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ISSN 0554-6397
Stručni članak
(*Professional paper*)

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Abstract

For the last couple of decades, environmental protection awareness within port areas is gaining ever more importance. Ports can have a tremendous impact on the environment, especially in terms of air pollution. The main pollution sources are various port activities such as road and rail traffic, cargo handling and marine vessel operations. Air quality models can be of great help in estimating the effect on the ambient air quality from one or more sources emitting pollutants to the atmosphere. One of those models is the widely used Gaussian Plume dispersion approach. Based on existing measurements and port activity data, models can simulate the dispersion of air pollutants caused by activities and operations taking place within the port. By using historical data, they can simulate the current state of the air quality in the port and with the help of weather predictions simulate possible future situation. Simulations can assist the port manager/operator in the decision-making process in order to optimize various activities within the port and minimize their impact on the environment. One of the main objectives of the Horizon 2020 Project PIXEL (Port IoT for environmental leverage) is the deployment of environmental pollution models which can aid in the decision-making processes within the port domain. This paper reviews the current advances in the field of air pollution modelling with a special emphasis on port scenarios.

Keywords: environmental engineering, Gaussian Plume dispersion model, air quality, air pollution, seaports

1. Introduction

Due to the growth of the international trade, economic activity and transport of goods through ports have been steadily increasing and are likely to continue to do so in the future [1]. By being major hubs of economic activity, they are vital to the economic development of their surrounding areas. Furthermore, they are sources of vehicle emissions, air pollution from port and ship operations as well as noise and light pollution. Other environmental concerns are contamination of water and soil, hazardous waste generation and traffic congestion. Being close to urban areas ports also have an impact on the inhabitants in the area. Some of the health risks include respiratory diseases, cancer, cardiovascular disease, bronchitis and premature mortality [1]. Therefore, environmental protection is of great importance in port areas. Several initiatives like EcoPorts and Green Marine were established to make ports more environmentally sustainable and to raise awareness on environmental protection. In the EcoPorts 2018 report, (Table 1.) a trend of increasing priority of clean air and energy consumption can be observed [2].

Table 1: Port Priorities [2]

Top 10 environmental priorities in participating ports							
	1996	**2004**	**2009**	**2013**	**2016**	**2017**	**2018**
1.	Port development (water)	Garbage/ Port waste	Noise	Air quality	Air quality	Air quality	Air quality
2.	Water quality	Dredging operations	Air quality	Garbage/ Port waste	Energy consumption	Energy consumption	Energy consumption
3.	Dredging disposal	Dredging disposal	Garbage/ Port waste	Energy consumption	Noise	Noise	Noise
4.	Dredging operations	Dust	Dredging operations	Noise	Relationship with the community	Water quality	Relationship with the community
5.	Dust	Noise	Dredging disposal	Ship waste	Garbage/ Port waste	Dredging operations	Ship waste
6.	Port development (land)	Air quality	Relationship with the community	Relationship with the community	Ship waste	Garbage/ Port waste	Port development (land)
7.	Contaminated land	Hazardous cargo	Energy consumption	Dredging operations	Port development (land)	Port development (land)	Climate change
8.	Habitat loss/ degradation	Bunkering	Dust	Dust	Water quality		Water quality
9.	Traffic volume	Port development (land)	Port development (water)	Port development (land)	Dust	Ship waste	Dredging operations
10.	Industrial effluent	Ship discharge (bilge)	Port development (land)	Water quality	Dredging operations	Climate change	Garbage/ Port waste

To manage air quality several laws and policies are put in place and different methods of air pollution modelling are being developed and used. Those models are useful tools for estimating air pollution concentrations in space and time. They can simulate the dispersion of air pollutants caused by activities in the port area. The resulting simulations can assist the port manager/operator in the decision-making process and make the ports more environmentally sustainable.

2. Air pollution Sources in Seaports

As mentioned before, ports have a negative impact on the environment. They are sources of air pollutants, which notably contribute to regional air pollution problems and affect the health of people in the local communities (Table 2.). Port operations such as on-site fuel combustion, ship emissions, logistic activities of dredging and bunkering result in air emissions. The main air pollutants related to port activities include Particulate matter (PM), diesel exhaust, Carbon monoxide (CO), Carbon dioxide (CO_2), Sulphur dioxide (SO_2), Nitrogen oxides (NO_x) and volatile organic compounds (VOCs). Other air pollutants hazardous to the environment and health are heavy metals, dioxins and formaldehyde, [3,4].

Table 2: Air emission sources in ports [3,4]

Source	Pollutants	Effects	
Dry bulk	Sulphur dioxide (SO_2), Hydro carbons (HCs), Particulate matters (PM_{10}, $PM_{2.5}$), Lead (Pb), Nitrogen oxides (NO_x), volatile organic compounds (VOCs) Ozone (O_3), Hydrogen fluoride (HF), Carbon monoxide (CO), Hydrogen fluoride (HF), Heavy metals (e.g. Hg, Pb, Cd etc.)	Human Health (acute and chronic)	Local, Regional and Global
Liquid bulk			
General cargo			
Cargo handling storage		Ecosystem (acute and chronic)	Local, Regional and Global
Vehicle and equipment maintenance			
Users Handling and storage of chemicals (non-bulk)		Greenhouse gas emission	Global
Fueling and bunkering		Acid rain	Global
Building and open area maintenance			
Transshipment (Ro-Ro, Passenger, Container, …)		Stratospheric ozone depletion	Global
Ship movement		Long-range transport	Global
Maintenance dredging & disposal			
Towing			
Mooring			

3. Air dispersion modeling

Air pollution modeling is used to predict the way pollutants behave in the ambient atmosphere. They are mathematical simulations of the chemistry and physics governing the transformation, transport and dispersion of pollutants in the atmosphere. These simulations show the environmental impact under different weather conditions, emission rates and development scenarios.

Today, there is a great range of different techniques and methods available for making assessments of pollutant impact over a study area. The most commonly used dispersion models are steady state Gaussian dispersion plume models which are simple mathematical models used to estimate pollutant concertation at some distance from an emission source. Recently more sophisticated approaches are being developed which describe the dispersion and diffusion by using fundamental properties of the atmosphere rather than calculating ground level concentrations of pollutants [5].

There are two main groups of air dispersion models available today:

- Gaussian-plume models such as
  - AERMOD - a steady state atmospheric dispersion modeling system designed for short-range dispersion of air pollutants [6]
  - AUSPLUME - a regulatory Gaussian plume model which predicts ground level concentrations. The main difference between AERMOD and AUSPLUME is the whey the models handle terrain [7]
  - ISCST3 - Industrial Source Complex (ISC3) for short term air dispersion modeling in industrial areas. Similar to AUSPLUME, the ISCST3 models is principally designed for flat terrain regions [8]
  - CTDMPLUS - the Complex Terrain Dispersion Model-Plus, is a Gaussian plume dispersion model which estimates hourly plume concentrations from elevated point sources at receptors on isolated terrain features [8]
- advanced models such as CALPUFF which is a non- steady state air quality and meteorological modeling system [6]

4. Air dispersion model integration in the PIXEL project

The Pixel project solution aims to optimize port operation through an IoT (Internet of things) based platform to lower the environmental impact of port operations. One of the objectives is the development and application of an air dispersion model for the use cases of pilot ports in PIXEL [9]. Based on existing measurements and port activity data, the air quality model should simulate the air pollutant dispersion from port operations. Port operators in the pilot ports can use the resulting simulations to optimize activities within the port and minimize their impact on the environment.

The air dispersion model that will be deployed is the American Meteorological Society (AMS) and the United States Environmental Protection Agency (EPA)

Regulatory Model – AERMOD. It is a steady-state Gaussian plume air dispersion model which predicts downwind pollutant concentrations based on source emissions, site parameters (terrain features, land use, etc.), meteorological fields, building locations and more. The AERMOD modeling systems includes five preprocessors, one dispersion model and one post processors [6].

5. Model Input data requirements

For any model to work and produce reliable results it is crucial to acquire the needed data sets.

Information needed to calculate pollutants concertation downwind of a source are [5]:

1. Meteorological data
2. Emission inventory
3. Local topography
4. Building and obstacle locations

5.1. Meteorological data

Ground-level concentrations caused by the constant discharge of pollutants change depending on the current weather conditions. Meteorology is an imperative for the dispersion of pollutants as it is the main factor determining the atmosphere's diluting effect. Therefore, it is important to carefully consider meteorology when modeling the dispersion of pollutants in the atmosphere. Meteorological data needed for modeling purposes is usually acquired from nearby stations. AERMOD'S meteorological preprocessor AERMET in order to work properly needs several different meteorological data sets. Data needed are hourly surface data and upper air mixing data which can be both easily accessed from the National Oceanic and Atmospheric Administration's website [10,11].

5.2. Emission Inventory

The Emission Inventory (EI) is a comprehensive list of pollutants emitted from all sources in a geographic area over a specified period. An EI database is very important for air quality management and it is a great help in managing the main air pollution sources. Emission inventories are crucial for all air pollution modeling methods and techniques [12].

5.2.1. Total emission and emission intensity

Total emission is the aggregated emission for a given activity, for example, in a time period or traveled distance and it is expressed in mass units. Emission intensity is the emission rate of a pollutant in relation to a specific activity and it is expressed in mass units per activity, like time, distance or energy consumption. Both total emission and emission intensity can be calculated with energy-based or fuel consumption-based equations, depending on the available data.

5.3. Emission source characteristics

Air pollutants are defined as substances in the atmosphere that result from the activities of humans or natural processes, which cause harm to humans, animals or plants and changes in weather.

Six common air pollutants (criteria pollutants) that are often found anywhere in the air are: Carbon monoxide (CO), lead, Ground-level Ozone, Sulphur dioxide (SO_2), Nitrogen oxides (NO_x) and Particulate matter (PM) [3].

5.3.1. Point sources

Point sources are stationary sources, which are usually large production facilities that include chimneys or stationary emission points. There may be several combustion units within a given point source, such as several boilers. Exact sources can be hospital incinerators, hospital boilers, crematoriums and industries.

5.3.2. Area sources

Area sources are defined as sources that are too numerous to be considered point sources. Collectively, these sources can contribute to a significant share of total emissions to the atmosphere. Area sources include a wide variety of sources, such as construction activities, auto repair facilities, paint spraying plants or cargo handling terminals in seaports.

5.3.3. Line sources

Line sources are engines, vehicles and equipment that generate air pollution. These sources, also considered as mobile sources, move or can move from place to place. Subgroups of line sources are road and non-road sources. Road sources are cars used on the road to transport passengers or cargo, such as trucks, passenger cars and motorcycles that are fueled with diesel, gasoline or alternative fuels. Non-road sources are vehicles fouled with gasoline and diesel, equipment and engines used in transportation, agriculture, construction and many other uses. For example, non-road sources are ocean and sea going vessels, railways and aircraft.

5.3.4. Volume source

Volume sources are three-dimensional pollution sources. Volume sources can be uncovered sand, gravel or coal piles.

5.4. Pollutant emission calculation

A crucial part for any method or technique of air pollution modeling is the quantification of emissions to air. Depending on the type of emission and the related activities there are different ways to calculate the needed emissions. Also, modeling software's like the AERMOD Modeling System require source type specification for successful simulation runs.

5.4.1. Point sources calculation

A source that is large enough and contributes to a large amount of emissions can be considered a point source. Data required to make a point source inventory are: factory type and size, geographical coordinates, type of industrial activity, combustion operating conditions, fuel specification and consumption, raw materials used in industry process, equipment age, stack height (and if available: flow volume in m3 / hour, internal diameter), operating hours per year.

Emissions for each source category are calculated using Eq. 1 and emission factors.

5.4.2. Area sources calculation

Area sources similar to point sources include small sources with insignificant emissions by them self, distributed evenly over a wide domain. Collecting all these sources contributes to significant emissions in air quality.

Source categories are different depending on the feature of the chosen domain. Some categories can be solid waste, open burning, biomass (straw) burning, gas stations, construction and processing of concrete. Total Area source emissions are calculated with the same approach as point source emissions (Eq. 1).

$$TE = A \times EF, \quad (1)$$

Where:
TE = total emission
A= activity rate
EF= emission factor

5.4.3. Line sources calculation

Line sources can be divided between road sources and non-road sources. Mobile sources are emissions from traffic in a given area, which directly affects human health. Non- road sources are emissions from ports, airports and railways.

Total emissions from mobile sources can be estimated from fuel consumption in the study area and average emission factor, with Eq. 2. The categories of vehicles considered are passenger cars, motorcycles, light heavy vehicles, heavy vehicles and buses running on diesel, gasoline, liquid petroleum gas (LPG) and natural gas.

$$TE = \sum_{i=1}^{n} \left(FC \times EF \right), \tag{2}$$

Where:
TE= total emission [g]
FC = fuel consumption [l fuel or kWh]
EF = emission factor [g/kg fuel g/kWh]

Input data for emission models usually require the following information which is collected from surveys, analysis, previous researches, and observation from the study area: average daily traffic, defining road categories, length and width of road, number of lanes, speed limit, vehicle type/category, weight, vehicle engine type, fuel use, and vehicle traffic curve [12].

5.5. Local topography

Local topography can have a considerable impact on the transport of pollutants in the ambient air. Upwind terrain can influence turbulence characteristics and wind flow which can differ from the measurement taken from the nearest meteorological station. Rough terrain and hills can alter wind directions, speed and characteristics of turbulence and nearby water bodies can significantly reduce turbulence levels. Ports have a specific topography by being in coastal areas which needs to be taken into count when performing air pollution modeling [5].

5.6. Buildings in port area

Building location and dimension information are required input data for many air pollution modeling methods mainly because of the building downwash effect which occurs when the wind flows around and over buildings. This can affect plume rise and the dispersion of pollutants in the atmosphere. Building downwash is also important in port areas because of the numerous port facilities and container storage areas. For example, the Port of Thessaloniki, one of the PIXEL pilot ports, has more than 200 buildings of various purposes and dimensions in its premises. The AERMOD Modeling System provides a building preprocessor Building Profile Input Program (***BPIP***) which considers the occurrence of building downwash which requires buildings dimensions and coordinates as input [6].

6. Quantifying air emissions and air dispersion modeling in seaports

Seaport activities and operations greatly contribute to environmental pollution especially in terms of air pollution.

By implementing Environmental Air Quality Monitoring Programs ports have the means to identify, evaluate and quantify air emissions. Using the resulting data and information they are able to develop appropriate actions and operational techniques for protecting and improving air quality within the port areas.

Air emissions are generated at different locations of the terminal as a product of different operations, i.e. energy consumption from cargo handling machinery.

To successfully model air pollution in port areas a comprehensive emission inventory is needed and its necessary to determine which type of emission source the polluting port operations and activity include. One way of classifying types of emission sources is shown in Table 3.

Table 3: Source types in ports [14]

Emission source	**Source Type**
Ships (Harbor Transit)	Volume
Ships (At Berth - Auxiliary Engines)	Volume
Ships (Turning and Docking Near Berth)	Volume
Ships (At Berth - Auxiliary Engines)	Point
Ships (At Berth – Boilers)	Point
Ships (At Anchorage)	Area
Tugboats	Volume
Locomotives	Point
Cargo Handling Equipment	Area
Trucks	Point
Worker Vehicles	Point

Such emission inventory requires detailed information on the characteristics and activities of vessels and land equipment, as well as detailed information on the geography of the port and the ship routes within the port.

The main three air pollution sources are: vessels, cargo handling equipment and vehicles.

6.1. Ocean going vessels (OGVs)

Air emissions from ships in a seaport depend on the size and type of the ship and the specificity of the energy system. A method for calculating total emissions from seagoing ships uses energy-based emission factors is shown in Eq. 3 [12].

$$TE = P \times LF \times A \times EF, \tag{3}$$

Where:
TE = total emission [g],
P = maximum continuous power rating [kW],
LF = load factor [%],
A = activity [h]
EF = emission factor [g/kWh].

$$LF = \left(\frac{AS}{MS}\right)^3, \tag{4}$$

Where:
LF = load factor [%]
AS = actual speed [m/s]
MS = maximum speed [m/s]

6.2. Cargo-handling equipment (CHE)

Cargo handling equipment can be considered as numerous point sources in container handling areas. When modeling such activities, they are classified as area pollution sources. Besides determining the type of pollution source, it is also necessary to quantify emissions from them. Total emission can be calculated with the following equation: [12].

$$TE = N \times P \times LF \times A \times EF, \tag{5}$$

Where:
TE = emissions [g],
N = number of items
P = maximum continuous power rating [kW],
LF = load factor [%]
A = activity [h]
EF = emission factor [g/kWh]

6.3. Truck and vehicles traffic

Truck and vehicles traffic is classified as a line emission source. It is necessary to estimate the amount of air emissions generated by the operation of trucks and vehicles at the port. Total emissions are estimated using the following expressions [15].

$$TE = FC \times EF \times N, \tag{6}$$

Where:
TE = mobile emission rate [g]
EF = emission factor [kWh]
N = number of trucks,
FC = fuel consumption [g/kWh]

6.4. Rail traffic

Similar to road traffic, the impact of rail traffic on the ambient air needs to be evaluated. Rail traffic is a non-road emission source and it can be considered as a line emission source. Total emissions within ports from diesel trains are calculated as follows [15]:

$$E = EF \times d \times c \times N, \tag{7}$$

Where:
TE = mobile emission rate [g]
EF = emission factor [g/kg fuel]
d = distance of rail transport within the port [km]
c = diesel consumption [kg diesel/km]
N = number of diesel trains

7. Conclusion

Ports are rapidly developing information and economical hubs with adverse side effect on the environment and human health. Those negative side effects are consequences of exhausts of particles, SO_2, NO_x and CO_2 emissions from cargo handling equipment, ships' main and auxiliary engine noise, dust from handling cargo and pollutant emissions from ship engines and machinery used in port areas. To address and reduce those environmental impacts a wide range of tools are available. Air dispersion of pollutants in ports is one of the biggest concerns both on the local and global scale, and beside numerous regulations various air pollution modelling method and techniques can be of great help in the decision-making processes within the port domain. Resulting simulations can assist in optimizing various activities within the port and minimize their impact on the environment. For successful model runs it is important to have reliable meteorological and terrain data, a comprehensive emission inventory which includes source type and location and data on buildings and their locations.

Abbreviations

AERMOD	American Meteorological Society (AMS) and the United States Environmental Protection Agency (EPA) Regulatory Mode
AERMET	AERMOD Meteorological Preprocessor
BPIP	Building Profile Input Program
CALPUFF	Puff Air Dispersion Model
CHE	Cargo-handling equipment
CO	carbon monoxide
CTDMPLUS	The Complex Terrain Dispersion Model
EI	Emission Inventory
EPA	Environmental Protection Agency
IoT	Internet of Things
ISCTST3	Industrial Source Complex Short-Term Model
NOx	nitrogen oxides
OGV	Ocean going vessels
PM	particulate matter
PPA	Port of Piraeus
Sox	sulfur oxides
VOC	volatile organic compounds
ThPA	Port of Thessaloniki

Acknowledgements

This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 769355 ('Port IoT for Environmental Leverage' — PIXEL).

9. Nomenclature and units

activity	A	h
actual speed	AS	m/s
diesel consumption	c	kg diesel/km
distance of rail transport within the harbor	d	km
total emission	E	g
emission factor	EF	g/kg fuel
		g/kWh
fuel consumption	FC	l fuel
		kWh
load factor	LF	%
maximum continuous power rating	P	kW
maximum speed	MS	m/s
number of items	N	
the vehicle's working time in the port	T	h

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