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How can ports act to reduce underwater noise from shipping? Identifying effective management frameworks

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ABSTRACT

This paper aims to find mechanisms to align commercial interests with underwater noise reductions from commercial shipping. Through a survey and a series of interviews with representative stakeholders, we find that while acknowledging the wide variations in ports' specificities, port actions could support the reduction in underwater noise emissions from commercial shipping through changes in hull, propeller and engine design, and through operational measures associated with reduced speed, change of route and travel in convoy. Though the impact of underwater noise emissions on marine fauna is increasingly shown to be serious and wide-spread, there is uncertainty in the mechanisms, the contexts, and the levels which should lead to action, requiring precautionary management. Vessels owners are already dealing with significant investment and operating costs to comply with fuel, ballast water, NOx and CO2 requirements. To be successful, underwater noise programs should align with these factors.

Based on a multiple criteria decision making (MCDM) approach, we find a set of compromise solutions for a wide range of stakeholders. Ports could propose actions such as discounted port fees and reduced ship waiting times at ports, both depending on underwater noise performance. Cooperation between ports to scale up actions through environmental indexes and classification societies' notations, and integration with other ports' actions could help support this. However, few vessels know their underwater noise baseline as there are very few hydrophone stations, and measurement methodologies are not standardized. Costs increase and availability decreases dramatically if the vessel buyer wants to improve the noise profile. Local demands regarding airborne noise close to airports boosted global pressure on the aviation industry to adopt existing quieting technology. This experience of the aviation noise control could inform the underwater noise process.

1. Introduction

The sounds in the ocean may come from natural sources, such as breaking waves, rain, earthquakes, ice and marine life. Sound in the ocean is referred to as underwater 'noise' only when it has the potential to cause negative impacts on marine life. Humans can add underwater noise to the marine environment. Anthropogenic underwater noise can have a series of adverse effects on marine biodiversity and ecosystems, ranging from masking effects whereby noise interferes with biologically important signals to behavioural disturbance, tissue damage and death (OSPAR, 2009a; CBD, 2012; NOAA, 2016; Weilgart, 2018). Such noise is generated by an increasingly large number and variety of anthropogenic activities in the marine environment. It is classified under two broad categories (EC, 2010; TSG UW Noise, 2013; OSPAR, 2014). Underwater impulsive or acute noise typically comes from seismic research surveys and oil and gas exploration, pile driving for offshore oil and gas platforms and wind farms, active sonar for naval, commercial, fishing and research operations, controlled explosions for naval operations and harbour deepening, and acoustic mitigation devices (Rijkswaterstaat, 2015). Underwater ambient or chronic noise is usually generated by shipping, energy installations and construction, i.e. dredging for shipping lanes, sand mining, and laying pipes and cables (HELCOM, 2016a).

Underwater impulsive noise is generally characterized by relatively short-term and spatially more limited high intensity acoustic energy

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linked to a single activity (NOAA, 2016). High intensity noise from naval sonar and seismic surveys has been correlated with mortality events of marine mammals, often involving atypical mass strandings of beaked whales (Azzellino et al., 2011). Underwater ambient noise, on the other hand, is associated with continuous and lower intensity energy across large areas and is due to multiple activities (OSPAR, 2009b; NOAA, 2016). It may lead to chronic effects extending over several thousand kilometres within the frequency ranges used by marine animals for reproduction, detection of predators and prey, navigation and group cohesion (Stojanovic and Beaujean, 2013; Buscaino et al., 2016). For instance, low frequency tones from a single large vessel can be heard as far away as 139 km (Ross, 1976). Even if both underwater impulsive and ambient noise may result in a decrease in survival, the bulk of research on the impacts of anthropogenic underwater noise on marine animals has focused on impulsive noise. However, there have been several studies on the effects of shipping noise on marine fauna, observing stress, behavioural changes and potential effects on foraging efficiency (Aguilar de Soto et al., 2006; Dyndo et al., 2015; Wisniewska et al., 2018). These studies show how shipping noise can affect marine fauna, even if the effects of chronic anthropogenic changes in ambient noise have been traditionally more difficult to detect (NOAA, 2016).

Shipping noise is the dominant anthropogenic contribution to underwater ambient noise (Edmonds et al., 2016; OSPAR, 2009a). It is also the most widespread and persistent source of underwater noise at the global scale (Merchant, 2019). Underwater ambient noise increased by about 3.3 dB per decade between 1950 and 2007 in some areas, doubling every 10 years, primarily attributed to the increase in the number and size of commercial ships (Frisk, 2012). Underwater ambient noise due to commercial shipping is set to continue to rise in the coming years, particularly in and around shipping lanes and in the Northern hemisphere (Hatch et al., 2008).[1] As at January 2017, there were 93,161 commercial ships worldwide (UNCTAD, 2017). They increased 2.7 times between 1980 and 2017 in terms of weight-carrying capacity, the growth being over fivefold in the merchant fleets of developing countries which account for 76% of the world fleet (UNCTAD, 2018). The largest commercial ships measure between 300 and 400 m, independently of their type, with larger sizes usually reflecting higher cost savings (OECD/ITF, 2015).

The effect of ocean traffic on the underwater ambient noise level depends, among other factors, on the local sound propagation characteristics, the shipping speed, the shipping load and level of maintenance, the number of ships and the distance from the ship (Recuero Lopez, 1995; Lurton, 2010; Bassett et al., 2010; IMO, 2014; Bureau Verita, DNV GL, 2015; Berkowitz and Dumez, 2017). Underwater noise from shipping can come from propeller cavitation, machinery noise and hydrodynamic noise, i.e. the motion of the vessel through the water (U.S. Office of Naval Research, 1998). According to the 'Ships oriented innovative solutions to reduce noise and vibrations' (SILENV) project, the machinery and propellers are the main contributors to underwater noise in the European fleet (Beltran Palomo, 2014). More precisely, machinery noise is dominant at low shipping speeds and low frequencies, particularly at speeds of up to 27 km/h (14.6 knots); otherwise, propeller noise is predominant (Curtis, 1951). In general terms, underwater noise ranges from 150 dB re 1μPa at 1 m for small fishing vessels to 195 dB re 1μPa at 1 m for oil tankers (Bassett et al., 2010). These levels are comparable to those emitted by biological sources, mainly marine mammals but also fish and invertebrates such as shrimp (Cato, 2001; Kuperman, 2013). Especially for long-lived species, such as whales, and in cases of rapidly increasing background noise levels, animals are highly unlikely to be able to genetically adapt at a pace similar to that of habitat change (Rabin and Greene, 2002).

Underwater noise from ships is strongly contingent on the type of vessel, particularly on propeller cavitation (MAPAMA, 2012). Underwater noise from large commercial ships of over 100 m is concentrated in low frequency ranges between 5 and 500 Hz.[2] Commercial vessels are the dominant source of underwater noise in this low frequency band (Joint Working Group on Vessel Strikes and Acoustic Impacts, 2012). This noise is often present near large ports and along shipping lanes, and can propagate over very long distances due to its low frequencies (Jasny, 2014).[3] Noise levels produced by medium-size ships in the range of 50 to 100 m, such as modern freighters or fast-ferries, can be found in higher frequencies, of up to about 600 Hz–2 kHz with the potential to interfere with the vocalizations of many species of odontocete cetaceans (Evans, 2003).[4] Small and medium boats and recreational vessels of fewer than 50 m generate noise at higher frequencies, above 1 kHz, due to higher propeller rotation speeds (Abdulla and Linden, 2008).[5]

Underwater acoustic energy is fundamental for marine animals since underwater communication typically depends on it. A large number of marine animals rely on acoustic energy for communication and sensing (CBD, 2012; Radford et al., 2012). These range from marine mammals and some fish which primarily detect acoustic pressure through their auditory system, to other fish and invertebrates which mainly detect particle motion, i.e. vibrations associated with acoustic energy, through sensory organs such as external sensory hairs and internal statocysts (Brumm, 2013; Nedelec et al., 2016). For instance, low-frequency sounds (15–30 Hz) of blue and fin whales can be detected from 400 to 1600 km away, an illustration of their ability to communicate across long distances (Sirovic et al., 2007). Odontocetes produce a series of fast clicks and the return echoes, as energy bounces off distant objects, provide information about their surroundings (Berta and Sumich, 1999). Settlement-stage invertebrates such as corals and crustaceans use reef noise as a cue for orientation (Simpson et al., 2004; Montgomery et al., 2006; Mann et al., 2007; Vermeij et al., 2010).

Depending on the acoustic intensity and the frequency, the effects of underwater noise on marine mammals can be detectable in the hearing zone, can induce behavioural changes, can mask biologically important information, can cause hearing damage including temporary and permanent threshold shifts as well as other physical injuries or even death (van der Graaf et al., 2012).[6] To date, most research has explored the impacts of anthropogenic underwater noise on marine mammals, mainly cetaceans whose auditory sensitivity ranges from 7 Hz to 180 kHz (Richardson and Würsig, 1997; Southall et al., 2007; Bejder et al., 2009; CBD, 2012;). There is less but growing evidence on the impact of anthropogenic underwater noise on fish, turtles and invertebrates (CBD, 2012; Rijkswaterstaat, 2015; IMO, 2015; NOAA, 2016). The majority of fish detect acoustic energy from below 50 Hz to 500–1000 Hz, with most communication signals in the range of 100 Hz to 1 kHz (CBD, 2012). Marine turtles are sensitive to low frequency acoustic energy in the

[1] For instance, total container ship costs per container have been reduced by one third with the doubling of the size of vessels in the last decade. By contrast, the global fishing fleet is mainly composed of small vessels measuring fewer than 12 m in length and about a third is not motorized (UN, 2010). Industrial fishing vessels are relatively stable in number and gross tonnage (FAO, 2008). There are about 2.1 million active motorized vessels under 12 m worldwide, 320,000 between 12 and 24 m and 50,913 over 24 m, the largest ranging from 100 to 150 m (Kroodsma et al., 2018).

[2] Noise can attain up to 220 dB re 1μPa at 1 m (Sadaf et al., 2015).

[3] Noise from nearby shipping may be present in a wide spectrum of frequencies, but only the lower frequencies below about 200 Hz attain a certain distance since high frequencies are attenuated in deep water (Jasny, 2014).

[4] Such ships produce noise levels in the range of 165 to 180 re 1μPa at 1 m which contribute to marine ambient noise to varying degrees depending on their age and level of maintenance (OSPAR, 2009a).

[5] They may produce noise levels of the order of 160 to 175 dB re 1 μPa at 1 m (Tejedor et al., 2012).

[6] On a broader scale, the long-term consequences of anthropogenic underwater noise on marine animals at the level of the population as a whole are still largely unknown, both when considering this stressor alone and when accounting for cumulative impacts (CBD, 2012; NOAA, 2016; IMO, 2018a).

range of 100 to 1 kHz with the greatest sensitivity between 200 and 400 Hz (Southwood et al., 2008). Some recent evidence suggests that underwater noise can lead to physical, behavioural and masking effects in fish (Weilgart, 2018). Very roughly 66 species of fish and 36 species of invertebrates have shown documented impacts from underwater noise pollution (Weilgart, 2018). Crustaceans are sensitive to acoustic energy of less than 1 kHz and detect up to 3 kHz, and cephalopods between <20 and 1500 Hz (Jézéquiel et al., 2018). Anthropogenic noise may cause physical damage to invertebrates, including cephalopods (André et al., 2011; Solé et al., 2013a, 2013b; Aguilar de Soto et al., 2013; André et al., 2016; Solé et al., 2016; NOAA, 2016; Solé et al., 2017, 2018, 2019). There is also evidence of behavioural and masking effects in crustaceans (Lagardère, 1982; Simpson et al., 2011).

The scientific understanding of the impacts of underwater noise from shipping on marine animals is limited (OSPAR, 2009a; CBD, 2012; IMO, 2018a). There is mainly evidence of the masking effects of underwater noise from shipping on marine mammals (IMO, 2018a). In fact, an overlap exists between the frequency ranges of noise from commercial vessels and the sounds used by many cetacean species (Clark et al., 2009).[7] Ice-breakers can cause temporary hearing threshold shifts in beluga whales (Erbe and Farmer, 2000). Underwater noise from vessels has also been associated with short and long-term behavioural impacts in marine mammals, including habitat abandonment, disruption of foraging activity, and suppression or alteration of vocalization (Weilgart, 2007; Joint Working Group on Vessel Strikes and Acoustic Impacts, 2012; Blair et al., 2016; Marley et al., 2017; Bittencourt et al., 2017). This type of noise can lead to chronic stress which can affect the health of the populations resulting in changes in fertility, mortality and growth rates (Wright et al., 2009; IMO, 2018a). To a lesser extent, there is also evidence of the impact of underwater noise from shipping on the communication and the behaviour of fish, including stress responses and survival rates.[8] Underwater noise from shipping is likely to affect marine invertebrates because of their sensitivity to low frequencies (CBD, 2012). There is some evidence of an impact on stress and behaviour in crustaceans (Wale et al., 2013; Filiciotto et al., 2016).

It is important to highlight that the topic of ships as noise sources has been studied not only concerning underwater noise but also airborne noise. In particular, continuous onboard noise can have an adverse impact on human health for both passengers and crew. This issue is being dealt with from a regulatory perspective.[9] Moreover, the subject of airborne port noise is increasingly gaining attention due to the complaints from people living in the nearby areas. For instance, local population complaints to noise produced by ships have been reported in Dublin and Athens (Murphy and King, 2014; Paschalidou et al., 2019). The current normative framework related to the impact of port noise on the surrounding urban areas is in general inadequate (Borelli, 2019a, 2019b). Some projects are assisting authorities to assess the impact of port operations on the city soundscape since specific directives or guidelines are lacking (Bolognese et al., 2020; NEPTUNES Project).[10]

Similarly to airborne port noise, underwater noise from shipping is a topic which has also aroused growing interest in recent years, particularly at the international level. However, it is subject to scientific uncertainties, especially regarding species-contingent thresholds. This does not mean that no action should be taken. Targets can be set based on the views of the relevant stakeholders that represent different views of society as a whole: port authorities and administrations, the shipping sector, the fisheries sector, analysts (academics and environmental consulting firms), and the biodiversity conservation community. This paper provides data-based guidance on the characteristics of a management framework conducive to reducing underwater noise from commercial shipping, the dominant source of underwater noise.

2. What progress has there been on actions to reduce underwater noise from shipping?

An increasing number of international institutions acknowledge the contribution of shipping to underwater noise (Table A1.1 in the appendix).[11] Underwater noise from shipping, however, remains unregulated at the international level despite its transboundary nature (McCarthy, 2004; CBD, 2012; Dolman and Jasny, 2015).

There are nevertheless some initiatives on underwater noise at the level of international institutions (Table A1.2 in the appendix). Most international initiatives focus on the development of noise mapping for shipping, for instance, through the definition of indicators (EC, 2012; EC, 2017; HELCOM, 2016a). The Marine Strategy Framework Directive requires Member States of the European Union to evaluate and monitor the Good Environmental Status of ambient underwater noise (EC, 2010; Berkowitz and Dumez, 2017). There are, in turn, some guidelines for monitoring ambient noise under the Directive's pressure indicator 11.2, which are applied regionally (OSPAR, 2014; HELCOM, 2018a), as well as monitoring sub-programmes (HELCOM, 2018b). Moreover, the International Whaling Commission (IWC) recommends an approach for identifying the noisiest ships, quantifying their contribution to overall ocean noise and assigning a priority to replacing/modifying those ships that contribute disproportionately to ocean noise (IWC, 2017a, 2017b).

There are also a relatively large number of international institutions that focus on options to mitigate underwater noise from shipping. Most options proposed build on the voluntary guidelines of the United Nations agency specialized in setting global standards for international shipping, the International Maritime Organization (IMO). In particular, the IMO issued voluntary Guidelines in 2014 for quieting underwater noise radiated from commercial ships (IMO, 2014). Except for fishing research vessels, there are no underwater noise requirements in contract specifications in Europe. The absence of contractual requirements is one of the main causes of the unavailability of underwater radiated noise data (Beltran Palomo et al., 2012). It also explains why it is not possible to make an assessment of the environmental impact of the European fleet (Beltran Palomo, 2014).

Technology to reduce underwater ship noise from machinery and propellers is already available (Berkowitz and Dumez, 2017), however not all factors and combinations are understood. Cost/benefit ratios, fuel efficiency and technical viability should be considered (Beltran Palomo

[7] Underwater noise from commercial shipping can mask communications or foraging signals of baleen whales, belugas, bottlenose dolphins, short-finned pilot whales, killer whales and Cuvier's beaked whales (Aguilar de Soto et al., 2006; CBD, 2012). Large commercial vessels can hinder the ability of endangered whales to communicate within sanctuary waters (Hatch et al., 2008). There is also evidence that recreational and ice-breaker vessels negatively impact communication with conspecifics for marine mammals (CBD, 2012).

[8] See Scholik and Yan (2002), Wysocki et al. (2006), Sara et al. (2007), Vasconcelos et al. (2007); Graham and Cooke (2008), Stanley et al. (2011), Holles et al. (2013), Kaplan and Mooney (2015), Sprague et al. (2016), Celi et al. (2016), Stanley et al. (2017), Ferrari et al. (2018), McCormick et al. (2018).

[9] The International Convention for the Safety of Life at Sea (SOLAS) in its regulation II-1/3-12 requires ships to be compliant with the International Maritime Organization (IMO) resolution MSC.337(91) "Code on noise levels onboard ships".

[10] See Fredianelli et al. (2021), Borelli (2019a, 2019b) and Borelli (2019a, 2019b, 2020) on the prevention and the mapping of noise in port areas and Bernardini et al. (2019) et Fredianelli et al. (2020) on the characterization of noise emissions from shipping through measurements.

[11] In 2018, for instance, the focus topic of the United Nations Open-ended Informal Consultative Process on Oceans and the Law of the Sea was anthropogenic noise which includes shipping (UN, 2018).

et al., 2012). Overall, there is no one-size-fits-all solution to underwater noise from vessels (Berkowitz and Dumez, 2017). Mitigation options on vessels should preferably be applied during the design phase (Beltran Palomo, 2014; Berkowitz and Dumez, 2017). Some noise reduction methods incorporated in the design phase also increase efficiency (Jasny, 2014). In the design phase, a 3–5 dB underwater noise reduction could be achieved at about 1% of the total cost of the vessel (Berkowitz and Dumez, 2017). Some experts consider that retrofitting to improve the current environmental impact of old vessels is not technically and economically feasible on a broad scale (Beltran Palomo, 2014). Moreover, there is insufficient information for wide-ranging cost-benefit analyses (Rijkswaterstaat, 2015). Imposing regulatory limits on the noisiest vessels could be the most effective solution (Bureau Verita, DNV GL, 2015). This process might be done more quickly by publishing lists of the noisiest vessels and recognizing the best ones.

Given the difficulty in applying design measures, operational measures can provide a short-term solution to tackling underwater noise from shipping. Such operational measures can involve limiting or optimizing speed, traffic regulation, zoning and the creation of marine protected areas (Bureau Verita, DNV GL, 2015). However, for certain vessels, namely large research vessels and coastal tankers, the propeller can generate high noise levels at low ship speeds. And by traveling at a lower speed, the vessel will remain for a longer time in the area concerned. The best solutions need to be found by exploring ship traffic scenarios using appropriate propagation models which should be verified by measurements.

Since there is very little information available on the effects of the increased ambient noise level on marine biodiversity and ecosystems, it is yet not possible to give concrete advice on how to interpret the results of the measurements (OSPAR, 2014). Indeed, in order to link a pressure indicator on underwater noise to a good environmental status, there is a need to establish thresholds which are consistent with the status indicators for biodiversity (HELCOM, 2016a).[12] Some preliminary analyses and tools for chronic and cumulative multi-sector noise exposure levels are available for marine mammals (Wright, 2009; Wright et al., 2009; Dolman and Jasny, 2015).

The harmonization and the improvement of measuring procedures, as well as an agreement on the thresholds between analysts and the marine industry are key (TSG UW Noise, 2013; Bahtiarian, 2017; Bureau Verita, DNV GL, 2015; appendix A1.4). ICES No.209 limits for fishing research vessels, for instance, are too permissive according to some scientists. Conversely, they are considered as excessive by shipbuilders (Beltran Palomo et al., 2012). Moreover, there is no clear evidence that the investment in noise abatement in research vessels associated with ICES recommendations has reduced fish avoidance reactions (De Robertis and Handegard, 2013).

Some countries have developed monitoring programs on underwater noise from shipping, as well as studies (Table A1.3 in the appendix). Moreover, there are a limited number of countries where regulations are already in place or are planned. In the United States, the Greater Farallones and Cordell Bank sanctuaries have experimented with voluntary speed reductions for vessels to protect whales from strikes and acoustic impacts (Joint Working Group on Vessel Strikes and Acoustic Impacts, 2012). In Germany and in Sweden, noise generating activities are excluded from certain areas, for instance, by moving shipping lanes (HELCOM, 2017b). In Sweden, there are also design and onboard machinery measures aimed at mitigating the noise from ship traffic on a voluntary basis. These measures should improve fuel efficiency and maintenance (HELCOM, 2017a). In Malta, noise and light emissions from navigation and other sea-based recreational activities are regulated in two special marine areas. In Australia, there are speed limitations in certain zones for cetaceans (Commonwealth Department of the Environment and Energy, 2000).

The most important actions on underwater noise from shipping have taken place in Canada. Since 2014 the Vancouver Fraser Port Authority is working with stakeholders through the Enhancing Cetacean Habitat and Observation (ECHO) Program (IMO, 2018b). It is monitoring noise from shipping and sounds from marine mammal vocalizations (Vancouver Fraser Port Authority, 2018). To our knowledge, it is the first port with a permanent noise monitoring system (Bahtiarian, 2017). Since 2017, the port authority has also been implementing a voluntary vessel slowdown trial for commercial vessels in important known foraging areas for southern resident killer whales. The Vancouver Fraser Port Authority and the Prince Rupert Port Authority have offered incentives to ships using quieting technology or with quiet notations since 2017, making Canada the first country to provide such incentives.[13] In 2019, both ports added the Green Marine performance indicator that integrates new criteria for underwater noise. Its goal is to reduce the impact of this noise on marine mammals (Jasny, 2014).

3. The methodology

3.1. The scope of the project

A steering committee was set up in 2018 to provide guidance on the analysis reported in this paper on underwater noise from shipping (Appendix 2). The members of the steering committee are key experts or major players in the field of underwater noise. There are 36 members from the following social groups: port authorities and administrations, the shipping sector, the fisheries sector, analysts and the biodiversity conservation community. 24 members of the steering committee are from Europe, 11 members from North America and one member from South Africa.

The IMO has already issued guidance on ship-quieting measures to address adverse impacts on marine life, but these are non-mandatory recommendations (IMO, 2014). Moreover, IMO's mandatory recommendations in the past concerning onboard noise on ships have taken several decades to be approved by Member States and some experts consider they are not sufficiently effective (high emission thresholds), even though this noise directly affects humans. In order to develop short-term management actions on underwater noise from shipping it was decided to work at the scale of ports. Ports have an important role in supporting the shipping sector to successfully manage the transition to clean shipping, including reducing underwater noise. In particular, the actions ports take to reduce underwater noise can play an important supporting role in driving behavioural change.

3.2. The design of the survey

The objective of the survey was to find the best compromise solutions which will act on underwater noise from shipping and integrate the needs of the target audience, namely, port authorities, the maritime affairs administration, the shipping sector, the fisheries sector, analysts and the biodiversity conservation community (Appendix 2). The target audience for the survey was selected with the information provided by the members of the steering committee. The first version of the survey

[12] Species-contingent limits should integrate behavioural and masking effects (IWC, 2014; IWC, 2015). Such limits should ideally also take into account the chronic and cumulative impacts of noise-generating and non-noise-generating activities that exert pressure over biodiversity and ecosystems (HELCOM, 2018c).

[13] Vessels with cavitation reduction or wake flow improvement technologies, including Becker Mewis ducts, MMG Energy Savings Cap, Nakashima ECO-Cap, Nakashima Ultimate Rudder, Propeller Boss Caps Fin (PBCF), Schneekluth duct and Wärtsilä EnergoProFin are eligible for a 10% (Prince Rupert Port Authority) or 23% (Vancouver Fraser Port Authority) discount in harbour dues (Vancouver Fraser Port Authority, 2018, 2020; Port of Prince Rupert, 2019, Appendix A1.5).

was tested in a case study of the port of Le Havre (Recuero Virto et al., 2019).

The first conclusion that can be drawn from the survey is that underwater noise solutions will depend on the particular port's characteristics and local fauna. This fact was taken into account to consolidate all the survey responses into one cohesive set of conclusions. The survey is composed of three main questions. In the first two questions, the survey conveys two perspectives (Appendix 3). The first perspective is an individual ship as a point source and its impact on near and medium range receivers. The second perspective is shipping as a whole and its contribution to ambient noise levels at the port, regional and ocean basin levels. The first question in the survey proposes a set of options that ports could support to reduce underwater noise from shipping (AQUO consortium, 2014; Vakili, 2018; Merchant, 2019; Vard Marine Inc., 2019).[14] Respondents are required to provide a score between 1 and 10, where 1 means a very low value and 10 a very high value.

Concerning design measures, while structural solutions (structural damping, increasing hull thickness, using lightweight materials like fibre reinforced plastic) should be added at the shipbuilding stage, they can sometimes be expensive. Other solutions associated with the propeller and the hull (EnergoProFin – Wärtsilä, high skew propellers, Schneekluth ducts, Becker Mewis ducts, ECO-Cap – Nakashima, propeller boss cap fins, decoupling of hull coating) can be implemented during dry dockings and can have relatively short payback times. Design options to reduce machinery noise in existing vessels include the use of elastic mountings, considered to be a cost-efficient solution, and the inclusion of an active insulation, which is very effective but too expensive for commercial shipping. Larger ships mean fewer total transits, and more cargo carried at smaller increases in engine size. Both of these factors should help reduce underwater noise from shipping. The use of fuel cells can reduce radiated noise, but they are more expensive than ordinary fuel and require new propulsion systems (Tronstad et al., 2017). Noise requirements could be aligned with transport capacity. This would enable heavier vessels to be noisier as is the case in the aircraft industry. In turn, it would provide incentives to use fewer and larger vessels (Merchant, 2019).

Regarding operational measures, propeller and hull maintenance solutions (propeller repair or maintenance, hull cleaning) can be implemented during docking periods and result in modest reductions in noise emissions with costs depending on the size of the propeller and hull. The optimal condition of trim and ballast improve fuel consumption and may also reduce noise propagation. Indeed, vessels are designed to operate at specific speed and load conditions. Traffic control solutions (speed reduction, travel in convoy, regulated areas) may reduce underwater noise emissions but increase traveling time and hence have an impact on time efficiency. An optimal trade-off between intensity and the length of exposure may be reached at a speed of about 8 knots (McKenna et al., 2013). Moreover, although ports have a certain jurisdictional power within their territorial waters, it is usually limited to a very small geographical area. Hence, when ports ask ships coming into port to slowdown, or reroute, the geographical area affected is very small with the exception of some ports that play an important leadership role beyond their territorial waters such as the Vancouver Fraser Port Authority. The use of onshore power facilities at ports reduces underwater noise locally but requires a significant investment by ports and ship owners and is reliant on the local electricity market to be implemented successfully.

For each option proposed in this question, the synergies between underwater noise reductions, energy efficiency increases and air emission reductions are described in Appendix 3 (Gassmann et al., 2017; Vakili, 2018; OCDE/ITF, 2018a). It is important to emphasize that increasing efficiency does not necessarily result in a reduction in underwater noise emissions. In general, this is the case for energy efficiency, but typically not for other forms of efficiency such as the utilization of capacity (number of ships needed), time efficiency and cost efficiency. The survey focuses on energy efficiency because it is perceived as a major issue for the shipping sector given the weight of fuel consumption on operational costs. It also focuses on air emissions since ports are concerned about this type of pollution due to local pressure.

The second question in the survey proposes a set of actions that ports should preferably take to reduce underwater noise from shipping. Respondents are required to provide a score between 1 and 10, where 1 means a very low value and 10 a very high value. Many of the actions in Appendix 3 are inspired by the actions made available to ports to reduce greenhouse gas emissions (OCDE/ITF, 2018b). These emissions have impacts at the global scale, like underwater noise emissions, in contrast to other air emissions that are mainly of a local concern such as sulphur oxides, nitrogen oxides and particulate matter. Environmental port fees for energy efficiency were applied by 28 of the world's major ports as measured by tonnage or container volume in 2018. Environmental port fees have been used as an incentive for speed reductions in four ports (12 knots at a distance of 20 to 40 nautical miles from the port): Los Angeles, Long Beach, New York-New Jersey and San Diego. They have also been used to support the use of low-carbon fuels/energy, in particular liquefied natural gas, to support the reduction of air emissions in six ports: Antwerp, Bremerhaven, Gothenburg, Hamburg, Rotterdam, Singapore and the Panama Canal Authority. Some ports and countries also provide financial incentives for ships that use onshore power facilities to reduce local air emissions: Port of Vancouver (discounts on port fees), Stockholm (subsidy) and Sweden (tax exemption).

Most of these environmental port fees are based on one or more indexes relating to the environmental performance of the ship, particularly energy efficiency and air emissions. Most port fee rebates range from 5% to 20%, although some ports offer a 50% discount.[15] Some ports offer a fixed amount that is regularly revised upwards to increase the incentives for ships to adopt the suggested changes. Rebates remain marginal with respect to total operating costs. Incentives are economically meaningful for ships to adopt changes only once a large number of ports join a specific initiative. As such, coordination between ports in setting priorities, as well as the harmonization of indexes and their widespread use by ports will favour the adoption of the requested changes by the shipping sector. While higher degrees of differentiation in port fees between "green" and "dirty" ships could probably drive more change, ports typically only offer discounts to higher performance ships. This means the costs are paid for only by ports and therefore there is no leakage effect associated with port competition. This is not consistent however, with the polluter-pays principle since lower performance ships are not penalized.

Greener ships have priority in the allocation of berth slots through the Environmental Premium Program in Panama that has been in place since 2017. Similarly, ports are only beginning to focus on reducing waiting and turn-around time at ports. Ship waiting and turn-around time impacts the operational costs of ships associated with speed slowdown but also emissions. However, minimizing this time requires the engagement of port authorities and terminal operators and they do not necessarily have the incentives to set up such programs. In terms of

[14] Technical solutions not included in the first question in Appendix 3 may be very specific, may have an important drawback or have not been sufficiently tested. These technical solutions include changes in propellers (water jets, forward skew propellers in ducts, contracted and loaded tip propellers), propulsion types (pod propulsion), reductions in turns per knot, the optimization of hull design, acoustic enclosure, wake conditioning devices (nozzles, Grothues spoilers), double hulls, Nautronix signal acoustic digital spread and Sonardyne signal Wideband.

[15] The Port of Long Beach CA offers a 100% rebate for vessels that use shore power while at berth and slow to less than 12 knots inside 40 nautical miles both inbound and outbound.

Table 3.1
Question 3: Using the comparison scale, which of the following options can help support port actions to reduce underwater noise from shipping?

Designation	Options
O_1	Raising awareness (among port staff and the general public; through training, ports' corporate social responsibility reports)
O_2	Actions of a voluntary nature
O_3	Focus on key priorities (noisiest ships, biodiversity hotspots)
O_4	Integration with other actions (other actions on air emissions and energy efficiency; for example, by making underwater noise a key green indicator)
O_5	Different actions applied to green and dirty ships (not only positive actions for green ships)
O_6	Broad stakeholder participation
O_7	Cooperation between ports to scale up actions (greater harmonization of green actions and indicators; joint request for action by the IMO)
O_8	Political and/or social demand
O_9	Effectiveness assessment (through monitoring, reporting, verification)

green procurement, many European ports use environmental criteria to award concessions to terminal operators. Environmental criteria are rarely taken into account in licenses or contracts with towage or dredging companies. Furthermore, some researchers argue that onshore power could reduce underwater noise impacts on marine species, but also the spread of invasive species among vessels in ports (Weilgart, 2018). However, an appropriate port design may involve significant costs for the port and has only a very local impact on underwater noise emissions (Merk, 2013). The use of devices to displace marine fauna such as acoustic deterrents or to act as a barrier against noise such as air bubble curtains should be used only in the local presence of species that can be potentially impacted by underwater noise emissions from shipping. Acoustic deterrents are problematic in that they add yet more noise and often do not just displace the species of interest, but a broader number of species.

The third question in the survey proposes nine management options ($q = 9$) that can help support port actions to reduce underwater noise from shipping (Table 3.1). Best practices in past marine spatial planning experiments have been explored to analyse their degree of effectiveness and efficiency in addressing coordination problems between stakeholders in coastal and marine areas, and to find out to what extent they can apply to underwater acoustic pollution from shipping (Jay, 2017). The answers to question 3 are used as input to feed a group decision making model valid for the aggregation of the individual preferences to obtain group preferences (González-Pachón and Romero, 1999; Linares and Romero, 2002). This type of methodology is based upon the decision-making approach known as goal programming belonging to the multiple criteria decision making (MCDM) paradigm (Ignizio, 1985; Romero, 1991). Using this methodology, respondents are required to compare two options at a time (Appendix 3).[16]

There are two parts to this MCDM methodology. First, for each social group, the individual member weights associated with each criterion are aggregated to achieve the social group's preference for each criterion. Second, the solutions obtained for each social group are then aggregated to achieve the preferences of society as a whole on each criterion. In the first part of the analysis, aggregation of the answers of each social group's members can be performed using a median weight. Indeed, the members of the same social group are supposed to have similar social perceptions. In the second part of the analysis, the aggregation method should take into account the fact that the social groups' preferences for each criterion may reflect a wide range of social perceptions. In this context, the following extended goal programming model is proposed for the aggregation of the social groups' preferences (Romero, 2001; Linares and Romero, 2002):

Achievement function:

$$Min\ (1-\lambda)D + \lambda \sum_{i=1}^{q} \sum_{j=1}^{m} \left(\overline{n}_{ij} + \overline{p}_{ij}\right) \tag{1}$$

such that

Goals:

$$\begin{aligned} &\sum_{i=1}^{q} (\overline{n}_{i1} + \overline{p}_{i1}) - D \leq 0 \\ &\cdots \\ &\sum_{i=1}^{q} (\overline{n}_{im} + \overline{p}_{im}) - D \leq 0 \end{aligned} \tag{1.1}$$

…

$$W_i^s + \overline{n}_{ij} - \overline{p}_{ij} = W_i^j, i \in \{1,\dots,q\}, j \in \{1,\dots,m\} \tag{1.2}$$
$$\overline{n} \geq 0, \overline{p} \geq 0, \lambda \in [01]$$

Accounting rows:

$$\begin{aligned} &\sum_{i=1}^{q} (\overline{n}_{i1} + \overline{p}_{i1}) - D_1 = 0 \\ &\cdots \\ &\sum_{i=1}^{q} (\overline{n}_{im} + \overline{p}_{im}) - D_m = 0 \end{aligned} \tag{1.3}$$

…

$$\sum_{i=1}^{q} \sum_{j=1}^{m} (\overline{n}_{ij} + \overline{p}_{ij}) - Z = 0 \tag{1.4}$$

where $i = \{1,\dots,q\}$ are the criteria with $q = 9$, $j = \{1,\dots,m\}$ are the social groups with $m = 6$, $\overline{n}_{ij}$ and $\overline{p}_{ij}$ are the negative and positive deviation auxiliary variables measuring the difference between the consensus value for the ith criterion and the value attributed to the ith criterion by the jth social group, λ is the control parameter, D represents the disagreement of the social group with the preferences that are most different from the consensus obtained, D_1, …, D_m represent the disagreement of each group with respect to the consensus obtained, W_i^j is the preference weight attached to the ith criterion by the jth social group, W_i^s is the preference weight attached to the ith criterion by society and $Z = \sum_{i=1}{}^{m} D_i$.

The achievement function (1) is used to derive the final weights W_i^s attached to each criterion by society from the intermediate weights W_i^j attached to each criterion by each social group. For $\lambda = 0$, the achievement function is Min D subject to Eqs. (1.1)–(1.4), where the model finds a consensus for society that minimizes the disagreement of the most displaced social group, the minority consensus. For $\lambda = 1$, the achievement function is $Min \sum_{i=1}^{q} \sum_{j=1}^{m} \left(\overline{n}_{ij} + \overline{p}_{ij}\right)$ subject to Eq. (1.2), where the model instead finds a consensus for society that maximizes the average agreement, the majority consensus. For the intermediate values of λ, the model derives compromise solutions between the minority and the majority consensus.

4. The survey results

The data from 38 respondents were collected between March and June 2019. The respondents worked in institutions located in 15 countries in the European Union and in North America. There were a larger number of respondents from the United States (6), France (6), Canada (4), Sweden (4), the Netherlands (3) and Denmark (3) than from the remainder of the countries (Table A4.1 in the Appendix). The number of social groups is designated by m, where $m = 5$. Indeed, there were eight respondents from port authorities, four respondents from maritime affairs administrations, 10 from the shipping sector, 12 from the academic or environmental consulting sector, and four from non-governmental

[16] The weights for the criteria are determined for each of the matrices with preference values using the eigenvalue technique (Nordström *et al.,* 2012). Under this methodology, the eigenvector corresponding to the largest eigenvalue is found for each pairwise comparison (Saaty 1997, 1980).

Table 4.1
Social groups.

Designation	Social groups	Stakeholders
D_1	Port authorities	Port authorities
D_2	Maritime affairs administration	Maritime affairs administration
D_3	The shipping sector	Ship owners and industry, shipyards including engineering consulting firms and ship classification societies and marine-life-watching sea cruises.
D_4	Analysts	Academics and environmental consulting firms.
D_5	The biodiversity conservation community	Institutions specializing in marine mammals and non-governmental organizations.

Concerning question 1, "while acknowledging the wide variations in ports' specificities, which of the following options should port actions preferably seek to support to reduce underwater noise from shipping?", at the aggregate level (last column in Table 4.2) there are two options that are preferred. Firstly, respondents preferred changes in the design of the hull, the propeller or the engine with an 8.4 score out of 10. Secondly, respondents preferred operational measures associated with reduced speed, change of route and travel in convoy with a 7.9 score out of 10. At the aggregate level, ship maintenance was the third option preferred by respondents with a 6.9 score out of 10. Respondents gave the lowest score to changes in design to produce larger ships with a 5.5 score out of 10. A respondent noted that larger vessels are not a possible option in marine areas such as the Baltic Sea. Respondents had a slight preference for options with local impacts on underwater noise (7.2) compared to global impacts on underwater noise (6.6). Respondents gave an overall score of 6.7 out of 10 to the options proposed with global and local impacts on underwater noise.

Table 4.2
While acknowledging the wide variations in ports' specificities, which of the following options should port actions preferably seek to support to reduce underwater noise from shipping? (mean values, question 1).

	Port authority	Maritime affairs administration	Shipping sector	Analysts	Biodiversity conservation community	All groups
Design: Hull, propeller, engine	6.5	9.0	8.7	9.0	8.8	8.4
Design: Type of fuel	7.0	7.3	5.3	5.5	5.3	6.1
Design: Larger vessels	5.4	6.0	5.6	5.3	5.3	5.5
Operational: Ship maintenance	6.1	7.3	6.9	7.1	7.3	6.9
Operational: Ships operate at design load conditions	4.9	6.0	6.4	6.3	6.3	6.0
OPTIONS WITH GLOBAL IMPACTS ON UNDERWATER NOISE	6.0	7.1	6.6	6.6	6.6	6.6
Operational: Reduced speed, change of route, travel in convoy	5.6	8.5	8.5	7.8	9.0	7.9
Operational: Ships use onshore power supply facilities at ports	4.9	7.0	7.5	7.4	5.7	6.5
OPTIONS WITH LOCAL IMPACTS ON UNDERWATER NOISE	5.3	7.8	8.0	7.6	7.3	7.2
OPTIONS WITH GLOBAL AND LOCAL IMPACTS ON UNDERWATER NOISE	5.8	7.3	7.0	6.9	6.8	6.7

Note: Respondents were requested to enter a number between 1 and 10, where 1 means a very low value and 10 a very high value.

Table 4.3
While acknowledging the wide variations in ports' specificities, which of the following actions should ports preferably take to reduce underwater noise from shipping? (mean values, question 2).

	Port authority	Maritime affairs administration	Shipping sector	Analysts	Biodiversity conservation community	All groups
Port fees charged according to underwater noise performance	5.6	7.0	8.4	7.8	9.0	7.6
Priority in the allocation of berth slots for ships generating less underwater noise	5.0	7.3	6.9	5.3	8.5	6.7
ACTIONS WITH GLOBAL IMPACTS ON UNDERWATER NOISE	5.3	7.1	7.7	6.8	8.8	7.1
Underwater noise criteria in selecting port service providers	4.4	6.5	5.9	6.2	8.3	6.2
Reduction in ship waiting time at ports through collaboration along the entire logistical maritime chain	6.0	8.8	6.7	7.0	8.3	7.3
Proper port and barrier design, onshore energy facilities	5.1	8.3	7.4	6.4	5.7	6.6
Underwater noise mitigation equipment to protect local fauna	3.9	5.0	5.1	5.9	2.7	4.5
ACTIONS WITH LOCAL IMPACTS ON UNDERWATER NOISE	4.8	7.2	6.3	6.4	6.2	6.2
ACTIONS WITH GLOBAL AND LOCAL IMPACTS ON UNDERWATER NOISE	5.0	7.1	6.7	6.5	7.1	6.5

Note: Respondents were requested to enter a number between 1 and 10, where 1 means a very low value and 10 a very high value.

institutions (Table A4.2 in the appendix). The eight respondents from ports came from six countries and they all worked for ports that are considered large in terms of container and/or cargo volume.[17] The final set of social groups that were part of the analysis can be found in Table 4.1.

In Tables 4.2 and 4.3, the mean values of the answers of each group of respondents to questions 1 and 2 in the survey are presented.

Two key differences show up when analysing responses from each interest group to question 1. Firstly, respondents from port authorities gave much lower scores to the options proposed in Table 4.2 than the respondents from the other interest groups. This is particularly the case for changes in the design of the hull, the propeller and the engine, and for operational options associated with reduced speed, change of route and travel in convoy. In addition, there is a large variance in the scores attributed by ports compared to the other interest groups (Table A4.3 in

[17] There were no respondents from the fisheries sector. This is consistent with the preliminary findings which showed that the fisheries sector considered underwater noise to be a minor problem among other sectoral concerns.

Table 4.4
Using the Saaty comparison scale, which of the following options can help support port actions to reduce underwater noise from shipping? (median values in percentage, question 3).

	Port authority	Maritime affairs administration	Shipping sector	Analysts	Biodiversity conservation community
Raising awareness	3	2	3	10	4
Actions of a voluntary nature	9	2	2	2	3
Focus on key priorities	11	16	14	11	18
Integration with other actions	15	30	19	15	17
Different actions applied to green and dirty ships	12	8	12	11	12
Broad stakeholder participation	18	9	15	18	11
Cooperation between ports to scale up actions	20	19	18	15	15
Political and/or social demand	7	8	9	12	15
Effectiveness	6	7	9	7	7

Note: Respondents were requested to enter a number between one and nine, where one means that the option is as important as the other options and nine implies the option is extremely more important than the other options. The table reports the group median for the individual weights of preferences (in percentage).

the appendix). Some respondents from ports noted that the polluters are moving ships, so ship owners, crew and cargo owners should be the first actors to be addressed to put in place mitigation measures. Respondents from port authorities gave the lowest score to ships using onshore power supply facilities at ports and to having ships operating at design load conditions with a 4.9 score out of 10 in both cases. A respondent noted that shore power is a very costly solution that is unlikely to reduce the impact of underwater noise on marine species. The economic viability of this option depends on the local energy market. A respondent from the shipping sector also argued that in the case of ensuring that ships operate at design load conditions, there is a need to understand how these mechanisms would be defined, measured and inspected at the port.

The other key difference when analysing responses from each interest group to question 1 is that respondents from all groups, with the exception of those from port authorities, gave very similar scores across all options. There are only two exceptions. Respondents from the maritime affairs administration gave a high score to design options associated with alternative fuels (as did respondents from ports authorities) compared to respondents from the shipping sector, analysts and non-governmental organizations. Moreover, analysts gave a lower score to operational options associated with lower speed, change of route and travel in convoy compared to the maritime affairs administration, the shipping sector and non-governmental organizations. Some respondents from the analyst sector argued that the impact of travel in convoy on underwater noise needs further investigation. There is a trade-off between the time that sensitive species are exposed to sound (which would be reduced by vessels in convoys) and the level at which they are exposed (which could be increased by convoys). A respondent from the shipping sector noted that the science for speed optimization regarding underwater noise for different vessel types is not yet clearly defined or understood.

In Table 4.3, the mean values of the answers given by each group of respondents to question 2 of the survey, "while acknowledging the wide variations in ports' specificities, which of the following actions should ports preferably take to reduce underwater noise from shipping?", are presented. At the aggregate level, there are two preferred options. Firstly, respondents preferred port fees charged according to underwater noise performance with a score of 7.6 out of 10.[18] Secondly, respondents preferred a reduction in ship waiting time at ports through collaboration along the entire logistical maritime chain with a score of 7.3 out of 10. A respondent from a maritime affairs administration stated that fees based on an acoustic "footprint" need further examination as local acoustic measurements may vary widely depending on the environment and local acoustics. Moreover, measuring acoustic footprints requires significant investments, which so far have been paid for by the public sector. Therefore, at this stage these kinds of fees should be based only on the values given by the classification societies and thus remain simple and cost-effective. Ideally, ships should be able to see whether they are eligible for a port fee reduction based on the vessel's specifications.

At the aggregate level, the lowest score for question 2 was attributed to the use of underwater noise mitigation equipment to protect local fauna (4.5 out of 10). The effectiveness of acoustic deterrent devices can be questioned. Shipping generates continuous noise and local intermittent noise, which is sub-lethal. The introduction of acoustic deterrent devices would only worsen the situation by adding yet another continuous/intermittent noise source to a noisy environment. A respondent from a non-governmental organization supported air bubble curtains that can be quite effective at reducing noise levels. Another respondent from a maritime affairs administration agreed with the use of bubble curtains and other noise reduction technology but disagreed with the use of deterrents as they simply add noise and there is little/no research to prove that marine fauna such as whales will behave as planned. At the aggregate level, respondents had a preference for actions with global impacts on underwater noise (7.1) compared to local impacts on underwater noise (6.2). Respondents gave an overall score of 6.5 out of 10 to the actions proposed with global and local impacts on underwater noise.

There are two key differences when analysing responses from each interest group to question 2. Firstly, as in question 1, respondents from port authorities almost systematically gave much lower scores to the options proposed in question 2 than the respondents from the other interest groups. This is particularly the case for the use of port fees charged according to underwater noise performance. In addition, as in question 1, there is a large variance in the scores attributed by ports (and by analysts) compared to the other interest groups (Appendix 3). Secondly, there are systematic and significant differences between the scores of respondents from the analytical sector and the scores of respondents from non-governmental organizations, probably reflecting the absence of sufficient scientific evidence on the impact of the proposed actions on underwater noise.

In order to analyse the data in question 3 of the survey, "using the Saaty comparison scale, which of the following options can help support port actions to reduce underwater noise from shipping?", we proceed in four steps. In the first step of the analysis, a q • q matrix is derived for each respondent through the pairwise comparison procedure described in the previous section. There are 33 responses to question 3 that could be exploited: port authorities (5), maritime affairs administrations (3), the shipping sector (10), analysts (11) and the biodiversity conservation community (4). In the second step of the analysis, weights for criteria are determined for each of the 33 matrices with preference values given using the eigenvalue technique. As a result, for each of the 33 individual responses, nine weights are obtained corresponding to the nine criteria under a 9 • 1 matrix.

[18] A State could adopt regulations that require, as a condition of port entry, that vessels are compliant with its national acoustic regulations whenever those vessels are in its territorial waters. This strategy could prove problematic for much of the world since vessels can trade with another port State.

Table 4.5
Social weights used with the extended goal programming model (question 3).

Z	D	D_1	D_2	D_3	D_4	D_5	W_1^s	W_2^s	W_3^s	W_4^s	W_5^s	W_6^s	W_7^s	W_8^s	W_9^s
Majority consensus ($\lambda = 1$)															
0.93	0.28	0.20	0.28	0.04	0.22	0.19	3	2	14	17	12	15	18	9	7
Minority consensus ($\lambda = 0$)															
0.99	0.24	0.24	0.24	0.10	0.24	0.17	3	2	14	17	11	12	17	8	7
Compromise solution ($\lambda = 0.5$)															
0.97	0.24	0.22	0.24	0.08	0.24	0.19	3	2	14	17	11	13	18	8	7

Note: This table shows the results of the MDCM model in Table A4.7. Z is the sum of D_1-D_5, D measures the maximum of the values D_1-D_5, D_1-D_5 represent the disagreement of each group as listed in Table 4.1 with respect to the consensus that is obtained, and W_1^s-W_9^s are the reference weights (in percentage) attached by society to each criteria as listed in Table 3.1.

In the third part of the analysis, the data are aggregated per group of respondents. The model (1) was applied to the individual responses from each group. Five extended programming models were solved, one per group of respondents.[19] In Table 4.4, the median values of the answers of each group of respondents to question 3 in the survey, "using the Saaty comparison scale, which of the following options can help support port actions to reduce underwater noise from shipping?", are presented. Two criteria received the highest scores from the different groups of respondents: cooperation between ports to scale up actions and integration with other actions. Each group of respondents attributed a very low score (lower or equal to 10) to three of the proposed criteria: raising awareness, actions of a voluntary nature and effectiveness. The score given to the "broad stakeholder participation" criterion was particularly low for maritime affairs administration, 9%, whereas the other groups attributed scores of between 11% and 18%. In particular, ports and analysts attributed a score of 18% to these criteria. The biodiversity conservation community attributed a score of 15% to political and/or social demand, whereas the scores for this criterion were below 10% for ports, maritime affairs administrations and the shipping sector.

In the second step of the analysis of question 3 in the survey, "using the Saaty comparison scale, which of the following options can help support port actions to reduce underwater noise from shipping?", the data corresponding to each group are aggregated. Table A4.7 in the appendix shows the formulation of the associated extended goal programming model, and Table 4.5 shows the results of the estimation. The second row in Table 4.5 corresponds to the solution that maximizes the average agreement, the third row corresponds to the solution that minimizes the disagreement of the most displaced group, and the fourth line corresponds to a compromise solution.

The results are very robust as they are similar across rows 2–4 in Table A4.7 in the appendix shows the formulation of the associated extended goal programming model, and Table 4.5. The remainder of the paper will refer to the compromise solution results.[20] At the aggregated level, the highest scores for question 3 were attributed to cooperation between ports to scale up actions (W_7^s with a score of 18%) and to integration with other actions (W_4^s with a score of 17%). Two options were also attributed relatively high scores: the focus on key priorities and broad stakeholder participation (W_3^s and W_6^s with scores of 14% and 13%, respectively).[21] The "different actions applied to green and dirty ships" option had a score of 11%.

The largest difference between the solution that maximizes the average agreement and the solution that minimizes the disagreement of the most displaced group is associated with the "broad stakeholder participation" option (with scores between 13% and 15%). Otherwise, the W_1^s-W_9^s scores are similar across the different groups. Therefore, changing the assumption in our estimation that each group has the same social influence should not have a significant impact on the final results. Moreover, the lowest scores are attributed to raising awareness and actions of a voluntary nature (W_1^s and W_2^s with scores of 3% and 2%, respectively). Political and/or social demands and effectiveness are also attributed very low scores (8% and 7%, respectively).[22][23]

5. Conclusion

This paper provides data-based guidance on the characteristics of management frameworks conducive to reducing underwater noise from commercial shipping, the dominant source of underwater noise. While acknowledging the wide variations in ports' specificities, according to the results of the survey there are two options that port actions should preferably seek to support to reduce underwater noise from shipping. Firstly, respondents preferred changes in the design of the hull, the propeller or the engine. Secondly, respondents preferred operational

[19] Table A4.5 in the appendix shows, for instance, the formulation of the extended goal programming model for the group of non-governmental organizations, and Table A4.6 in the appendix shows the results of the associated estimation.

[20] In the second row in Table 4.5, the most displaced group are the maritime affairs administrations (with a 0.28 score for D_2) and the sum of the disagreements across all groups has a score of 0.93 for Z. In the third row in Table 4.6, when minimizing the disagreement of the most displaced group, the groups have less dispersed disagreement values with respect to the consensus (with values between 0.10 and 0.24 for D_1-D_5), but the sum of the disagreements across all groups has a higher score than when maximizing the average agreement (with a score of 0.99 for Z). In the fourth row in Table 4.6, the compromise solution enables a lower score to be obtained for the maximum disagreement of the maritime affairs administrations than when maximizing the average agreement (with a score of 0.24 for D_2 and D), while achieving a lower value for the sum of the disagreements across all groups compared to the solution minimizing the disagreement of the most displaced group (with a score of 0.97 for Z).

[21] According to one respondent, the Vancouver Fraser Port Authority ECHO Program's key findings highlight the role of consultation of stakeholders. The most relevant lessons learned about participation are the following: building knowledge and trust takes time, challenging conversations are healthy and help map a better path forward for all, and early and frequent face-to-face interaction with multi-interests raises engagement levels and is key to identifying gaps and developing research questions.

[22] A respondent from the maritime affairs administration stated that pressure from the public on underwater noise from shipping is unlikely, as the link between consumer choice and the way goods are transported is too diffuse. A respondent from the shipping sector stated that political and social demands will definitely help ports prioritize decisions with regard to investments to reduce their environmental footprint. However, underwater noise is not currently one of their main priorities as opposed to air emissions, for example.

[23] A representative from the shipping sector argued that a monitoring, reporting and verification scheme for underwater noise is too cumbersome and implies too many costs for ship owners. This type of scheme is already in place for carbon dioxide emissions from fuel consumption. In contrast, according to one respondent, among the Vancouver Fraser Port Authority ECHO Program's key findings are the following topics: technical working groups are essential for formulating work plans, robust data and multiple account evaluation are essential for informed, evidence-based decision-making and finding the best solutions requires tests, trials and adaptive management.

options associated with reduced speed, change of route and travel in convoy. Moreover, there are two actions that ports should preferably take to reduce underwater noise from shipping. Firstly, respondents preferred port fees charged according to underwater noise performance. Secondly, respondents preferred a reduction in ship waiting times at ports through collaboration along the entire logistical maritime chain. According to the survey, cooperation between ports to scale up actions and integration with other actions were the preferred actions. Two other options were also attributed relatively high scores: the focus on key priorities and broad stakeholder participation.

In order to complement these results from the survey, between November 2018 and August 2019 a series of interviews was held with some major European and North American ports: Port of Antwerp, Bremen Port, Hamburg Port, Port of Le Havre, Port of Rotterdam, Prince Rupert Port Authority and Vancouver Fraser Port Authority. Underwater noise is a concern for ports when there are marine mammals nearby, particularly when they are endangered and emblematic, and current or forecasted shipping traffic is high. According to noise modelling and scientific thresholds, the 2018 voluntary slowdown in the Haro Strait reduced underwater noise in nearby habitats, improving foraging conditions for endangered southern resident killer whales (Vancouver Fraser Port Authority, 2019).[24]

Ports are typically concerned with local air pollution, particularly large ports near urban populations. In particular, port and governmental air quality programs typically focus on criteria pollutants with known health impacts, including SOx, NOx and PM (fine particles). Underwater noise is rarely a local concern, however. Most ports suffer from a wide range of types of local pollution where it is difficult to uncover causal effects. There is little or no knowledge about the impacts of underwater noise on local fauna, there are often no critically endangered marine mammals near ports and the local human population is primarily concerned with air and water quality, and often depends economically on the port's activities.

Moreover, global pollutants (that is, pollutants with effects at the global scale such as greenhouse gas emissions) are not a major issue for ports. Ports do take into account, however, the synergies between actions on air pollution with local effects from sulphur oxide and nitrogen oxide emissions with global effects from greenhouse gas emissions. Given this framework, a solution based on a good understanding of how underwater noise is addressed through different energy efficiency, air quality or water quality measures can result in priority being given to those solutions that are also beneficial for underwater noise. The solutions implemented by ports can be then scaled up, through the development of environmental indexes and classification societies' notations. The scaling-up across a large number of major ports is a necessary condition for the shipping industry to have the incentive to invest in the required solutions, and hence to influence shipyards to change specifications. Overall, a good understanding of the effectiveness of the measures taken to reduce underwater noise is key to tackling this issue, as acknowledged by the European Commission. This type of proposals are coming at a time where vessels owners are already dealing with significant investment requirements and operating costs for the 2020 fuel, ballast water treatment systems, Tier 2 and 3 NOx for new ships, and the upcoming IMO and corporate low/zero CO2 requirements. To be successful, underwater noise programs must align with these factors.

Six Northwest European ports, namely Hamburg, Bremen, Antwerp, Rotterdam, Amsterdam and Le Havre, decided to develop a simple methodology to create an indicator that ship owners could easily provide and that would enable to classify them. As a result, the Environmental Ship Index (ESI) was established in 2011 as an international program developed through the International Association of Ports and Harbors. By 2019, 57 ports were using the indicator which currently covers air emissions (sulphur oxides, nitrogen oxides and carbon dioxide). Given this participation rate from ports, some preliminary evidence suggests that the shipping industry has the incentive to make investments for cost and energy efficiency and for low greenhouse gas operations. While the inclusion of underwater noise is not currently under discussion, airborne noise may be introduced as a new component of the indicator. In this latter case, synergies between airborne and underwater noise could be explored and exploited.

In fact, underwater noise has not been included in the most widely used indexes, i.e. the ESI (5500 ships, 47 ports), the Green Award (835 ships, 33 ports), the Clean Shipping Index (CSI) (2300 ships, 5 ports) and the RightShip (76,000 ships, 2 ports) (OCDE/ITF, 2018b). As an exception, Green Marine has included performance indicators on underwater noise for vessels and ports in its index since 2017 (Green Marine, 2019). These performance indicators aim to reduce the underwater noise made by vessels in order to reduce impacts on marine mammals. Actions include, among other features, incorporating vessel quieting technologies in retrofits or new constructions, and working with ports to estimate vessel noise levels for at least one in three vessels in their fleet.

Design and operational options can be used to reduce noise levels and also to improve energy efficiency. The degree of efficiency is very important for the shipping industry because of the significance of fuel consumption on operational costs. If ships of a similar type and size are compared, the noisiest ships are likely to be among those which are less efficient (Leaper et al., 2014). Moreover, there is evidence that half of the total power radiated by modern vessels comes from 15% of the fleet (Veirs et al., 2017). However, the relationship between energy efficiency and underwater noise emissions needs to be analysed for each technology (Vakili, 2018).[25][26]

In addition, measures exist to reduce carbon dioxide emissions that can also contribute to reducing underwater noise emissions. In particular, design options linked to the propeller and the hull, to the type of fuel, to the size of vessels and operational options associated with ship maintenance (hull, propeller), operating at design load conditions, and the use of onshore power supply facilities at ports, can reduce carbon dioxide and underwater noise emissions (OCDE/ITF, 2018a; Vakili, 2018). Nowadays, carbon dioxide emissions are only taken into account marginally by the Green Award (OCDE/ITF, 2018b).

Speed can be reduced to decrease a vessel's greenhouse gas emissions and potentially its underwater noise emissions. It can also be reduced for safety, local environmental factors (particulate matter and sulphur emissions) and sailing conditions (waves) close to the port (OCDE/ITF, 2018b). However, costs increase when the speed falls below the energy efficiency-speed levels for which the vessel was designed. A number of ports have set regulations or incentive programs to reduce vessel speed: Los Angeles and Long Beach since 2001, San Diego since 2009, New

[24] According to observed data, an increase in underwater noise level is correlated to an increased probability that whales will stop or not start foraging.

[25] A propeller designed for maximum efficiency will likely not be the quietest one. However, improvements in propeller design can be made that are more efficient as well as quieter, especially when the propeller is optimized to the hull. Design options related to the machinery and the hull exist that can improve efficiency and reduce underwater noise emissions. In addition, operational options such as slow steaming, just-in-time, hull and propeller cleaning and maintenance, which are recommended to increase efficiency, can also reduce underwater noise emissions.

[26] The relationships between energy efficiency and underwater noise should be clearly identified. In turn, the following indicators on energy efficiency could be used to reduce underwater noise emissions: the Energy Efficiency Design Index (EEDI), the Ship Energy Efficiency Management Plan (SEEMP) and the Existing Vessel Design Index (EVDI) (Rightship, 2013). The EEDI relates to design options and applies to vessels of 400 gross tonnage and above built after January 1, 2013. The EVDI is a similar indicator that applies to existing vessels. The SEEMP deals with operational options that improve the vessel's efficiency through better management and implementation of best practices (Lloyds Register, 2011).

York-New Jersey since 2010 and Vancouver (First Narrows) since 2019 (trial in 2018). These initiatives mainly aim to reduce local air pollution (Los Angeles, Long Beach, New York-New Jersey) and address safety issues under heavy traffic conditions (Vancouver). Some offer financial incentives through fee rebates (Los Angeles, Long Beach, New York-New Jersey), while others provide public acknowledgement (San Diego). In Vancouver, the speed reduction in First Narrows is now compulsory after a voluntary trial in 2018. This compulsory slowdown is in addition to the voluntary slowdown implemented by the ECHO program in Vancouver since 2017 with the specific goal of reducing underwater noise emissions. Moreover, the use of onshore energy facilities at ports can be beneficial in terms of greenhouse gas emissions and also help reduce underwater noise (OCDE/ITF, 2018a). Financial incentives have been proposed by several ports or countries: Vancouver (port discount fee), Stockholm (subsidy) and Sweden (tax exemption) (OCDE/ITF, 2018b).

A series of ports is engaging in actions on airborne noise from shipping. These actions have been introduced because airborne noise is a local concern that impacts the population living near ports. These actions can have an impact on lowering underwater noise emissions. They can be used to establish some principles or, more broadly, a framework to address underwater noise emissions directly. To date, the results of the NoMEPorts initiative on noise management in European ports and the NEPTUNES project could be used to draw up some principles on airborne noise emissions that could be integrated in the ESI index (NoMEPorts, 2008; NEPTUNES, 2019).[27][28]

In order to achieve a long-term solution to the impact of underwater noise emissions from commercial vessels on marine fauna, the Member States of the IMO could create a legally binding international commitment. Canada has submitted a work output proposal to the Marine Environmental Protection Committee of the IMO to review the *2014 Guidelines* and identify next steps. For example, next steps could include amending the annex to MARPOL 1973/78 (Nowacek et al., 2015).[29] In the short term, given the significant uncertainties in determining the biological impacts of underwater noise emissions from shipping at individual and population levels, management should be based on the precautionary approach (CBD, 2012). Determining the effective level of precaution is a significant obstacle in applying this approach, however (McCarthy, 2004). Moreover, ports are particularly concerned about the level of investments that local underwater noise actions could require, particularly acoustic monitoring equipment.[30]

In addition, there is no clear evidence that the past investment in noise abatement in research vessels associated with ICES recommendations has reduced fish avoidance reactions (De Robertis and Handegard, 2013). The development of scientific maps on underwater noise vulnerability per port would be useful both for ports and for ship owners. Individual ports' decisions will depend on the local presence of fauna. The experience gained from aviation noise control could also provide some guidance in terms of the lessons learned, the process, incentive building, monitoring tools and criteria, among other factors. Local demands regarding airborne noise close to airports have boosted the global pressure on the aviation industry to adopt existing quieting technology.[31][32]

CRediT authorship contribution statement

Laura Recuero Virto: Conceptualization, Methodology, Software, Data curation, Writing – original draft. **Hervé Dumez:** Conceptualization, Investigation, Writing – review & editing. **Carlos Romero:** Methodology, Resources, Writing – review & editing. **Denis Bailly:** Conceptualization, Writing – review & editing.

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.

Appendix A. Actions concerning underwater noise from shipping

Table A1.1
International institutions acknowledging the contribution of shipping to underwater noise.

International institution	References
ACCOBAMS	ACCOBAMS (2004, 2007a).
Arctic Council	Arctic Council (2009, 2013).
ASCOBANS	ASCOBANS (2003, 2006).
CMS	CMS (2008, 2011, 2017b).
FAO	FAO (2012).
HELCOM	HELCOM (2013).
IMO	IMO (2007).
IUCN	IUCN (2004).
IWC	IWC (1998, 2011, 2017b).
OSPAR	OSPAR (2009b, 2009c).
UNEP/MAP	UNEP/MAP (2012).
UN	UN (2018).

[27] The partner ports in the NoMEPorts initiative were Amsterdam, Civitaveccia, Copenhagen/Malmo, Hamburg, Livorno and Valencia. Observer ports were Bremen, Gothenburg, Oslo, Rotterdam and Tenerife.

[28] The NEPTUNES project was launched by eleven ports in north-west Europe, Australia and Canada: Amsterdam, Cork, Copenhagen, Malmo, Gothenburg, Hamburg, Koper, New South Wales, Rotterdam, Stockholm, Turku and Vancouver. The Barge Terminal Tilburg in the Netherlands and the Intermodal Terminal WienCont in Vienna in Austria are also putting in place actions to reduce airborne noise, due to their close proximity to residential areas and the volume of their activities.

[29] Note that MARPOL typically phases in new regulations, either by the new building date or by the date of the next out of water survey. The first of these options would mean a 20–30 year turnover for the fleet after the full IMO approval, and the second would take 5–7 years after the years to finalize the IMO requirements.

[30] Ports and vessel owners are all concerned about how to obtain reliable, verifiable underwater noise measurements, and from what entities and at what costs. Should this, for example, be available from shipyards and out-of-water maintenance facilities, and become part of the sea trials process? The variations from location to location might be too significant.

[31] Some information on air noise from the airline industry in the EU context is available at the following link: https://www.aef.org.uk/issues/aircraft-noise/.

[32] The regulation at the IMO concerning asbestos also progressed following pressure at the global scale.

Source: Authors' elaboration (alphabetical order).

Table A1.2
International institutions proposing actions to reduce underwater noise from shipping.

International institution, references	Noise mapping of shipping	Impact of underwater noise from shipping on marine fauna	Options for mitigating underwater noise from shipping
ACCOBAMS (2007b).			X
ACCOBAMS (2010).			X (brief)
ACCOBAMS, forthcoming.			X
Arctic Council (2009).			X
Arctic Council (2019).	X		
CBD (2014).	X	X	
CMS (2017a).			X
EC (2008).	X (work plan)		
EC (2012).	X (green label)		
EC in AQUO-SONIC (2015).			X
EC in BIAS (2016).	X		
EC (2017).	X (definition of indicators)		
EC, forthcoming.		X (thresholds for indicators)	
HELCOM (2016b).	X	X	X (work plan)
HELCOM (2016a).	X (definition of indicator)		
HELCOM (2017a, 2017b).			X (survey)
HELCOM (2017c) .	X (sound map for the Baltic region)		
HELCOM (2018a).	X		
HELCOM (2018b).	X	X (cumulative pressures and impacts)	
HELCOM (2019).		X	
ICES (1995).		X (fishery research vessels)	
IMO (2005).			X (PSSAs)
IMO (2014).	X		X (rerouting; voluntary guidelines)
IMO, forthcoming.			X (Member States experience sharing)
IWC (2009).		X (reduction noise targets)	
IWC (2014, 2015).		X (stress and masking)	
IWC (2015).			X (IMO voluntary guidelines)
IWC (2017a, 2017b).	X (noisiest ships)		
OSPAR at Dekeling et al. (2014).	X		
OSPAR (2015).	X		
OSPAR, forthcoming.			X
UNEP/MAP (2012).	X	X (indicators)	

Source: Authors' elaboration (alphabetical order).

Table A1.3
Countries engaged in regulating underwater noise from shipping.

Country	Regulations already in place (1) or planned (2), only monitoring programs or studies are reported (3)	References
Australia	1	Commonwealth Department of the Environment and Energy (2000), CBD (2016), Commonwealth of Australia (2017).
Canada	1	Bahtiarian (2017), Vancouver Fraser Port Authority (2018), DFO (2018).
Estonia	3	EC (2018).
Finland	3	CBD (2016), EC (2018).
France	3	CBD (2016), EC (2018).
Germany	1	HELCOM (2017a, 2017b).
Latvia	3	CBD (2016).
Lithuania	2	HELCOM (2017b), EC (2018).
Malta	1	EC (2018).
The Netherlands	3	UN (2018).
Poland	3	UN (2018).
Russia	3	HELCOM (2017b).
Sweden	1	HELCOM (2017b), UN (2018).
United States	1	GFNMS and CBNMS (2015), Joint Working Group on Vessel Strikes and Acoustic Impacts, 2012, CBD (2016), Gassmann et al. (2017).

Source: authors' elaboration (alphabetical order).

Table A1.4
Underwater noise measurement standards relevant for shipping.

Institution and date	Content
NATO, 1995	Standardization agreement No.1136 (STANAG), "Standards for use when measuring and reporting radiated noise characteristics of surface ships, submarines, helicopters, etc. in relation to sonar detection and torpedo risk", May 29.
ANSI-ASA, 2009	Quantities and procedures for description and measurement of underwater sound from ships - Part 1: General requirements. ANSI-ASA S12.64–2009/Part1.
DNV, 2010	Part 6, chapter 24 - Silent class notation. Rules for classification of ships. s.l.: DNV, 2010.

(*continued on next page*)

Table A1.4 (*continued*)

Institution and date	Content
TNO, 2011	"Standard for measurement and monitoring of underwater noise, Part 1: physical quantities and their units", TNO-DV 2011 C235.
ISO, 2012	"Acoustics-Quantities and procedures for description and measurement of underwater sound from ships, Part 1: General requirements for measurements in deep water", ISO/PAS 17208–1: 2012(E).
ISO, 2013	"Ships and marine technology- Protecting marine ecosystem from underwater radiated noise- Measurement and reporting of Underwater sound radiated from merchant ships", ISO/CD 16554.012.
ISO, 2014	"Ships and marine technology - Measurement and reporting of underwater sound radiated from merchant ships - Survey measurement in deep-water", ISO 16554.3.
AQUO, 2014	European Collaborative Project, deliverable D3.1, European URN Standard Measurement Method, April 2014.
ITTC, 2014	Underwater Noise from Ships, Full Scale Measurements. Recommended Procedures and Guidelines.
ISO, 2016	"Acoustics – Quantities and procedures for description and measurement of underwater sound from ships – Part 1: General requirements", ISO/DPAS 17208–1.
Lloyd's Register Group Limited, 2018	Additional Design and Construction Procedure for the Determination of a Vessel's Underwater Radiated Noise. ShipRight. Design and Construction. Additional Design Procedures.
ISO, 2019	"Underwater acoustics - Quantities and procedures for description and measurement of underwater sound from ships – Part 2: Determination of source levels from deep water measurements", ISO/FDIS 17208–2. Under development.

Source: Authors' elaboration based on ITTC (2014) and Rodriguez et al. (2015) (chronological order).

Table A1.5
Underwater noise notation for shipping.

Institution and date	Designation
ICES, 1995	"Underwater Noise of Research Vessels Review and Recommendations".
DNV GL, 2010	DNV GL Silent class notation (part of "Rules for classification of ships, new buildings").
Bureau Veritas, 2014	Rule Note NR614 DT R00E – Underwater Radiated Noise (URN).
RINA, 2014	RINA Dolphin.
ABS, 2018	Guide for classification notation. Underwater noise. July 2018. American Bureau of Shipping.
Lloyd's Register, 2018	Underwater notation on underwater radiated noise.

Source: Authors' elaboration (chronological order).

Appendix B. The steering committee

The role of the members of the steering committee was the following. Each member of the steering committee was required to provide input three times during the project to validate: (i) the scope and the methodology of the project, and the key actors to interview before designing the survey; (ii) the survey content; and (iii) the final output of the data processing exercise and the associated policy recommendations. The steering committee members could also provide advice and guidance throughout the development of the different phases of the project. Each meeting or exchange was flexible and was held by teleconference, telephone or email.

Members of the project steering committee.

Port authorities and administrations.

Port authorities.

Carrie Brown, Director, Environmental programs, Vancouver Fraser Port Authority, Canada.

Pascal Galichon, Directeur du développement durable et du pilotage, Grand Port Maritime du Havre, France.

Kirsti Tarnanen-Sariola, Deputy director, Finnish Port Association, Finland.

Global and regional institutions.

(Observer: Andrew Birchenough, Technical officer, Office for London Convention/Protocol & Ocean Affairs, Marine Environment Division, International Maritime Organization, United Kingdom.)

Maud Casier, National expert on secondment, Directorate-General for Environment, European Commission, Belgium.

(Observer: Marta Ruiz, Associate Professional Secretary, Baltic Marine Environment Protection Commission (HELCOM), Finland.)

National administrations.

Leila Hatch, Co-leader, Ocean Noise Strategy, the U.S. National Oceanic and Atmospheric Administration (NOAA), United States.

Nathan Merchant, Lead scientist, Noise & Bioacoustics Team, Centre for Environment, Fisheries and Aquaculture Science (CEFAS), United Kingdom.

Michelle Sanders, Director, Clean Water Policy, Transport Canada, Canada.

The shipping sector.

Ship owners and industry.

Anais Guerin, Responsable Environnement et Foncier, CAN – Groupe Roullier, France.

Lee Kindberg, Director, Environment & Sustainability, Maersk Line North America, United States.

Kathy Metcalf, President and CEO, Chamber of Shipping of America, United States.

Caroline Roux, Coordinatrice environnement, CMA-CGM, France.

Shipyards including engineering consulting firms and ship classification societies.

Publio Beltran, Director General, TSI, Spain.

Caroline Fonti, Naval architect, CMA-CGM, France.

François Frey, President, Esprit de VELOX, France.

Alfonso Moreno, Expert, TSI, Spain.

Eric Baudin, Head of the Test & Measurements Section, Bureau Veritas, France.

Veronique Nolet, Program Manager, Green Marine, Canada.

Marine life watching sea cruises.

Jake Keeton, Manager, Raggy Charters, South Africa.

Sophie Lewis, Responsible whale watching partner project manager, World Cetacean Alliance, United Kingdom.

The fisheries sector.

Fisheries including small-scale and indigenous fishing communities.

Ignacio Belmonte Rincón, President, ARESTRECHO (Asociación Armadores del Estrecho), Spain.

Andrés Cisneros-Montemayor, Program manager / Research associate, Nippon Foundation, Nereus Program, Fisheries Economics Research Unit, The University of British Columbia, Canada.

Ricardo Federizon, Senior fisheries management coordinator, Northwest Atlantic Fisheries Organization, Canada.

Analysts

Academics

Natacha Aguilar de Soto, Director, Cetacean research, Grupo de Investigación en Biodiversidad, Ecología Marina y Conservación, La Laguna University, Spain**.**

Michel André, Director, Laboratory of Applied Bioacoustics, Polytechnic University of Cataluña, Spain.

Cedric Gervaise, Senior scientist, Chorus chair, France.

Environmental consulting firms.

Thomas Folegot, President and CEO, Quiet Oceans, France.

Michele Halvorsen, Manager, Ocean Sound & Marine Life Services, United States.

Alessio Maglio,Cchargé d'études en environnement marin, Sinay, France.

John V. Young, Consultant, DHI Environment and Water, United States.

The biodiversity conservation community.

Institutions specializing in marine mammals.

Florence Descrois-Comanducci, Executive secretary, the Agreement on the Conservation of Cetaceans in the Black Sea, Mediterranean Sea and contiguous Atlantic area (ACCOBAMS), Monaco.

Non-governmental organizations.

Cato C. ten Hallers-Tjabbes, Marine scientist, the International Union for Conservation of Nature (IUCN) representative for underwater acoustic pollution, the Netherlands.

Michael Jasny, director, Marine Mammal Protection, Natural Resources Defense Council, United States.

Rickard Lindström, Director, Clean Shipping Index, Sweden.

Sigrid Lüber, The European Coalition for Silent Oceans, Oceancare, President, Switzerland.

Appendix C. Survey

Please submit your ***individual view*** *and not that of the country or institution you represent.*

Personal information will not be disclosed.

Note that underwater noise solutions will depend on the particular port's characteristics and local fauna.

- In which country is the institution you work for located? …………………………………………
- With which group do you identify yourself **predominantly** (select one category only)? *Please mark with an X.*

Port authorities
Maritime affairs administration
Shipping sector (ship owners, industry, classification societies, engineering firms)
Fisheries sector
Analysts (academics, environmental consulting firms)
Biodiversity conservation community
Other (please specify:………………………………………………………………..…..)

- **Question 1.** While acknowledging the wide variations in ports' specificities, which of the following options should port actions **preferably** seek to support to reduce underwater noise from shipping? *Please enter a number between 1 and 10, where 1 means a very low value and 10 a very high value. Please enter NA for not applicable/do not know.*

Options with global impacts on underwater noise	Value (1 to 10 or NA)
Design: Hull, propeller, engine	
(when the measures increase energy efficiency and reduce underwater noise and air emissions)	
Design: Type of fuel (LNG, methanol, fuel cells, battery hybrid)	
(to reduce underwater noise and air emissions; not all solutions are mature)	
Design: Larger vessels	
(to reduce underwater noise and air emissions)	
Operational: Ship maintenance (hull, propeller)	
(to increase energy efficiency and to reduce underwater noise and air emissions)	
Operational: Ships operate at design load conditions	
(to increase energy efficiency and reduce underwater noise and air emissions)	
(optimum trim and ballast conditions for a certain speed)	
Options with local impacts on underwater noise	

(*continued on next page*)

(*continued*)

Options with global impacts on underwater noise	Value (1 to 10 or NA)
	Value (1 to 10 or NA)
Operational: Ships at reduced speed, change of route, travel in convoy (can reduce underwater noise; can increase shipping costs) (usually limited to a small geographical area, their applicability depending on the port's characteristics)	
Operational: Ships use onshore power supply facilities at ports (to reduce underwater noise and air emissions)	

- **Question 2.** While acknowledging the wide variations in ports' specificities, which of the following actions should ports **preferably** take to reduce underwater noise from shipping? *Please enter a number between 1 and 10, where 1 means a very low value and 10 a very high value. Please enter NA for not applicable/do not know.*

Actions with global impacts on underwater noise	Value (1 to 10 or NA)
Port fees charged according to underwater noise performance (rebates for ships with better performance or differentiated fees according to performance)	
Priority in the allocation of berth slots for ships generating less underwater noise	
ACTIONS WITH LOCAL IMPACTS ON UNDERWATER NOISE	**Value (1 to 10 or NA)**
Underwater noise criteria in selecting port service providers (terminal operators, towage operators, dredgers)	
Reduction in ship waiting time at ports through collaboration along the entire logistical maritime chain (mooring, berthing, anchoring, cargo handling; possibly leading to mutual benefits, for instance, through the reduction in the waiting time compensation paid by ports)	
Proper port and barrier design, onshore energy facilities (relocation of noisiest activities, physical barriers against noise propagation, containers on rubber insulation, onshore power supply, electric charging systems, bunkering facilities for alternative fuels, etc.)	
Underwater noise mitigation equipment to protect local fauna (devices to displace marine fauna such as acoustic deterrents or to act as a barrier against noise such as air bubble curtains)	

- **Question 3: Explanations to complete the table on the next page.**

Your answers to question 3 will be used to develop analyses to prioritize decision-making alternatives involving multiple social groups and multiple goals (see Linares and Romero, 2002). In particular, the comparison scale is used to express the importance of one alternative over another:

Explanation of the comparison scale	Numeric values to enter
If option A and B are EQUALLY important	1
If option A is MODERATELY more important than option B	3
If option A is STRONGLY more important than option B	5
If option A is VERY STRONGLY more important than option B	7
If option A is EXTREMELY more important than option B	9

Example of use of the comparison scale.
Given alternatives A and B in the table below, you can assess their relative importance:

- In the first row of the table below, if you think that option A “Effectiveness assessment” is STRONGLY more important than option B “Raising awareness”, then enter “A” in the *Preference* column (you indicate that you prefer A over B), and 5 in the *Intensity* Column (you indicate that you have a strong preference for A over B).
- In the second row of the table below, if you think that option B “Actions of a voluntary nature” is EXTREMELY more important than option A “Effectiveness assessment”, then enter “B” in the *Preference* column (you indicate that you prefer B over A), and 9 in the Intensity Column (you indicate that you have an extremely strong preference for B over A).
- In the third row of the table below, if you think that option A “Focus on key priorities” and option B “Actions of a voluntary nature” are EQUALLY important, then enter “A” or “B” in the *Preference* column, and 1 in the *Intensity* Column (you indicate that you have the same preference for A and B).

Comparison of options		Preference	Intensity
Option A	Option B		
Effectiveness assessment	Raising awareness	A	5
Effectiveness assessment	Actions of a voluntary nature	B	9
Effectiveness assessment	Focus on key priorities	A	1

- **Question 3.** Using the comparison scale, which of the following options can help support port actions to reduce underwater noise from shipping?

Please enter A or B in the Preference column.
Then, enter the intensity of your preference in the Intensity column by using the scale 1 to 9 (Equal = 1 Moderate = 3 Strong = 5 Very strong = 7 Extremely = 9).

Comparison of options		Preference	Intensity
Option A	Option B		
Effectiveness assessment (through monitoring, reporting, verification)	**Raising awareness** (among port staff and the general public; through training, ports' corporate social responsibility reports)		
Effectiveness assessment (through monitoring, reporting, verification)	**Actions of a voluntary nature**		
Effectiveness assessment (through monitoring, reporting, verification)	**Focus on key priorities** (noisiest ships, biodiversity hotspots)		
Effectiveness assessment (through monitoring, reporting, verification)	**Integration with other actions** (other actions on air emissions and energy efficiency; for example, by making underwater noise a key green indicator)		
Effectiveness assessment (through monitoring, reporting, verification)	**Different actions applied to green and dirty ships** (not only positive actions for green ships)		
Effectiveness assessment (through monitoring, reporting, verification)	**Broad stakeholder participation**		
Effectiveness assessment (through monitoring, reporting, verification)	**Cooperation between ports to scale up actions** (greater harmonization of green actions and indicators; joint request for action by the International Maritime Organization)		
Effectiveness assessment (through monitoring, reporting, verification)	**Political and/or social demand**		

- Do you want to share any comments?...

....
....
....
....

- This survey is anonymous. If you wish to receive its results, please provide an email address: ……………………………… ……………...

Appendix D. Other results of the survey

Table A4.1
In which country is the institution you work for located?

Country	Number of respondents
Belgium	2
Canada	4
Denmark	3
Estonia	1
Finland	1
France	6
Germany	2
Italy	2
Lithuania	1

(*continued on next page*)

Table A4.1 (*continued*)

Country	Number of respondents
Norway	1
Portugal	1
Spain	1
Sweden	4
The Netherlands	3
United States	6

Table A4.2
With which group do you identify yourself predominantly?

Stakeholders	Number of respondents
Port authorities	8
Maritime affairs administration	4
Shipping sector (ship owners, industry, classification societies, engineering firms)	10
Fisheries sector	0
Analysts (academics, environmental consulting firms)	12
Biodiversity conservation community	4
Other (please specify:……………………………………………………….)	0

Note: The respondent could only select one stakeholder category.

Table A4.3
While acknowledging the wide variations in ports' specificities, which of the following options should port actions preferably seek to support to reduce underwater noise from shipping? (standard deviation values, question 1).

	Port authority	Maritime affairs administration	Shipping sector	Analysts	Biodiversity conservation community	All groups
Design: Hull, propeller, engine	3.7	1.0	1.2	1.2	1.3	1.7
Design: Type of fuel	1.1	1.4	1.8	2.2	1.8	1.7
Design: Larger vessels	3.1	2.7	2.4	2.1	1.3	2.3
Operational: Ship maintenance	2.9	0.4	1.0	1.4	1.8	1.5
Operational: Ships operate at design load conditions	2.7	2.5	1.7	2.1	1.6	2.1
OPTIONS WITH GLOBAL IMPACTS ON UNDERWATER NOISE	2.7	1.6	1.6	1.8	1.5	1.8
Operational: Reduced speed, change of route, travel in convoy	2.9	1.0	1.6	1.8	1.0	1.7
Operational: Ships use onshore power supply facilities at ports	19	2.0	2.2	1.7	0.9	1.7
OPTIONS WITH LOCAL IMPACTS ON UNDERWATER NOISE	2.4	1.6	1.9	1.8	0.9	1.7
OPTIONS WITH GLOBAL AND LOCAL IMPACTS ON UNDERWATER NOISE	2.6	1.5	1.7	1.8	1.3	1.8

Note: This table reports standard deviation values. Respondents were requested to enter a number between 1 and 10, where 1 means a very low value and 10 a very high value.

Table A4.4
While acknowledging the wide variations in ports' specificities, which of the following actions should ports preferably take to reduce underwater noise from shipping? (standard deviation values, question 2).

	Port authority	Maritime affairs administration	Shipping sector	Analysts	Biodiversity conservation community	All groups
Port fees charged according to underwater noise performance	2.4	2.0	1.4	1.7	1.0	1.7
Priority in the allocation of berth slots for ships generating less underwater noise	2.0	2.3	1.7	3.2	1.5	2.1
ACTIONS WITH GLOBAL IMPACTS ON UNDERWATER NOISE	2.2	2.1	1.6	2.5	1.3	1.9
Underwater noise criteria in selecting port service providers	2.9	1.0	1.7	2.8	0.8	1.8
Reduction in ship waiting time at ports through collaboration along the entire logistical maritime chain	1.8	0.9	1.6	2.5	1.3	1.6
Proper port and barrier design, onshore energy facilities	2.4	1.6	2.1	1.8	1.8	2.0
Underwater noise mitigation equipment to protect local fauna	2.1	2.0	3.0	1.8	1.6	2.0
ACTIONS WITH LOCAL IMPACTS ON UNDERWATER NOISE	2.3	1.4	2.1	2.3	1.3	1.9
ACTIONS WITH GLOBAL AND LOCAL IMPACTS ON UNDERWATER NOISE	2.4	1.6	1.9	2.3	1.3	1.7

Note: This table reports mean values. Respondents were requested to enter a number between 1 and 10, where 1 means a very low value and 10 a very high value.

Table A4.5
Determination of the social preferences by the extended goal programming model: Non-governmental organizations.

Achievement function		
$Min\ (1-\lambda)D+\lambda\sum_{i=1}^{9}\sum_{j=1}^{4}\left(\overline{n}_{ij}+\overline{p}_{ij}\right)$		
Subject to:		
Goals	$W_1^s+\overline{n}_{11}-\overline{p}_{11}=x_1^{12}$	$W_2^s+\overline{n}_{21}-\overline{p}_{21}=x_2^{12}$
$\sum_{i=1}^{9}(\overline{n}_{i1}+\overline{p}_{i1})-D\leq 0$	$W_1^s+\overline{n}_{12}-\overline{p}_{12}=x_1^{22}$	$W_2^s+\overline{n}_{22}-\overline{p}_{22}=x_2^{22}$
$\sum_{i=1}^{9}(\overline{n}_{i2}+\overline{p}_{i2})-D\leq 0$	$W_1^s+\overline{n}_{13}-\overline{p}_{13}=x_1^{32}$	$W_2^s+\overline{n}_{23}-\overline{p}_{23}=x_2^{32}$
$\sum_{i=1}^{9}(\overline{n}_{i3}+\overline{p}_{i3})-D\leq 0$	$W_1^s+\overline{n}_{14}-\overline{p}_{14}=x_1^{42}$	$W_2^s+\overline{n}_{24}-\overline{p}_{24}=x_2^{42}$
$\sum_{i=1}^{9}(\overline{n}_{i4}+\overline{p}_{i4})-D\leq 0$		
$W_3^s+\overline{n}_{31}-\overline{p}_{31}=x_3^{12}$	$W_4^s+\overline{n}_{41}-\overline{p}_{41}=x_4^{12}$	$W_5^s+\overline{n}_{51}-\overline{p}_{51}=x_5^{12}$
$W_3^s+\overline{n}_{32}-\overline{p}_{32}=x_3^{22}$	$W_4^s+\overline{n}_{42}-\overline{p}_{42}=x_4^{22}$	$W_5^s+\overline{n}_{52}-\overline{p}_{52}=x_5^{22}$
$W_3^s+\overline{n}_{33}-\overline{p}_{33}=x_3^{32}$	$W_4^s+\overline{n}_{43}-\overline{p}_{43}=x_4^{32}$	$W_5^s+\overline{n}_{53}-\overline{p}_{53}=x_5^{32}$
$W_3^s+\overline{n}_{34}-\overline{p}_{34}=x_3^{42}$	$W_4^s+\overline{n}_{44}-\overline{p}_{44}=x_4^{42}$	$W_5^s+\overline{n}_{54}-\overline{p}_{54}=x_5^{42}$
$W_6^s+\overline{n}_{61}-\overline{p}_{61}=x_6^{12}$	$W_7^s+\overline{n}_{72}-\overline{p}_{72}=x_7^{22}$	$W_8^s+\overline{n}_{82}-\overline{p}_{82}=x_8^{22}$
$W_6^s+\overline{n}_{62}-\overline{p}_{62}=x_6^{22}$	$W_7^s+\overline{n}_{73}-\overline{p}_{73}=x_7^{32}$	$W_8^s+\overline{n}_{83}-\overline{p}_{83}=x_8^{32}$
$W_6^s+\overline{n}_{63}-\overline{p}_{63}=x_6^{32}$	$W_7^s+\overline{n}_{74}-\overline{p}_{74}=x_7^{42}$	$W_8^s+\overline{n}_{84}-\overline{p}_{84}=x_8^{42}$
$W_6^s+\overline{n}_{64}-\overline{p}_{64}=x_6^{42}$	$W_8^s+\overline{n}_{81}-\overline{p}_{81}=x_8^{12}$	
$W_7^s+\overline{n}_{71}-\overline{p}_{71}=x_7^{12}$		
$W_9^s+\overline{n}_{91}-\overline{p}_{91}=x_9^{12}$		
$W_9^s+\overline{n}_{92}-\overline{p}_{92}=x_9^{22}$		
$W_9^s+\overline{n}_{93}-\overline{p}_{93}=x_9^{32}$		
$W_9^s+\overline{n}_{94}-\overline{p}_{94}=x_9^{42}$		
Accounting rows	$\sum_{i=1}^{9}\sum_{j=1}^{4}\left(\overline{n}_{ij}+\overline{p}_{ij}\right)-Z=0$	
$\sum_{i=1}^{9}(\overline{n}_{i1}+\overline{p}_{i1})-D_1=0$		
$\sum_{i=1}^{9}(\overline{n}_{i2}+\overline{p}_{i2})-D_2=0$		
$\sum_{i=1}^{9}(\overline{n}_{i3}+\overline{p}_{i3})-D_3=0$		
$\sum_{i=1}^{9}(\overline{n}_{i4}+\overline{p}_{i4})-D_4=0$		

Note: See Section 3.2 for the definition of these variables. In this model, x_i^{k2} is the preference weight attached to the ith criterion by the kth member of the 2nd group. The x_i^{k2}variable is not disclosed since it reveals individual data and is therefore confidential. Note m = 4 since there are four members in the biodiversity conservation community social group.

Table A4.6
Social weights used with the extended goal programming model: Non-governmental organizations.

Z	D	D_1	D_2	D_3	D_4	W_1^s	W_2^s	W_3^s	W_4^s	W_5^s	W_6^s	W_7^s	W_8^s	W_9^s
Majority consensus ($\lambda=1$)														
1.70	0.67	0.54	0.67	0.19	0.36	3	3	14	13	13	7	13	14	4
Minority consensus ($\lambda=0$)														
1.90	0.50	0.50	0.50	0.40	0.48	3	2	2	13	11.5	7	3	13	8

Note: This table shows the results of the MCDM model in Table A4.5. Z is the sum of D_1-D_4, D measures the maximum of the values D_1-D_4, D_1-D_4 represents the disagreement of each of the four individuals in the group of non-governmental organizations with respect to the consensus that is obtained, and W_1^s-W_9^s are the reference weights (in percentage) attached by society to each criterion as listed in Table 3.3.

The results in Table A4.6 show a first consensus by maximizing the average agreement which corresponds to the median value from a statistical point of view, and a second consensus by minimizing the disagreement of the most displaced individual. In Table A4.6, both consensuses are relatively similar which is quite common when aggregating data from individuals belonging to the same social group, with two exceptions: the focus on key priorities (O_3) and cooperation between ports to scale up actions (O_7). In these two cases, a majority consensus is appropriate for respondents from the same group of respondents. As a result, the individual data in each group are aggregated through the median value which corresponds to the maximization of the average agreement. It should be noted that all the computations are undertaken by solving linear programming models with sparse matrices, which makes the existence of alternative optimal solutions very likely. Because of this, in some cases the consensus weight for the maximum average agreement is not given by the median (Table 4.4) but for instance by the average (Table 4.5). In fact, in these cases both statistical parameters give the same optimum value.

Table A4.7
Determination of the social preferences using the extended goal programming model (question 3).

Achievement function		
$Min\ (1-\lambda)D+\lambda\sum_{i=1}^{9}\sum_{j=1}^{5}\left(\overline{n}_{ij}+\overline{p}_{ij}\right)$		
subject to:		
Goals:	$W_1^s+\overline{n}_{11}-\overline{p}_{11}=0.03$	$W_2^s+\overline{n}_{21}-\overline{p}_{21}=0.09$
$\sum_{i=1}^{9}(\overline{n}_{i1}+\overline{p}_{i1})-D\leq 0$	$W_1^s+\overline{n}_{12}-\overline{p}_{12}=0.02$	$W_2^s+\overline{n}_{22}-\overline{p}_{22}=0.02$
$\sum_{i=1}^{9}(\overline{n}_{i2}+\overline{p}_{i2})-D\leq 0$	$W_1^s+\overline{n}_{13}-\overline{p}_{13}=0.03$	$W_2^s+\overline{n}_{23}-\overline{p}_{23}=0.02$
$\sum_{i=1}^{9}(\overline{n}_{i3}+\overline{p}_{i3})-D\leq 0$	$W_1^s+\overline{n}_{14}-\overline{p}_{14}=0.10$	$W_2^s+\overline{n}_{24}-\overline{p}_{24}=0.02$
$\sum_{i=1}^{9}(\overline{n}_{i4}+\overline{p}_{i4})-D\leq 0$	$W_1^s+\overline{n}_{15}-\overline{p}_{15}=0.04$	$W_2^s+\overline{n}_{25}-\overline{p}_{25}=0.03$

(continued on next page)

Table A4.7 (*continued*)

Achievement function		
$\sum_{i=1}^{9}(\bar{n}_{i5}+\bar{p}_{i5}) - D \le 0$		
$W_3^s+\bar{n}_{31}-\bar{p}_{31}=0.11$	$W_4^s+\bar{n}_{41}-\bar{p}_{41}=0.15$	$W_5^s+\bar{n}_{51}-\bar{p}_{51}=0.12$
$W_3^s+\bar{n}_{32}-\bar{p}_{32}=0.16$	$W_4^s+\bar{n}_{42}-\bar{p}_{42}=0.30$	$W_5^s+\bar{n}_{52}-\bar{p}_{52}=0.08$
$W_3^s+\bar{n}_{33}-\bar{p}_{33}=0.14$	$W_4^s+\bar{n}_{43}-\bar{p}_{43}=0.19$	$W_5^s+\bar{n}_{53}-\bar{p}_{53}=0.12$
$W_3^s+\bar{n}_{34}-\bar{p}_{34}=0.11$	$W_4^s+\bar{n}_{44}-\bar{p}_{44}=0.15$	$W_5^s+\bar{n}_{54}-\bar{p}_{54}=0.11$
$W_3^s+\bar{n}_{35}-\bar{p}_{35}=0.18$	$W_4^s+\bar{n}_{45}-\bar{p}_{45}=0.17$	$W_5^s+\bar{n}_{55}-\bar{p}_{55}=0.12$
$W_6^s+\bar{n}_{61}-\bar{p}_{61}=0.18$	$W_7^s+\bar{n}_{71}-\bar{p}_{71}=0.20$	$W_8^s+\bar{n}_{81}-\bar{p}_{81}=0.07$
$W_6^s+\bar{n}_{62}-\bar{p}_{62}=0.09$	$W_7^s+\bar{n}_{72}-\bar{p}_{72}=0.19$	$W_8^s+\bar{n}_{82}-\bar{p}_{82}=0.08$
$W_6^s+\bar{n}_{63}-\bar{p}_{63}=0.15$	$W_7^s+\bar{n}_{73}-\bar{p}_{73}=0.18$	$W_8^s+\bar{n}_{83}-\bar{p}_{83}=0.09$
$W_6^s+\bar{n}_{64}-\bar{p}_{64}=0.18$	$W_7^s+\bar{n}_{74}-\bar{p}_{74}=0.15$	$W_8^s+\bar{n}_{84}-\bar{p}_{84}=0.12$
$W_6^s+\bar{n}_{65}-\bar{p}_{65}=0.15$	$W_7^s+\bar{n}_{75}-\bar{p}_{75}=0.15$	$W_8^s+\bar{n}_{85}-\bar{p}_{85}=0.15$
$W_9^s+\bar{n}_{91}-\bar{p}_{91}=0.06$		
$W_9^s+\bar{n}_{92}-\bar{p}_{92}=0.07$		
$W_9^s+\bar{n}_{93}-\bar{p}_{93}=0.09$		
$W_9^s+\bar{n}_{94}-\bar{p}_{94}=0.07$		
$W_9^s+\bar{n}_{95}-\bar{p}_{95}=0.07$		
Accounting rows	$\sum_{i=1}^{9}\sum_{j=1}^{5}\left(\bar{n}_{ij}+\bar{p}_{ij}\right) - Z = 0$	
$\sum_{i=1}^{9}(\bar{n}_{i1}+\bar{p}_{i1}) - D_1 = 0$		
$\sum_{i=1}^{9}(\bar{n}_{i2}+\bar{p}_{i2}) - D_2 = 0$		
$\sum_{i=1}^{9}(\bar{n}_{i3}+\bar{p}_{i3}) - D_3 = 0$		
$\sum_{i=1}^{9}(\bar{n}_{i4}+\bar{p}_{i4}) - D_4 = 0$		
$\sum_{i=1}^{9}(\bar{n}_{i5}+\bar{p}_{i5}) - D_5 = 0$		

Note: See Section 3.2 for the definition of these variables.

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