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Impact of COVID-19 on environmental noise emitted from the port

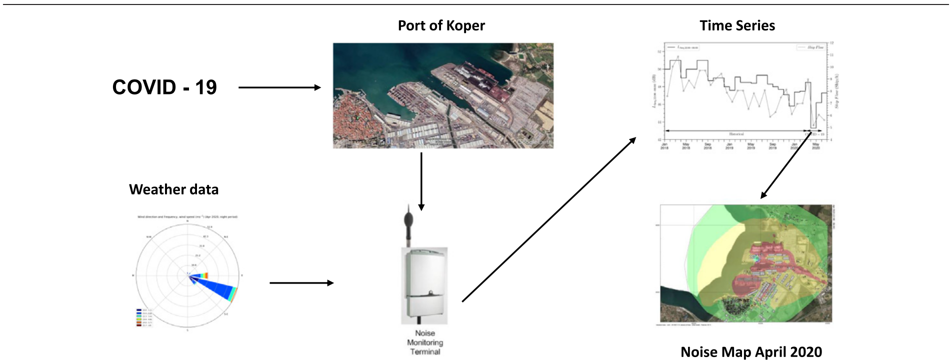
Luka Čurović [a,]*, Sonja Jeram [b], Jure Murovec [a], Tadej Novaković [a], Klara Rupnik [c], Jurij Prezelj [a]

[a] University of Ljubljana, Faculty of Mechanical Engineering, Aškerčeva 6, 1000 Ljubljana, Slovenia
[b] National Institute of Public Health, Trubarjeva cesta 2, 1000 Ljubljana, Slovenia
[c] Institute of Occupational Safety, Chengdujska cesta 25, 1260 Ljubljana, Polje, Slovenia

HIGHLIGHTS

- The COVID -19 epidemic has led to a worldwide decline in commercial shipping activities.
- Time comparative analysis of shipping traffic, meteorological conditions, and noise emissions from the port was carried out.
- The number of ships decreased by 35% and the noise levels during the night period decreased by 2.2 dB to 5.7 dB.
- The results show that moored ships and industrial activities were the most dominant source.
- Noise generated by moored ships should be regulated internationally.

GRAPHICAL ABSTRACT



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ABSTRACT

Identification of noise sources and their ranking is a crucial part of any noise abatement program. This is a particularly difficult task when a complex source, such as a seaport, is considered. COVID-19 epidemic has had a significant impact on environmental noise related to road, rail, air and ship traffic and provided a unique opportunity to observe immediate noise reduction. In order to identify the noise sources, whose reduction was most effective in reducing noise from the port area, this study compared and quantified noise emissions between the historical and epidemic periods. Environmental noise measurements from three noise monitoring stations at the port boundary were analysed. In addition, noise emissions from ship, road, rail and industry as well as meteorological data in the historical pre – COVID-19 (January 2018–February 2020) and COVID-19 (April 2020) period were analysed in detail. The characteristics of the noise sources mentioned, geographical data and noise measurements were used to develop and validate a noise model of the port area, which was used to calculate noise contour maps. Our results show that the reduction in noise levels observed at all monitoring stations coincides with the reduced shipping traffic. The A weighted equivalent sound pressure levels in the day, evening and night periods were reduced by 2.2 dB to 5.7 dB compared to the long-term averages, and the area of the 55 dB day-evening-night noise contour was reduced by 23%. Compared to the historical period, the number of people exposed to noise levels above 55 dB(A) in the day-evening-night period due to shipping and industrial activities was reduced by 20% in the COVID-19 period. Such results show that environmental noise generated by moored ships is a problem for port cities that should be regulated internationally. In addition, this paper provides precise guidance on noise emission characteristics, ship categorisation and the post-processing of long-term measurement data, taking into account wind conditions and undesired sound events, which can be applied to future research at other locations near shipping ports and used to prepare strategies for noise reduction in ports.

* Corresponding author.
E-mail address: luka.curovic@fs.uni-lj.si (L. Čurović).

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1. Introduction

The global coronavirus pandemic has had a major impact on public health, the economy, human behaviour and the environment. The first confirmed case of SARS CoV-2 infection in Slovenia was detected on 4 March 2020. The epidemic was declared on 12 March 2020, when the first measures were taken to control the spread of the infection, including testing, isolation of patients, finding contacts, social distancing, promotion of work from home, closure of schools and non-essential businesses and the closure of public transport (ULRS, 2020a). The government declared the end of the COVID-19 epidemic on 15 May 2020, but the measures adopted since the beginning of the epidemic remained in force until 31 May 2020 (ULRS, 2020b).

Noise pollution is considered a major environmental problem, which has been shown to cause sleep disturbance and annoyance (WHO, 2009; Muzet, 2007). Exposure to excessive noise can lead to learning difficulties and reduced concentration (WHO, 1999; WHO, 2018). Of particular concern is long-term exposure to persistent noise, which can lead to serious health effects such as high blood pressure, effects on cardiovascular, respiratory and metabolic systems (Münzel and Sørensen, 2017; WHO, 1999; WHO, 2018). The WHO estimates that more than 1,550,000 years of healthy life are lost in Western Europe (WHO, 2011) due to sleep disturbances and annoyance alone. Noise also has a significant impact on the economy and the housing market, e.g. Zambrano-Monserrate and Ruano (2019) have recently shown that noise levels have a negative impact on housing rental prices in Machala, Ecuador.

The COVID-19 emergency measures accepted worldwide had a significant impact on air quality, e.g. the study carried out by Sicard et al. (2020) showed a reduction in $PM_{2.5}$, PM_{10} and nitrous dioxide emission and an increase in ozone concentrations due to a lower NO titration in the urban environment. With the changes in human and commercial activities and the decrease in public and private transport during the COVID-19 measures, environmental noise levels (Zambrano-Monserrate et al., 2020) and vibrations (Lecocq et al., 2020) are assumed to have decreased, e.g. Baldasano (2020) reported a 6 dB decrease in sound pressure levels due to the reduction of road traffic in Barcelona and Mandal and Pal (2020) reported a 20 dB decrease of A-weighted sound pressure level in stone quarrying and crushing areas during the closure period.

In recent years, environmental noise caused by commercial shipping and port activities has attracted increasing attention (Schenone et al., 2016), as it affects residential areas close to ports, particularly in the case of intensive shipping traffic or frequent loading and unloading operations (Bernardini et al., 2019). The effects of COVID-19 induced lockdown measures on environmental noise caused by changes in port activities and ship traffic have not yet been investigated and quantified in the literature. In this paper we not only focus on the changes of acoustic energy measured by the noise monitoring network as described in previous studies (Asensio et al., 2020b), but also analyse in detail the changes in meteorological conditions, noise emissions and exposure of the population, taking into account all sources in the port area.

Understanding how noise pollution is affected by extreme changes in the operating conditions of the noise source could provide important information on the ability of the noise monitoring network to detect short term-changes and long-term trends in environmental noise, improve protocols for noise monitoring and mapping, help identify the dominant noise sources and assist in preparation of noise abatement strategies in the port.

2. Materials and methods

The study area, selection of data used to describe activity of the port, selection of acoustical and meteorological data and port noise modelling method are presented in this section.

2.1. Study area

The study area including the port of Koper and the adjacent residential areas in Koper and Ankaran is shown in Fig. 1a. Koper is the largest coastal town and the fifth largest city in Slovenia. The population in Koper is estimated to be 25,611 inhabitants over 13 km^2 and the population of Ankaran is estimated to be 3278 inhabitants over 5 km^2. Koper is located in the region of Istria in the southwestern part of the country, about five kilometres (3.1 miles) south of the border with Italy and 20 km (12 miles) from Trieste. Koper is characterized by a humid subtropical climate with an annual mean air temperature of 14 °C (7.8 °C in January, 27.5 °C in July) and an annual mean rainfall of 1056 mm (Climate-Data.org, 2020). The northern part of Koper and the southern part of Ankaran area are largely taken up by the Port of Koper, which is the largest and busiest maritime infrastructure in the country and therefore an important employer and economic factor for Slovenia. The port is located between 45°32′48″ and 45°34′12″ N latitudes and 13°43′16″ and 13°45′26″ E longitudes and covers an area of 2.73 km^2 on land and 1.79 km^2 on water and extends for 3.2 km along the coastline. The Port of Koper consists of 12 specialized terminals, including container and Ro-Ro terminal, car terminal, general cargo terminal, fruit terminal, timber terminal, terminal for minerals, terminal for cereals and fodder, alumina terminal, European energy terminal, liquid cargoes terminal, livestock terminal and passenger terminal. Citizens most affected by the activities of the port live close to the port in the historical part of Koper opposite the first basin.

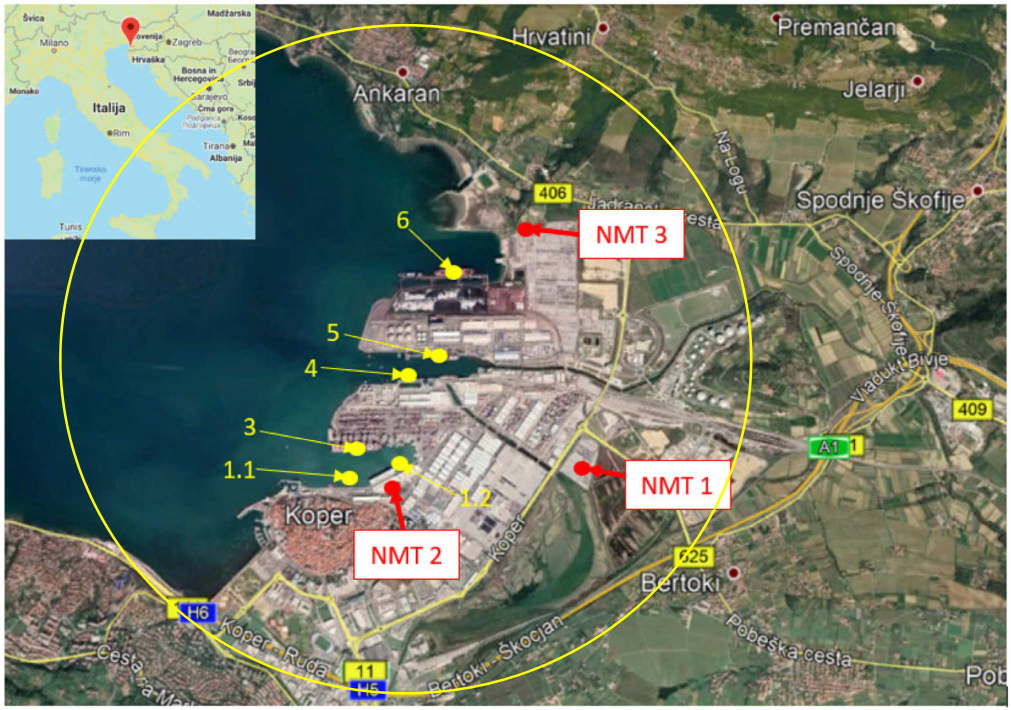
In Slovenia, industrial, road and rail traffic noise from the port area is regulated, while noise from ships is excluded as there is no maritime jurisdiction for international ships in ports. But even if the statutory noise limits (ULRS, 2019b) are not exceeded due to port operations at the most exposed dwellings, noise pollution is one of the main environmental concerns for the Port Authority (Luka Koper, 2019), as a large number of complaints from residents are due to the noise of ships moored in the port. The Port of Koper therefore regularly carries out noise abatement measures, including continuous noise measurements which are publicly available (Living with the port, 2020), calculation and analysis of noise maps, implementation of complaint management procedures, active communication with ship owners and the community, education of port personnel, road surface repair, keeping port traffic away from city traffic, community participation in land-use planning, localisation of noise sources and larger vessels at a greater distance from residential areas, use of machinery with the lowest sound emission levels, use of containers as noise barriers, electrification of equipment, reduced intensity in the night-time and participation in projects which aim to reduce noise pollution (Luka Koper, 2019).

2.2. Data selection and methodology

In this chapter, the data used to describe the activity of the port, the monitoring system used to obtain acoustical and meteorological data and the noise modelling process are presented separately.

2.2.1. Port activity

The operation of the port is usually assessed on the basis of road and rail traffic volume, terminal working hours and operational data of industrial noise sources (NoMEPorts, 2008). The operational characteristics of the port in a time window are correlated with the average number of ships per hour present in the port during that time window. The information on the type of ship, arrival and departure time has been obtained from the Port of Koper website (Luka Koper, 2019). Berthing time of a ship varies between different types of ships and can vary even for the same ship. For example, in 2018, 330 general cargo ships docked in Koper. Their average berthing time was 20 h, but values varied between 4 and 129 h. For this reason, we show the average number of ships present in the port per hour. For example, 10 ships per hour in the day period means that there were always 10 ships present in the



(a)

(b)

Fig. 1. (a) The study area (yellow circle), locations of the noise monitoring terminals - NMTs (red dots) and locations of berths (yellow dots). (b) Road (blue) and rail (orange) network.

port between 6:00 and 18:00. The ship data have been divided into night, day and evening periods. Such a presentation of emission data in terms of traffic flow is also common for other major infrastructure sources such as road and rail traffic (Kephalopoulos et al., 2012). Additional information on port activity (yearly data for the 2018–2019 period) was found in the port of Koper Sustainability report (Luka Koper, 2019). The trade activity data for Slovenia was obtained from the Slovenian statistics website (SURS, 2020). The working hours of the industrial noise sources were estimated for the day, evening and night periods on the basis of the operational data provided by the port authorities and by field observations. Road and rail traffic data were estimated from information provided by port authorities, the Slovenian National Railway Operator (Slovenian Railways, 2020) and by counting.

2.2.2. Acoustic and meteorological data

The noise monitoring system in the Port of Koper consists of three Bruel and Kjaer Type 3639 long-term noise monitoring terminals (NMT) which provide continuous measurements of environmental noise levels. The locations of the noise monitoring terminals designated as NMT1, NMT2 and NMT3 are shown in Fig. 1a. All noise monitoring terminals are equipped with Class 1 Bruel and Kjaer Type 4952 microphones. NMT3 also includes a weather station which collects meteorological data which was used in this study. The NMTs are located above hard ground. The main noise sources in the port area are located at considerable heights above ground level (e.g. ship exhaust is 25 m to 50 m above sea level). In such cases, microphone heights greater than 4 m are preferred to minimize interference effects with ground reflections (ISO20906, 2009). For this reason, NMT1 and NMT3 are placed at 5 m above the ground. Furthermore, due to the terrain configuration, the noise sensitive residential areas around the port are located above the port. NMT2, which is 5 m above the roof of an abandoned warehouse, is actually at the same height as the nearest residential areas in Koper.

The sound pressure levels are determined according to standard ISO 1996-2 (ISO1996, 2017). The ground between the port area and the microphones is an acoustically hard surface (concrete and water). The integrity of a condenser microphone measurement channel, including the microphone cartridge, is verified by the Charge Injection Calibration (CIC) method, which is performed automatically four times a day. The signals associated with the test are automatically excluded and not included in the further calculation (ISO20906, 2009). The acoustical verification of the measuring system is carried out at regular intervals not exceeding 2 years. The basic noise analyses are performed in real time and the calculated values, noise descriptors and statistical parameters are sent to a server located at the Institute for Occupational Safety in Ljubljana, where they are stored in a database.

In this study, the hourly A-weighted equivalent sound pressure levels ($L_{\mathrm{Aeq,1h}}$) from 1 January 2018 to 30 June 2020 were processed. Due to factors such as proximity to and intensity of local emissions and meteorological conditions, the hourly noise levels vary, also additional post-processing of the data was required where non-port-related signals (such as wind, rain and animal sounds) were identified by means of sound recordings and excluded from integration of L_{Aeq}. The meteorological conditions were monitored by a weather station at the NMT3 station at a height of 10 m. The proportion of unfavourable, neutral, favourable and very favourable sound propagation conditions in day, evening and night periods was calculated according to the simplified method described in ISO 1996-2 (ISO1996, 2017) using wind direction and wind speed data. Information on precipitation and wind speed was used to reject background noise caused by precipitation and wind speeds above 5 ms^{-1}. Valid hourly values were then used to calculate monthly averages or A-weighted equivalent sound pressure levels in relation to port activity over all the day ($L_{\mathrm{Aeq,06:00–18:00}}$), evening ($L_{\mathrm{Aeq,18:00–22:00}}$) and night ($L_{\mathrm{Aeq,22:00–06:00}}$) periods of a month, where the intervals for day, evening and night periods were selected according to Decree on the assessment and management of environmental noise (ULRS, 2019a).

Long-term averages were used because they are less sensitive to the occurrence and magnitude of local, unidentified noise events. The monthly averages were calculated separately for each location. Average noise levels from the historical period from January 2018 to February 2020 were used as baseline values. The baseline values were then used to quantify changes in monthly noise levels during the epidemic period in March, April, May and June 2020.

Residual and background noise sources (such as public road traffic and industrial noise) are usually difficult to identify, separate and exclude. As the locations of ships in port change from day to day, a sufficient signal-to-noise ratio is difficult to achieve in residential areas. Fig. 2a and b show immission directivity measurements based on beamforming taken in the residential area opposite the first basin of the Port of Koper (Prezelj, 2018). If the ships with low noise emission are located further away from the measurement site (ML), their noise is not dominant and the background noise influences the measured values considerably. In the next time interval, the situation may change and the noise from the sources on a seagoing vessel becomes dominant, even if the background remains the same. For this reason, the measuring stations in the port area are placed at locations where a sufficient signal-to-noise ratio is achieved, but which are still in the acoustic far field, so that an extrapolation of the measurements to the residential area is possible.

2.2.3. Port noise modelling

In terms of modelling, port noise is a mixture of point, line and area industrial noise sources with ship, road and railway noise. Due to the presence of numerous, often large noise sources, their high spatiotemporal variation and a large number of parameters that influence the propagation of environmental sound makes the identification and quantification of noise sources in a port area a very difficult task. Moored seagoing ships (which are excluded from the scope of Slovenian noise regulation (ULRS, 2019b)) and the infrastructure for handling and transporting of goods can be the main sources of environmental noise, especially when the emitted sound is tonal, intermittent, impulsive or low frequency in nature (Murphy and King, 2014). The acoustic properties (sound power, directivity, height) of the dominant noise sources are usually not known in detail but can be evaluated by measurements (Di Bella and Remigi, 2013) or by the use of noise source databases (NoMEPorts, 2008).

In this study the standard ISO 9613-2 (ISO9613, 1996) was used to calculate the propagation of noise from industrial noise sources and moored ships into the environment. The locations of the dominant industrial noise sources were surveyed on site. The emission characteristics of industrial sources, including ships, were first determined using the IMAGINE noise source database SourcedB, which is part of the calculation software (Predictor, 2020). Since multiple emission characteristics can be selected from the database for each noise source, the final values used in the model were determined by direct noise measurements according to ISO 1996 - 2 (ISO1996, 2017) standard and reverse engineering techniques (Bernardini et al., 2019; Di Bella and Remigi, 2013; Sari et al., 2014). The measurements were carried out in the far field, but not too far from the noise source, in order to reduce the influence of residual sound and to enable reliable measurements. For example, the final emission values of the RTG cranes used in the model were determined by sound pressure level measurements at a distance of 10 m to 30 m from the crane in four directions and by calculating the attenuation factors according to the standard ISO 9613-2.

Road traffic noise calculations were carried out according to NMPB/XPS 31-133 (NMPB, 1995; XPS, 2001). The number of vehicles (light and heavy) per hour for each time period (day, evening, night) for the historical pre-COVID-19 period was determined by counting, which was carried out for each of the 19 road sections included in the noise model in the years 2018 and 2019. The road traffic flows in the April 2020 period were assessed based on the number of vehicles counted at the entrance gate. The speed of the vehicles, the road surface and the type of road traffic flow were determined based on field observations.

The “in situ” weather conditions at NMT3, expressed as a percentage of favourable conditions during the day, evening and night hours, were used for road traffic noise calculations. RMR (1996) was used for railway noise. The model input parameters were selected based on available input data collected from various sources. The port authorities only provided information on the total number of trains entering and leaving the port area in one year. The number, the category of vehicles and the temporal and spatial distribution of trains was supplemented by information on the number and type of trains observed during several measurement campaigns in 2017. The decrease in rail traffic to the port area was determined on the basis of data from the Slovenian national railway operator, which reported a 25% decrease in rail traffic to the port of Koper in April (Slovenian Railways, 2020). The characteristics of the track structure, including the average speed of the units and the percentage of breaking trains were determined on the basis of field observations.

All calculations were performed with the Predictor - LimA ver. 9.1 Software (Predictor, 2020) and include knowledge of the terrain topography, the absorption properties of the ground and the acoustic properties

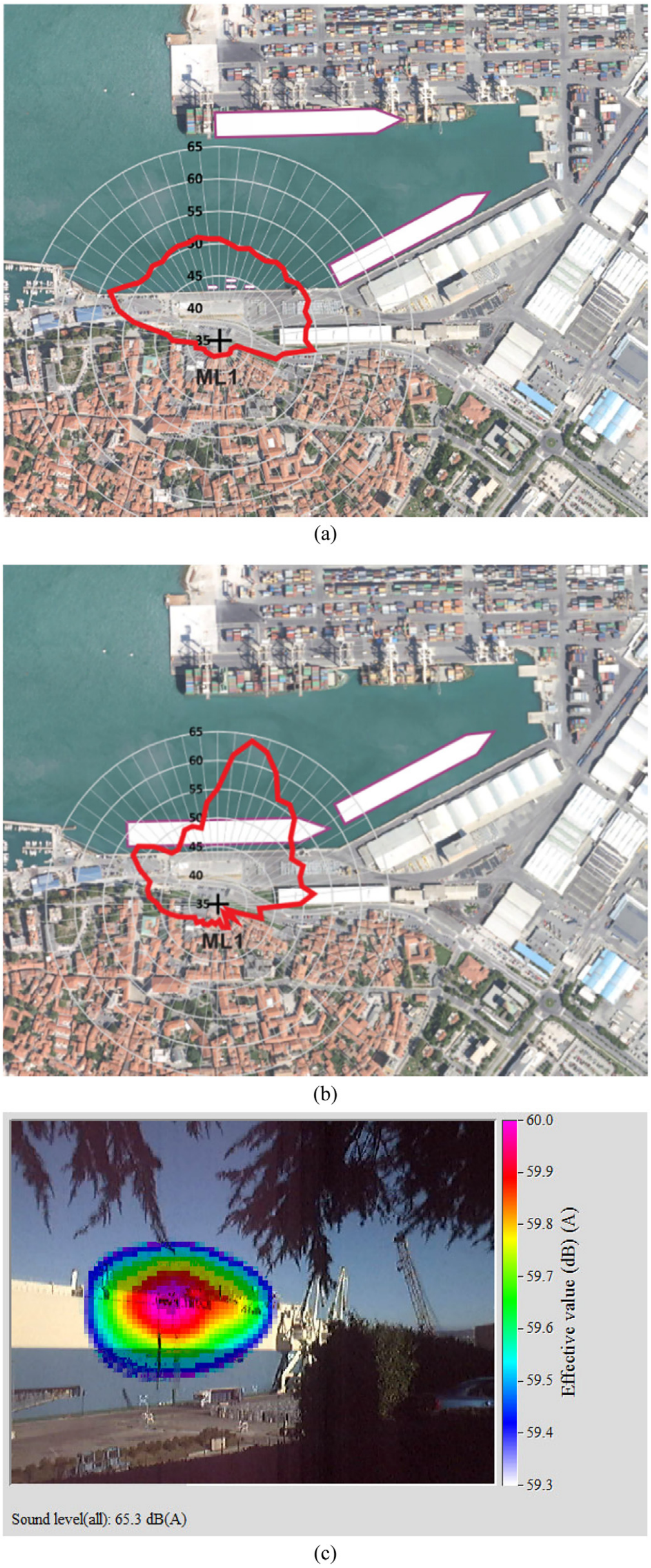


Fig. 2. Noise immission directivity at ML1 in two different time intervals with individual noise propagation conditions. (a) Situation where background noise influences the measurement results of a specific source. (b) Situation where the specific source is dominant and background noise is not relevant. (c) Acoustic photo.

Table 1
Average dead weight tonnage (*DWT*), length (*LOA*), width, sound power level (L_{WA}) and source height by ship type.

Ship type	DWT	Length overall (LOA) [m]	Width [m]	L_{WA}	Source height [m]
Vehicle carrier	12,325	174	29	115	25
Container ship	22,054	180	26	110	25
General cargo ship	5545	97,4	16,5	100	25
Bulk carrier	30,242	154	24	102	25
Oil/chemical tanker	39,304	180	29	110	25
Passenger ship	6806	260	33	98	30

Table 2
Number of ships present per hour in the port of Koper in the day evening and night periods. Hourly numbers are shown for all ships and per each ship type separately for historic pre-COVID-19 and COVID-19 periods (March 2020–June 2020).

	January 2018–February 2020	March 2020	April.20	May 2020	June 2020
	Number of ships present per hour [h^{-1}]				
All					
Day	8,4	9,2	5,5	6,7	6,1
Evening	7,7	8,9	5,3	6,4	5,4
Night	8	9	5,2	6,1	5,6
Vehicle carrier					
Day	1,2	1,4	0,6	0,7	0,9
Evening	1,3	1,3	0,5	0,6	0,8
Night	1,2	1,3	0,5	0,7	0,9
Container ship					
Day	1,5	1,4	1,5	1,4	1,4
Evening	1,4	1,3	1,7	1,3	1,1
Night	1,3	1,3	1,5	1,1	1,2
General cargo ship					
Day	2,2	3,4	1,9	1,2	1,8
Evening	2,1	3,2	1,8	1,1	1,6
Night	2	3,3	1,7	1,1	1,7
Bulk carrier					
Day	2,1	1,7	0,9	2,4	1,2
Evening	2,1	1,8	0,9	2,3	1,1
Night	2,1	1,8	0,9	2,2	1,1
Oil/chemical tanker					
Day	0,7	0,7	0,3	0,7	0,5
Evening	0,8	0,7	0,3	0,7	0,6
Night	0,7	0,7	0,3	0,8	0,5
Passenger ship					
Day	0,2	0	0	0	0
Evening	0,1	0	0	0	0
Night	0	0	0	0	0

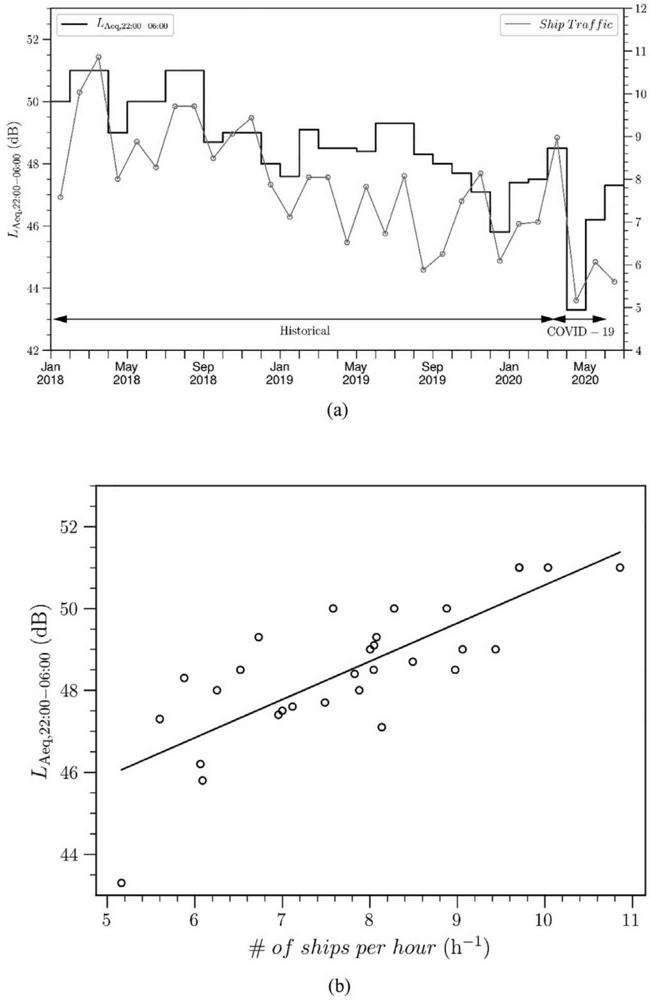


Fig. 3. (a) Monthly $L_{Aeq,22:00-06:00}$ noise levels and the number of ships per hour present in the port for NMT3. (b) Correlation between monthly noise levels for the night period at NMT3 ($L_{Aeq,22:00-06:00}$) and the number of ships per hour present in the port. The data for other locations and time periods shows similar ship traffic against noise dependency.

of the obstacles (e.g. dwellings, city walls, container stacks, etc.) including height and reflection coefficients. Ground, road and railway infrastructure and building data was obtained from The Surveying and Mapping Authority of Slovenia and terrain heights were obtained from Lidar (2020). Population data was obtained from the central population register. Calculation parameters including the number of reflections, the size of the grid and techniques to shorten the calculation time were selected according to the Good Practice Guide for Strategic Noise Mapping (EC WG-AEN, 2007).

The calculations were compared with long-term measurements, which is an essential step to obtain models that accurately reflect the noise properties of a given complex source under different conditions occurring over an annual cycle (Mioduszewski et al., 2011; Ozkurt et al., 2014; Prezelj and Murovec, 2017; Paschalidou et al., 2019; Tezel et al., 2019). Finally, noise maps at a height of 4 m above the ground were calculated for the historical period and for the month of April, when the lowest noise levels were measured, for the night and the day-evening-night period. The night and day-evening-night noise levels were used to assess the noise exposure (END, 2002; Ozkurt et al., 2014; Tezel et al., 2019; Paschalidou et al., 2019).

3. Results

The results of the study are presented in five parts. First, the port activity is analysed. Then the meteorological conditions and the reduction of environmental noise levels measured by the monitoring network are presented. Furthermore, the results of the noise calculation are compared with the measurement results and the results of the analysis of the noise maps are presented.

3.1. Port activity

Port activities can be analysed in terms of ship traffic, operation of industrial noise sources, road and rail traffic.

3.1.1. Ship traffic

The Port of Koper publishes an annual sustainability report (Luka Koper, 2019) with information on the cargo traffic. Total tonnage of cargo was already reduced in 2019 as a result of the global economic downturn, which was evident in various industries, especially in the automotive, electronics and iron products industries. The number of ships has been on the decline since 2016 as larger ships and ships with heavier loads are coming to Koper.

Statistics Slovenia (SURS, 2020) publishes monthly trading data. Import and export numbers in EUR reached their lowest values of 2,010,969 $\times$ 10^3 EUR and 1,861,630 $\times$ 10^3 EUR in April 2020, which means that import and export activity in April 2020 decreased by 30% and 26%, respectively, compared to the averages for the period Jan 2018 to Feb 2020. The data for May 2020 was showing a recovery trend. As the port of Koper plays an important role in the Slovenian economy, the effect of the slowdown in trade is also reflected in a lower number of ship arrivals in the Port of Koper and the length of their stay, both of which would have an impact on noise emissions to the environment.

Six types of ships, which are most frequently encountered in the port of Koper, were considered in this paper. Vehicles carrier ships are used to transport wheeled vehicles such as trucks and cars. The main sources of noise on a moored vehicle carrier are ventilation fans and the exhaust from auxiliary engines. The fans are used to supply fresh air to the decks where vehicles are kept. The exhaust and fans are located on the upper deck of the vessel at a height of approximately 25 m to 35 m above sea level. The sound power level of the vehicle carrier depends on the number of fans in operation, their direction and their volume flow. Container ships carry all their cargo in truck-sized containers. The containers are loaded and unloaded with port dockside cranes, and the operation of the container terminal is closely linked to the presence of a container ship. Cargo ships carry special cargo, goods and materials and are often equipped with customized cranes. Bulk carriers are specially designed to carry unpackaged bulk cargoes such as grain, coal, ore, steel coils and cement in their holds. The main sources of noise on container ships, cargo ships and bulk carriers are the exhaust from auxiliary engines and the ventilation of the engine room. An oil/chemical tanker is

Table 3
Spatial distribution of ships in the historic and April 2020 (in parenthesis) periods.

Location	Berth 1.1	Berth 1.2	Berth 3	Berth 4	Berth 5	Berth 6
Vehicles carrier	16% (10%)	43% (30%)	–	1% (10%)	26% (20%)	14% (30%)
Container ships	–	–	100% (100%)		–	–
General cargo	12% (8%)	16% (8%)	3% (0%)	43% (36%)	24% (32%)	2% (16%)
Bulk carrier	2% (20%)	1% (0%)	–	22% (80%)	10% (0%)	65% (0%)
Oil/chemical tanker	–	–	–	14% (0%)	86% (100%)	–
Passenger ships	87% (0%)	13% (0%)	–	–	–	–

a ship designed to carry oil or chemicals in bulk. The main sources of noise from moored tankers are pumps used to pump oil from the ship to shore and exhaust gas noise. Passenger ships have the function of transporting passengers at sea. The main sources of noise from passenger ships at berth include the exhaust and ventilation openings. The average size of the ships (length and width), the dead weight tonnage, the sound power level and source height found in the port area are given in Table 1.

Fig. 2c shows an acoustic photo taken with a microphone array directed at a vehicle carrier. It can be clearly seen that the main source of noise in the ship is a fan located on the upper deck of the ship. Since the dominant sources on a ship are fans and exhausts which are small in relation to the size of the ship, all ships were considered as point sources in this study.

The average number of ships per hour is given in the Table 2. The data are stratified into day, evening and night periods. The number of ships was above average in March 2020. In April 2020, the port saw a decline in transhipment activities of about 35% compared to the long-term average between January 2018 and February 2020. Vehicle, general cargo, bulk cargo and oil handling was the most affected, declining between 50% and 62%, while container activities recorded a slight increase of 7–15%. Cruise (passenger) activities were completely stopped in 2020. The considerable drop in shipping and economic activity due to COVID-19 has also been reported in the port of Vancouver (Thomson and Barclay, 2020) and the Adriatic Sea (Depellegrin et al., 2020; Braga et al., 2020).

As seen in Table 2, the lowest average of 5.2 ships per hour were present in the port area during the night period in April 2020, whereas the historical average number of ships during the night period was 8 per hour. Similar numbers are observed for the day and evening periods. Time series of monthly average noise levels at NMT3 and corresponding number of ships present per hour for the night periods are shown in Fig. 3a. The monthly noise levels are not constant and show a variability that can be explained to some extent by the number of ships present in the port area per hour. Fig. 3b shows the relationship between the monthly $L_{\mathrm{Aeq},22:00–06:00}$ values at NMT3 from January 2018 until June 2020 and the corresponding number of ships present per hour. A positive correlation between the noise levels and the number of ships present per hour in the port area can be observed.

Fig. 1a shows the location of the berths and the spatial distribution of the vessels is shown in Table 3. In the historical period, 59% of the vehicle carriers were moored at berths 1.1 and 1.2, which are closest to the residential areas in Koper. In April 2020 most of the vehicle carriers were moored at berths 4, 5 and 6, which are more distant. The spatial distribution of the other types of vessels did not differ significantly between the two periods. The distribution was not considered in this study as dependent on day, evening and night time.

3.1.2. Operation of industrial noise sources

Among the dominant industrial noise sources in the port are cooling units, dockside cranes, RTG cranes, parking areas and various activities on the terminal yards. Cooling units located on the fruit terminal warehouse were modelled as a point source with a sound power level of 96 dBA. The cooling units were in operation throughout the historical and COVID-19 closure. There are nine dockside cranes at the container terminal. The sound power level of the individual dockside cranes was estimated at 108 dBA. The crane was modelled as a point source at a height of 30 m above sea level. The 22 stocking RTG cranes are located at the container terminal. Each crane was modelled as a 145 m long line source at a height of 3 m with a total sound power level of 100 dBA. The rest of the sources found in the terminal area (e.g. forklift trucks, auxiliary equipment) were modelled as area source at a height of 0.5 m with an average area sound power level of 55 dBA/m^2. In the historical period each crane was in operation for about 50% of the total time during the day, evening and night. In April 2020 the operating time was changed to 50%, 61%, 58% for the day, evening and night period, corresponding to the change in the number of container ships as shown in Table 2. The operational characteristics of the auxiliary equipment found in the terminal area have not been changed for the April 2020 period. Three main car parking areas were modelled as area sources with an area sound power level of 51 dBA/m^2 at a height of 0.5 m. In the historical period, the car parks were in operation during the day, in the evening and at night 100% of the time. In April 2020 their operating times were changed to 50%, 38% and 41% of the total time in day, evening and night time due to the decrease in the number of vehicle carrier ships. The transhipment at the European Energy Terminal was modelled as an area source with an area sound power level of 61 dBA/m^2. The grain and feed terminal, alumina terminal, liquid cargo terminal and livestock terminal were modelled as area sources with an area sound power level of 55 dBA/m^2. Transhipments at the European energy terminal were reduced by 35% in April in all day periods, due to the decrease in bulk and general cargo vessels.

Table 4
Road traffic intensity in the historic period and lengths of the road sections. Road network is shown in Fig. 1b where road sections can be identified by their ID.

ID of the road section	Road section length [m]	Hourly vehicle number (light/heavy) [h^{-1}]		
		Day	Evening	Night
a	307	242/66	81/40	27/5
b	231	52/8	9/3	4/1
c	570	57/12	13/8	6/1
d	214	55/10	12/6	6/1
e	503	313/89	102/55	33/7
f	652	201/54	77/32	26/2
g	677	123/41	40/25	12/3
h	425	88/25	29/11	9/1
i	262	476/139	146/83	50/10
j	108	453/137	142/82	46/10
k	386	98/23	32/15	13/1
l	487	108/31	35/19	12/2
m	276	81/22	19/14	9/2
n	407	86/27	29/16	9/2
o	522	493/145	154/86	52/11
p	461	190/44	62/25	21/2
q	753	182/51	57/30	18/4
r	241	437/121	145/72	45/9
s	553	83/22	21/12	10/2

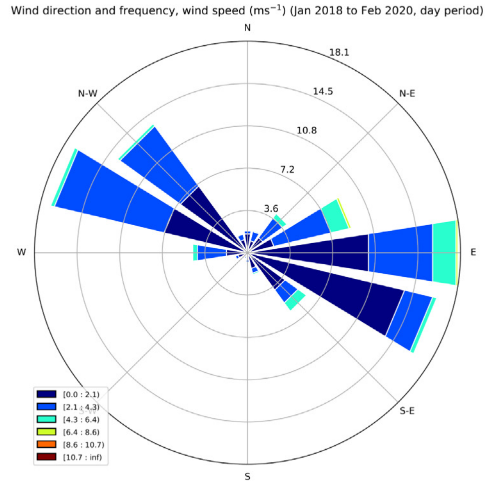
3.1.3. Road traffic activity

The traffic flow characteristics of the 19 road sections for the historical period are shown in Table 4. The road network is shown in Fig. 1b. In April 2020 the number of vehicles entering the port was reduced by 30%. Based on field observations, it was found that all road surfaces in

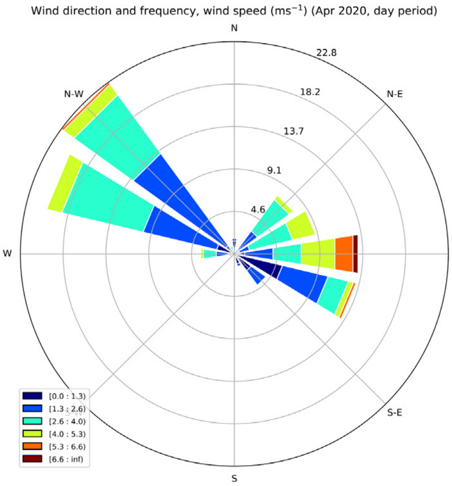
Table 5
Rail traffic intensity, type and length of track sections in the historic period and lengths of the road sections.

ID	Hourly unit quantity [h^{-1}] (Cat5/Cat4)	Type of track [−]	Length of the emission route [m]
I	0,8/8,7	A	1992
II	3,6/43,5	A	156
III	0,8/8,7	B	1050
IV	0,8/8,7	A	890
V	1,5/17,4	A	677
VI	1,5/17,4	B	198
VII	0,8/8,7	A	1053
VIII	0,2/2,6	B	440
IX	0,5/6,1	B	1238
X	0,8/8,7	B	926
XI	0,8/8,7	B	921
XII	0,8/8,7	C	188

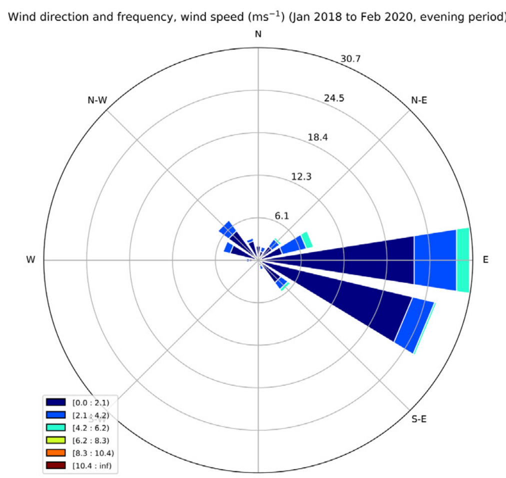
A – Embedded rail. More than 2 switches per 100 m.
B – Embedded rail. Track with joints.
C - Embedded rail. 2 switches per 100 m.



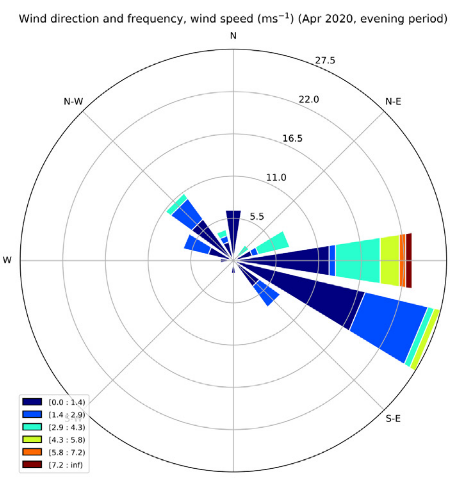
(a) Jan 2018 - Feb 2020, day.



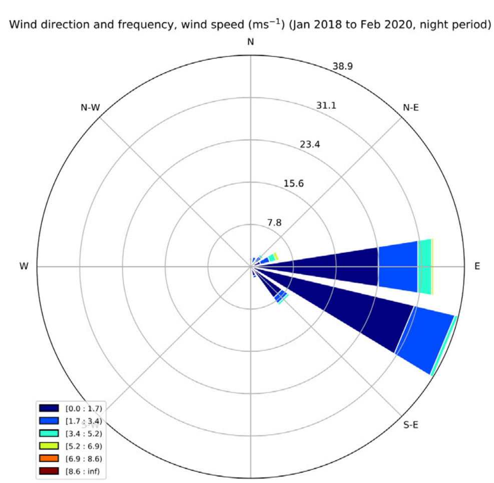
(d) Apr 2020, day.



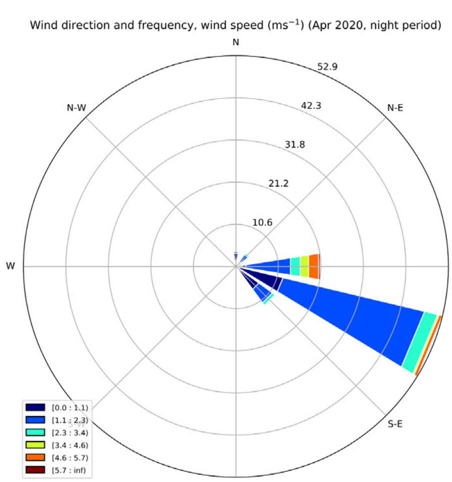
(b) Jan 2018 - Feb 2020, evening.



(e) Apr 2020, evening.



(c) Jan 2018 - Feb 2020, night.



(f) Apr 2020, night.

Fig. 4. Windrose in Koper for the periods Jan 2018 to Feb 2020 and April 2020.

the port area are covered with smooth asphalt and the traffic flow is intermittent. The gradients of the road sections were calculated by the software from the digital terrain model. The speed of all types of vehicles was estimated at 20 km/h, which is also the speed limit set in the port area.

3.1.4. Rail traffic activity

The rail network is shown in Fig. 1b and its operational characteristics are given in Table 5. In the April 2020 model, traffic flows were reduced by 25% according to the Slovenian National Railway Operator. Two categories of rail vehicles, differentiated by propulsion system and wheel braking system, were considered in the study: block-braked freight wagons with cast iron block brakes (Cat 4) and block-braked diesel locomotives (Cat 5). The rail system was characterized by embedded jointless rails. The track sections with crossings were also identified and a correction for isolated switches was applied. The speed of the rail units observed in the field observations was between 0 and 30 km/h. An average speed of 20 km/h was used for all units. 50% of the units in the terminal area were qualified as breaking trains. All rail sections were modelled as one track with corresponding emission parameters.

3.2. Meteorological conditions

Meteorological conditions have an important influence on sound propagation (Rossing, 2007) and can affect the operation of some noise sources (e.g. heating and cooling). Strong winds and precipitation are sources of additional noise, and measurements carried out under such conditions are excluded. Wind speed and direction are the most important parameters that determine how the sound propagates from the sound source to the receiver. Meteorological conditions are considered favourable if the wind direction is from the receiver to the source and if the sound paths are curved downwards. The epidemic had the greatest impact on noise emission in April 2020. The distribution of wind speeds and directions measured with a meteorological station located at NMT3 is shown in Fig. 4. The wind roses are plotted separately for day, evening and night periods. The wind directions in all periods (day, evening and night) show a similar pattern. In the day period the wind comes from either east or northwest direction, while in the evening and night periods east is the predominant direction. Wind speeds were higher in the April period compared to the historical average. The frequencies of occurrence of meteorological windows in the direction of Koper calculated according to the simplified method of ISO 1996-2 (ISO1996, 2017) are given in Table 6. The propagation conditions were mostly unfavourable and neutral during the day period between 6:00 and 18:00. Slightly more favourable prevailed in the April 2020 period. In April 2020 the occurrence of favourable and very favourable meteorological conditions in the day period was 15.6%, which was 4.5% more than in the historical period. Similar results were calculated for the evening period. Meteorological conditions were favourable 100% of the time during the night in the April 2020 period, which was 1% more than in the historical period. As there was a larger percentage of favourable meteorological conditions in the April 2020 period, we would expect slightly higher noise levels in Koper in the April 2020 period if the noise emission characteristics were the same.

3.3. Noise level reduction

In Table 7 we illustrate the monthly noise levels in the historical period compared to the periods between March and June 2020. During the COVID-19 period day ($L_{\mathrm{Aeq},06:00\text{–}18:00}$), evening ($L_{\mathrm{Aeq},18:00\text{–}22:00}$) and night ($L_{\mathrm{Aeq},22:00\text{–}06:00}$) noise levels were lower compared to the long-term historical averages. The statistical significance of the measured results is shown by calculating the standard uncertainties of the mean values.

In April 2020 (NMT2, NMT3) and May 2020 (NMT1) noise levels reached their lowest monthly levels for 30 months period. As shown in the Table 2, the number of ships in the port area decreased significantly in April and May 2020. These results suggest that the observed decrease in noise levels is due to a decrease in ship activity.

Table 6
Meteorological conditions.

	January 2018–May 2020	March 2020	April 2020	May 2020	June 2020
Day					
Unfavourable	88,9%	76,6%	84,4%	83,3%	99,4%
Favourable	11,1%	23,4%	15,6%	16,7%	0,6%
Evening					
Unfavourable	91,2%	82,3%	85,0%	92,7%	99,2%
Favourable	8,8%	17,7%	15,0%	7,3%	0,8%
Night					
Unfavourable	1,1%	1,2%	0,0%	0,0%	1,3%
Favourable	98,9%	98,8%	100,0%	100,0%	98,8%

The NMT2 station is located opposite the first basin of the port of Koper. The station is closest to the main noise sources and the noise levels are about 10 to 12 dBA higher than at NMT1 and NMT3 stations. Night-time noise levels at NMT2 are often above 60 dBA and day-evening-night levels above 66 dBA, which are also the values typically associated with larger infrastructures such as roads (Paschalidou et al., 2019), railways (Němec et al., 2020), airports (Sari et al., 2014) and ports (Murphy and King, 2014). Noise levels at the NMT2 station decreased in April 2020 compared to historical averages by 3.1 dBA, 2.4 dBA and 3.2 dBA during day, evening and night periods respectively. In May and June noise levels increased again, but were still lower than the long-term historical averages.

At the NMT1 station, noise levels in April 2020 decreased by 3.2 dBA, 3.9 dBA and 2.2 dBA in the daytime, evening and night time hours, respectively, compared to historical averages. The decrease in April is similar to the decrease at NMT2 station and noise levels remained low in May 2020. The NMT1 terminal is mainly influenced by the movement of vehicles from the vehicle carriers to the car depots where the station is located. Car turnover remained low in May as the automotive industry is still facing a decline in production as seen in Table 2.

The lowest noise levels were measured at the NMT3 station. Compared to historical averages, noise levels at NMT3 in April 2020 decreased by 3.3 dBA, 4.3 dBA and 5.7 dBA during the day, evening and night periods. A 5.7 dBA decrease in noise level means a 3.7-fold decrease in acoustic energy. A similar road traffic-related decrease of acoustic noise was measured for a central area in the city of Barcelona (Baldasano, 2020). Interestingly, due to changes in human activity global seismic noise has also been reduced by the same amount (Lecocq et al., 2020).

A stronger decrease of the noise level measured at NMT3 in April compared to the other two stations can be contributed to the fact that the NMT3 station is also influenced by road traffic outside the port area. 230 m north of the station is an important state-managed road. In April, there was a significant decrease in road traffic as the borders were closed and traffic between the municipalities was banned. In May, traffic between the municipalities was allowed again. The level remained low in May and was above historical averages in June 2020. The higher noise levels in June may be contributed to the increase in construction work near the station.

3.4. Validation of the noise model

The model was validated by a spatial comparison between the calculated result and the measured noise levels at the three NMTs. In order to capture different conditions that occur over a longer time window, long-term measurements were used to validate the model. The calculated

Table 7
Average noise levels during the historical (January 2018–February 2020) period and March, April, May and June 2020 periods.

Noise monitoring terminal/noise level [dB]	January 2018–February 2020	March 2020	April 2020	May 2020	June 2020
NMT1					
$L_{Aeq,06:00–18:00}$	52.9 ± 0.6	52.0 ± 0.7	49.7 ± 0.7	50.8 ± 0.7	51.5 ± 0.7
$L_{Aeq,18:00–22:00}$	50.9 ± 0.6	48.9 ± 0.7	47.0 ± 0.7	47.0 ± 0.7	49.5 ± 0.7
$L_{Aeq,22:00–06:00}$	48.4 ± 0.6	47.5 ± 0.7	46.2 ± 0.7	46.0 ± 0.7	47.0 ± 0.7
$L_{Aeq,00:00–24:00}$	55.9 ± 0.4	54.9 ± 0.5	53.3 ± 0.5	53.4 ± 0.5	54.5 ± 0.5
NMT2					
$L_{Aeq,06:00–18:00}$	62.4 ± 0.6	61.9 ± 0.7	59.3 ± 0.7	61.6 ± 0.7	60.5 ± 0.7
$L_{Aeq,18:00–22:00}$	61.8 ± 0.6	61.1 ± 0.7	59.4 ± 0.7	60.9 ± 0.7	60.3 ± 0.7
$L_{Aeq,22:00–06:00}$	61.2 ± 0.6	60.5 ± 0.7	58.0 ± 0.7	60.2 ± 0.7	59.5 ± 0.7
$L_{Aeq,00:00–24:00}$	67.8 ± 0.4	67.2 ± 0.5	64.8 ± 0.5	66.9 ± 0.5	66.1 ± 0.5
NMT3					
$L_{Aeq,06:00–18:00}$	52.6 ± 0.6	51.8 ± 0.7	49.3 ± 0.7	50.2 ± 0.7	52.9 ± 0.7
$L_{Aeq,18:00–22:00}$	50.5 ± 0.6	49.2 ± 0.7	46.2 ± 0.7	45.8 ± 0.7	51.5 ± 0.7
$L_{Aeq,22:00–06:00}$	49.0 ± 0.6	48.5 ± 0.7	43.3 ± 0.7	46.2 ± 0.7	50.3 ± 0.7
$L_{Aeq,00:00–24:00}$	56.2 ± 0.4	55.5 ± 0.5	51.3 ± 0.5	53.3 ± 0.5	57.2 ± 0.5

values of the noise levels ($L_{Aeq,06:00–18:00}$, $L_{Aeq,18:00–22:00}$, $L_{Aeq,22:00–06:00}$ and $L_{Aeq,00:00–24:00}$) for receptor points where continuous measurement stations are located and the results of the measurements at the NMTs are shown in Fig. 5a–c.

The differences between the measured and calculated noise levels ranged from 0 to 0.7 dBA in the historic period and from −0.2 to 2.0 dBA in April 2020. As expected, the differences were greater for the April period, as the unknown calculation parameters of the model, such as e.g. the number of reflections and ground absorption, were initially estimated based on long-term noise measurements for the historical period.

The largest difference of 2.0 dBA observed for the night period April 2020 at the NMT 3 station can still be considered acceptable, considering that NMT3 is more than 600 m away from the main noise sources of the port and where the lowest noise levels were measured (EC WG-AEN, 2007; Tezel et al., 2019). The validation of the model using data from the April 2020 period suggests that the noise model used is robust and capable of capturing the noise characteristics of the port under study under different operational and meteorological conditions.

Good agreement between the measured and calculated values for both historic and COVID-19 periods could only be achieved after the long-term noise measurements were post-processed as described

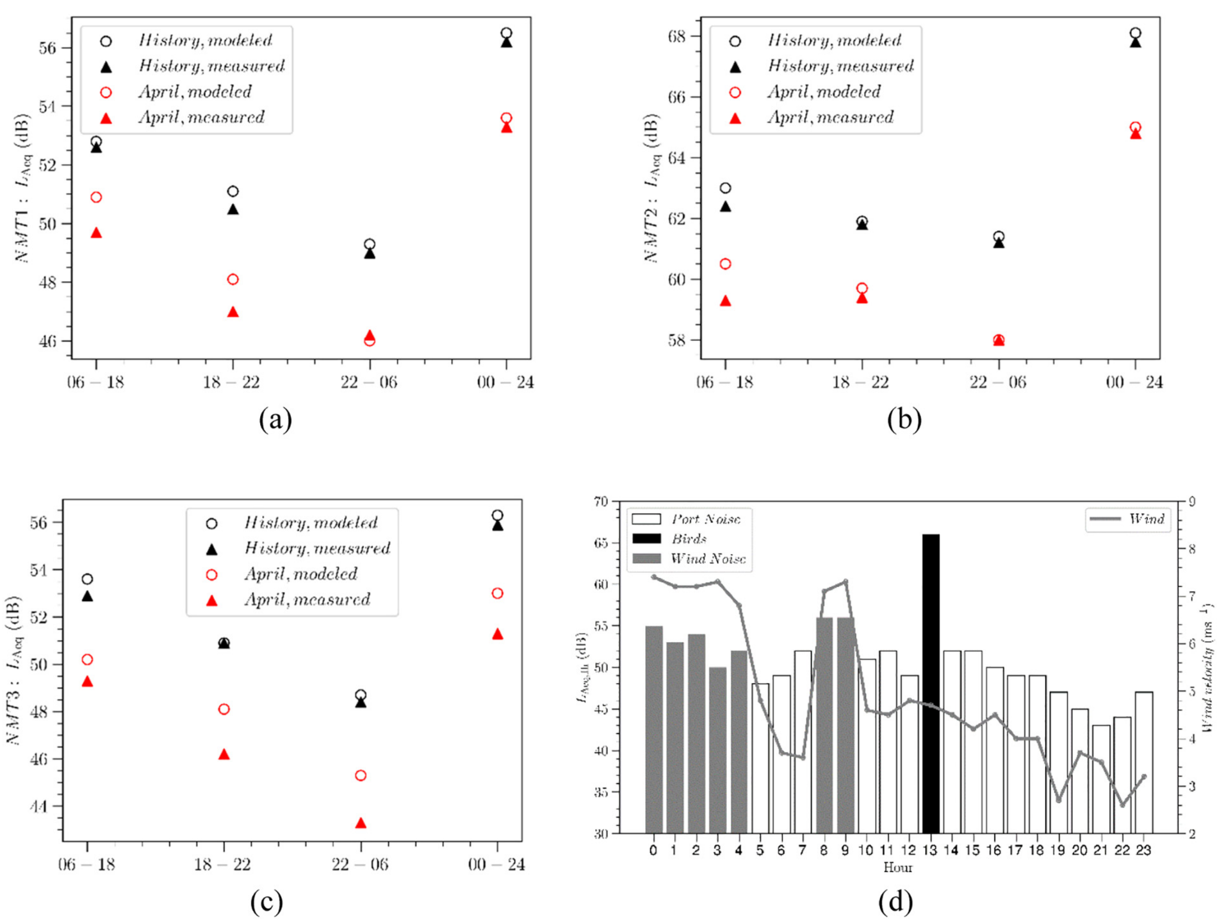
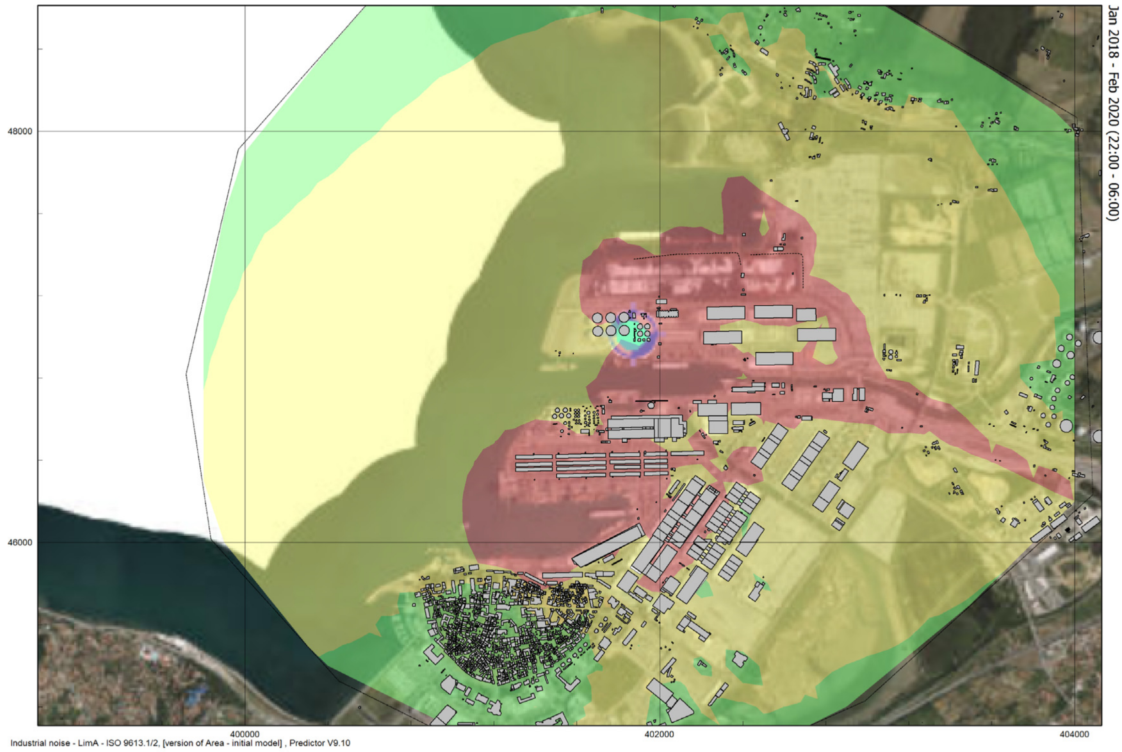
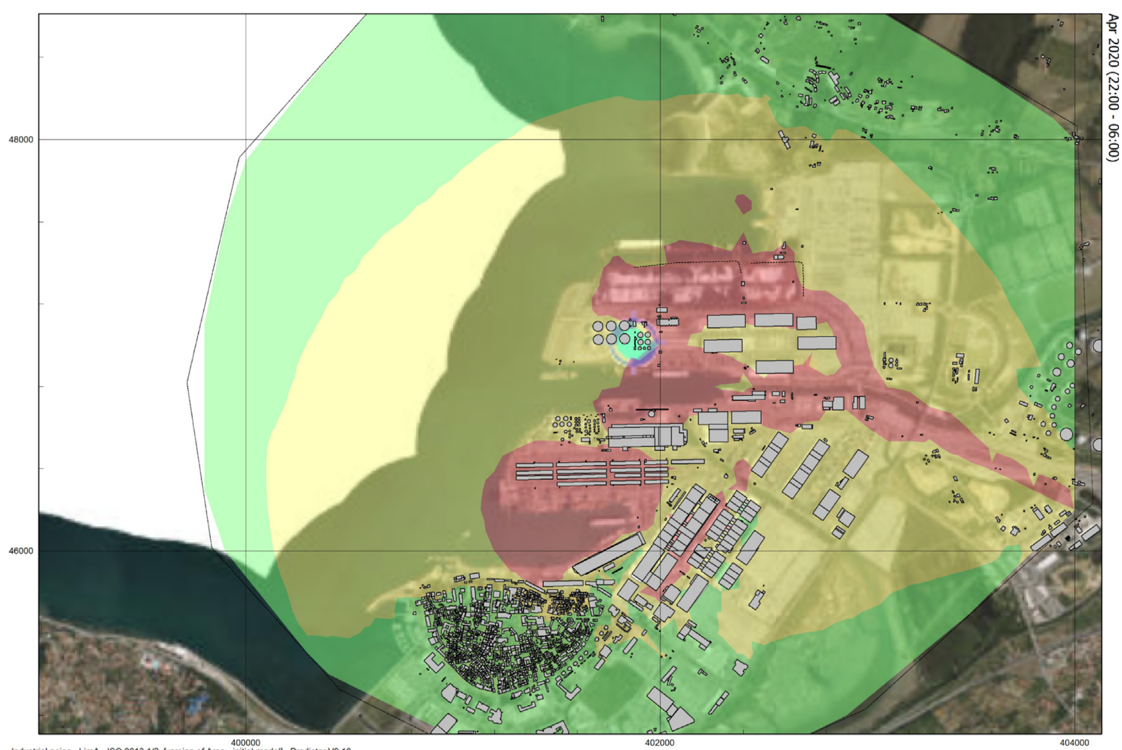


Fig. 5. Comparison between calculated and measured noise levels at (a) NMT1, (b) NMT2 and (c) NMT3. (d) Wind velocity and $L_{Aeq,1h}$ noise levels at NMT3 on 11.12.2019.

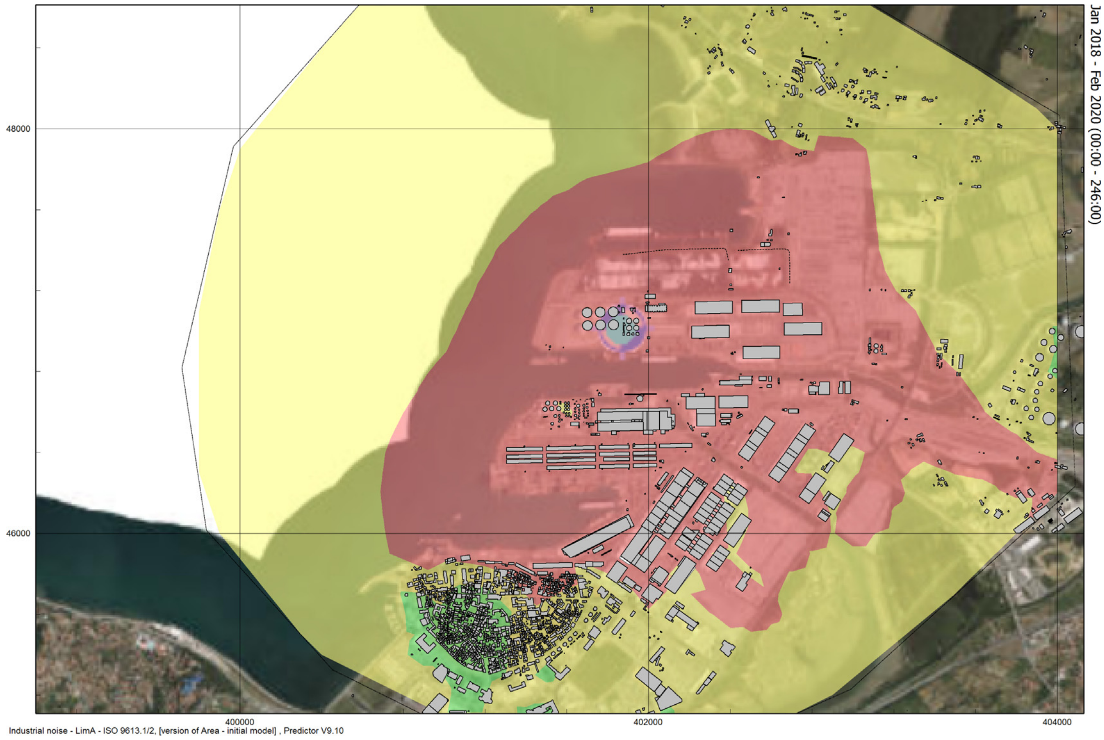


(a) Jan 2018 - Feb 2020, night period.

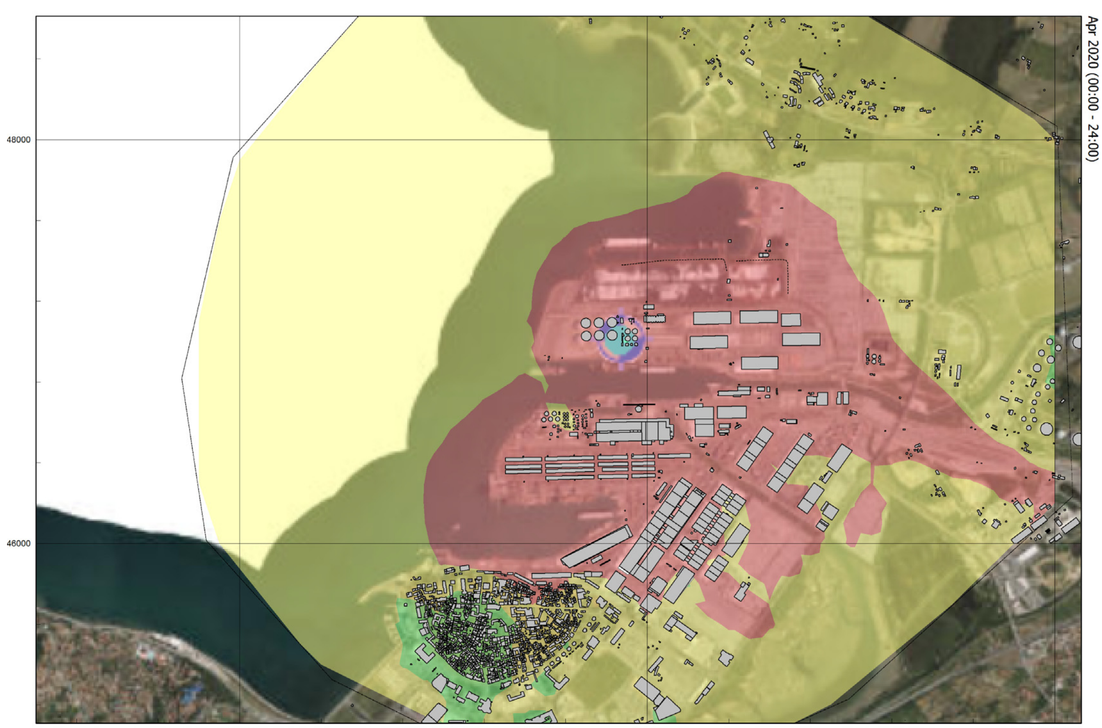


(b) April 2020, night period.

Fig. 6. Spatial distribution of night ((a) and (b)) and day-evening-night ((c) and (d)) A-weighted noise levels. Noise maps are shown for historical Jan 2018 to Feb 2020 period and for April 2020 when the lowest noise levels were measured (green: <40. Yellow: 40 dB–55 dB. Red: >55 dB).



(c) Jan 2018 - Feb 2020, day-evening-night period.



(d) Apr 2020, day-evening-night period.

Fig. 6 (*continued*).

Table 8
Noise exposure in the historic and April 2020 (in parenthesis) periods.

Noise source	Number of people exposed to		Number of schools exposed to	
	$L_n > 50$ dBA	$L_{den} > 55$ dBA	$L_n > 50$ dBA	$L_{den} > 55$ dBA
Ship and industrial noise	423 (336)	461 (381)	1 (1)	1 (1)
Road traffic noise	0 (0)	149 (134)	0 (0)	0 (0)
Rail traffic noise	0 (0)	0 (0)	0 (0)	0 (0)

above. Fig. 5d. shows $L_{Aeq,1h}$ measurements taken at the NMT3 station on 11.12.2019. Weather conditions with wind speeds above 5 ms^{-1} had a significant impact on the noise measurements between hours 0 and 4 and 8 and 9. The measurement at 13:00 was unusually high due to birdsong at the station, which was detected by the sound recording. Such data processing is essential to obtain measurements that relate to port activities and not to meteorological conditions or unusual sound events.

3.5. Noise maps

Noise contour maps in the night (22:00–06:00) period for the historical period and the month of April 2020 are shown in Fig. 6. The boundaries of the calculation area are shown in Fig. 1a. The chosen grid of 10 m × 10 m includes the port area and the adjacent residential areas influenced by the port, where L_{den} is above 55 and L_d is above 50 dBA (NoMEPorts, 2008). The noise contours are divided into <40 dB (green colour), 40 dB–55 dB (yellow colour) and >55 dB (red colour) A-weighted noise level classes. The 40 dB night level is representative of sleep disturbance and is used as a target value of the night noise guidelines (WHO, 2009) to protect public health, including the most vulnerable groups such as children, the chronically ill and the elderly and a night level of 55 dB is recommended as an interim target where the NNG (WHO, 2009) cannot be achieved. In April 2020, the >55 dB area was reduced by 22% and the 40–55 dB area by 26% at night-time compared to the historical period. The >55 dB area in the day-evening-night period decreased by 23%.

The estimated number of people exposed to noise per noise source according to END (2002), where all occupants of a building were assigned to the level of the most exposed façade at 4 m from the ground, is given in Table 8. The result shows that 423 people living in 152 dwellings and 1 school were exposed to night-time noise levels of more than 50 dBA during the historic period due to shipping and industrial activities in the port. In April 2020, the number of people exposed to the same noise source during the night period was reduced by 87. Due to the decrease in road traffic in the port area, the number of people exposed to road traffic noise was reduced by 15. This is to be expected, as road traffic at night is already decreased. Such results indicate that the decrease in noise levels and noise exposure is mainly a result of the decrease in ship traffic near residential areas (e.g. vehicle carriers and container ships).

4. Conclusions

The identification of the dominant sources of environmental noise is one of the most important components of any noise abatement strategy and is a major challenge in ports where road and rail traffic noise, industrial noise and noise from moored ships is emitted simultaneously.

The analysis carried out in this study shows that the impact of COVID-19 on the activities in the port of Koper has led to a significant reduction of environmental noise from the largest Slovenian port. The reduction in noise levels during the epidemic was observed at three noise monitoring stations in the port. The sound pressure levels in the day, evening and night hours at two monitoring stations were reduced by about 3 dBA in April 2020 compared to the long-term average values in the period between January 2018 and February 2020. The most significant decrease in night-time noise level by 5.7 dBA was observed at the NMT3 measuring station in April 2020. In May 2020 and June 2020, shipping traffic, domestic road traffic and noise levels started to increase, but have still not reached the levels of the previous, normal periods. The decrease in noise levels was not related to weather conditions, as noise propagation conditions during the COVID-19 epidemic were more favourable compared to the historical period used to determine the baseline.

The reduction of acoustic energy during a pandemic by noise monitoring terminals has been analysed in the literature (Asensio et al., 2020b); however, none of the studies examined the noise emitted from the port. The main objective of this study was to use the unique acoustic situation during the epidemic to identify the noise sources that have the greatest impact on noise reduction. Although port noise has already been discussed (Paschalidou et al., 2019) and even an EU funded Good Practice Guide on Port Area Noise Mapping and Management has been developed, a clear and precise guide that takes into account the noise characteristics of all sources in the port area in detail is not yet described in the literature. Therefore, the noise emission from the port was described using emission data of industrial noise sources including ships and from road and rail traffic flows (Paschalidou et al., 2019; Tezel et al., 2019) for the historic (January 2018–February 2020) and epidemic period of April 2020, during which the lowest noise levels were observed. In April 2020, the port of Koper recorded a decrease in shipping traffic of about 35% compared to the long-term average of previous years. Thus, the shipping activity was described by the average number of ships present in the port area per hour and by the spatial distribution of the mooring vessels.

The noise, operational, geographical, spatial and measurement data were used to prepare and validate the noise model for the historic and COVID-19 periods, which was then used to produce the noise contour maps. It was found that in the COVID-19 period the number of people exposed to high noise levels during the day-evening-night period by commercial shipping near residential areas (at distances of up to 600 m from the main terminals) was reduced by about 20% compared to the historical period before COVID-19.

The methodology presented has some reservations. Some of the unattended long-term measurements can be influenced by strong winds and unwanted sound events, which can be easily detected by wind speed measurements and sound recordings. In order to obtain reliable and robust sound data reflecting the actual noise levels emitted by the port, the removal of such data is essential. The post-processing was done in the laboratory, it required human effort, which was time consuming and costly. On the other hand, short-term measurements (e.g. 24-hour measurements) could not capture all noise emission characteristics of an average year. The emission (sound power) levels of the ships used in this study are based on ships that docked in the port of Koper between 2018 and 2020 and may therefore reflect the situation in ports of similar size. The largest difference of 2.0 dBA between measured and calculated values was observed at NMT3 for the night period April 2020. The additional noise reduction is likely to be associated with reduced road traffic on roads outside the port area, as unnecessary movements between municipalities were prohibited in April 2020. The observed difference indicates that emission levels are still influenced by residual noise and the uncertainty of measurements and modelling should be taken into account.

The results presented are useful for policy makers, port authorities, shipbuilders and environmental noise specialists, as this paper provides evidence that environmental noise generated by moored ships and not regulated internationally is a problem for port cities. Given that the noise sources on a ship and the port cranes are high above ground, typical noise abatement techniques such as noise barriers would be ineffective. Restricting shipping traffic can be effective, but it can only be implemented at high cost, e.g. the port of Koper recorded a 40% loss of profit in the first half of 2020 due to reduced commercial activities (RTVSLO, 2020). In the future, shipbuilders should step up their efforts to reduce noise emissions from ships. Until then, a reduction of road traffic during the night time, an appropriate allocation of terminals, reduced air flow of fans, lower energy consumption of ships and the use of on –shore power supplies, especially at night, seems to be a good solution.

Finally, the noise emission values presented in this paper, the categorisation of ships and the post-processing of long-term measurement data, which take into account wind conditions and undesired sound events, can also be applied to other locations near shipping ports and used in strategies for noise reduction in ports. In the future, additional relevant noise indicators (Asensio et al., 2020a, 2020b; Can et al., 2016) and parameters describing port activities could be applied to improve the description and understanding of the noise environment in the port area.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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