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Research article

Source characterization guidelines for noise mapping of port areas

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ABSTRACT

Maritime transport for both passengers and freight is continuously increasing and, consequently, the global attention toward its sustainability is growing. Ships offer advantages in terms of environmental impact compared to other transportation systems but the increasing traffic volume is expected to increase pollutants. Noise produced in port areas has been neglected for too long, until the INTERREG Maritime programme Italy-France 2014–2020 has brought to light how citizen complaints are emerging for some of the main ports in the Mediterranean. However, port noise prevention and management is difficult as knowledge on specific sources is very limited in the literature. Furthermore, on field measurements are difficult to be performed given the complexity of the port area, where multiple types of sound emitters mix and confuse each other.

Noise maps represent the first important step in order to align ports to the requirements set by the Environmental Noise Directive to the transportation infrastructures. Once computed, they are an excellent tool supporting port management towards the reduction of citizens' noise exposure while ensuring traffic growth.

The present paper reports a guideline for the characterization of noise sources needed as inputs for the noise maps, as developed in the framework of the INTERREG Maritime programme Italy-France 2014–2020. On the basis of the current state of the art, a procedure has been elaborated for different categories of noise sources acting in port, ranging from stationary to moving ships, from mooring operations to loading/unloading operations, from industrial activities to road and railway traffic.

1. Introduction

Sea travel still represents the most used means of transport for freights over long distances because of its reduced costs, large cargo capability of modern vessels and almost omnipresence of maritime structures in the world. Maritime transportation constantly saw consistent increases of traffic on a yearly basis until 2019 [1]. Consequent to the economic crisis following the pandemic, the United Nations' review on maritime transport of [2] foresees the first negative trend in 2020.

While ship transportation has a reduced environmental impact if compared to ground or air transportations, it is not emission-free. During navigation, ships have been demonstrated to influence marine mammals' communications [3, 4] and, when they are in ports, they can represent a serious threat for air [5, 6] and noise [7] pollution. Considering that also ferries and tourist cruises add to the freight maritime traffic and their ground operations, the potential noise sources can be many. Moreover, many ports are close to inhabited areas, resulting in occasions for possible noise disturbance and complaints as emerged, for instance, in coastal cities like Dublin [8], Athens [9], La Spezia and Nice [10].

Even if the situation is just slightly below the critical level, port noise has never been properly treated and has been marginalized at the regulatory level [11, 12]. In fact, it has been at first excluded from the noise action plans, a requirement of the European Union's Environmental Noise Directive (END) [13] initially regarding only the main roads, railways [14], airports [15] and agglomerations [16]. Consequently, most of the funds aimed at studying noise impact have been focused on ground and air infrastructures, which also attracted lots of attention from the scientific community in order to study and reduce their noise emissions [17],

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to map their impact in the territory and to mitigate it with innovative solution such as low-noise pavements [18, 19], real time monitoring systems [20, 21], sustainable metamaterial absorbers [22, 23].

This inattention of the legislation led to very few assessments of citizens' exposure to port noise performed around the world, even if the growing complaints would soon represent a major hindrance to the natural growth of maritime traffic. Moreover, noise sources specifically related to ports have been studied much less than the other infrastructures, perhaps, also because of their complexity. Only in recent years some international projects concerning the noise impact came out [24, 25, 26, 27, 28, 29, 30]. Following these projects, attention has grown and Paschalidou, et al. [31] showed that port is a complex environment, where many different sources can be present and disturbe people living in the surroundings. Schenone, et al. [32] and Hanaoka, et al. [33] reported that annexed road traffic and industrial activities are the main sources. Same conclusions have been reported in the port of Barcelona and Dublin [34, 35, 36] with criticalities that possibly rose during the night [37].

Some scientific papers recently focused on the acoustic characterization of ships, marked as noise emitters from multiple spots and during different operations [38]. In fact, different ships have proper noise emissions while moving, maneuvering, mooring and performing ground operations. Witte, et al. [39], Santander, et al. [40] and Badino, et al. [41] studied sound emitted in the environment by internal machinery propagating through hull and funnels, heating and ventilation systems. Still Badino, et al. [42], Di Bella, et al. [43] and Fausti, et al. [44] were the first studying moving ships, while a proper characterization have only been published recently by Bernardini, et al. [45] for small vessels, Nastasi, et al. [46] for ferries, and by Fredianelli, et al. [47] for roll-on/roll-off (RORO), container ships, oil tankers and chemical tankers.

However, many other sound sources can simultaneously act with the aforementioned ones in a port environment, making it a very complex environment in which to perform measurements. Cranes, forklifts, reach stackers, are just some of the service vehicles operating during ships loading/unloading operations and each of them still needs to be acoustically characterized.

The European Union (EU) Interreg Programme supports cooperation across borders through project funding, aiming to find shared solutions to common challenges in different fields (such as research, sustainability, environment, etc.) with a budget of 10.1 billion Euro invested in the cooperation programmes. The Interreg Maritime Programme Italy-France 2014–2020 [48] is conceived to fill the gap in knowledge regarding port noise. Part of the Interreg initiative and funded by the European Regional Development Fund, this cross-border cooperation programme aims in achieving the Europe 2020 Strategy goals in the North Mediterranean area, in accordance with the EU Cohesion Policy, and in its previous programming phase funded 87 different projects. Within the framework of the axis 3 - lot 2 of the programme, the improvement of the sustainability of commercial ports and logistics platforms to reduce noise pollution is the specific objective. Different projects were funded and are in progress, with the aim of describing the actual status and designing best practices looking for a long-term sustainability in the eligible area. The partners involved are many and various, mixed Italian and French, ranging from port authorities (Cagliari, Genoa, La Spezia, Livorno, Portoferraio), Universities (Cagliari, Genoa, Pisa, Corse), the French research center CSTB, Municipalities (Nice), Region of Liguria, Environmental Protection Agency of Tuscany Region (ARPAT), Chambers of Commerce and Industries (Bastia et de la Haute-Corse), the Corsica's Transports Office. The projects aiming to assess different aspects of the port noise inside the programme are:

- DECIBEL, which aims to realize infrastructures for noise reduction in small ports;
- L.I.S.T. Port, focused on vehicle traffic around ports;
- TRIPLO, which studies noise in the area included between the ports and the logistic platforms connected to them;
- RUMBLE, REPORT and MON ACUMEN to which the present work mainly refers.

RUMBLE has the target of mitigating noise emission in ports and annexed areas. In its first phase it dealt with the analysis of modern technologies for reducing port noise and understanding citizens' perception. A survey [49] has been conducted in order to collect the available data on port noise in the area of interest and to evaluate eventual citizens' complaints. The results showed a "ground zero" situation in which the acoustic issue has, almost never been addressed. The project led to the construction of several mitigation works: a large green barrier in Genoa, low-emission road pavements in Cagliari, Portoferraio, and Bastia. In addition, other ports have been sensitized, such as Nice bought sound level meters and control units for noise monitoring, while Ile Rousse and Bastia bought battery charging stations for electric vehicles, which should be used in the future for loading and unloading operations. REPORT looks at port noise from a more theoretical point of view. Modelization of noise sources of ships, aiming at an integrated tool in a software, is ongoing. Furthermore, a neural network specialized in traffic flow analysis is under development in order to allow real-time prediction of noise levels based on traffic data. In the meanwhile, greener propulsion technologies, such as those involving electric, hybrid, fuel cell, liquified natural gas, applied to cargo handling units are under investigation for their noise reduction. Also, an econometric evaluation of social costs generated by noise pollution in the port area is underway. MON ACUMEN is directed towards port noise monitoring and sustainable management. After an in-depth analysis of the state-of-the-art of port noise monitoring, measurements and characterization of specific noise sources, the project aims to build an integrated monitoring system according to the same rules for all the ports. This will represent a normalized and real-time noise-monitoring of all the ports that, eventually, will warn when a noise exceedance emerges and will identify the responsible source. Thus, noise maps of the involved ports are needed for a proper positioning of the monitoring infrastructure.

Noise maps are not only the basis on which action plans are designed, but they are also the keystone for evaluating the average citizen's noise exposure. In this specific context, a relation between the different port activities and their noise levels evaluated in the surrounding areas would allow the project to correctly pinpoint the monitoring position.

The present paper defines the guidelines for the acoustic mapping in port environments, elaborated in the INTERREG Maritime programme Italy-France 2014–2020. As it is known that the quality of a noise model output is directly related to the quality of its inputs [50], all kinds of sources present in a port environment should be considered as inputs for a proper acoustic map. At the same time, measurement activities should be carried out without interfering with the port and ship operations, or at least minimizing the interaction. A specific measurement procedure is reported for the characterization of each of the sources, divided into categories as reported in Fredianelli, et al. [51]. Road, railways, ship, port, and industrial sources are then considered separate noise sources, each with further subdivisions according to their working operation mode or position. While noise from transport infrastructure is already well defined in the acoustic model, the needed procedures for ship, port and industrial noise sources characterization are based on the following assumptions:

- Collaboration of ship owners is not available, thus on-board measurements are avoided and the machinery cannot be switched off/on on demand.
- Terminals' activities cannot be stopped to create ideal test sites and reduce background noise.
- The use of additional tools, such as cranes or cherry pickers, to reach higher measurement positions would be difficult and too expensive for the technicians who will apply the procedures.

- The overall noise emitted from ships is assumed to be symmetric about the stern to bow axis. This assumption allows measuring only the ship's side at the quay, thus avoiding measurements with boats on the seaside.

All the procedures gather information on the acoustic emission specifically intended for noise mapping purpose, thus resulting in a compromise between the possibility of acquiring information in a complex and confusing environment, and their best quality in order to have sufficient outputs for the consequent acoustic model.

The present work will then promote and allow port noise mapping under the same methodology for input data acquisition and source characterization. Ports who will follow the guidelines will have noise maps aligned to the same standard and their results would also be comparable.

2. Methodology

Every noise map is the output of a noise model based on several fundamental inputs: a 3D model of the investigated area, a list of all the noise sources with their position and, of course, their acoustical characterization.

2.1. Preliminary data gathering

Morphological and topographical data are the starting points for the elaboration of the Digital Terrain Model (DTM) that, together with buildings and obstacles' layers, compose the 3D space in which sound propagates or is reflected. In this regard, when designing a 3D port environment model, the author has to pay particular attention to appropriately include stacks of containers, as they can act as noise barriers. Furthermore, the number of inhabitants of each residential building, as well as the number of students in schools and patients in hospitals, should also be retrieved for the action plan phase, consequent to the mapping phase according to the END. This information, combined with the exceedances that may arise after comparing noise map results with local noise limits, will be used to calculate the priority index, which regulates how future mitigations are chosen [52, 53].

Whilst it will likely take port authorities a considerable effort to assemble from scratch the database of all the noise sources, its maintenance and updates should be less cumbersome. The size of the initial effort is dictated by the volume and complexity of the information that needs to be gathered such as the position of a huge variety of machinery, infrastructure and more. Once these are in place, it is fair to expect only minor additions and edits over time, as new sources come into play or obsolete ones get deprecated. On the contrary, a proper acoustical characterization of the main sources acting in ports has been an unsolved task because issues arise when performing measurements in a complex environment with non-negligible background noise and where security protocols or geographic impediments do not allow a free choice of the measuring positions.

2.2. Macro categories of noise sources

More than anything else, there are many types of sources requiring tailored procedures, which can be considerably different from each other. The present paper reports a procedure for each of them, following the division in categories and sub-categories presented in [51]:

- Road:
  - o internal traffic;
  - o port related external traffic;
  - o external traffic not generated by port.
- Railways:
  - o internal traffic;
  - o port related external traffic;
  - o external traffic not generated by port.
- Ships:
  - o sailing at reduced speed approaching the quay;
  - o moored in stationary conditions;
  - o mooring operations;
  - o moored during loading/unloading operations (without auxiliary machinery).
- Port and industrial:
  - o fixed sources;
  - o mobile sources;
  - o area sources.

Roads and railways in port areas do not differ substantially from others, thus their requested information for noise mapping are those suggested by the already well developed CNOSSOS-EU protocol [54].

Ships sources include all the activities related to movement and stationing of the more frequent and noisy vessels in the investigated port. For example, cargo and passenger vessels should be included, while recreational and law enforcement vessels, fishing boats or local water transport can be excluded from the modeling except in special cases.

Defining measurement procedures for ship noise is critical as, at present, it is not regulated nor at the national nor at the European level. Recently, some classification societies (DNV, LR, ABS and RINA [55, 56, 57, 58, 59]), the ISO 2922:2020 [60], the ISO 14509–1:2008 for small crafts [61] and the NEPTUNES Project [62] issued their own procedure for the characterization of noise emitted by moving or moored ships. However, each presents specific major issues preventing its global diffusion and application. The requirement of low levels of background noise for a sufficient noise-to-signal ratio at tens of meters from the ship, the requirement of not having deflecting surfaces close to microphone positions, the use of specific cranes or cherry pickers in order to reach the measurement positions or microphone height and the significant budget needed for such campaigns are examples of such issues. Also, Curcuruto et al. [63] highlighted critical aspects in the application of such methodologies to operating ships, as they require close collaboration with the vessel owners, for instance when asking to switch off the onboard sources during measurements. As it is reasonable to expect, such collaboration is hard to get consistently. Moreover, none of the methodologies proposed above considers the loading/unloading operations.

It follows that none of these procedures can be applied to characterize the ship noise when such activity is performed in the context of mapping port areas. In fact, in this case, measurements must be carried out by minimizing the impact on port activities. Moreover, the port configuration generally does not allow great distances from the ship to take the measures. Plus, the measurements methodology must be simple enough to be easily applicable worldwide.

When it comes to cooperating with ship owners, this is not sustainable in large ports, where dozens of different ships for each category pass through. Therefore, the guideline proposed in this paper is based on indirect measurements at the berth, while direct measurements on board would be suggested only in exceptional cases where cooperation of ships can be obtained.

Port sources refer to port related activities, such as load and unload of freights and ships' service operations. Container load/unloads from container ships, refueling, boarding and landing of vehicles due to RoRo vessels, containers load/unloads on freight trains are some of the many different machinery and operations that fall into this category. Most of these machineries can be used also in operation not related to port activities but connected to the industrial fabric connected to the port area. Thus, port sources and industrial sources have been subdivided [51] into two separate categories in order to correctly identify legal responsibilities in case of exceeding of the emission limits. With the exception that the industrial category can also include other sources such as pumps, ventilation systems, air conditioning systems, etc., there are no technical differences between the specific sources in the two categories and their noise emission characterization procedure can be the same. The sound power of some of these sources should be available in accordance with the Directive 2000/14/EC of the European Parliament [64]. Unfortunately, in most cases this information is not available to the owners. Irrespective of that, the acoustic characterization prescribed by the directive is aimed at serving different purposes and does not consider the different phases of operation. In fact, a unique definition is not sufficient for these sources that operate in different ways, with different acoustical properties, while they are moving, handling cargo or loading/unloading them.

2.3. Sound power level computation

Thus, while some categories have well-known noise emitters with thoroughly defined noise models, the others need their own characterization procedure for each one of the defined categories and operational phase. All of these are described in the following of the paper.

All the suggested noise measurements are intended to be performed with a class I sound level meter compliant with IEC 61672-1 recommendations [65].

Once the sound pressure level (L_p) has been obtained from measurements, a sound power level (L_w) of the sources involved in the relative operation should be calculated, as this value is the parameter used by noise propagation prediction models.

Starting from one or more L_p measurements, the L_w can be reconstructed using Eq. (1), possibly applied to each octave band level or, preferably, third octave bands.

$$L_w = L_p + 10log\left(\frac{Q}{4\pi r^2}\right) \tag{1}$$

where Q is the directivity factor and r is the distance to sound source.

The number of L_p must be at least equal to the number of sources to be characterized, but a greater number of L_p measured in different positions can increase the precision of the results. Specific software are designed to facilitate these calculations.

3. Transport infrastructure

3.1. Road sources

In order to properly comply with the CNOSSOS-EU requirements [54], traffic flow and other data points must be acquired in correspondence of each road axis in the model in accordance with the form reported in Table 1. The authors expect that data like pavement type and the number of months with studded tyres could be difficult to gather. When this is the case, models or standard values can be used in order to provide an estimate. According to CNOSSOS-EU, the vehicle categories are:

- Category 1 - Light motor vehicles (passenger cars, delivery vans ≤3:5 tons).
- Category 2 - Medium heavy vehicles (medium heavy vehicles, delivery vans >3:5 tons, buses, etc. with two axles and twin tyre mounting on rear axle).
- Category 3 - Heavy vehicles (heavy-duty vehicles, touring cars, buses, with three or more axles).
- Category 4 - Powered two-wheelers (mopeds, motorcycles).
- Category 5 - Open category (future needs, not used already).

Around industrial port areas, heavy traffic is expected to represent the vast majority of most of the total traffic. Moreover, inside ports, trucks usually have very low speed. Therefore, specific measurements for validation are recommended, as these conditions are close to the noise model limits of validity. The proper set of data needed for each road axes includes:

- type of road and pavement;
- average temperature in degrees Celsius;
- number of lanes and their width;
- traffic divider and their width;
- Average daytime (06–20) hourly flow for each CNOSSOS-EU category;
- Average evening (20–22) hourly flow for each CNOSSOS-EU category;
- Average night time (22-06) hourly flow for each CNOSSOS-EU category;
- Average speed for each CNOSSOS-EU category;
- Percentage of vehicles with studded tyres for each CNOSSOS-EU category;
- N° months with studded tyres for each CNOSSOS-EU category.

3.2. Railway sources

Railways source characterization follows the same criteria applied to the road one, as it is based entirely on the CNOSSOS-EU specifications. The following bulleted list reports the main information to be collected to allow the model to properly estimate railway noise emissions. The proper set of data needed for each railway axe includes:

- begin and end position (coordinates);
- number and type of rails;
- type of structure;
- rail roughness;
- presence of elements in the layout (crosses, exchanges, etc.);
- radius of curvature of the section;
- bridge, if present, and type;
- maximum speed allowed.

In ports, most of the railway traffic is freight and, usually, at reduced speeds. In such conditions, the CNOSSOS-EU model for railways may lose reliability. Thus, in case of railway segments with only freight movements, the suggestion is to perform noise measurements to characterize trains' transits and use the "mobile point" source in the noise mobile. During the acquisitions, the microphone should be placed at 4 m height, in a far field condition and at a distance not allowing other sound sources to significantly influence the signal acquisition during the train transits. At least 3 transits of the same kind of train should be acquired and the average speed and sound power level should be used as input in the noise model, as well as the daily traffic flow.

4. Ships

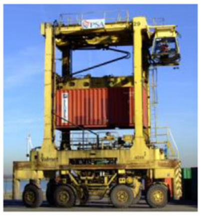
A procedure aimed at characterizing the noise emitted by ships during all the different phases that they can encounter in ports (moored, loading/unloading) represents a novelty and a mandatory step towards a proper acoustic mapping of port areas. In fact, no standards exist at present for marine vessels, except for the previously mentioned ISO 2922:2020 [60] for inland waterways.

Given the evident difficulties of measuring big and multiple noise sources in a complex and noisy environment [51], non-standard and sophisticated techniques are needed, including simultaneous measurements of several sound level meters. These may be obtained by varying the height above ground and distance from the ship side. Particular attention shall be paid to shadow effects occurring, for example, for the funnel that can be shielded from the ship itself at short distances.

The different phases to be differently measured are:

- Moored in stationary conditions.
- Mooring operations.
- Moored during loading/unloading operations (without auxiliary machinery).
- Sailing at reduced speed approaching the quay.

Table 1. Characterizations of port sources.

Measurement protocol for CARGO HANDLING UNITS		
Source type		**The measurement of the noise emitted must include:**
straddle carrier 	**Front lift** 	Controlled pass-by test with container. Controlled pass-by test without container. Measurement of an entire operating cycle: • container pick-up; • displacement; • container laying.
Contstacker 	**Fork lifts** 	
Transtainer on wheels 	**Transtainer on rails** 	Measurement of an entire operating cycle: • container pick-up; • displacement; • container laying.
Mobile Harbour Crane 	**Container cranes** 	
Dock tractor 	**Dry load handling scrapers** 	Measurement of an entire operating cycle: • load pick-up; • displacement; • load laying.

A specific characterization should be performed for each of the different types of ship (Ferries, RoRo, Container ships, Cruises; Chemical tankers, Tankers, Pilote and Tugboats) and their flow data should be obtained from data collected by the Maritime Advisor on all movements in port during the year.

In order to properly produce a noise map of the ship noise, for each ship category, the noise model needs the following information:

- Average sound power level for each activity in octaves or thirds of an octave.
- Height of the noise source.
- Dock usage, meant as average annual occupancy time that different vessel categories have in it during day, evening and night.
- Number of departures per single dock per year.
- Number of internal movements and most used route.

While moving ships should be implemented as line sources, the other ship activities can be implemented as point or area sources.

4.1. Moored ship in stationary conditions

Different categories of ships emit noise differently when at berth. Also, different ships in the same category may have the noise sources placed in different positions along the hull. Therefore, the methodology for noise measurement should be tailored to the specific scenario and the following guidelines interpreted by the operators once they are on the real measurements site.

Generally, noise sources acting on stationary ships are mainly the ventilation systems and the generators. The former can be arranged along the entire hull, whilst the latter are placed in the bow and the lower part of the stern and propagate internal noises by emitting them from the external structure. This phenomenon vanishes at short distance from the hull, while the noise produced by the ventilation is generally well audible at greater distance. Given the complexity of the sources and the dimensions of the ships, multiple measurements at different distances are mandatory in order to sufficiently reconstruct the sound power level of the noise sources acting on a moored ship. Generally, these kinds of sources are constant in time, thus the required measurements to characterize the source can be carried over in a relatively short time span.

A minimum of 9 measurements must be performed at the quay over a grid of measuring points defined by the ship's dimension. In all of them, the microphone should be placed at 4 m height.

As sketched in Figure 1, measurement positions are distributed on the quay along an axis perpendicular to the ship at three different distances from the ship in order to avoid the shadow effect. Reference distances are set to 1 m, 11 m and 19 m from the edge of the quay and perpendicular to the plane of the boat on the side of the ship:

- In a central position.
- 11 m away from the bow end towards the center of the ship.
- 11 m away from the stern end towards the center of the ship.

In order to properly evaluate the ship sources, additional measurements can be performed at higher distances if the geography and background noise allows it. Moreover, in case of more audible sources in different positions, additional lines of measurements can be performed.

In the reconstruction of L_w from the L_p obtained, particular attention should be given in the positioning of the sources, which can result in a complex task. Moreover, in situations where background noise is significant, it is recommended to perform a measurement of it and subtract to the various measurements in each third octave band.

While all commercial and freight ships are known noise emitters during their stationing, which should not be neglected, pleasure craft and cruise ships have received more attention on the reduction of noise emissions and have low noise emissions during stationing.

Sound sources identified, for which the L_w is reconstructed, can be implemented in the noise model mainly as point source or area source if particularly wide.

4.2. Mooring operations

During mooring operations, engines often work in off-design conditions resulting in noise emissions that can have significantly higher levels than design speed conditions. During maneuvers the high-pressure pulses generated by the propeller can also induce vibrations in the stern zones resulting in a further source of noise. Moreover, bow and stern thrusters are in function and they can produce significant noise. Nevertheless, the above conditions are transient conditions that can last from a few seconds to a few minutes. They can represent an annoying situation mainly in harbours, where quays are very close to houses, characterised by an intense ferry traffic mainly during the tourist high season, with many arrivals and departures maneuvers taking place.

A simultaneous measurement performed in two different positions is the minimum requirement for characterizing the noise emitted by a departure/arrival of a ship (Figure 2). Microphones should be placed at 4 m height. A measurement position should be chosen at the quay in the center of the rear of the ship, at a distance of about 20 m compatible with the measurement site. The other location is on the quay at the stern side of the ship.

Once the L_w is computed from the L_ps, an area source can be inserted in the noise model.

4.3. Moored ships during loading/unloading operations

Loading/unloading operations are, probably, the most ship specific of the four ways a ship produces noise in a port environment. In fact, different ship categories transport different goods with consequently different methodology of loading/unloading operation. Container carriers always make use of container cranes (ship-to-shore) or mobile harbor cranes. Ferries, as well as Ro-Ro, only embark/disembark vehicles, yet different ships can have different positioning of the opening in the hull. Lo-Lo (Lift-on/lift-off) are ships that can load and unload their freights with their own cranes. Thus, container carriers, tankers, bulk carriers and others need the support of port vehicles, whose measurement procedures are included in the port sources described in the following chapter.

Ro-Ro and ferries loading and unloading operations can be treated as standard disembarkment operations of vehicles, which are only trucks for

Figure 1. Measurement positions for moored ship in stationary conditions.

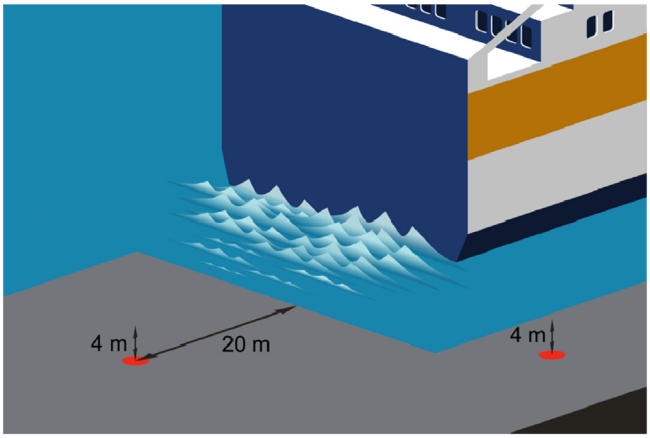


Figure 2. Measurement positions for mooring operations.

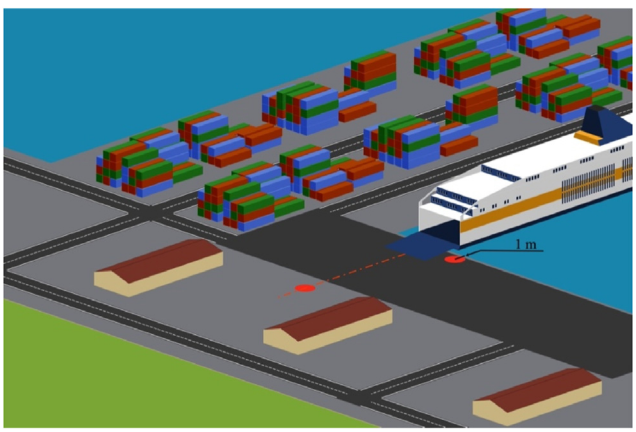


Figure 3. Measurement positions for loading/unloading operations.

Ro-Ro. Thus, the duration of the event depends on the vehicles carried, generally in the order of 1 h.

Given the relative simplicity of the source, the measurement procedure requires to place a sound level meters to the side of the ship's ramp, at 1 m from the quay, possibly without interfering with the operation itself (Figure 3). Otherwise, the closest feasible distance should be chosen. The acquisition should last enough to characterize the event. A simultaneous measurement at a greater distance from the hull would also be beneficial for evaluating the contribution of low frequencies at medium-long distance and for better computing the L_w (see Figure 2). The operation can be modeled as an area source at 1 m height in front of where the ship loads/unloads. The authors recommend taking note of the traffic flows and consider them as road traffic sources in the port area, with the emitting lines starting from the load/unload operation area source.

For Lo-Lo operations, the procedure for stationary conditions can be applied also in this phase, choosing the microphone positioning in order to avoid interfering with the ship's activities. A source can be modeled in the place where the container is placed over the truck, resulting in noise emitted by the hit, at 1 m height, and the rest of the operation, if detected from the quay, would be placed over the ship in correspondence with the cranes. Truck movements are included in port activities.

At last, even if loading and unloading operations from cruise ships are much lighter than those of cargo ships, they are always characterized by land activities connected with the refueling, maintenance of the ship and to the movement of goods/people by means of transport. These latter operations must be acoustically characterized in the same way as mobile sources for port and industrial noise as described in the next chapter. Therefore, a sufficient number of measurements should be performed at a known distance from the path most used by the vehicles, in a manner similar to pass-by measurements. The sources are then modeled as emission lines.

4.4. *Ships sailing at reduced speed approaching the quay*

The pass-by procedure firstly applied in the port of Leghorn [46, 47] can be considered as a generally reliable method for noise emission characterization of moving ships.

A sound pressure level meter with free field microphone equipped with windshield should be placed at 4 m height and at least 1.5 m away from every reflective object along ships' route. Meteorological data should be acquired in order to exclude the periods with more than 5 m/s wind speed or with rain. Condition of sea should not be greater than 3 on the Beaufort scale. The length of measurements should be set accordingly to the duration of the single transit, which generally ranges from 30 s to 3 min depending on the ship category. One third octave acquisition and a 100 ms time base are needed to perform the spectral analysis.

Due to the peculiarities of naval transits, lasting more than the vehicular ones, the method follows the modified sound pass-by SPB standard [66], instead of the traditional SPB. The calculation of the Sound Exposure Level (SEL) of each pass-by event is performed on the signal between the maximum and the maximum -10dB(A). The analysis is performed separately for each ship category and tugboats, when present, are included in the correspondent event as a part of it.

The calculation of L_w is performed by using SEL and it is also recommended to use a software that will help in assessing the specific scenario of the measurement setup, including buildings, background noise as well as positioning and height for both microphone and source. Since the ship transits are simulated as line source within the noise model, the final output is the sound power level per unit of length.

The analysis of ships pass-by measurements presents can prove itself challenging s due to the specific characteristics of ships transit. Nastasi et al. [46] reported that draught should not be a significant variable in noise power levels of moving ships, in contrast with distance of the ship from the measurement position and its speed. Inside ports, speed is limited by regulations. The result is that not knowing the exact average transit speed can lead to an error on the sound power estimate of about only $\pm$1dB. On the contrary, ships can sail at various distances from the microphone because of the high ratio between typical waterway size and typical ships width. With multiple sailing routes, distance has a bigger impact on the results and should not be neglected.

Collaborative measurements are almost impossible to carry out, preventing the agent from controlling the speed transit and the transit distance from the microphone. In order to reconstruct the sailed routes and, therefore, the minimum transit distance and the transit speed, three methods can be followed:

- Measuring distance and speed with long range laser meter.
- Acquisition of GPS data provided by the automatic identification system (AIS).
- Reconstruction through video recordings of ships' transits acquired from close circuit camera systems or other video support.

5. Port and industrial sources

As previously reported, port and industrial sources belong to two different categories when it comes to correctly identifying legal responsibilities for exceeding emission limits. However, the machinery and vehicles employed by both can be the same and, consequently, their noise emission characterization protocol should be the same.

Both categories resulted to be so wide that it needs a further subdivision for a proper characterization of the sources. The chosen criterion is to split the sources whether it is moving or it is fixed. In particular cases, as described later, an area source can be considered. Thus, for port and industrial sources the procedure is divided into fixed, moving or area.

5.1. Fixed sources

Pumps, generators, ventilators, air conditioners, machinery of any type, fixed cranes, conveyor belts and refrigerated containers are some of the fixed sources that can be found in a port environment. Some of these may have a sound power so low as to be considered negligible for the noise mapping purpose. when this is not the case, the following data should be collected as input for the noise model:

- Type of source.
- Model and manufacturer.
- Position.
- Type of operation (loading, unloading, stopping, lifting, etc.).
- Broadband sound power.
- The octave or third octave sound power of the source during the operation.
- Height of the machine and height of the source if different.
- Directivity (diagram).
- Activity during day, evening and night time.
- Seasonality.

Such information should be provided by the respective activities to which the sources pertain. However, the activities do not always have this information and, in this case, a source database can be queried to find the missing requests. Even this opportunity is not always feasible and it is therefore necessary to provide for a characterization of the sources through on-site measurements according to EU directive 2006/42/CE [67] and ISO 3744:2010 series [68].

When the required information has been acquired, the sources can be implemented in the noise model as point sources, or sum of points, most of the time. Particular sources like conveyor belts, on the other hand, should be implemented as linear sources.

Mobile noise sources appearing in port areas include a huge variety of vehicles or machinery, the most important of which are straddle carriers, frontlifts, contstacker, fork lifts, transtainers, cranes, dock tractors and other cargo handling units.

The same data needed for fixed sources are also needed for moving sources, except that a georeferenced path is required instead of the position.

In general, each of the sources included in this category can perform different activities with proper sound emissions. A unique definition is not sufficient for these sources and the following different phases should be considered as separate sources:

- Transit.
- Handling.
- Loading/unloading operations.

Transit and handling phases are similar, except for the increased noise emitted due to a greater effort of the engines to keep the load raised. Both should be modeled as linear sources following the source's most used path, with height to be defined according to the source. Controlled pass by (CPB) measurements should be performed on the basis of the standard NF S31-119-2, 2000 [69], with appropriate modifications due to the complexity of the port environment. The distance of the microphone should be chosen as close as possible for a correct recognition of the sound source while avoiding interfering with the operations. A sufficient detail for the noise mapping purpose would be obtained with at least three transits for each operation.

For loading/unloading operations, the microphone should be placed close to the operation area, still without interfering, and the measurement should last enough to measure all the operation. A minimum number of three operations should be measured and the average noise level should be taken. A simultaneous second measurement in a different position is suggested to increase the estimate of the L_W. The source can be modeled as an area with height to be chosen according to the source. Table 1 reports the characterization protocols related to the different operational phases of the mobile sources.

6. Area sources

Industrial plants or loading/unloading areas can be very rich in terms of number of sources and gathering all the information can represent a difficult task. When details are not available and/or eventual receivers are far, those areas can be characterized with a single area source instead of a multitude of single operating sources.

The proper characterization of an area source passes through a series of noise emission and background noise measurements performed around the boundaries of the area. In this regard, the ISO standard 8297:1994 [70] can be used as reference as it describes a method for determining the sound power levels of large multi-source industrial plants based on sound pressure levels acquired in the surrounding environment. The method is conceived for industrial areas with the largest horizontal dimension is between 16 m and 320 m and where most of the equipment operates outdoors and/or there are moving sources performing cyclic or continuous operations. For this reason, the measurements should represent at least one cycle of operations. Significantly elevated noise sources and/or sources with directional characteristics should be identified and evaluated in accordance with other applicable standards.

The method is chosen as the proper way to determine the sound power level of area sources in port areas as it is applicable to all sources regardless of the frequency of the sound they emit (broad-band, narrow-band, discrete tones, repetitive impulsive noise and their combinations) and their evolution in time (steady or not).

Following the sketch reported in Figure 4, the procedure starts from a simply shaped closed measurement contour surrounding the plant area where the octave-band sound pressure level measurements are performed at equidistant microphone positions along the contour. The average octave-band sound pressure level is then calculated by means of the following equation:

$$\overline{L_p} = 10\lg\left[\frac{1}{N}\sum_{i=1}^{N}10^{0.1L_{pi}}\right]\text{dB} \quad (2)$$

The measurement positions should not have reflecting surfaces in the surroundings and background noise levels should be at least 6 dB below the source levels in each frequency band. Moreover, the wind speed and direction shall not change significantly during a set of measurements around the measurement contour.

If the plant operates in various modes, separate measurement campaigns shall be conducted leading to a sound power level for each mode. The mode of operation shall be long enough and steady enough for one complete measurement around the measurement contour to be carried out. If this does not happen, the mode shall be sufficiently repeatable for the measurements to be made at different measurement positions during its successive occurrences. The measurement duration at each measurement position should be sufficient to include all the variations of noise emission during the mode, including any repetitive impulsive noise, if present.

If any of the measured L_{pi} exceeds the average by more than 5 dB, a new measurement contour at a greater distance from the previous should be set. Whenever this is not possible, all these exceeding values have to be replaced by:

$$L_{pi}^{*} = \overline{L_p} + 5\text{dB} \quad (3)$$

Then, the area term ΔL_S for the measurement surface according to ISO 3744:2010 [68], a proximity correction term ΔL_F, a microphone correction term ΔL_M and a sound attenuation term ΔL_α due to atmospheric absorption, should calculated by means of the following equations:

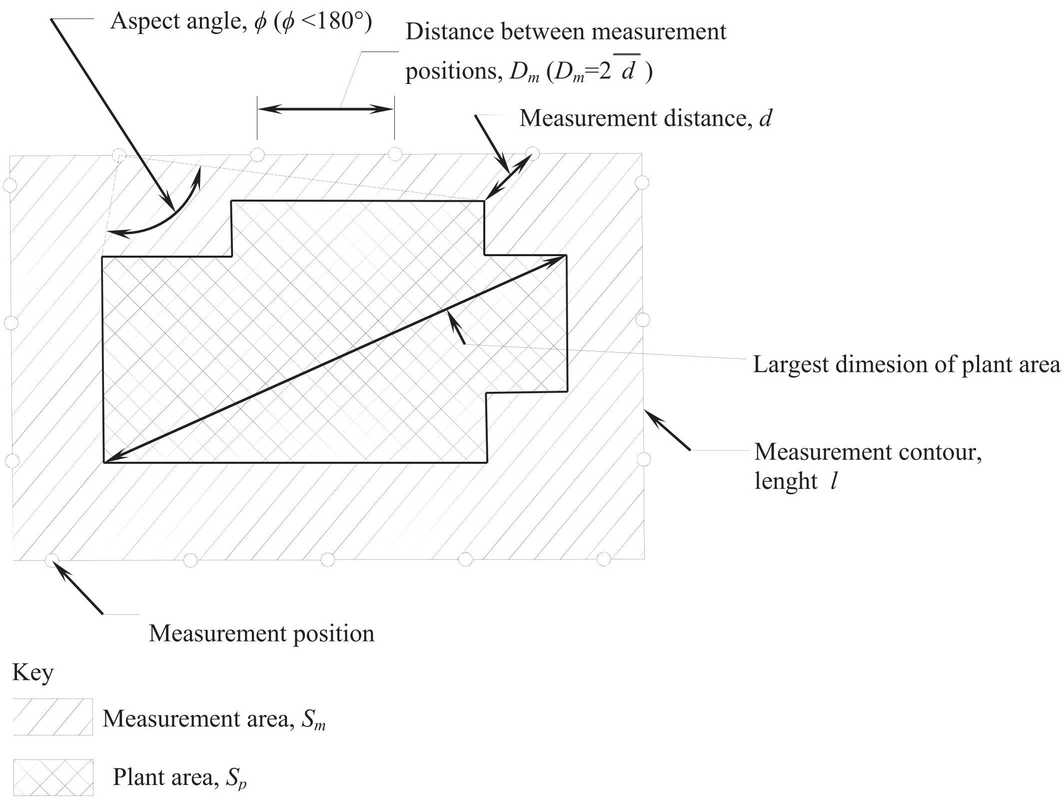


Figure 4. General arrangement of measurement positions on the measurement contour around the plant(adapted from [70]).

$$\Delta L_S = 10\lg\left(\frac{2S_m + hl}{S_0}\right)\text{dB} \tag{4}$$

$$\Delta L_F = \lg\left(\frac{\bar{d}}{4\sqrt{S_p}}\right)\text{dB} \tag{5}$$

$$\Delta L_M = 3\left(1 - \frac{\theta}{90}\right)\text{dB} \tag{6}$$

$$\Delta L_\alpha = 0.5\alpha\sqrt{S_m}\text{dB} \tag{7}$$

where:

- h is the height of the microphone above the ground, to be assumed as the greatest value between 5 m or $h = H + 0.025\sqrt{S_m}$ (where H is the average height of the noise sources in the plant);
- S_0 is a reference area equal to 1 m^2;
- $\bar{d}$ is the average measurement distance which shall exceed $0.05{*}S_p^{0.5}$ or 5 m, whichever is the greater, but shall not exceed $0.5{*}S_p^{0.5}$ or 35 m, whichever is the lesser.
- Typical values of α can be taken from ISO 9613–1:1993 [71].

Finally, the sound power level can be calculated with Eq. (8):

$$\Delta L_W = \overline{L_p} + \Delta L_S + \Delta L_F + \Delta L_M + \Delta L_\alpha\text{dB} \tag{8}$$

7. Conclusions

The INTERREG Maritime programme aim was to develop a best practice guidance for the assessment and management of noise in ports. A set of different projects (REPORT, MON ACUMEN, RUMBLE, TRIPLO, DECIBEL, L.I.S.T. Port) were funded in order to do so. Specifically in MON ACUMEN, the installation of noise monitoring networks able to describe noise in the harbor was a requirement. Noise mapping is vital for the proper positioning of such noise monitoring stations, which make it possible to describe the time evolution of noise produced by different sources. This solution will allow ports to identify the causes of annoyance suffered by citizens and later promote specific action plans to address their pain points.

Literature review showed that noise mapping in ports was poorly studied, with only few authors reporting accurately noise conditions. In fact, the Environmental Noise Directive in 2002 did not include ports as a whole, but it only requests a description of industrial and transport infrastructures sources involved, without considering the complexity of the environmental situation. The need to compare noise exposure in different ports and the urgency to perform effective mitigation actions require clear indications and guidelines specifically designed for ports.

This paper attempts to fill such a gap presenting a specific measurement procedure for the assessment of noise emissions of the different sources, divided into five macro-categories (roads, railways, ships, port and industrial), each with dedicated sub-categories, according to a previous work [50]. All the sound characterization is aimed at gathering information needed as noise models input for the noise map of the entire port area. Roads and railways already had their specific measuring procedure and proper noise models, thus, only minor adjustments for port environment scenarios were proposed within the guidelines. The latter three categories, Ships, port and industrial areas required more attention when defining the set of guidelines. Leveraging research, international scientific literature and the authors' experience, this paper can offer a measurement procedure and a methodology to derive the sound power level of the measured source was provided for ships sailing at reduced speed, moored in stationary conditions, during mooring operations, moored during loading/unloading operations, and for port and industrial sources divided into fixed, mobile or area sources.

All the choices assumed that the measurements should be carried with the lowest possible interference with the port and ship operations, which involves the impossibility to measure on board. Moreover, it is not supposed to have collaboration from both ships or terminal owners, and it is not possible to switch off/on the machinery on request to reduce the background noise. The use of additional means (cranes, cherry pickers) to reach specific positions at higher heights has been avoided in order to make the procedure simpler and cheaper for the operators. For the specific target of this work, ships' emission has been considered symmetric, thus it is sufficient to measure only one side of the ship.

The obtained L_w must be inserted in the noise model according to the real emission point of each source. If the exact position is not evident even following the different techniques reported in the guidelines, it is recommended to use an acoustic camera. Future works of the authors will be dedicated to its use in the characterization of ships and port sources.

The expectation is that by issuing these guidelines, the authors are facilitating the proliferation of sector studies and that the acoustic mapping of ports will follow a common approach, making it possible to compare population exposure levels. With proper characterization measurements, it is also expected to start collecting information on the sound emitted by the sources in port, still too unknown in their various operations, hoping to concurrently stimulate the collaboration of the entire scientific community in creating a database accessible to all. All of this, sustained by the growing attention for this sector, lays the foundation for an ideal future where each new ship will be acoustically certified in terms of the noise emitted to the outside, as is the case for machinery.

Declarations

Author contribution statement

Luca Fredianelli, Tomaso Gaggero, Matteo Bolognese & Davide Borelli: Analyzed and interpreted the data; Wrote the paper.

Francesco Fidecaro, Corrado Schenone & Gaetano Licitra: Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Data availability statement

No data was used for the research described in the article.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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