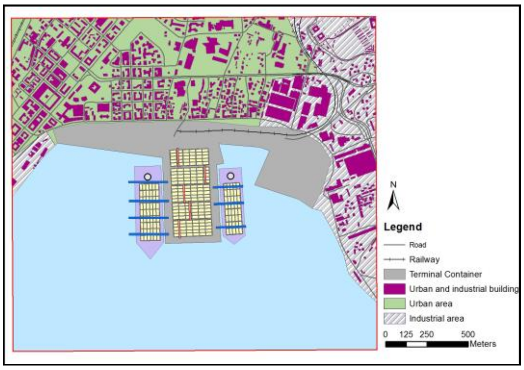


Figure 1: Study area

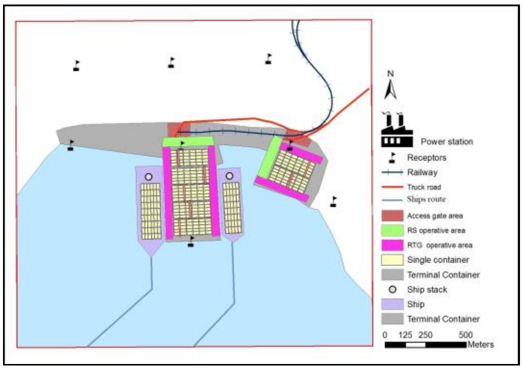


Figure 2: Distribution of emission sources and receptors

The containers are handled within a total terminal area of 600,000 m^2, equipped with two docking points for ships. We divided the ships arriving at the terminal into two categories: ships with a capacity greater (class 1) or lower (class 2) than 12,000 TEUs.

Each quay is served by electric "ship-to-shore" cranes. The main yard used for the containers' storage and handling has a total area of 250,000 m^2, separated into import and export areas. There is also an area for the management of container handling (referred to in this study as "yard2" on the right of the study area), which occupies an area of 150,000 m^2 used in one of the alternative scenarios studied. In the main yard, container handling is carried out by ten rubber tyred gantry cranes (RTGs) and ten reach stackers (RSs). "Yard2" uses three RTGs and five RSs (which are moved from the main yard). The containers that are moved from the main yard to "yard2" use electric port shuttles. Railway locomotives and trucks are used for handling in and out of the terminal.

We analysed five scenarios (Table 2) and applied some solutions from Table 1. A base scenario was defined and compared with four alternatives, which differ in terms of the technological and operational factors selected to reduce the impact of the terminal on air quality.

In addition to the fuel-based means shown in Table 2, also uses equipment and transport run on electricity e.g. quay cranes and port shuttles.

Table 2: Main characteristics of each scenario

Scenario	Sources	Fuel
BASE	139 class 1 ships /year 256 class 2 ships /year	BFO (navigation) and MGO/MDO (hotelling)
	3 tugs/class 1 ship 2 tugs class 1 ship	MGO/MDO
	5 RTG main yard	Diesel
	10 RS main yard	Diesel
	5000 hours/year for railway	Diesel
	300,000 trucks/year	Diesel
LAY	Trucks and railways operate only at "yard2", 3 RTGs and 5 RS are moved from the main yard to "yard2"	Same of "BASE" scenario
CI	Same of "BASE" scenario	Ships powered by electricity during the hotelling phase
CImet	Same of "BASE" scenario Addition of the methane power plant	Ships powered by electricity during the hotelling phase Central powered by methane
LNG	Same of "BASE" scenario	Ships powered with LNG during maneuvering and hotelling phases

In the "LAY" scenario, all container transfers from/to trucks and rail are relocated at "yard2", including the access gates to the handling areas. Containers are moved from the main yard to "yard2" using electric port shuttles.

Consequently, our goal was to assess whether, without directly intervening in the emission sources and with only spatial displacement, the impact of the terminal on the urban area could decrease.

In scenario CI, it is assumed that the ship, after docking on the quay, can turn off its engines and use the electricity from the quay to maintain its functions (Innes and Monios, 2020; Spengler and Tovar, 2021; Zis, 2019). In the "CImet" scenario, it is assumed that the electrified quay will be powered by the energy generated by a thermoelectric power station located near the port (outside the study area reported in Figure 2).

The production of energy has a direct and local impact on air quality, and is calculated only in terms of the amount needed to power the ships (approximately 2% of its annual power station production). The plant fuelled by methane has an electrical power of 840 MW. Finally, the "LNG" scenario considers the use of Liquefied Natural Gas (LNG) as a fuel for powering ships.

Several studies have analysed the reduction of NOx emissions thanks to the use of LNG. The reductions vary between 60% and 92% (European Commission, 2015; Gilbert et al., 2020; Lindstad and Rialland, 2020; Matthias et al., 2016). In this study, an average value of 76% was used.

3.2 Operative workflow

The study was conducted following the workflow shown in Figure 3, which reports the impacting sources for each scenario and estimates their emissions into the atmosphere. The data collected, together with the spatial distribution of the emission sources, the definition of the physical and meteorological characteristics of the study area and the selection of sensitive receptors, enable the mathematical model to simulate the dispersion of pollutants into the atmosphere.

Based on the results, we used statistical analysis techniques and geographic tools to compare each scenario and build thematic maps. We used the methodology proposed by EMEP/EEE (2019) for the inventory of air pollutant emissions and the ADMS-5 mathematical model (CERC, 2011) to simulate the dispersion of pollutants into the atmosphere ADMS-5 is an advanced stationary analytical model that is part of the family of Gaussian models (with non-Gaussian vertical concentration profile under convective conditions). The emission sources were treated as point sources (stationary ships), linear (trucks, railways and moving ships) and areal (RTG, RS, access gate and loading / unloading area in the yards). The concentration values simulated by the model for each scenario were compared using the percentage difference as a statistical index. The evaluations were carried out at some sensitive points, identified as receptors in the modelling simulation. Three receptors in the urban area and five receptors in the port / industrial area were chosen (Figure 2).

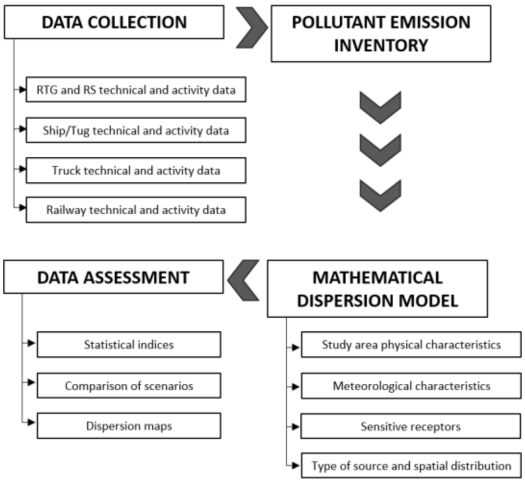


Figure 3: Research workflow

4.Results and discussion

4.1 Emission inventory

Table 3 shows the estimated annual NOx emissions due to terminal activities. The data for each scenario analysed are reported, disaggregated by the type of emission source analysed. Maritime traffic is responsible for the greatest contribution of NOx in all the considered scenarios. In the "BASE" and "LAY" scenarios, ships are responsible for 90% of total NOx emissions, especially during the hotelling phase. The contribution of maritime traffic is lower in the other scenarios: 72%, 59% and 70% of the total emissions for "CI", "Cimet" and "LNG", respectively. The choices that characterize the "LAY" scenario have a minimal impact on the quantities of NOx emitted, and are 1% lower than in the "BASE" scenario due to the shorter distance travelled by the trucks and trains to reach the loading/discharge areas.

By acting directly on the most impacting sources, the other scenarios show a considerable reduction in the NOx emitted. In the "CI" and "CImet" scenarios, maritime emissions are reduced to zero during hotelling, while the "LNG" scenario reduces emissions for both operating phases of ships. The percentage differences compared to the "BASE" scenario are -66%, -58% and -68% for "CI", "Cimet" and "LNG", respectively.

Table 3: NOx emissions estimate for each scenario (t/y)

Emission source	Scenario BASE	LAY	CI	CImet	LNG
Heavy trucks	25	18	25	25	25
Railway	42	39	42	42	42
RTG	8	8	8.2	8	8
RS	14	14	14.5	14	14
Maritime traffic	848	848	231	231	207
Ship man.	221	221	221	221	53
Ship hot.	601	601	0	0	144
Tug	10	10	10	10	10
Elec. prod.	0	0	0	72.7	0
TOTAL	**938**	**928**	**321**	**394**	**297**

4.2 Modelling simulations and scenarios' comparison

Table 4 shows the results of the modelling simulations conducted for each scenario, and the average annual concentrations at each selected receptor are indicated. Table 5 reports the respective percentage differences, comparing each scenario with respect to the "BASE" scenario. Figure 4 reports the average concentrations for each scenario.

Table 4: Average annual NO_2 concentration at each receptor ($\mu g/m^3$)

Scenario	Receptor 1	2	3	4	5	6	7	8
BASE	18	13	3	9	15	5	11	61
LAY	14	9	4	6	8	16	8	6
CI	4	3	2	5	4	3	5	2
CImet	5	3	2	7	5	3	7	2
LNG	4	3	1	2	4	2	2	1

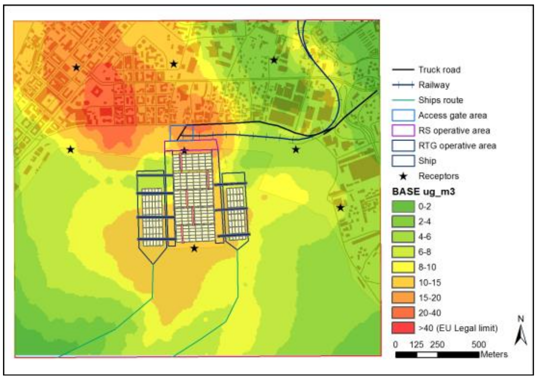
Table 5: Percentage differences in average annual NO_2 concentrations at each receptor with respect to each scenario (Difference %)

Scenario	Receptor 1	2	3	4	5	6	7	8
BASE vs LAY	-23	-27	+42	-35	-45	+216	-7	-5
BASE vs CI	-79	-78	-35	-42	-72	-45	-40	-72
BASE vs CImet	-71	-75	-31	-16	-63	-37	-15	-71
BASE vs LNG	-80	-78	-50	-78	-75	-53	-69	-79

Figure 4: Average annual NO_2 concentration at each receptor point and for each scenario analysed

At each receptor, the average annual concentrations always have the highest values in the "BASE" and "LAY" scenarios, despite not exceeding the EU limits (40 $\mu g/m^3$ as mean annual value). The "BASE" scenario shows high concentrations near the access gate to the terminal and near the urban area. At receptors "1" and "5", in the "BASE" scenario, there are excess hourly concentration limits (200 µg/m^3), which were not identified in the other scenarios. The "BASE" and "LAY" scenarios present a substantial decoupling especially at the "5" and "6" receptors due to the different distributions of the emission sources, with percentage differences of 45% and 216%, respectively. The "CI" scenario gives a substantial improvement in the average annual pollutant concentrations, with reductions compared to the "BASE" scenario of between 35% and 79%. The greatest reductions are at receptors 1 and 2 in the urban area, with concentrations decreasing from 18.2 µg/m^3 to 3.9 µg/m^3 and 13.0 µg/m^3 to 2.9 µg/m^3. The "CImet" scenario, which includes the impact of the power plant, shows a general increase compared to the "CI" scenario. On average, there is a 20% increase in concentrations, especially at receptors 4 and 7. In this scenario, the concentrations are always lower than in the "BASE" one, with more than 70% differences at receptors 1, 2 and 8. Finally, the "LNG" scenario has the lowest annual average concentrations for each receptor. The concentration values are never above 3.6 µg/m3 (receptor "1" in urban areas). In this case, the differences compared to the "BASE" scenario are always greater than 50%, with higher values at points "1", "2" and "4", all present in the urban area.

Finally, Figure 5 reports the isoconcentration maps of the spatial distribution of pollutant concentrations (expressed as an annual average value) for each scenario analysed. These maps highlight the areas that are most exposed to air pollutants. In the "BASE" scenario, the urban area and the area inside the terminal have the greatest concentrations, underlining the importance of providing mitigation solutions. The "LAY" scenario shows how the highest concentrations are lower in the urban area, and are above all in "yard2" which is part of an industrial environment. In the other scenarios, concentrations drop significantly in the urban environment, and are mainly at the terminal access area or at the connection routes for ground vehicles.



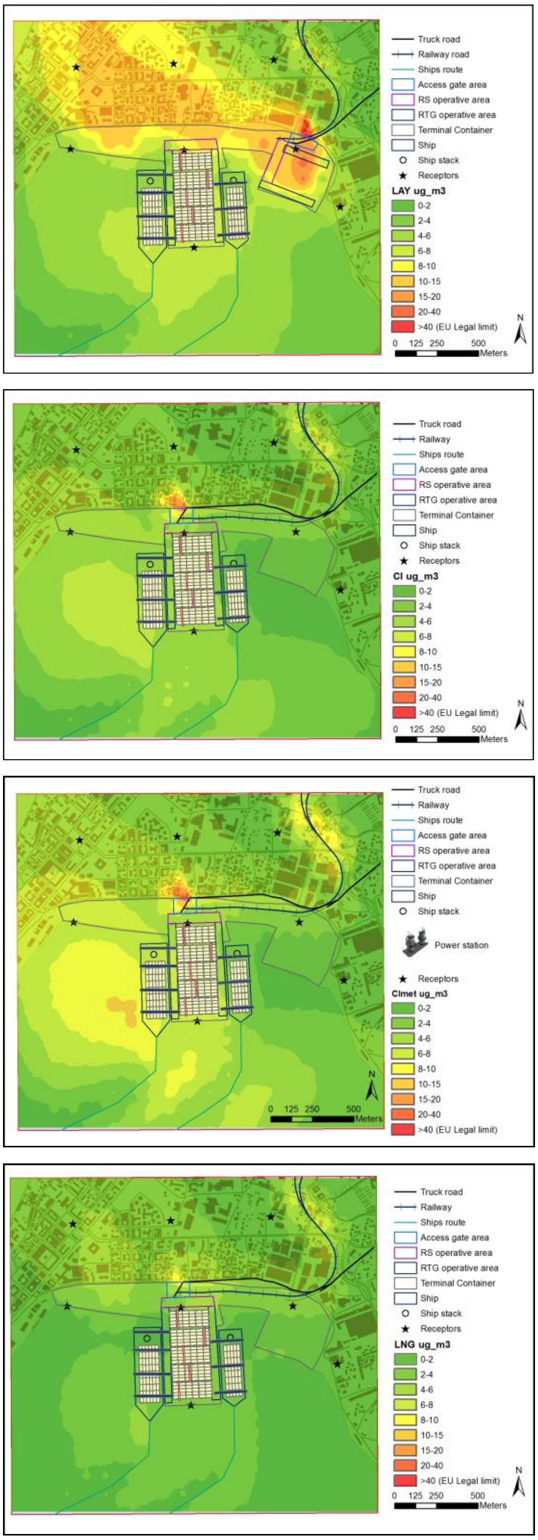


Figure 5: Average annual isoconcentrations of NO$_2$ for each scenario analysed

5. Conclusions

Over 80% of international merchandise trade by volume uses shipping. This makes transport-related activities an important multiplier of positive economic and social impacts for the areas in which they are carried out. Ports that handle goods are an example of this condition. At the same time, however, port activities negatively impact the environment. Air quality is one of the most impacted environmental matrices. Using a structured methodological approach, the goal of this paper was to assess the pressure of the maritime terminals on the surrounding areas, comparing different alternative scenarios that adopt organizational and technological solutions to reduce the impact of transport activities on air quality. .

We confirmed that maritime activities have a significant impact from an atmospheric point of view in terms of polluting emissions and concentrations, and land-based activities have a lower and localized effect in the immediate vicinity of the area of operation. Mitigating the impact of land-based sources only benefits the local area. On the other hand, reducing emissions due to maritime traffic has a much greater impact on air quality, also at long distances from the sources. Our simulations highlighted the great benefits associated with cold ironing or using LNG as a fuel. This allows for improvements of up to 70-80% in soil concentrations.

In evaluating these alternatives, two key aspects must be considered. The first is the competence (decision-making and financial) of the interventions. In the analysed scenarios, the modification of the layout of the handling processes is the responsibility of the terminal management company. If there is sufficient space, the activities on the ground can be organized differently and the use of the means can be optimized. Simply moving the access gate to the terminal avoids creating interference between the truck and the urban area. Adding cold ironing technology to ship management requires the support of local authorities for the necessary infrastructures, and shipowners need to adapt their ships. Changing the type of fuel for the ships requires the same synergies as cold ironing.

The second key aspect is economic. Making changes to a port terminal entails high costs. The modification of the layout requires adequate connection infrastructures and additional means (an electric port shuttle costs more than €250,000). Cold ironing costs tens of millions of euros for ground infrastructures, while the adaptation of each ship involves a cost of 1-2 M €. LNG is also very costly: adapting a ship can cost more than €25,000 per ship.

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