**Erasmus University Rotterdam**

## MSc in Maritime Economics and Logistics

2020/2021

# *To what extent is noise pollution an issue and how can it be mitigated in the shipping sector?*

## *An Interdisciplinary Analysis of Underwater Noise Pollution*

By

Alba Coelho

# Abstract

The ocean covers 71% of the Earth but most of it is still undiscovered. In the last decades the exploitation of the oceans has drastically increased. Maritime transportation is a pillar for the global economy, and shipping activities have increased exponentially in the last years. This however came at a price, pollution due to GHGs emissions, acidification, eutrophication, and invasive species are currently threatening the health of the oceans and its inhabitants. The IMO is actively dealing with the most known forms of pollution such as CO2 emissions. Due to the intensification of shipping activities, the increase in vessels' number, dimensions and speed, a new pollution, invisible to the human eye is posing a new lethal threat to the inhabitants of the oceans: underwater noise pollution. Due to the novelty of the issue, and considering the lack of research on the topic, this thesis aims to investigate to what extent noise pollution is an issue and why it is underestimated in the shipping sector. The research was carried out using a mixed methodology, including a case study focusing on the Wadden Sea. Successively, a model was developed to understand the relationship between a vessel's speed, fuel consumption and noise emission. Finally, some interviews were carried out to test the results obtained from the model and to generalize results.

The investigation provided clear evidence confirming the huge impacts that noise emissions have on marine mammals. The thesis provides various solutions that could be implemented to limit underwater noise pollution. The developed model demonstrates that the most efficient solution is imposing a speed limitation. The model explains the direct relationship between speed, fuel consumption and noise emissions by calculating the costs of imposing specific speed limitations. This thesis demonstrates that a speed reduction results in a fuel consumption reduction therefore in a lower total cost, up to a certain point where the trend varies due to the non-linearity of the relationship. The model also provides evidence supporting the initial hypothesis that a lower velocity results in a lower noise emission. Other solutions concerning more technical and design aspects of the vessels are proposed taking into consideration their costs and feasibility.

## Table of Contents

# 1. Introduction

Ecology is the study of all living organisms and how they interact among themselves and with the environment around them, also known as their habitat. Ecology is fundamental in our society and is crucial for human well-being and prosperity (British Ecological Society, 2021). It offers knowledge to better understand the relationship between people and nature. This is essential for food production, keeping a good quality of air and water, and supporting biodiversity in a changing climate. In other words, ecology provides the basis for nature conservation. The presence of a variety of species is essential for the health of the numerous ecosystems and this is possible only by preserving a mosaic of habitats (British Ecological Society, 2021). Fortunately, the awareness of governments and populations is increasing throughout the world. Experiments and observations on the reactions of various organisms to different atmospheric and ecological conditions allows researchers to gain a deeper knowledge on pollution and make predictions regarding future climate change.

In the coming decades, inhabitants and all forms of life in the ocean will encounter environmental conditions not comparable in all human history. It is therefore vital understanding which marine species will be able to adapt and which will go extinct. Throughout centuries, oceans covering around 71% of the Earth, have been essential for humanity and its survival. For millennia, the oceans have been home for a great diversity of life and offered humans a variety of ecosystem goods and services. In turn, humans negatively impacted marine species and ecosystems because of exploitation and habitat degradation. Even if constantly used and exploited, 80% of the oceans is still unknown. Human impacts have increased throughout the decades, and this is unsurprisingly related to the rapid population growth, technological advancement and changes in the activities and the use of land. The most known issues at sea are for example over-fishing, pollution, and the introduction of invasive species. In addition, the oceans are facing the indirect effects of greenhouse gas emissions which have huge impacts on water temperature, pH and sea level. Studying the oceans' past is the key to understand present and future consequences of human impacts on marine ecosystems. However, it is still not possible to have clear predictions of how organisms will react to future environmental conditions.

Marine species are believed to be less sensitive to extinction compared to terrestrial species. However, 15 ocean animals have gone extinct in the last century and 72 are currently facing the risk of extinction. Past extinctions are demonstrated in marine fossil records and the present risk of extinctions for various marine species is high (corals, marine mammals, seagrasses, etc.). Many marine species are decreasing in number and becoming regionally or functionally extinct. For this reason, marine species' resilience is into question and an urgent, better understanding of marine extinctions and risk is needed.  The urge is due to the fact that a growing body of evidence indicates that the planet is currently facing a sixth mass extinction (Woodward, 2019). Indeed, according to reports provided by the United Nations up to 1 million plants and animals species are at risk of extinction, many in the next decades. Human activities are to blame for this trend: pollution, deforestation and habitat destruction have already altered 75% of all land and 40% of marine environments (Woodward, 2019). More precisely, 33% of reef-forming corals and one third of the world's marine mammals are threatened with extinction. Today the most endangered marine mammal is the vaquita, a porpoise that inhabits the waters of the Gulf of California (Woodward, 2019).

One of the main exponents of the human activities affecting marine ecosystems is commercial shipping. Maritime transport is extremely important and plays one of the most significant roles in the economy and the international trade system. It is known that the maritime sector transports more than 80% of the world trade volume, representing around 70% of the world trade value (Kalouptsidi, 2021). Therefore, shipping services have a strong impact on the trade flows and price fluctuations. The total world fleet has increased drastically throughout the years, observing a 4.1% rise only in 2019 (UNCTAD, 2020). Other than increasing in number, in the last 20 years vessels have faced a significant increase in size. The average size of a container ship has grown more than double since 1996. This resulted in positive effects such as an increase in the economy of scale, a higher capacity of the vessels and thus greater revenues. However, these advantages came at a price: higher GHGs emissions, a more significant impact on biodiversity and the ecosystems affected by shipping and, one of the most underrated, underwater noise pollution. Indeed, increasing the world fleet, the vessel's sizes and the ship's speed have a tremendous effect and drastically increase the noise perceived by the flora and the fauna.

Underwater noise pollution is less known compared to other types of pollution, generated by commercial shipping, such as air pollution, GHGs emissions, issues caused by the release of ballast water, etc. This is probably due to the fact that underwater noise, differently from other forms of pollution, is invisible to the human eye, and this results in public unawareness. This research is relevant and provides a first essential insight on the issue because ocean noise pollution is becoming one of the more lethal and incisive threats against life and health in the ocean. Noise affects animals in various ways. It is demonstrated that anthropogenic sounds change the behaviour of the inhabitants of the affected area. The majority of the studies concerning the impact of underwater noise on marine mammals are observational and not experimental, resulting in a significant limitation when considering data control. Despite this, it has been demonstrated that noise can affect the auditory system and cause a shift in the hearing threshold (Erbe, 2012). The negative effects are not limited only to the hearing abilities, but they may also affect the vestibular, reproductive and nervous system.

The most common response to a noise input, which is perceived as a threat by the animal, is stress. Prolonged stress may end in a serious health problem (Erbe, 2012).

Underwater noise is caused by various human activities such as commercial shipping, seismic surveys, oil exploration, military sonar, etc (Ferrari, 2020). In addition to these activities, the increase in the use of green energies, which require huge amounts of space, results in the construction of windfarms in the middle of the ocean that add up to the overall underwater noise. Indeed, the operational noise due to windfarms' operations is characterised by low intensities and low frequencies and this local continuous noise has huge impacts on species that use sound to communicate (Tougaard, et al., 2008).

This issue and its impacts are undoubtedly significant but still too unnoticed in our society. A clear research gap is present, and this thesis' main aim is providing some solid basis to fill it. Even if the effects of underwater noise pollution are numerous and are strongly affecting the ocean's fauna, due to the lack in research and objective results, regulations do not and cannot exist. The goal of this research is providing evidence and results that could be used in future public policy by setting the ground for mandatory measures and regulations. This will be done by answering the main question: to what extent noise pollution is an issue and why it is underestimated in the shipping sector?

The thesis is structured as follows. Firstly, the topic of underwater noise and its significance are outlined, including an explanation of human induced noises and their effects on marine mammals. Secondly, a theoretical explanation of the issue based on the theory of the tragedy of the commons is carried out. These knowledge and principles are then used successively in the discussion to provide options on how the various actors should behave as a community when facing the issue of underwater noise pollution in the global common of the ocean. Thirdly, the thesis presents a chapter analysing how and by whom the oceans are regulated. This is used to understand how the regulations at sea are imposed and it can be useful to outline the various steps that must be followed for future regulations regarding underwater noise pollution. Moreover, I include a chapter explaining how the research question previously presented is answered. The methodology consists of mixed methods. The research uses a case study, a model, and interviews to gain a broad and deep knowledge of the topic. I chose the case study of the Wadden Sea because that area has two main features: it is a protected area, rich in biodiversity including a wide mosaic of ecosystems and it is an area characterized by an extremely intense shipping activity. This allows to analyse underwater noise in pollution in a limited area but in a wide range of ecosystems, making the generalization of the results possible. The model is carried out to reach numerical cost results regarding the relationship between a vessel's speed, fuel consumption and noise emission, not present in the available research, setting the baseline for future regulations. The interviews are carried out to gain knowledge regarding topics that cannot be analysed through the model, such as the behaviour of marine mammals and possible innovative technical solutions that could be used to limit the problem. The interviews also serve to generalize results since the interviewees do not belong to a limited area. The thesis will then reach a conclusion on the most efficient ways of facing the problem on underwater noise pollution, discussing the possible costs and benefits of these solutions, and providing insight for future research.

# 2. Underwater Noise

The ocean environment has always been and will always be a sound-full system. Sounds originated from natural sources are numerous and fundamental for the well-being of the underwater environment. Sound propagates from various natural origins such as wind-drive waves, earthquakes, rainfalls, bioacoustics sound generation, thermal agitation of the sea water etc. Sound is an efficient way of propagating energy through the ocean and marine organisms have evolved and have started exploiting this property (Hildebrand, 2009). Fish use sound for navigation, mating, choosing a habitat, communication; marine mammals use it for communication and sensing; toothed whales are able to sense the presence of prays through sound; baleen whales have developed long range acoustic systems to facilitate mating and social interaction (Hildebrand, 2009). In general, sound is essential for marine mammals, to communicate, reproduce and feed. Without sound the ocean ecosystem could not survive. A sound becomes a noise when it impacts and disturbs the marine environment and its inhabitants (Giannoumis, 2017). Sounds that often result in noise are those generated by human activities. These are also known as anthropogenic sounds and to better understand them they can be divided into three main categories: high frequencies, medium frequencies, and low frequencies. The first group is caused for example by seismic sonars; the second group is emitted by military sonars and the third one is due to commercial shipping (propulsion and cavitation of ships) (Giannoumis, 2017). Some of these sounds are unavoidable, others, such as the low frequency ones, have been constantly increasing throughout the years with the increase in commercial activities, and a lack in mandatory regulations to limit this propagation is transforming these noises into a serious issue that must be controlled in order to re-establish and maintain the wellbeing of the ocean's environment.

First of all, the definition of noise is unwanted sound that has an impact on the functioning of a system. No mechanical process can successfully happen without generating vibrations that consequently generate sound. Noise is therefore unavoidable. When considering a machine, each force able to produce work is associated with a small unsteadiness, also known as vibrations, that transmitted on the surface of the machine generate sound (Trucco, n.d.). In addition, when a body moves through a fluid it generated turbulence motions that result in heat and a small amount of sound (Trucco, n.d.). The sound generated by ships, submarines, etc do not always result in a negative factor. Indeed, sounds radiated from ships and submarines can reveal their presence to an enemy, and, in turn, acoustic noise (including self-noise) limits the performance of sonar systems that ships and submarines use (Trucco, n.d.). A small part of the mechanical power necessary for the operation of a vessel is converted in underwater sound. A vessel proceeding at slow speed emits from 5 to 100 W (Trucco, n.d.).

Acoustic signals are sinusoidal vibrations maintained over time (Trucco, n.d.) and they are characterized by three main variables: frequency, wavelength, and amplitude. The unit of measurement of frequency is the Hertz (Hz) and it represents the number of vibrations per second. Humans are able to perceive sounds that vary between 20 Hz and 20,000 Hz (Giannoumis, 2017). Frequencies underwater may vary from a few hertz to 1MHz (Trucco, n.d.). The wavelength is used to measure the distance a sound can travel, and it is usually measured in meters. In particular, the wavelength is defined as the distance travelled by the wave in one period of the signal at a certain velocity (Trucco, n.d.). Wavelength and frequency are strictly related, the lower the frequency the longer the wavelength. The amplitude represents the power, or the intensity of a sound and it is measured in decibel (dB). The decibel scale is logarithmic, and it measures the amplitude of a sound signal using a pressure value that represents the ratio between the measured pressure and the reference pressure (NOAA - National Oceanic and Atmospheric Administration, 2015). It is important to notice that decibels perceived in water are different from those in air. In other words, 100 dB in water are not equal to 100 dB in the air. Sounds signals propagate differently and with different speeds through air and water. It is known that sound velocity is 340 meters per seconds in air. In ideal water conditions (temperature and pressure) sound travels more than 4 times faster. Indeed, sound velocity in sea water varies from 1450 to 1550 meters per second and depends on the following variables: temperature, salinity, and depth. A change in one degree Celsius corresponds to a variation of 3.4 meters per seconds in speed; a change in one ppt results in a variation of 1.2 meters per second in speed; a change in 1000 meters in depth results in a variation of 17m/s in speed (Trucco, n.d.). Moreover, it is known that sound velocity at a depth of zero, at 10 degrees Celsius, with a salinity of 35 ppt is 1490 m/s.

In oceans, temperature and density of water change as the depth increases, this is also known as the thermocline. Due to this property, initially the sound length of travel decreases until the bottom of the thermocline where it starts increasing again thanks to the increase in pressure. Sound in the ocean can in some way be trapped and therefore travel very long distances. Indeed, sound signals, especially low-frequency ones can travel thousands of meters with a minimal loss of signal (NOAA - National Oceanic and Atmospheric Administration, 2015). This characteristic of the ocean can be explained through the deep sound channel, also known as SOFAR (Sound Fixing and Ranging Channel) (NOAA - National Oceanic and Atmospheric Administration, 2015). This channel is better explained starting from sound velocity profiles. The ocean can be approximated as a horizontal stratification where sound velocity is highly influenced by temperature in the upper layers and by pressure in the deeper levels. Sound velocity profiles are graphs that show the relation between the speed of sound in the ocean and depth. They depend on location, season, time of the day, the current and the weather

(Trucco, n.d.). We can distinguish 3 main phases: the surface channel, the thermocline, and the isothermal. The isothermal sound velocity profile generates a non-homogenous field (Trucco, n.d.). A general sound velocity profile shows that as one moves away from the surface of the ocean, a decrease in temperature causes a reduction in the speed of sound until it reaches a minimum. This first section of the graph is known as the thermocline. The depth at which the minimum is reached is known as the “deep sound channel”. Below the thermocline, temperature remains constant and a further increase in depth results in an increase in pressure which causes sound speed to increase again (NOAA - National Oceanic and Atmospheric Administration, 2015). At this point sound waves refract towards the deep sound channel which traps it generating this up and down movement, allowing wave to travel for thousands of meters almost undisturbed. The depth of the SOFAR varies and depends on salinity, temperature, and depth of the water (NOAA, 2010). The channel axis is found 600 to 1200 meters below the sea surface, it is deepest in the subtropics and closer to the surface in high latitudes (NOAA, 2010). The SOFAR is extremely important also for scientific research. Scientists are able to record and hear various sound signals that occur at extremely high distances such as whale calls, earthquakes and noises due to human activities, just by placing hydrophones at the correct depth (NOAA, 2010). Ocean acoustics allows scientists to quantitatively describe sound in the sea and learn more on the oceanic environment and its inhabitants (NOAA - National Oceanic and Atmospheric Administration, 2015).

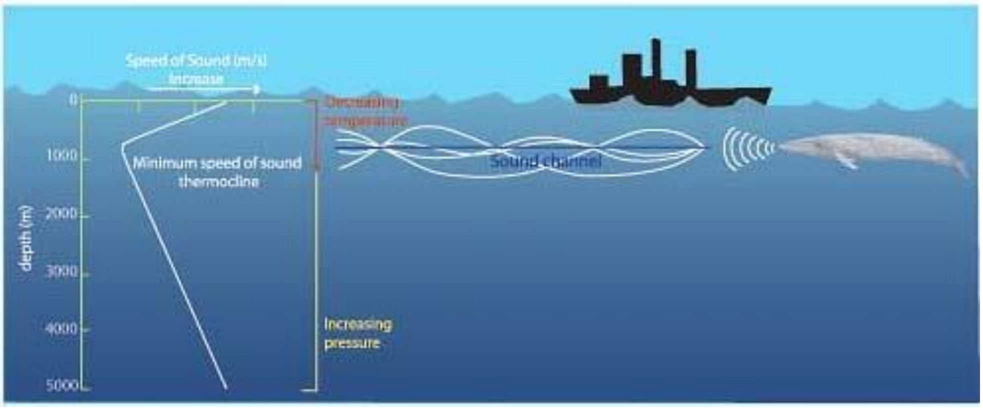


*Figure 1: Graphical Explanation of the SOFAR channel (NOAA, 2010)*

## 2.1. Human Induced Noises

Even though sounds in the ocean are fundamental, most of those generated by human activities are a threat for the ocean environment. Noises related to tourism and fishing activities vary depending on the season: they have peaks in certain limited periods and are reduced in others. Other, more significant, anthropogenic noises are those generated by commercial shipping, industrial offshore activities, sonar systems and oil and gas exploration. Anthropogenic noises are rapidly becoming more numerous and powerful, increasing both oceanic background noise levels and peak intensity levels (Hildebrand, 2009). In addition, these noises are concentrated in certain areas (for example the most used shipping routes) including coastal waters including more sensitive areas, that embrace important marine habitats (Hildebrand, 2009).

### 2.1.1. Explosions

Chemical explosions are used for different activities such as removal of structures, ship shock trials, military mines (Hildebrand, 2009). Explosions generate a pressure impulse that may vary in frequency. The amplitude and the characteristics of the signal emitted depend on the charge of the weight and the depth at which it is placed. In addition, sounds generated by explosions can travel huge distances (OSPAR Commission, 2009). The underwater propagation of the generated signal is complex and follows different steps. We can distinguish two main phases: a shock pulse and subsequent oscillating bubble pulses. These signals propagate homogeneously in all directions and are often perceivable at a regional level, some extreme cases have been detected over several ocean basins (Hildebrand, 2009).

### 2.1.2. Seismic Exploration

Air-gun arrays are used to explore the layers of the sea floor and to locate oil and gas deposits. They operate releasing a volume of air under high pressure that results in a bubble. A sound signal is emitted once the bubble is released, generated by the expansion and contraction of the air bubble (Hildebrand, 2009). The sound emitted travels through the ocean until it reaches the sea floor which causes the reflection of some the sound energy making it travel back to the sea surface where it is recorded by hydrophone arrays (University of Rhode Island, 2021). The acoustic characteristics of the signal that reaches the surface can be analysed, and information regarding the geological characteristics of the seabed can be determined. When exploration is carried out, multiple airguns arranged in a rectangular pattern are used, emitting a much louder sound compared to the use of a single airgun. This activity produces intense, broadband, impulsive sounds that can travel hundreds of kilometres from the source (University of Rhode Island, 2021). Seismic airguns can cause severe injuries, hearing loss, behavioural changes in marine mammals, fishes and possibly invertebrates.

### 2.1.3. Sonar

Also known as sound navigation and ranging, it is a technology that allows to detect objects in the water or on the seabed. We can distinguish two kinds of sonars: passive and active. The first ones listen to underwater sounds and by analysing these signals, obstacles are localised. The second ones emit sound signals and use echoes to detect, locate and classify objects in the environment (University of Rhode Island, 2021). This technology can use the echoes received to distinguish, for example, a submarine from a rock or a whale. Effects on animals and fish due to active sonars are still being studied but there is evidence that demonstrate behavioural changes due to the emitted signals. Active sonars can emit various frequencies, waveforms, and durations. Considering the frequencies emitted we can divide them in low-frequency (less than 1kHz), mid-frequency (1-10 kHz) and high-frequency (more than 10 kHz). The lower the frequency the larger the distance the signal may travel. Another important characteristic of the emitted signal is the duration. This variable is fundamental in understanding the reactions and the potential effects on marine mammals or fish. In particular, active sonars can emit signals that range from continuous active sonar (CAS) to short pulses each lasting less than one second (University of Rhode Island, 2021). Sonars are used for both military and commercial or leisure activities. Civil and commercial sonars emit signals at lower source levels compared to military ones but are more abundant due to the large number of commercial vessels equipped with this technology (Hildebrand, 2009).

### 2.1.4. Industrial Noise (Offshore)

This includes noise due to the construction and operation of offshore windfarms, oil and gas rigs, etc (Harland, et al., 2005). The construction of offshore facilities involves pile driving, a very noisy operation. The structures that are created offshore require supports given by piles which are driven into the seafloor. Piles can be made of different materials and can penetrate the bottom by many meters, sometimes reaching the bed rock (University of Rhode Island, 2021). Pile driving consists of a hydraulic hammer, repeatedly striking the top of the pile. Various factors affect the duration of this activity: the diameter of the pile, the dimensions of the hammer, the required penetration, and the sea floor properties. This operation can take various hours and up to 5000 strikes for each pile (University of Rhode Island, 2021). As the pile is inserted in the seafloor, sound is radiated both into the sea water and through the seafloor. Pile driving induce broadband, impulsive sounds that may travel large distances (University of Rhode Island, 2021). Oil and gas rigs radiate sound signals generated in the machinery transmitted through the platform and successively propagated into the water. These generate mainly low-frequency noises due to the rotation of the machinery (Harland, et al., 2005). When considering windfarms, the intensity and the duration of the sound depends on the phase (construction or operational). During the construction they create low-frequency noise at high source levels. During the operational phase, source levels decrease, low frequency sounds are emitted as the blades spin. As the turbine operates, vibrations in the nacelle are propagated down the main shaft, into the foundation and then propagate in the water and seafloor (University of Rhode Island, 2021). Sound levels vary depending on the wind speed.

### 2.1.5. Leisure Crafts

Over the years the number and the power of leisure crafts have increased (Harland, et al., 2005). This results in a significant impact (that was minimal in the past) on underwater noise. This source of noise is concentrated in certain areas (such as holiday and touristic destinations) and in specific periods during the year, mainly in the summer season. Research has been carried out to gather data and information on leisure craft traffic and its impact on environmental issues (Gibbons 2000 and Haviland et Al. 2001). Leisure crafts can be divided in: sail powered craft, slow motorboats, high-speed motorboats, and personal watercraft (Harland, et al., 2005). High-speed motorboats have a higher impact on underwater noise pollution compared to the others. They can use more than one engine causing disturbance to the water surface. These crafts emit both low and high frequencies. The noise is often in the area between 5-25 kHz (Harland, et al., 2005).

### 2.1.6. Commercial Shipping

At a global scale, shipping is the most significant, common, and constant source of anthropogenic noise. Shipping is the main exponent of global trade, transporting 80% in volume of the global trade. The impact of shipping on underwater noise is strictly related to the economic activity (Merchant, 2019). The shipping activity has drastically increased during the years and its impact on underwater noise has been studied and can be demonstrated. Indeed, between 1963-1965 and 1994-2001 noise levels have increased by 10 dB at low frequencies (which are those emitted by vessels) (Andrew, et al., 2002). This increase is also correlated to a boost in the world Gross Domestic Product (Frisk, 2012). In addition, the growth in vessel traffic in the last years gives research reasons to project a drastic increase in traffic in the next decade, resulting in even higher levels of noise (Kaplan & Solomonc, 2016). Sound signals emitted by commercial vessels vary from 20 Hz to 300 Hz and can travel huge distances, up to 4000 km (Conservation and Development Problem Solving, 2000). The noise emitted is strictly related to the dimensions of the vessel and to its speed. Indeed, in general a larger ship generates more noise than a smaller one (Conservation and Development Problem Solving, 2000). The noise propagated from vessels is due to three main components: propeller singing, propeller cavitation and propulsion machinery (Conservation and Development Problem Solving, 2000). When the vortex shedding frequency, generated by the movement of the propeller, matches its resonance frequency, the propeller starts vibrating and emits a sound, often between 100 and 1000 Hz (Conservation and Development Problem Solving, 2000). The *singing propeller* is a characteristic more common in older and in poor condition vessels. The most significant factor generating underwater noise is the cavitation of the propeller. Cavitation is defined as "the sudden formation and collapse of low-pressure bubbles due to the movement of a vessel's propellers" (Conservation and Development Problem Solving, 2000). The bubbles generated during cavitation cause significant sound activity under the water surface (Giannoumis, 2017). Cavitation happens more often when the ship is fully loaded (Conservation and Development Problem Solving, 2000). This happens because a heavier ship is more submerged compared to a lighter ship. As a result, a more submerged vessel has the propeller's blades situated entirely under the water surface resulting in louder underwater noises. When the propeller is not totally submerged it breaks the water surface limiting the sound emitted underwater (Giannoumis, 2017). Also in this case, older vessels or ships in bad conditions are more likely to generate cavitation. A third source of noise, due to the propulsion machinery, originates in the hull of the vessel and is then transmitted into the water (Conservation and Development Problem Solving, 2000).

As previously mentioned, the size of a ship is a factor that significantly affects noise emission. In general, it has been demonstrated that large commercial vessels generate sound signals characterized by strong tones with low frequencies. A practical example was the study carried out by Ross in 1976 where the sound emission of the Chevron super tanker *London* was measured. The researchers measured the frequencies perceived obtaining a signal of 6.8 Hz from over 140 km away. The stronger tones measured were 40 to 70 Hz. Medium vessels generate tones of around 50 Hz (Conservation and Development Problem Solving, 2000). Small vessels have and average length of 55-85 m, they normally have a diesel engine and two propellers. The frequencies that this class of ships emits is broadband and varies from 20 to 1000 Hz (Conservation and Development Problem Solving, 2000).The sound emission is related to the dimensions of a ship which is strictly related to the engine's characteristics. Large vessels often have powerful engines and slow propellers. The most common propeller configurations in this class of vessels are a single five blade propeller or a twin 3 or 5 blades. The powerful engine and the slow motion of the propeller blades result in the generation of lower frequencies (Conservation and Development Problem Solving, 2000). Smaller ships are often characterised by smaller diesel engines with two propellers. The higher frequencies generated by this class of vessels is due to the high rotation rates of the propellers that causes cavitation noise at higher frequencies. In addition to the vessel's dimensions, noise emission depends also on the type of vessel. For example, containerships emit around 170 dB at source, equivalent to 111 decibels in air; a sound signal comparable to a rock concert (Cord, 2019).

The anthropogenic noise caused by commercial shipping is not homogeneously distributed in the oceans. The amount of low frequency sound signals is greater in areas characterised by heavy shipping traffic (The University of Rhode Island, 2021). Thanks to shipping maps it is possible to obtain the most used shipping routes throughout the world. Marine traffic is much more intense in the northern hemisphere. Indeed, low-frequency ambient noise levels are substantially higher in this area. Obtaining the required data to make accurate predictions of the background noise levels due to shipping is a challenge. Many details of numerous individual ships are required (distribution, density, acoustic characteristics, etc) and hypothesis of future developments will be area-specific considering seafloor properties, salinity, etc (The University of Rhode Island, 2021).

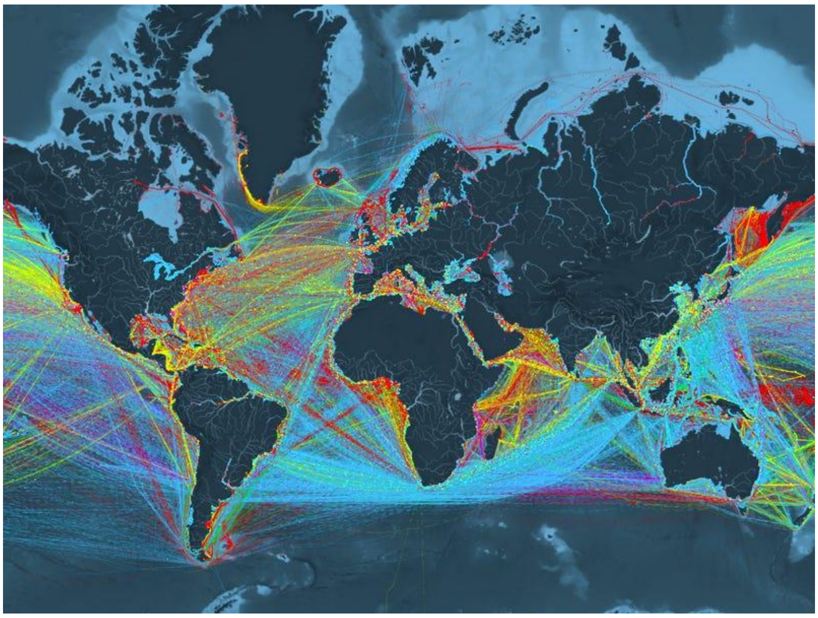

*Figure 2: Example of a Shipping Map showing Traffic Intensity (Martin, 2017)*

## 2.2. Effects on Marine Mammals

Understanding the effects of underwater noise pollution is essential to determine the extent to which noise pollution is an issue and it is the starting point based on which the solutions and measures mentioned in the next chapters are based on. As previously mentioned, the ocean is far from being the "silent world" described by Jacques Cousteau's and it is full of various natural sounds. The most known are, for example, those belonging to the acoustic carapace vibrations of the American lobster, the small grunts emitted by the Atlantic cod, the echolocation clicks of orca and the vocalizations of the huge blue whales (WWF, 2021). Underwater sound is the most effective means of communication for numerous species that inhabit the oceans. However, the increase of industrialization such as port expansion, shipping intensification, oil and gas exploration is causing human induced noise to cover and overwhelm natural sounds. This issue has been ignored and underestimated for years and has started to be researched only recently. Studies demonstrate that anthropogenic noises have huge impacts on marine mammals and many other inhabitants of the oceans. Indeed, even though noise due to the shipping industry has not yet been proven to have lethal impacts on marine mammals, it has been proven that anthropogenic noises cause behavioural changes in marine mammals (Giannoumis, 2017). For example, there is evidence confirming that noise increase stress levels in mammals. In addition, mammals use sounds underwater to navigate, feed, mate and communicate. In particular, toothed whales have specific bio-sonar capabilities to feed and navigate, baleen whales developed long-range communication systems to facilitate reproduction and social interaction, pinnipeds both emit and listen to sounds for critical communicative functions (OSPAR Commission, 2009). As previously mentioned, shipping activities generate sounds at low frequencies which belong to the same band as the ones used by certain marine animals. This interaction makes it difficult, sometimes impossible, for the inhabitants of the area to carry out certain activities. This causes behavioural changes and may put species in danger. Low frequencies generated by shipping activities overlap primarily with those used by large whales, seals and sealions. The three main effects on marine mammals are behavioural changes, masking and hearing loss or damages.

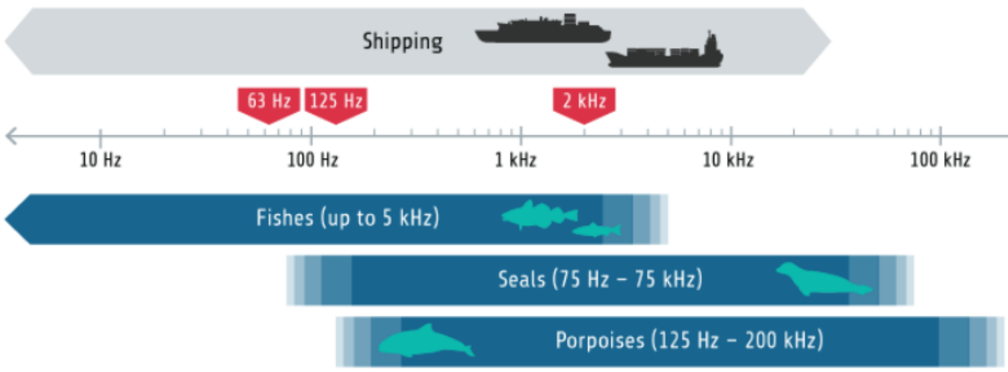


*Figure 3: How sound frequencies generated by shipping overlap with the auditory range of some marine species (WWF, 2021)*

Studies analysing and observing behavioural changes in marine mammals have various limitations: they are observational rather than experimental therefore, often available data lacks appropriate control. Moreover, to study a certain reaction to noise, many variables must be considered, such as species, individual, sex, age and environment (OSPAR Commission, 2009). In addition, also the type of ship must be considered. Different ship types emit different frequencies resulting in different effects on marine mammals. The issue of underwater noise pollution is relatively new, thus the methods used to gather objective data are still being perfectionated. Often researchers carry out recordings of the underwater environment and the sounds are then measured using hydrophones (devices that transmit electrical signals when they are subject to a change in pressure underwater). However, it is complicated to have continuous recordings which are normally limited to a specific period of time, making it challenging to generalise results. For this reason, it is difficult to reach and demonstrate a cause-and-effect relationship between underwater noise pollution and the changes in behaviour or injuries in marine mammals.

### 2.2.1. Behavioural Changes

The effect of anthropogenic sounds on marine mammals' behaviour depends on various factors. Some sounds may not cause any effect while others can cause significant changes in behaviour such as diving, surfacing, vocalizing, feeding, and mating (The University of Rhode Island, 2021). Anthropogenic sounds do not always have concerning effects on animals. Sometimes responses are inconsequential and momentaneous such as turning their heads towards the sound source. In some cases, responses are more significant but still fall in the limits if variations. For example, due to Acoustic Thermometry of Ocean Climate sounds, a slight increase in humpback whales' diving time and underwater travel distance was recorded (The University of Rhode Island, 2021). These changes were not significant compared to the whales' behaviour prior to the introduction of the sounds in the environment and this was confirmed by the absence in change of sighting rates of the whales in the considered area. Another example of non-significant behavioural change in marine mammals was recorded in Hawaii. In this case the anthropogenic sound was due to the Surveillance Towed Array Sensor System Low Frequency Active sonar which was emitted during the singing of humpback whales. This external noise, resulted in the whale's songs to increase 29% in length and remained 10% longer until two hours after the exposure (The University of Rhode Island, 2021). However, unfortunately more significant and concerning behavioural changes have been recorded. For example, when approached by ice-breaking vessels, beluga whales immediately stopped their feeding activities and swam rapidly away. This escape led the beluga whales 80 kilometres away from their feeding site and did not return there for more than 2 days after the passage of the vessel (The University of Rhode Island, 2021). Studies, such as those carried out by Nowacek between 2000 and 2004, demonstrate that various dolphin and whale species may alter motor behaviour when exposed to physical approaches and noises of vessels (OSPAR Commission, 2009). In addition, the reaction of the animals is more severe when the anthropogenic sounds are similar to those emitted by predators. Other concerning reactions were observed in California: manatees decreased their use and presence in certain areas when repeatedly disturbed by the presence of boats; grey whales left one of their breeding lagoons when the shipping activity reached the peak and only returned there once it decreased again (The University of Rhode Island, 2021). Nevertheless, it is complicated to demonstrate that all these changes are a consequence of noise and not due to other factors.

### 2.2.2. Masking

Differently from what might be expected, the greatest concern regarding underwater noise pollution isn't the acute exposure to which animals may be subject to but the continuous background noise due to vessel operations that results in masking. This phenomenon happens when noise interferes with an animal's ability to detect, interpret, and differentiate a specific sound (The University of Rhode Island, 2021). Both natural and anthropogenic sounds generate noise in the underwater environment. Masking impacts depend on different factors such as the sound's level, frequency, and duration. The greatest effect of masking is present when the frequency of the noises belongs to the same band as the sounds used by the animals for their communication systems (such as social activities, breeding calls, etc.) (The University of Rhode Island, 2021). Masking can result in the disruption of breeding or feeding activities for animals that use sound as a reproductive tool or for detecting preys (OSPAR Commission, 2009). Indeed, in some cases marine mammals have decreased or also completely ceased their vocalizations in response to noise for up to months, therefore having consequences on breeding, feeding and social cohesion (Weilgart, 2007). In addition, many animals use the perception of certain signals and sounds for navigation and most importantly for the detection of predators. In 1940 Fletcher demonstrated that noise masks hearing for humans and this phenomenon is similar for numerous mammalian species, also underwater. Many studies have analysed and modelled how low frequency anthropogenic noises, specifically the ones due to shipping activities, result in huge impacts in marine mammals disrupting their communication systems. The continuous noise emitted by shipping activities is causing changes in the vocalization of certain species. Indeed, McDonald in 2006 and Parks in 2007, recorded changes in the vocalizations of blue whales and North Atlantic right whales, such as increasing the number of length of calls or shifting the frequency of the calls (The University of Rhode Island, 2021), in order to adjust to the background noises (OSPAR Commission, 2009). Additionally, the vocal behaviour of the beluga whales in the St. Lawrence River estuary was analysed. This area is famous for being a continuous shipping activity area and commonly used for whale watching. Beluga whales changed the frequency band used for communication. Another study also demonstrated that beluga whales emitted louder sounds when exposed to greater noises; this reaction is also known as the Lombard Effect (The University of Rhode Island, 2021). As previously mentioned, masking is more impactful for species that use low frequencies sounds to communicate which are more similar to the frequencies emitted by ships. Masking at higher frequencies (1-25 kHz) is still possible and happens when the vessel is close to the animal (OSPAR Commission, 2009). Moreover, due to the logarithmic nature of sound and based on what it is known about mammals' communication systems, small changes in background noises may cause a large reduction in mammals' communication (OSPAR Commission, 2009). Also in this case, the effects of masking on marine mammals are uncertain and are still being studied.

### 2.2.3. Injuries

All mammals share the same way of detecting and interpreting a sound. Sound waves are transformed in neural impulses which are then interpreted by the brain (The University of Rhode Island, 2021). A constant exposure to loud noises can interfere this process resulting in loss of hearing sensitivity, known as threshold shift. This shift can be temporary or permanent depending on whether the hearing sensitivity goes back to normal after some time (Erbe, 2012). Scientists use specific auditory testing measures to evaluate hearing sensitivity in mammals. All the information available for hearing loss in humans can be used to better understand hearing damages and loss in marine mammals since they use the same process to detect sounds. Hearing loss depends on many variables such as the intensity of the sound, the frequency and the duration (The University of Rhode Island, 2021). A damage may be due to a short sound with extremely high intensity, but it can also be caused by a sound with lower intensity but continuous in time. Noise can also have effects on non-auditory systems. Stress is a physiological response intended to efficiently react when facing a threat. This reaction causes a release in the hormone adrenaline which increases heart rate, gas exchange, blood flow to the brain and muscles to be ready for a fight-or-flight response (Erbe, 2012). These responses increase survival rate however prolonged stress can have negative effects on health in the long run (Erbe, 2012). For example, it is known that in humans chronic stress may cause coronary diseases, anxiety, depression or infertility (Erbe, 2012).

# 3. Tragedy of the Commons

Taking into consideration the previous chapter that demonstrates the effects of underwater noise on marine mammals, some theory is required to understand how the noise pollution issue should be managed. This chapter outlines the theory behind the management of a common resource such as the ocean, providing insights on future actions that could be taken and will therefore be further discussed in the thesis' conclusion

Environmental problems may be a consequence of exploitation of environmental goods, or they may be due to an incorrect or inefficient government of these resources. Generally, environmental goods may be divided in private goods, public goods, club goods and common resources. These categories are differentiated based on two main characteristics: excludability and rivalry in consumption. Excludability represents the degree to which a good is limited to paying customers, while rivalry in consumption is the degree to which one individual consuming a particular unit of a good limits others from consuming that same unit of that good (Beggs, 2019). This division is better explained by the below table.

| Excludability / Rivalry in Consumption | high | low |
|---|---|---|
| high | private goods | club goods |
| low | common resources | public goods |

*Figure 4: 4 different types of goods (Beggs, 2019)*

Private goods are defined as *"a tangible commodity or product that is consumed by one or a few individuals and hence is not available to others"* (Ban, et al., 2015). Public goods are defined as *"a tangible commodity or product that can be accessed and enjoyed by everyone without subtracting from the enjoyment of others"* (Ban, et al., 2015). Club goods are products *"for which access is restricted, yet use by one does not subtract from the enjoyment of others"* (Ban, et al., 2015) while a common resource is a *"natural or man-made resource system that is sufficiently large as to make it costly (but not impossible) to exclude potential beneficiaries from obtaining benefits from its use"*

(Ostrom, 1990). Governing common-pool resources is challenging because it is difficult and costly to exclude others from using these goods.

The ocean is indeed a common-pool resource, especially when considering the "high sees" that make up 50% of the planet. The high seas provide nearly 90% of the habitat for life on our planet (Gjerde, 2010). The oceans in total can be considered the global common as it belongs to all of us. However, it is managed and exploited by those who have the resources to do so. The protection of the "global ocean" is of extreme importance as it provides us with carbon, heat, and oxygen storage. Nevertheless, only 36% of it is being protected (Gjerde, 2010). Indeed, the current international laws, concerning for example the shipping activity, provide protection focusing on areas closer to the shore. In order to face this lack of regulations and responsibilities, social scientists and economists such as Elinor Ostrom are studying the phenomenon of the management of the commons. The management of common resources must be based on certain prerequisites such as shared responsibilities and norms with the goal of binding people together as a community (Gjerde, 2010). With her extensive work, that led her to the Nobel Prize in Economics in 2009, Elinor Ostrom suggested 8 principles to guide the government of the commons in a community and that can therefore be applied to better manage the ocean as a common resource.

Underwater noise pollution is a challenging issue to face and regulate. Indeed, it is difficult to exclude or limit economic actors from using the common resource of the ocean. This is due to one main factor which is difficult to control, limit and overcome: competition. All actors not only emit noise, but this emission increases due to competition. Consequently, sound emission transforms into pollution impacting the state and health of environmental resources such as the ocean and its inhabitants. Governing common-pool resource is challenging but is of extreme importance to come up with measures and regulations that push the various actors to work together as a community. These measures should limit and avoid the exploitation of environmental resources while providing benefits, and not only costs, for the main actors involved so that they are constantly pushed to work together.

# 4. Regulation of the Oceans

In order to reach conclusions and measures to face the problem of underwater noise pollution, it is important to analyse how the oceans are regulated. This chapter explains how and by whom regulations are developed, providing tools that will be further used in the final chapters to make suggestions on future regulations.

There are numerous organizations, frameworks, and agencies responsible for the ocean and its resources. Some of the most important and known international frameworks are the United Nation Convention on the Law of the Seas (UNCLOS), others more specific for the pollution issue in the oceans are the Convention for the Prevention of Pollution from Ships signed in 1973 successively modified in 1978 (also known as MARPOL 73/78), and the Safety of Life at Sea convention (SOLAS) firstly signed in 1914 and responsible for any form of life in the oceans. Differently from regulations and policies on land, those regarding the oceans include numerous nations. The agency responsible for the actions and cooperation between the member states is the International Maritime Organization (IMO). When dealing specifically with marine pollution issues, the agency involved to ensure the collaboration between the member states is the Marine Environment Protection Committee (MEPC) (Giannoumis, 2017). The conventions previously mentioned issue regulations, rules, recommendations regarding specific issues for the member states. In this way the member states can work jointly to achieve common goals. This is not a unidirectional relation; conventions may impose regulations for the member states but at the same time member states can suggest issues that must be faced, which will then be addressed and resolved in collaboration. In addition to the international conventions and policies, national regulations are also present. For example, the EU put forward the Integrated Maritime Policy (IMP) which is a holistic approach to all sea related EU policies with the aim of strengthening the so called blue-economy (Breuer & Dinkel, 2021).

## 4.1. International Maritime Organization (IMO)

The IMO was established in 1948 by the Geneva Convention and successively entered in force in 1958, allowing the IMO to come up with conventions, publish recommendations and facilitate cooperation and consultation between the member parties. From that moment on IMO became the main tool responsible for any issue or topic concerning commercial shipping (van Leeuwen & Kern, 2021). Initially, the IMO considered and analysed only issues strictly related to navigation. Successively, with the awareness increase regarding environmental matters, the IMO widened its duties and became responsible also for environmental impacts of shipping. The most importation convention concerning environmental impacts was the MARPOL Convention (International Convention for the Prevention of Pollution from Ships) firstly published in 1973 and then amended in 1978. This convention includes six annexes which are constantly updated. These annexes deal with various impacts of shipping: pollution due to chemicals, sewage, discharges of oil pollution, household waste and air pollution (van Leeuwen & Kern, 2021). As stated in the convention, three obligations must be followed, the sanctioning of violations, the issue of certificates and the drafting of report in case of an incident (Giannoumis, 2017).

The IMO recommendations and conventions work as a guideline for national regulations. Indeed, IMO does not impose mandatory regulations on member states, but these rules are often added and followed by national legislation (Giannoumis, 2017). As mentioned above, the IMO delegates to the Marine Environmental Committee (MEPC) technical work such as the analyses and negotiation of new conventions, changes to existing conventions and the elaboration of guidelines (van Leeuwen & Kern, 2021). Within the MEPC, the different international environmental standards are negotiated and discussed by flag states, port states and coastal states (van Leeuwen & Kern, 2021). The flag state represents the state under which a certain ship is registered and has unlimited jurisdiction on its ships. The larger flag states often put economic interests before environmental ones, preferring "uniform international standards over national standards because they ensure level playing field for shipping" (van Leeuwen & Kern, 2021). Large flag states in the EU are Greece, Malta, and Cyprus. Coastal states have a limited jurisdiction over a ship, but they are those suffering the most due to environmental damages caused by shipping. For this reason, they prefer environmental standards but, to obtain them, they have to negotiate with flag states (van Leeuwen & Kern, 2021). Port states have full jurisdiction on a ship in port. They have the power to set regulations that ships must respect to enter and use the port. Port states are also significantly affected by environmental damages such as emissions and discharges and for this reason they support environmental regulations (van Leeuwen & Kern, 2021). Ports have a significant economic importance in the EU since 90% of

Europe's external trade and 40% of the internal one pass through EU ports (van Leeuwen & Kern, 2021).

As any other organization, IMO requires financial support. This is obtained through membership fees which depend on the fleet size. In other words, flag states are the main income for the IMO. For this reason, flag States have some sort of decisional power that directly affects IMO decisions and regulations. The fact that the IMO is financially supported by its member states has certainly an impact on the final decisions and recommendations suggested by the organization. Indeed, this may lead to conflicts of interest. This mechanism of financial support generated a power imbalance that flag States use to push their interests, influencing IMO's committees (Giannoumis, 2017) . In addition, Haren in 2007 argued that most of the representatives of the different countries are in fact representatives of the shipping industry. Consequently, it may be argued that the IMO could act in favour of the shipping industry itself, that might be different from what is best for the environment.

## 4.2. UNCLOS – United Nations Convention on the Law of the Sea

From a governance perspective, before the UNCLOS, the law of the sea was known for its fragmentation, with various actors playing different and sometimes conflicting roles (Tladi, 2011). One of these main actors is the IMO. An important factor underlying the need of the UNCLOS is that the IMO includes treaties and regulations, but these are limited to maritime safety and pollution, it cannot and does not have the tools to preserve and regulate all aspects of the marine environment (Tladi, 2011). UNCLOS's main objective is obtaining a "more integrated, less fragmented system to govern the oceans" (Tladi, 2011). The convention should offer "a legal order for the seas and oceans which will promote the protection and preservation of the marine environment" (UNCLOS, 1982) (Tladi, 2011). The convention includes duties and rights of flag and coastal states, not underestimating the preservation of natural resources. These rights and duties depend on the maritime zones defined by the UNCLOS: internal waters (inside the baseline), territorial waters (12 nautical miles from the baseline), the exclusive economic zone also known as EEZ (from 12 to 200 nautical miles from the baseline). Based on the convention, the high seas start at 12 nautical miles unless mentioned to be the area after the 200 nautical miles area of EEZ (Giannoumis, 2017). Internal waters are an extension of the land thus they are subject to the laws of the coastal state. Territorial waters are also subject to the laws of the coastal states but this is limited and the coastal states must allow the "innocent passage of vessels through its territorial sea" (Giannoumis, 2017). In addition, within the EEZ the coastal state has sovereignty over economic activities. Therefore, all marine resources within the EEZ are under the jurisdiction of the coastal state, including their management and conservation. Regarding the high seas, no state has jurisdiction beyond their EEZ. In 2016, Warner stated that "in the absence of any global authority governing the high seas, the flag State model of jurisdiction has become the predominant method of regulating high seas activities" (p.20). The legal framework that flag States follow is given by the UNCLOS. As described by Beckman & Sun "UNCLOS functions as the *constitution convention* that establishes a legal framework for States and competent international organizations" (Beckman & Sun, 2017).

# 5. Methodology

This chapter outlines why and what methods were used and considered the best choice to answer the main research question. This thesis has three main objectives: firstly, to investigate the issue of underwater noise pollution caused by commercial shipping activities analysing the actual impact it has on the ecosystem. Secondly, it wants to discuss advantages and disadvantages of possible measure that could be enforced in order to control and limit the issue of underwater noise pollution. Thirdly, it wants to analyse the process followed to achieve these regulations and how this can be used by economics and political actors to set forward and give priority to other interests. In order to deeply analyse and reach reliable results concerning these three main aims, an interdisciplinary approach was chosen, investigating the topic form an ecological, technical and legislative point of view. Little research has been carried out on this topic, for this reason, to have a complete view of the issue, mixed methods were used. This chapter will describe the various methods used and their limitations.

## 5.1. Mixed Methods

This research analyses the issue of underwater noise pollution caused by shipping activities through the use of mixed methods. Mixed methods research originated in the social sciences and has developed and become more used in the last decades. This new method is defined as the *third paradigm* in social research, and it is now considered a valid alternative to quantitative and qualitative paradigms (Denscombe, 2008). As other methods, it has both strengths and limitations. In 1989, Green et al. suggested some reasons for combining quantitative and qualitative research. The published scheme consisted of five justifications for this combination:

*1. Triangulation: Finding correspondence on results from different methods. Triangulation focused on seeking evidence between quantitative and qualitative data.* (Bryman, 2006)

*2. Complementarity: "seeks elaboration, enhancement, illustration, clarification of the results from one method with the results from another"* (Greene, et al., 1989)

*3. Development: "seeks to use the results from one method to help develop or inform the other method, where development is broadly construed to include sampling and implementation, as well as measurement decisions"* (Greene, et al., 1989).

*4. Initiation: "seeks the discovery of paradox and contradiction, new perspectives of [sic] frameworks, the recasting of questions or results from one method with questions or results from the other method'* (Greene, et al., 1989).

*5. Expansion: "seeks to extend the breadth and range of enquiry by using different methods for different inquiry components"* (Greene, et al., 1989).

The use of mixed methods allows an eclectic approach to analyse the problem. The possibility of studying the topic through the case study, interviews, and a model, may provide a deeper understanding of the phenomenon. In this case I decided to use this method because considering the novelty of the issue, demonstrated by a lack in research regarding the topic, the use of both quantitative and qualitative data allows to reach more complete results. However, limitations are present. Indeed, generally mixed method studies result in an increase of the complexity of evaluations, they rely on multidisciplinary team of researchers, and they require increased resources (Wisdom & Creswell, 2013).

## 5.2. Data Collection

Data collection was carried out in three main phases. After analysing the issue of underwater noise pollution from a global perspective, the case study of the Wadden Sea was used to collect quantitative data, taking into consideration the three main ports of the Wadden Sea: Hamburg, Bremen/Bremerhaven and Wilhelmshaven. Information such as the number of calls per year in each port and the ship types were available on the ports' websites. In addition, in order to have more information regarding the shipping activity in the area, information regarding for example the ships' velocities was taken from the website *Marine Traffic*. This data was then used for the development of a model which is explained in the following chapters. The case study of the Wadden Sea and the model move hand in hand, they bring together numerical results related to fuel consumptions from the model and behavioural responses of marine mammals due to underwater noise pollution that the model cannot consider and analyse. Finally, interviews were carried out with 3 main goals. Firstly, assessing whether noise pollution is an issue that must be faced urgently. Secondly, to generalise the results obtained from the data and information collected from the case study. Thirdly, to better understand the reasons behind the presence or absence of regulations facing the issue of underwater noise pollution.

## 5.3. Case Study

The case study of the Wadden Sea was used to localise the issue in order to obtain reliable data to develop the model that will be successively discussed. In addition, an important part of the research is the analysis of the effects of underwater noise emissions on the flora and fauna of the ecosystem considered. This aspect was highlighted by some of the interviewees that argued that the research could not have been considered complete without carrying out experiments to test and observe the reactions of the inhabitants of the area. This specific research could not be carried out directly, due to the lack of time, tools, and resources. Indeed, to obtain reliable results, the behaviours must be observed repeatedly throughout a long period of time. For this reason, behavioural effects on the inhabitants of the area were studied and analysed focusing on research available on the Wadden Sea area. Research carried out by the University of Veterinary Medicine Hannover was used.

Case studies are commonly used in international business and social sciences in general. A recent review has classified case studies as the most popular qualitative research strategy (Welch, et al., 2011). Case studies have indeed the power to generate novel theories and insights. The dominant view represents case studies as a tool with the only scope of inductive theory-building. This limits their theorising potential including causal explanations and contextualising theory (Welch, et al., 2011). Indeed, as Bamberger argued in 2008, dominant views may be overestimating generalizability while giving less space to contextual sensitivity. Context has always been a fundamental part of case studies, and this is seen as an impediment for theorising. The obstacle consists in the fact that "*Since to theorise is to generalise away from context, "explaining" and "contextualising" are regarded as being fundamentally opposed*" (Welch, et al., 2011). However, new views on how case studies could be used are trying to reconcile the link between context and explanation. Indeed, the commonly used positivist approach is challenged by alternative traditions. We can identify four main methods of theorising from case studies.

1. Inductive Theory Building: supporters of this method suggest that the main scope of using case studies is the potential of reaching new theories from empirical data. The highest exponent of this approach is Eisenhardt (1989) who argues that the final goal is: *"the development of testable hypotheses and theory which are generalizable across settings"* (Welch, et al., 2011). This view tends to shift from a detail belonging to a particular context to a generalised proposition.
2. Natural Experiment: Yun (2009) argues how case studies can be used for explanatory rather than exploratory purposes (Welch, et al., 2011). This approach supports the fact that case studies may be used to verify and not only discover new theories. As natural experiments, case studies are characterized by a high degree of internal validity (Welch, et al., 2011). Yin

argues that, when considering generalization, case studies work as natural experiments: *"generalises to theoretical propositions and not to populations"* (Welch, et al., 2011).

3. Interpretative Sensemaking: this theory is based on an idiographic social science that aims to understand the particular rather than law-like explanations (Welch, et al., 2011). Stake (1995: 38) describes this concept as: *"the difference between case studies seeking to identify cause and effect relationships and those seeking understanding of human experience"* (Welch, et al., 2011) and considers cause-effect relationships simplistic.
4. Contextualised Explanation: this is an emerging view of theorising from case studies. This method is based on critical realism. One of the main exponents supporting this method is Roy Bhaskar (1998). He argues that the explanation of social phenomena is both causal and interpretive, in this way he creates a connection between explanation and understanding (Welch, et al., 2011). In addition, also supported by Lawson (2003), Bhaskar critical realism rejects the strength of regularity in a model. Indeed, often explanations start from something unexpected, in contrast with what was initially believed (Welch, et al., 2011).

In this research the case studies were used to develop a theory and raise questions and awareness regarding the topic of underwater noise pollution, especially analysing the projects, mitigation measures and frameworks considering the topic from a legal, ecological and technical point of view.

## 5.4. The Model

The topic of underwater noise pollution is broad and there is still a lot to discover. In order to have a more complete view of the issue the research design includes a quantitative approach. This method provides a correlation between two or more variables and numerical results that can then be used to discuss and develop theories by combining them with the qualitative data obtained. It is important to mention that the various approaches used as part of the mixed method do not follow a unidirectional path. More precisely, the model and the case study of the Wadden Sea were carried out simultaneously. The aim of the model is deepening the research level. Differently from the interviews, analysed in the next chapter, the model provides unbiased data since it does not include the interests of the different actors involved. The model allows to reach a first hypothesis that will be successively used to understand what can be done to limit the issue of underwater noise pollution and will raise other questions such as why governments are not imposing measures to tackle the problem.

As previously mentioned, the first step is narrowing the research to a limited number of variables and the relationship behind them. This allows to reach clear and specific results that can then be used to develop a theory. Based on the interviews carried out and previous studies and research, the independent variable chosen is the ship's velocity. Therefore, the model is based on the initial assumption that speed has a direct impact on noise emission. Velocity was chosen for three main reasons: it is demonstrated to have a direct impact on noise emission, it is easily modifiable thus future regulations regarding velocity and be implemented quickly, its direct impact is not only limited to the noise emitted but it also has a strong relationship with fuel consumption that allows us to reach numerical results concerning the costs of possible future regulations. In other words, analysing the ship's velocities allows us to reach results able to quantify both the environmental and economic impact of ships when dealing with underwater noise pollution.

After identifying the variables, it must be noticed that these are influenced by various factors. Indeed, results differ for example based on the ship type and on the area considered. For this reason, in order to reach reliable results, the model focuses on container ships in the Wadden Sea. The data collected is based on information available from the 3 main ports of the Wadden Sea and the surrounding areas: Hamburg, Bremen/Bremerhaven and Wilhelmshaven.

The first relationship considered is the one between a ship's velocity and fuel consumption. It is known that fuel consumption depends on the ship's dimensions (that can be expressed and linked to the transported TEUs) and the ship's velocity (expressed in nodes). Following material provided by the University of Genova, the relationship between fuel consumption, speed and TEUs can be expressed as follows:

$$Fuel\ Consumption = b * TEU^{c} * v^{d} \qquad \text{[Eq. 1]}$$

Where b, c and d are parameters: $b = 2.53 * 10^{-7}$ $c = 0.821$ $d = 3.147$

As it can be noticed, the TEU exponent is less than one and this means that the fuel consumption increases with a lower steepness compared to a linear relationship. Therefore, the specific fuel consumption (fuel consumption/TEU) decreases as the ship's dimensions increase. On the other hand, the coefficient of the speed is greater than one. This means that the fuel consumption increases more rapidly compared to a linear relationship. Thus, a greater velocity has a huge impact on fuel consumption, consequently on costs. Starting from the above equation, the model considers containerships of different dimensions, navigating at different velocities. The values regarding the dimensions and velocities considered are obtained starting from some initial values taken from the *Marine Traffic* website. Firstly, I limited the research to the area of the Wadden Sea, more specifically the zones surrounding the ports of Hamburg and Bremen/Bremerhaven. Secondly, throughout the whole duration of the research I periodically checked the dimensions and speeds of containerships navigating in the selected area. I then decided to focus on ships of 15000, 10000 and 5000 TEU and speeds of 19, 16 and 13 knots. The speeds were then reduced by 20% to see how this would have affected fuel consumption. The lowest speed considered, 13 knots, was chosen for a specific reason. The above formula, and consequently the entire model is valid for speeds greater than 10 knots, below this velocity the relationship between the variables changes thus the model is not valid anymore. For this reason, the lowest speed chosen is greater than 10 knots even after the 20% reduction. Another choice is the one regarding the travel distance subject to the speed reduction. Based on the length of the Wadden Sea coast and considering the huge distances travelled by sound the chosen distance is 200 km.

Two constant values must be considered: the bunker price and the operational costs. The bunker price considered is 473 $/ton, value registered in Rotterdam on August 25th 2021 (Ship&Bunker, 2021). Regarding the operational costs I considered a value of 462.96 dollars per hour, this cost is for a specific TEU containership (The Geography of Transport Systems, 2021). The cost was then adapted for the various TEUs considered.

The model was developed as follows. Firstly, the ship's dimensions (TEU) and velocity (kn) were chosen. Secondly, the time of travel was calculated as $t = distance/velocity$. Thirdly, the fuel consumption was calculated using the formula stated above. The same calculations were repeated with the speed reduced by 20%. At this point the differences in fuel consumption and operational time were calculated. Successively, the following calculations were carried out:

$\Delta\ Fuel\ Consumption\ [\$/h] = \Delta\ Fuel\ Consumption\ [t/h] * Bunker\ Price\ [\$/t]$ [Eq. 2]

$\Delta\ Operational\ Costs\ [\$/h] = \Delta\ Operational\ Time\ [h] * Operational\ Cost\ [\$/h]$ [Eq. 3]

$Total\ Cost\ [\$/h] = \Delta\ Fuel\ Consumption\ [\$/h] + \Delta\ Operational\ Costs\ [\$/h]$ [Eq. 4]

In this way the total costs due to the reduction in speed are calculated. A negative result represents a decrease in costs after the speed reduction.

After finding the relationship between velocity and fuel consumption, thus after analysing the issue from an economic point of view, I investigated the effect of the speed reduction on noise emissions. In this way, the model provides both an economics and environmental quantification of the issue.

The topic of underwater noise emissions and its relationship with a ship's velocity was firstly analysed by Ross in 1976. His research was based on vessel noise measurements and cavitation experiments (Leaper, 2019). Since Ross initial hypothesis, more data has become available. The difference in noise emissions is measured and studied through source levels. The definition of source level Is "*the amount of sound radiated by a sound source. It is defined as the intensity of the radiated sound at a distance of 1 meter from the source, where intensity is the amount of sound power transmitted through a unit area in a specified direction."* (The University of Rhode Island, 2021). Source levels are given in decibels (dB). When dealing with underwater sound propagation, decibels are assumed to be subject to a pressure of 1 micro-Pascal (µPa). Therefore, the unit representing source levels is dB re 1 µPa at 1 m (The University of Rhode Island, 2021). Researchers have developed different theories and approaches to analyse the topic. Some studies suggested a power relationship between broadband source level and vessel speed. One approach is expressing the difference in source level in terms of an initial speed, a final speed and a power exponent z as follows:

$\Delta SL = 10zlog(v_1) - 10zlog(v_0) = 10zlog(\frac{v_1}{v_0})$ (Leaper, 2019) [Eq. 5]

In the above formula, the difference in source level depends only on the ratio between the two velocities and does not depend on the original speed. MacGillivray and Li (2018) estimated values of z by ship types starting from a sample of 2765 source level measurements taken before and after the slow down trial (Leaper, 2019). Estimations of z varied from 5.1 for containerships to 8.1 for bulkers. Before them, Wittekind in 2014 suggested a value of 8 for low frequency propeller noise above cavitation speed (Leaper, 2019).

Another approach developed by researchers such as McKenna et al in 2013, Simard et al. in 2016, Veirs et al. in 2016 and Gassmann et al. in 2017 is considering the relationship as a linear regression as follows:

$\Delta SL = m(v_1 - v_0)$ (Leaper, 2019) [Eq. 6]

The goal of their research was estimating the slope m of the linear regression. In this case, differently from the previous approach, the difference in source level directly depends on the speed values. All the data and results available are based on experimental data. Therefore, researchers came up with different values of m based on their research methods. The values of m vary from 0.93 suggested by Veirs et al. in 2016 to 2.38 obtained by Gassmann et al. in 2017.

This second approach was used in the model. Therefore, this research assumes that the relationship between the difference in source levels and velocities follows a linear regression. This approach was chosen since it was supported by more evidence and was based on more recent studies. The value of m considered is 0.93 dB/knot as suggested by Veirs et al in 2016. This value was chosen because it was obtained starting from a larger sample, thus more generalisable, and supported by other studies carried out more recently.

## 5.5. Interviews

In this research qualitative, in depth, semi-structured interviews were carried out. This consists in an investigation where the interviewer follows a guide to ask various in-depth questions regarding a specific topic to an interviewee who, on the other side, still possesses a complete freedom in the response. This method allows interviewees to elaborate a response clearly showing their point of view. The main characteristics of this type of interview is its flexibility and the fact that "the emphasis must be on how the interviewee frames and understands issues and events" (Bryman, 2012).

In order to avoid biased results, 6 interviews were carried out and participants were chosen strategically from three main categories: economic actors (which are believed to support the economic interests of shipping activities), technical participants (that provided information on new technologies that can limit the issue of underwater noise emissions), and participants with a deep ecological knowledge (believed to support environmental interests over economic ones). Considering these main categories, as stated above, the interviews were carried out following a guide. However, the three groups received slightly different questions in order to reach a deeper understanding of the issue and impacts in all the sectors: economical, technical and ecological. The interviews were carried out for three major reasons: testing whether the results obtained from the model previously discussed could be considered realistic, understanding the reasons behind the lack of regulations and concern regarding the topic and suggesting possible measures that could be applied to limit underwater noise pollution caused by commercial shipping and its effects in the ecosystem.

Since the research used a mixed methodology, a limited number of interviews were carried out. These took place online during the month of September, 2021. An official coding was not possible since the interviews could not be recorded. Nevertheless, the interviews provide significant insight on the topic.

## 5.6. Limitations

Conducting research analysing the issue of underwater noise pollution caused by the shipping industry had various difficulties. As previously mentioned, the topic was analysed using an interdisciplinary approach. This requires the participation of different actors, also subject to time and geographical constraints. Due to time limits, only 6 interviews were carried out. Nevertheless, the results obtained from the interviews considering actors of the same category matched, already indicating a saturation point of the research. Another challenge faced while organizing and carrying out the interviews was avoiding biased results. The actors considered, consciously or unconsciously, answered the questions based on their interests. How previously mentioned, this biased in result was limited by interviewing actors belonging to different sectors: economic, ecological and technical. Another limitation of the interviewing process is that even though semi structured interviews were carried out, the actors of the different categories were asked slightly different questions. This is due to the fact that the research wanted to understand the different views of the various actors on common topics and at the same time obtaining a deeper understanding on topics strictly related to their specific sector.

Moreover, the model developed is based on assumptions that are made to simplify the problem and the cause-and-effect relationship considered. Indeed, differently from the issue of noise pollution, the relationship between speed and fuel consumption in ships has been analysed thoroughly by researchers and engineers in numerous studies, experiments and observations. The first simplification is assuming fuel consumption depending only on the dimensions of the ship and its velocity (see Eq. 1). In fact, the relationship between the two is more complicated and specific for each and every ship. Indeed, the data regarding the fuel consumption is strictly related to its engine. Once a particular engine is chosen for a ship, the engine constructor provides all the necessary information for the chosen engine. A graph that shows how the power of the engine (Pb) varies depending on the number of engine revolutions (n) is provided. This relationship between power and number of revolutions can then be used to determine the fuel consumption of a ship. This research does not focus on a particular ship therefore this procedure (which is specific for each ship) cannot be used. To reach results representing a group of ships, I chose to simplify the relationship to Eq. 1. Secondly, when analysing noise emission and ships' velocities, all the retrieved data is based on innovative and experimental research. There is still no solid and certain theory explaining how ships' noise emissions vary depending on the ship's velocity, indeed the topic is relatively new therefore it is currently being studied. A limitation in the calculation of the difference in source level is that the value of m (the slope of the linear regression) was hypothesized based on experimental data that does not consider the type of ship. Only after, It was discovered that the value of m depends on the type of ship considered.

However, the same value of m is still being used when analysing the topic of underwater noise pollution from ships. Thirdly, the above model, is only valid for speeds greater than 10kn, indeed the hypothesised linear regression is not valid below that specific speed. When the velocity is below the minimum one, new variables must be taken into consideration and the relationship between source level and velocity varies significantly. Lastly, the distance of 200km subject to the speed reduction is hypothetical and chosen based on the length of the Wadden Sea coast. Theoretically, the distance considered should be calculated starting from the speed of sound underwater. Generally, not underwater, knowing the speed and a given time allows to obtain the distance travelled. However, the distance travelled by sound underwater is not easily calculable. It is not a fixed value and does not only depend on speed and time. Indeed, it depends on various variables such as temperature, salinity, and depth of the water that vary significantly even in relatively small areas. The above variables were unknown therefore a hypothetical value was chosen based on available information.

# 6. The Case Study of the Wadden Sea

The chosen case study focuses on the area of the Wadden Sea. This research aims to obtain generalizable results. However, obtaining useful data to develop the model which will be discussed in the next chapter, requires the research to focus on a specific area. I chose the Wadden Sea area for two main reasons: it is a protected area, rich in biodiversity including a wide mosaic of ecosystems and it is an area characterized by an extremely intense shipping activity. These characteristics allow for an analysis of underwater noise pollution in a limited area but within a wide range of ecosystems, making the generalization of the results possible.

## 6.1. Ecology of the Wadden Sea

The Wadden Sea emerged about 8,000 years ago during the post-glacial sea levels rise giving birth to the largest flat system in the world where natural processes proceed undisturbed. It extends across the coasts of Denmark, Germany, and the Netherlands. Thanks to its unique geological and ecological traits and to the constant activities and progress concerning the management of the area, in 2009 it was inserted in the UNESCO's World Heritage list. The Wadden Sea is the only place in the world characterized by its biodiversity, numerous habitats, and a dynamic landscape; it's features must be preserved. The Wadden Sea World Heritage includes almost all the Wadden Sea area and extends over an area of almost 11,500 square kilometres, expanding on a coastal strip of about 500 km (Wadden Sea World Heritage, 2021). Areas with similar morphology exist throughout the world but they differ in climate, tides in size. Indeed, the Wadden Sea covers almost 60% of the intertidal area of the North-eastern Atlantic shores (Wadden Sea World Heritage, 2021). This area is considered a feeding sanctuary for 12 million migratory birds and it is the habitat of thousands of species of both plants and animals.

The Wadden Sea can be divided in 3 main areas: Southern, Central and Northern Wadden Sea. The first area is characterized by 12 main islands situated at a distance that varies between 5 and 15 km from the coast. Their function is to protect the tidal area from the waves generated by the winds that come from the North-west. The second area is characterized by tidal ranges that often exceed 3 metres. Four estuaries are present that cause lower and variable saline levels. The central area lacks barrier islands. Finally, the third area comprises 8 main islands that, with the help of numerous sandbars, create a barrier (5 to 25 Km from the coast) that protects the mainland from the waves generated by the winds from the West. From a hydrological point of view, the Wadden Sea includes 39 tidal basins, all characterized by salt marshes, tidal flats, tidal gullies, barrier islands and ebb-tidal deltas (Wadden Sea World Heritage, 2021). The Wadden Sea main traits exist thanks to the tides, winds and waves present in the area. Throughout one day, during a normal high tide, there is the movement of about 30 cubic kilometres of water. Strong winds are also present, these can cause high tides to increase up to 4 metres. Due to these strong winds tidal flats may remain hidden for days. This explains why there is a majority of marine organisms compared to terrestrial ones in the tidal zone (Wadden Sea World Heritage, 2021). West winds are more common than East winds, but when these occur, they may lead to low tides 1.5 metres below normal levels. Winds, storms and changes in sea level that occur in the area make the Wadden Sea a very dynamic environment, that can drastically change from one day to another. The area is so dynamic that new islands can emerge (Norderoog) and others vanish (Buise, Jordsand) (Wadden Sea World Heritage, 2021).

From an ecological point of view, the Wadden Sea is unique. It includes numerous habitats that are the proof of how physical and biological forces and activities may interact generating excellent life conditions in an environment which is theoretically fragile (Wadden Sea World Heritage, 2021). The various habitats throughout the cost differ in depth, salinity, dryness, wave exposure, etc. The Wadden Sea includes five different major habitats:

Offshore Belt: this area lacks tidal flats and develops uniformly towards the North Sea and there is a constant movement of water and sediments with the tidal area. The low turbidity of the water allows the bloom of phytoplankton which then reached the inshore zoobenthos via the numerous channels.

Tidal Area: this is the most characteristic area of the Wadden Sea. Twice a day the water retreats, leaving space to the land. At the contrary to what may be perceived after an initial glance, this area is full of life. The sediment is almost entirely covered by algae and bacterial colonies. In addition, one of the most important inhabitants of the area are the lugworms also known as *the gardeners of the tidal flat* (Wadden Sea World Heritage, 2021). They recycle the upper layer of the sediment 10 to 20 times per year and enrich the land with oxygen, increasing bacterial activity. The tidal area il also characterized by subtidal shoals and gullies offering a more protected environment for the intertidal fauna when conditions are harsh (Wadden Sea World Heritage, 2021). During low tide fish, shrimps and other species move to this area. These areas are also the primary sites for sponges, tunicates, mussels and oysters (Wadden Sea World Heritage, 2021).

Estuaries: The Wadden Sea comprises 5 main estuaries, Varde A in Denmark, Eider, Elbe and Weser in Germany and the Dutch-German Ems. Estuaries are not the main habitats in the Wadden Sea but they are fundamental for the ecosystem because of their supply of riverine inputs such as nutrients. They also serve as a passage for fish such as flounder, smelt and eel. However, unfortunately estuaries have been significantly affected by human activities.

Salt Marshes: also known as the Neptun's Garden, they are the section of land in between sea and land. They are inhabited by a variety of both specialised and more adaptable plants and flowers. The most tolerant plants are found in the upper zone, and they can adjust to salinity (Wadden Sea World Heritage, 2021).

Beaches and Dunes: sand moved by the wind in various directions is trapped by some plants giving birth to embryonic dunes. When the heights become too elevated, and the grass is not able to trap the sand anymore, migrant dunes arise (Wadden Sea World Heritage, 2021). Beaches and dunes are not an independent system and are needed by the other ecological systems. For example, birds use these areas to feed, rest and nest.

## 6.2. Biodiversity in the Wadden Sea

The various habitat systems previously mentioned allow the Wadden Sea to accommodate a significant number of both terrestrial and marine species. It is hypothesized that the Wadden Sea is house to 10,000 species: around 2,700 are of marine origin, 5,100 are terrestrial or semi-terrestrial, and the rest are numerous unicellular groups (Wadden Sea World Heritage , 2021). How it can be noticed, the Wadden Sea is characterised by its biodiversity, and it is one of the main exponents able to arrest or limit the loss of biodiversity in temperate coastal zones. The salt marshes are inhabited by numerous terrestrial and marine species. An extremely high number of arthropods inhabits this area and the main producers are vascular plants (45 species); waterfowls and insects feed on these plants. In addition, 100 species of birds feed and rest in this area. Adding all of these up give 1,600 terrestrial species plus the 500 aquatic species reaching a total of 2,300 (Wadden Sea World Heritage , 2021). The Wadden Sea is also inhabited by more than 140 fish species, 20 of which spend their whole lifetime in this area.

As mentioned above, the Wadden Sea is a paradise for numerous bird species. It is the perfect place to rest, nest and feed for 1% of the flyway population, seeing over 40 different species (4 breed in this area, 15 visit during migration and 24 do both). This gives the site international importance according to the Ramsar Convention (Wadden Sea World Heritage , 2021). Millions of birds visit this area because of the high large quantities of food, lack of human disturbance and absence of mammalian predators making it an actual sanctuary (Wadden Sea World Heritage , 2021).

The Wadden Sea is not only the habitat for unicellular species, insects, and birds, it is also home for various marine mammals. The indigenous species are the harbour seal, the grey seal, and the harbour porpoise. In the past, both seal species were hunted. As a result, only 4,000 harbour seals and no grey seals were left in the Wadden Sea (Wadden Sea World Heritage , 2021). In order to improve these conditions a large part of the area and the seals are now under protection. Successively, the environment improved, and the Wadden Sea is now home to 20 % of the Northeast-Atlantic subspecies of the harbour seal (Wadden Sea World Heritage , 2021). 40,000 harbour seals were counted in 2018 and 6,500 grey seals were observed during migration (Wadden Sea World Heritage , 2021).

## 6.3. The Trilateral Wadden Sea Cooperation

The Wadden Sea extends along the coast of Denmark, Germany and the Netherlands. These three countries have been cooperating to protect and jointly manage the Wadden Sea maintaining its precious characteristics (its ecological value and the variety of biodiversity). To achieve these goals, the three countries took part in the Trilateral Wadden Sea Cooperation (TWSC). This cooperation is based on one main principle: *"to achieve, as far as possible, a natural and sustainable ecosystem in which natural processes proceed in an undisturbed way"* (Wadden Sea World Heritage, 2021). In addition, the TWSC is based on the Joint Declaration on the Protection of the Wadden Sea, signed in 1982 with last update in 2010, that identifies the main goals and measures on which the cooperation is based. The TWSC has worked for the protection of the environment touching various subjects, from politics to ecology and nature. The nomination of the Wadden Sea as a World Heritage Site was based on the cooperation between the 3 countries. The TWSC constantly works to achieve the following (Wadden Sea World Heritage, 2021):

1. Applies and develop common policies and manages the area to protect the Wadden Sea and its ecological entity
2. With the collaboration of regional and national authorities measures and controls the quality of the ecosystem to develop efficient protective and management measures
3. cooperates internationally with other marine sites on protection, conservation, and management
4. Involves and focuses the public attention on the protection of the Wadden Sea organising awareness-raising activities and environmental education
5. Actively works on the sustainable development of the Wadden Sea Region focusing it on natural and cultural values (Wadden Sea World Heritage, 2021).

## 6.4. Management of the Wadden Sea

The Wadden Sea has outstanding characteristics that result in an international importance. For this reason, it must be protected and preserved but this is a continuous challenge. The governance of the area involves various institution and parties. Indeed, the area follows national and regional measures suggested by the 3 countries directly involved, but it also follows the European Union Directives, such as the Water Framework and Habitat Directive (Giebels, et al., 2013). Therefore, it can be argued that the Wadden Sea follows a polycentric governance (Giebels, et al., 2013). Decisions regarding this area are complex and must consider both the ecological and social aspects of the region. Throughout more than 50 years, the governance passed from a nature conservation management approach to a large-scale ecosystem-based management (Giebels, et al., 2013). In other words, it develops policies around a well-defined ecosystem-based area with the gaol of reaching knowledge-based solutions (gained from multidisciplinary research, different sources and areas).

The Wadden Sea is subject to active planning, management and monitoring through national and international measure, regulations, and conventions and thanks to the harmonious joint activity of Denmark, Germany and the Netherlands. Due to the variety of the area, ecosystem, countries and institutions involved, the overall management is guided by two main agreements:

The Wadden Sea Plan: it was adopted by the three countries in 1997 and constitutes a legally binding framework representing a joint policy and management scheme responsible for the protection and sustainable management of the Wadden Sea.

Integrated Coastal Zone Management Strategy (ICZM): this varies from the previous one as it acts at a European Level. Its main goal is considering recommendations from the European Parliament regarding the conservation and management of costal zones (IUCN, 2008).

Thanks to these instruments there have been significant improvements in the area during the last 20 years. Initially, the Wadden Sea conservation focused only on the natural and ecological aspects of the area. After years, it is now accepted that the ecological protection must be managed in conjunction with the cultural heritage. Another significant step forward in the management of the area was the recognition of the Wadden Sea as a Particularly Sensitive Sea Area (PSSA); in other words, an area that needs special protection and action by the International Maritime Organization (IMO) for outstanding ecological, socio-economic, scientific recognized features (Enemark, 2005). Despite this, the Wadden Sea remains subject to and can be easily damaged and ruined by the international maritime activities that take place in the North Sea, one of the seas with the highest maritime traffic concentrations due to the important routes it contains. As previously mentioned, the main principle of the trilateral Wadden Sea Policy is reaching a sustainable ecosystem where natural processes may proceed undisturbed (Enemark, 2005). In order to achieve this, policies and management measures have been applied as stated in the Wadden Sea Plan.

Even though Germany, Denmark and the Netherlands all follow the Wadden Sea Plan, there are some differences at a national level between the applied management measures. In Germany, nature conservation is controlled by the federal states following the federal Nature Conservation Act. The German Wadden Sea coastal states of Schleswig-Holstein, Lower Saxony and Hamburg established the Wadden Sea national parks in the 1980s (Enemark, 2005). The management of these national parks is regulated by a zoning system. The area is divided in two main zones: zone 1 and zone 2. No activity is allowed in the area with a higher level of protection (1), whereas activities are allowed in zone 2 under specific regulations. The management of the park is regulated by the national park authorities. In Denmark, the management of the area is very similar to the German one. There are a few differences: the zoning system is actively related, and the park does not have its own authority and is regulated by the authority of the Danish Forest and Nature Agency. In the Dutch area, regional and local plans have been developed, not the whole area is organized in zones, but some restricted areas do exist (mainly to limit fishing and public access) and there is not a special authority responsible for the Wadden Sea area. The overall achievements of the various targets outlined by the Wadden Sea Plan are assessed by the Trilateral Monitoring and Assessment Program (TMAP). This program was set up to check whether the regulations and measures are followed and has the power to create new ones if needed. In addition to the governmental institutions, the role of Non-Governmental Organizations (NGOs) is fundamental. They indeed support activities to protect the area and are the main exponents promoting environmental education and awareness raising activities (IUCN, 2008).

Some of the main threats that act against the main principle and goal of the trilateral cooperation are: fisheries, harbour & maritime traffic, oil & gas exploitation, tourism, natural disasters, climate change, wind energy, invasive alien species and, the more underestimated of all, noise pollution.

# 7. Results

## 7.1. Evidence of Behavioural Responses of Marine Mammals based on the Wadden Sea Case Study

Since underwater noise pollution is a relatively new issue, a fundamental aspect that must be considered when investigating anthropogenic noises is the monitoring of marine mammals for periods of time, to record their behavioural response due to noise emission. Indeed, the first question that must be answered is whether there is evidence supporting the negative impacts of this issue. Considering the novelty of the topic, it is important to obtain as much evidence as possible to set the ground for future mitigations measures or regulations.

The University of Veterinary Medicine Hannover carried out various studies to monitor the behavioural response of marine mammals in the area of the Wadden Sea and its surroundings. The main goal of the studies was indeed demonstrating that the changes in behaviours of the animals was a direct reaction due to vessel passages and their high velocities. During the initial experiment long-duration audio and 3D-movement tags were placed on three harbour seals and two grey seals. This allowed the continuous monitor of the animals for 21 days. The animals were subject to noise due to shipping activities for 2.2%-20.5% of their time in water (Mikkelsen, et al., 2018). This study was able to demonstrate the interruption of functional behaviour due to high level vessel noise. In addition, it provided an efficient technique of continuous monitoring that can be used in future research. Successively, another monitoring experiment was carried out where animal-borne acoustic tags were used to measure vessel noise exposure and foraging efforts on seven harbour porpoises (Wisniewska, et al., 2018). The study provides evidence of vigorous fluking, bottom diving, interrupted foraging, and cessation of echolocation due to noise emitted by vessels. Therefore, there is clear evidence of huge impacts of noise pollution due to vessels on marine mammals. The high noise levels may cause a cessation in foraging during the passage of the vessel, hypothesising a transit of 15 minutes, the noise precludes 23 prey capture attempts. Given the traffic intensity of certain areas this may cause severe effects on foraging. In addition, the sudden stop of echolocation increases the risk of swimming into fishing nets. This evidence supporting an urgent need of regulations to reduce underwater noise before reaching irreparable consequences allows us to proceed with the next chapters which discuss possible measures that could be applied to tackle the issue.

## 7.2. Cavitation: The main source of Underwater Noise Pollution

As previously mentioned in the chapter dealing with human induced noises, when considering commercial shipping, propellors, engines and gears are the main machines involved in the production of sound. This depends on the ship type, hull shape, propulsion system, speed, etc. Sounds emitted by ships are low frequency and contribute to the ocean ambient noise (The University of Rhode Island, 2021). The cavitation of the propeller is the main source of underwater sound emitted by ships.

Cavitation is a physical phenomenon and is explained in fluid dynamics, which deals with submerged bodies and their movement. Generally, cavitation happens when a difference in pressure is created in a fluid, consequently areas of vapor are created which result in bubbles which end up imploding on themselves. The classical and most known phenomenon of cavitation is created when something passes through a fluid at very high speed. A cavitating propellor is inefficient since it is not able to provide the necessary thrust to the ship. The transition from liquid to gas state that happens during the formation of the bubbles causes a loss in water resistance therefore the propellor starts to spin faster without increasing the ship's speed. This causes an increase in fuel consumption and stress for the engine. In addition to slowing down the ship and stressing the engine, it also damages the propellor itself. The implosion of millions of bubbles in contact with the propellor generate many small damages that in the long run ruin the propellor blade. Moreover, the damage to the propellor is also due to the fact that during cavitation the water around the propellor reaches high temperatures that create microcurrents which also damage the propellor. The cavitation-induced noise emitted by ships is due to the implosion of the bubbles that, for this reason, are the major responsible for underwater noise pollution cause by shipping activities (Andreatta, n.d.).

Cavitation must be avoided for two main reasons. Firstly, it is responsible for underwater noise pollution. Secondly, a cavitating propellor, in the worst case, must be replaced and this consists in a significant extra cost. The IMO recommends designing propellors and hulls together to obtain the most efficient solution and at the same time reduce noise pollution. The propeller's characteristics that must be considered and chosen appropriately to avoid cavitation are the propellor's diameter, blade number and pitch (The University of Rhode Island, 2021).

## 7.3. Technical Vessel Quieting Options

In addition to the noise generated by the propellor, machineries that are present on vessels also generate sound that propagates through the hull and consequently add up and result in underwater noise pollution. The intensity of noise transmitted in the ocean depends on the type of machinery, where it is placed in the vessel (noise propagates less when the machinery is placed towards the centre of the vessel), and generally on the vessel design. Machinery bolted to the hull are those resulting in greater noise emissions. Since the topic of underwater noise pollution is still being studied and monitored, an interesting way of understanding the most efficient techniques to limit ship noise is the use of acoustic propagations models which allow researchers to record the *noise footprint* generated by an individual vessel which can then be used to produce noise maps in order to provide a better understanding of the total contribution of multiple vessels to the ambient noise in a particular area (The University of Rhode Island, 2021). These models have already been successfully used, for example in the Glacier Bay Natural Park in Alaska where scientists used these models to analyse the acoustic exposure of humpback whales to vessel noise and reach the most efficient solution to limit this exposure. Therefore, these models provide an important tool when considering management decisions regarding the topic of underwater noise (The University of Rhode Island, 2021).

In addition to the solely monitoring of noise, there are various solutions that can be implemented to reduce noise emissions from ships. Thanks to the interviews carried out and to material provided by the University of Genova in the past years, one of the most innovative technologies capable of reducing the noise due to the propellor's cavitation is the PressurePores system developed by Strathclyde University and Oscar Propulsion (Hellenic Shipping News, 2021). This system consists in placing some holes in the propellor's blades to reduce root cavitation. Holes in the blades can reduce the propellor's thrust potential. However, models developed at Strathclyde University provide the exact position where the holes must be placed to obtain the maximum efficiency and the best noise reduction (Hellenic Shipping News, 2021). David Taylor, the CEO of Oscar Propulsion argues:

*"Underwater radiated noise is one of the most adverse environmental by-products from commercial shipping, yet unlike other forms of marine pollution, there is no legislation yet in place to prevent this type of environmental damage. Increased levels of shipping noise, especially in the low-frequency range, disorientate marine fauna and disrupt their communication signals, leading to behavioural changes or local extinction. We now have a cost-effective, easy-to-apply solution to prevent this from happening. Introducing holes in propeller blades to reduce root cavitation, for example, is not in itself new, but achieving high levels of noise reduction by strategically placing relatively few holes, while maintaining efficiency, is new."* (Hellenic Shipping News, 2021).

Computational fluid dynamics (CFD) models and cavitation tunnel tests carried out at Strathclyde demonstrate that the innovative system has the power to reduce cavitation volume by nearly 14%

and underwater noise emission by up to 21dB (Hellenic Shipping News, 2021). The results of the tests carried out also demonstrate that the optimal number of holes per blade tip is 17, if placed in the most effective positions. This technology has a great impact in the reduction of cavitation induced noises. However, as mentioned above, cavitation is not the only source of noise, other elements such as the hull and propellor flow, the ship's machinery and the electrical sources also play a role. The reduction in noise emission thanks to the PressurePores system can be seen in the below figure:

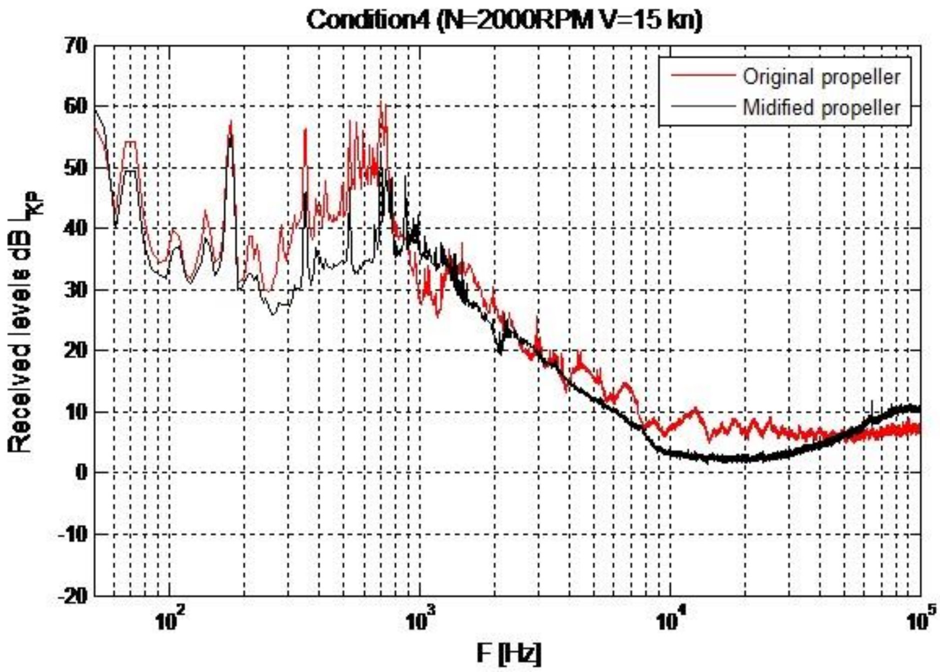


*Figure 5: Reduction in noise emission thanks to the Pressure Pores system (Hellenic Shipping News, 2021)*

Many other procedures and choices regarding technical aspects of vessels are possible and efficient in reducing noise. Also in this case, the interviews carried out provided significant information since the University of Genova is active and part of many projects concerning underwater noise pollution. In particular, the port of Vancouver carried out a study for the ECHO (Enhancing Cetacean Habitat and Observation) program with the aim of investigating technical ways to make vessels quieter. Researchers identified and analysed 30 design, technology and maintenance options to reduce vessel noise, and these can be grouped in 8 main categories (Port of Vancouver, 2017):

a. Regular propeller polishing and repair
b. Regular hull cleaning
c. Hull coating
d. Propeller design modified to reduce cavitation and improve wake flow
e. Alternate propulsion
f. Use of quieter engines
g. Reduced on-board engine and machinery noise (location, insulation)
h. Changes to hull form

These options were analysed and classified based on various criteria such as effectiveness at reducing noise, feasibility, availability of service, etc. In this research only the 3 most effective options will be discussed.

1. Regular propellor cleaning/polishing/repair: this procedure is the most effective one against underwater noise and it is easily accessible. It can be carried out in dry dock or underwater thanks to divers. Cleaning diminishes turbulence which at the same time increases efficiency by reducing losses of propulsive power caused by fouling (Port of Vancouver, 2017). In addition, polishing reduces the roughness of the surfaces by removing marine fouling. It is demonstrated that anti-fouling coatings can reduce noise and may be effective for up to 36 months (Port of Vancouver, 2017).
2. Decoupling coating: this is part of the hull coating category. This procedure is used to reduce machinery noise. It consists in an additional layer of material, up to a few centimetres thick containing air cavities, that plays a role in reducing the radiation efficiency of the hull, consequently reducing noise radiation (Port of Vancouver, 2017).
3. Propellor Boss Cap Fins (PBCF): it is part of the Propeller design modification category. It consists in attaching small fins to the propeller's hub. Their role is reducing hub vortices, therefore they recover the lost rotational energy and reduce cavitation (Port of Vancouver, 2017). Experiments carried out in cavitation tunnels provides evidence that this technology is able to reduce sound pressure level by 3-6 dB when dealing with frequencies greater than 1000 Hz (Port of Vancouver, 2017).

## 7.4. Speed Limitations

Recently, studies have been carried out to better understand the relationship between ships' speed and noise emissions. A third variable that must be considered, which may provide an explanation for the lack of regulations when dealing with underwater noise, is fuel consumption. This variable has a high impact on the total cost of a ship and therefore plays a significant role in decision making. Speed restrictions have already been considered to deal with a more popular environmental problem, GHGs emissions. Part of these results gained from previous research can be used also to deal with underwater noise emission. Indeed, it is known that engine power output and speed follow a third power relationship. In other words, a 10% decrease in speed causes a 27% decrease in engine power. With a speed reduction more time is needed to complete a voyage, thus the same speed reduction will cause a 19% reduction in the energy required for the trip. Starting from the case study of the Wadden Sea and talking to some exponents of the University of Veterinary Medicine Hannover, I found out that speed and noise emissions are indeed related, but more research must be carried out to understand the link between the two variables. At present, there is evidence of behavioural changes in animals due to noise emitted by shipping activities. However, it is still not clear what aspect of the noise is affecting the animals: the frequency, the cumulative energy involved in the passage of the vessel, the peak threshold, etc. In order to better understand this relationship, I developed a model that studies speed reductions based on the vessel's sizes, taking into consideration fuel consumption, the total costs due to the speed reduction and the difference in source level registered. The main aim of this model was understanding whether the overall costs generated by a speed reduction could be the reason explaining the absence of measures and regulation controlling underwater noise pollution.

# 8. Discussion

The choice of including the use of a case study, a model and interviews gives a broad vision of the topic and makes an interdisciplinary analysis of the issue possible. The Wadden Sea case study allows to focus on one area providing data for the model without preventing a generalization of the results. Indeed, the Wadden Sea is chosen because one of its characteristics is the variety of the mosaic of ecosystems and its inhabitants making a generalization of the findings possible. In addition, thanks to the case study I obtained information on essential aspects of the problem that could not have been observed directly, such as the behavioural changes in animals. The high traffic intensity of the Wadden Sea area also provides sufficient data to develop the model which is essential to obtain numerical cost results that have an important role in assessing possible solutions for the issue of underwater noise. The model provides the costs of a speed reduction and also gives insight on how speed affects noise emissions in ships. Numerical and objective results are currently the missing piece in research regarding the topic and are required to set the ground and provide public policy with material to develop future regulations. The generalizability of the results is also possible thanks to the interviews carried out. Indeed, the participants were not limited to a specific area. The interviews provide essential information to understand what aspects of the topic must be considered to obtain reliable results and also have an important role in outlining possible technical solutions to the issue.

Considering the results obtained, we can argue that the absence of measures cannot be due uniquely to the costs. Indeed, a speed reduction generates a decrease in costs up to a certain limit. More precisely, when considering the 15000 TEU ship with an initial speed of 19 knots, the 20% reduction in speed causes a reduction in the total cost of 1065 euro per ship. As the initial speed decreases, the reduction in costs decreases too until a certain point where the trend changes. Indeed, a 20% reduction in speed starting from an initial speed of 13 knots results in an extra cost of 440 euro per ship. This increase in costs is greater as the dimensions of the ships decrease. Indeed, when considering ships of 10000 and 5000 TEU there is an increase in costs already from an initial speed of 16 knots and the increase in costs at 13knots is greater when compared to the 15000 TEU ship. This trend is due to the SFOC (specific fuel oil consumption). The SFOC lines are provided with the engine and work best at an optimal point. The SFOC optimal point for container ships is relatively high and since these lines do not follow a linear relationship, a reduction starting from a higher speed have a lower impact on the total costs. The increase in costs is also due to the fact that a speed reduction causes an increase in the duration of the trip and therefore an increase in the operational costs that add up to the total ones.

The model also analyses the relationship between speed and noise emission by calculating the difference in source level due to a change in velocity. The model provides evidence and confirms the initial hypothesis that a speed reduction results in a noise emission reduction. Therefore, the model suggests that imposing regulations on the vessels' speeds navigating certain areas would help to limit the issue of underwater noise pollution.

In this research two main possible solutions are suggested and analysed: technical vessel quieting techniques and speed reduction. In both cases costs and benefits are present. As mentioned in the previous chapters, cavitation may generate up to 180dB of underwater radiated noise and can be heard 100 miles away. In addition, cavitation also causes damages to the propellor itself. The PressurePores system is able to reduce the cavitation volume by 14% and noise emission up to 21dB. The main advantage of this system is that it can be applied on new propellors, but the small holes can be inserted also on pre-existing propellors. Therefore, the solution is cost efficient, existing ships do not have to support the cost of a new propellor and since the pressure pores system reduces cavitation, it also reduces the damages to the propellor itself. In addition, in the long run, maintenance costs are also reduced. There are other numerous technical techniques that can be applied to reduce noise emission, but I decided to consider only those that do not involve a total replacement of the propellor system making the solution less feasible when considering the overall costs. All the techniques considered, in terms of costs are subject to an extra labour and maintenance expense which are much less compared to a total replace of the propellor which in the long run could be necessary due to cavitation damages.

The speed limitation option is considered the most efficient one. As demonstrated from the model, a speed reduction can result in a decrease in total costs. However, this depends on various factors such as the vessel's dimension, the initial speed and the distance considered. This solution is cost efficient if applied for limited distances. This is due to the fact that a slower speed results in a longer trip. This solution has also some disadvantages. Firstly, if considering longer distances subject to a speed limitation, more ships will be needed, and this will result in additional costs. Secondly, there would be an increase in inventory and monitoring costs. Thirdly, logistical chains should adjust to this transportation speed limit. A significant limitation of speed reduction, obtained thanks to the interviews carried out, is that it is still uncertain if marine mammals have more negative impacts when subject to loud noises for a limited time or when subject to lower noises for a longer time. However, a speed limit would have numerous benefits. Studies argue that a 20% speed reduction would result in a 66% reduction of underwater noise. A speed limitation would also decrease GHGs emissions which at the moment are particularly controlled by the IMO. In addition, a velocity limit would reduce whale strikes. A 20% speed reduction would reduce collision between ships and whales by 78%. Speed limitations are difficult to impose due to legal feasibility and loopholes previously discussed.

# 9. Conclusion

Through the use of the case study, the model and the interviews carried out, this research demonstrates that underwater noise pollution is an issue that must be faced and limited. Indeed, evidence gained from the case study of the Wadden Sea, which can be generalized to a wider range of marine mammals, shows behavioural changes, increase in stress levels and in the worsts cases the escape of species from certain areas. These effects, if not limited, will have drastic consequences on entire ecosystems. For example, since noise emitted from ships interferes with sounds that mammals use to interact for feeding or mating, a constant interference may result in the fleeing of species from certain areas or in the worst case, in the long term, it may cause the extinction of certain species.

Regarding the possible measures that could be applied to face the issue of underwater noise, the model and the interviews demonstrate that the two main possible solutions, considering costs and feasibility, are speed reduction and technical innovative solutions that can be applied to current and future propeller and hull systems. This research shows that speed reductions have a positive impact on noise emissions also resulting in a cost limitation up to a certain level, making this the most efficient solution. The technical solutions provided by the interviewees also play a role in the reduction of noise emitted by ships by acting mainly on the propulsive system.

This thesis sets the ground for public policy developments, but some limitations are present. Firstly, the topic is still undiscovered and due to the lack of research, the results and arguments obtained are based on experimental data, which is not based on solid theories supported by the replication of results. Secondly, analysing the issue using the example of the Wadden Sea area provides generalizable results thanks to the variety in ecosystems and species, however this cannot include the effect of noise emitted by ships on all the ecosystems and species present in the world, thus the generalizability is limited. Thirdly, the interviews involve various categories to limit biased results. A more inclusive sample could have been selected, considering for example ONGs.

Future steps are numerous and challenging. The main objective now is actively raising awareness of the issue. Indeed, as mentioned by Aurore Morin (IFAW's Marine Conservation campaigner), the biggest challenge that campaigns must face when dealing with underwater noise pollution is that the public is completely unaware of the issue. Invisible to the human eye, ocean noise pollution is easily ignorable even though it is currently one of the deadliest threats for marine mammals and the health of the ocean. This public unawareness makes legislative changes even more difficult. For this reason, it is important to emphasize, before any measures or regulations, that the pillar to face the issue of underwater noise successfully is raising awareness. This can be done by developing projects and campaigns. Nationally, some projects have already been and are currently carried out. For example, AQUO is a collaborative European Research Project with the aim of providing to policy makers practical guidelines, acceptable by shipyards and ship owners (AQUO Project Consortium, 2015). Another European project is the SATURN, involving numerous EU partners and with the aim of creating and testing innovative solutions to reduce the most harmful effects of underwater noise. The lack of awareness also limits the possible actions of the IMO. Indeed, Only in 2014 the IMO suggested the Guidelines for the Reduction of Underwater Noise from Commercial Shipping to Address Adverse Impacts on Marine Life. The document suggests outlines technologies, designs and recommendations to reduce underwater noise. However, the proposal emphasises that the document is non-mandatory. It is also important to notice that no future dB reduction goals are present.

From a legislative point of view, due to the numerous bureaucratic procedures the path is still long. The main problem when dealing with underwater noise pollution is the lack of mandatory regulations. As previously seen in the chapter regarding the regulation of the oceans, controlling the whole area that the ocean covers is challenging because the international law of the sea has to include and put together numerous countries. Underwater noise pollution must be faced internationally to obtain successful results limiting as much as possible any sort of way out for the various actors involved. For example, if measures are applied nationally, more precisely limited to ships navigating under a particular flag, if the regulation imposed goes against the personal interest if the party involved, the simple way out for the actor would be, for example changing flag. Facing the issue internationally would prevent this kind of loophole. In addition, law-making procedures are long and intricate. Laws are normally applied only after numerous and strong evidence supporting a particular issue. Researchers interviewed throughout this investigation argued that it is too soon to consider legal actions to limit the problem because the supporting evidence is not sufficient. Research in the field of underwater noise is still in the phase of monitoring and in some cases, as for example in the Wadden Sea, the absence of adequate tools makes the monitoring phase challenging and sometime not possible continuously. The paradox is that the evidence available is considered significant and sufficient to demonstrate the negative impacts on marine mammals but at the same time not enough to activate legal procedures. Sadly, too often legal measures are applied too late. For this reason, considering the issue from a larger perspective, to deal with certain issues promptly, actions should be taken to limit legislative inertia, making legislative decisions quicker and more efficient.

The issue of underwater noise is having drastic effects on the habitants of the ocean and must be faced immediately. The best and most efficient way to limit the problem is imposing international mandatory regulations. Future research should go the extra mile, moving from monitoring to actual analysis and results to widen the foundations allowing the development of regulations. As previously argued in the theory concerning the tragedy of the commons, the management of common-pool resources is complicated but essential for the well-being of humans and the environment around them. The foundation to an efficient management of the oceans is developing measures that push the various actors to work together as a community by providing benefits and not only costs to the parties involved. The 8 principles provided by Elinor Ostrom provide and can be used as the main pillars on which the management of the oceans should be based on.

# Bibliography


Andreatta, N., n.d. *La cavitazione dell'elica: una spiegazione completa.* [Online]
Available at: https://www.hinelson.com/blog/cavitazione-elica-barca/
[Accessed 26 September 2021].

Andrew, R. K., Howe, B. M. & Mercer, J. A., 2002. *Ocean ambient sound: Comparing the 1960s with the 1990s for a receiver off the California coast.* [Online]
Available at: https://asa.scitation.org/doi/10.1121/1.1461915
[Accessed 28 August 2021].

AQUO Project Consortium, 2015. *AQUO.* [Online]
Available at: http://www.aquo.eu/
[Accessed 23 September 2021].

Ban, N. . C., Evans, L. S., Nenadovic , M. & Schoon, M., 2015. Interplay of multiple goods, ecosystem services, and property rights in large social-ecological marine protected areas. *Ecology and Society,* Volume 20.

Beckman, R. & Sun, Z., 2017. The Relationship between unclos. *asia-pacific journal of ocean law and policy.*

Beggs, J., 2019. *The 4 Different Types of Goods.* [Online]
Available at: https://www.thoughtco.com/excludability-and-rivalry-in-consumption-1147876
[Accessed 26 September 2021].

Belibassakis, K., 2018. *Generation and propagation of underwater noise.* [Online]
Available at: https://www.euronoise2018.eu/docs/papers/466_Euronoise2018.pdf
[Accessed 21 August 2021].

Breuer, M. E. G. & Dinkel, T., 2021. *Integrated Maritime Policy of the European Union.* [Online]
Available at: https://www.europarl.europa.eu/factsheets/en/sheet/121/integrated-maritime-policy-of-the-european-union
[Accessed 13 September 2021].

British Ecological Society, 2021. *What is Ecology?.* [Online]
Available at: https://www.britishecologicalsociety.org/about/what-is-ecology/
[Accessed 6 October 2021].

Bryman, A., 2006. Integrating quantitative and qualitative research: how is it done?. *Qualitative Research,* Volume 6, pp. 97-106.

Bryman, A., 2012. *Social Research Methods.* 4th ed. s.l.:Oxford University Press.

Conservation and Development Problem Solving, 2000. *Anthropogenic Noise in the Marine Environment.* [Online]
Available at: https://nmssanctuaries.blob.core.windows.net/sanctuaries-prod/media/archive/management/pdfs/anthro_noise.pdf
[Accessed 28 August 2021].

Cord, D. J., 2019. *Battling noise pollution, underwater.* [Online]
Available at: https://www.wartsila.com/insights/article/battling-noise-pollution
[Accessed 29 August 2021].

Denscombe, M., 2008. Communities of Practice - A Research Paradigm for the Mixed Methods Approach. *Journal of Mixed Methods Research,* Volume 2, pp. 270-283.

Enemark, J., 2005. *Science Direct.* [Online]
Available at: https://pdf.sciencedirectassets.com/271816/1-s2.0-S0964569106X01023/1-s2.0-S0964569105000499/main.pdf?X-Amz-Security-Token=IQoJb3JpZ2luX2VjEOD%2F%2F%2F%2F%2F%2F%2F%2F%2F%2FwEaCXVzLWVhc3QtMSJIMEYCIQDgJCtUGwQQVKGrrJ%2By8aZbznOovwx4WnKahTIBNbMKhAIhAKsmAzB4Ac
[Accessed 24 August 2021].

Erbe, C., 2012. *Effects of Underwater Noise on Marine Mammals.* [Online]
Available at:
https://www.researchgate.net/publication/221778499_Effects_of_Underwater_Noise_on_Marine_Mammals
[Accessed 21 August 2021].

Ferrari, K., 2020. *understanding ocean noise pollution and its deadly impact on marine animals.* [Online]
Available at: https://www.ifaw.org/journal/interview-ocean-noise-pollution-impact-marine-animals
[Accessed 21 August 2021].

Frisk, G. V., 2012. *Noiseonomics: The relationship between ambient noise levels in the sea and global economic trends.* [Online]
Available at: https://www.nature.com/articles/srep00437
[Accessed 28 August 2021].

Giannoumis, J. K., 2017. *Underwater Noise Pollution: An Evaluation of the Voluntary Guidelines on Reduction of Underwater Noise from Commercial Shipping in the United States.* [Online]
Available at: https://nmbu.brage.unit.no/nmbu-xmlui/bitstream/handle/11250/2448967/Giannoumis_J_EnvStud_MasterThesis_2017_60cred.pdf?sequence=1
[Accessed 26 August 2021].

Giebels, D., van Buuren, A. & Edelenbos, J., 2013. *Science Direct.* [Online]
Available at:
https://www.sciencedirect.com/science/article/pii/S1385110112001906?casa_token=4a17Qk2AZAEAAAAA:lJJnmI-wgfTQiVVkNKj0199n1pZ7d1tH5GZD0b__e03gPpj6sBece9gqebIjQZVS8vutwskG5APE
[Accessed 24 August 2021].

Gjerde, K., 2010. *TED.* [Online]
Available at: https://www.ted.com/talks/kristina_gjerde_making_law_on_the_high_seas
[Accessed 26 September 2021].

Greene, C. J., Caracelli, V. J. & Graham, W. F., 1989. Toward a Conceptual Framework for Mixed-Method Evaluation Designs. *Educational Evaluation and Policy Analysis,* 11(3), pp. 255-274.

Harland, Jones & Clarke, 2005. *SEA 6 Technical report: Underwater Ambient Noise.* [Online]
Available at:
https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/197303/SEA6_Noise_QinetiQ.pdf
[Accessed 27 August 2021].

Hellenic Shipping News, 2021. *Revolutionary Propeller Technology Developed To Reduce Underwater Radiated Noise.* [Online]
Available at: https://www.hellenicshippingnews.com/revolutionary-propeller-technology-developed-to-reduce-underwater-radiated-noise/
[Accessed 27 Septemebr 2021].

Hildebrand, J. A., 2009. *Anthropogenic and natural sources of ambient.* [Online]
Available at: https://www.int-res.com/articles/theme/m395p005.pdf
[Accessed 26 August 2021].

IUCN, 2008. *The Wadden Sea - Germany/The Netherlands,* s.l.: s.n.

Kalouptsidi, M., 2021. *The Role of Shipping in World Trade.* [Online]
Available at: https://econofact.org/the-role-of-shipping-in-world-trade
[Accessed 21 August 2021].

Kaplan, M. B. & Solomonc, S., 2016. *A coming boom in commercial shipping? The potential for rapid growth of noise from commercial ships by 2030.* [Online]
Available at: https://www.sciencedirect.com/science/article/pii/S0308597X16303335?via%3Dihub
[Accessed 28 August 2021].

Leaper, R., 2019. *The Role of Slower Vessel Speeds in Reducing Greenhouse Gas Emissions, Underwater Noise and Collision Risk to Whales.* [Online]
Available at: https://www.frontiersin.org/articles/10.3389/fmars.2019.00505/full#B36
[Accessed 25 September 2021].

Martin, W., 2017. *Insider.* [Online]
Available at: https://www.businessinsider.com/map-of-global-shipping-interactive-2017-12?international=true&r=US&IR=T
[Accessed 1 October 2021].

Merchant, N. D., 2019. *Underwater noise abatement: Economic factors and policy options.* [Online]
Available at:
https://reader.elsevier.com/reader/sd/pii/S1462901118310748?token=16A43AD5E2CFA75A02178311D5D9985F0833462DBE705B298EB94E219BB30183EB19DE02389807D258025EB24DF784D3&originRegion=eu-west-1&originCreation=20210828142717
[Accessed 28 August 2021].

Mikkelsen, L. et al., 2018. Long-term sound and movement recording tags to study natural behavior and reaction to ship noise of seals. *Wiley Ecology and Evolution.*

NOAA - National Oceanic and Atmospheric Administration, 2015. *Understanding Ocean Acoustics.* [Online]
Available at:
https://oceanexplorer.noaa.gov/explorations/sound01/background/acoustics/acoustics.html
[Accessed 26 August 2021].

NOAA, 2010. *Ocean Explorer.* [Online]
Available at:
https://oceanexplorer.noaa.gov/explorations/sound01/background/acoustics/media/sofar.html
[Accessed 26 August 2021].

OSPAR Commission, 2009. *Overview of the impacts of anthropogenic underwater sound in the marine environment.* [Online]
Available at:
https://tethys.pnnl.gov/sites/default/files/publications/Anthropogenic_Underwater_Sound_in_the_Marine_Environment.pdf
[Accessed 27 August 2021].

Ostrom, E., 1990. *Governing the Commons.* Cambridge: Cambridge University Press.

Port of Vancouver, 2017. *An Evaluation of Vessel Quieting Design, Technology and Maintenance Options.* [Online]
Available at: https://www.portvancouver.com/wp-content/uploads/2017/01/Vessel-Quieting.pdf
[Accessed 27 September 2021].

Ross, D., 1976. In: *Mechanics of Underwater Noise.* s.l.:Pergamon Press, pp. 3,4.

Ship&Bunker, 2021. *Ship&Bunker.* [Online]
Available at: https://shipandbunker.com/prices
[Accessed 25 August 2021].

The Geography of Transport Systems, 2021. *Operating Costs of Panamax and Post-Panamax Containerships.* [Online]
Available at: https://transportgeography.org/contents/chapter5/maritime-transportation/containerships-operating-costs-panamax-post-panamax/
[Accessed 25 August 2021].

The University of Rhode Island, 2021. *Behavioral Changes in Mammals.* [Online]
Available at: https://dosits.org/animals/effects-of-sound/potential-effects-of-sound-on-marine-mammals/behavioral-changes-in-mammals/
[Accessed 12 September 2021].

The University of Rhode Island, 2021. *Hearing Loss in Mammals.* [Online]
Available at: https://dosits.org/animals/effects-of-sound/potential-effects-of-sound-on-marine-mammals/hearing-loss-in-mammals/
[Accessed 12 September 2021].

The University of Rhode Island, 2021. *How does shipping affect ocean sound levels?.* [Online]
Available at: https://dosits.org/science/sounds-in-the-sea/how-does-shipping-affect-ocean-sound-levels/
[Accessed 29 August 2021].

The University of Rhode Island, 2021. *Masking in Mammals.* [Online]
Available at: https://dosits.org/animals/effects-of-sound/potential-effects-of-sound-on-marine-mammals/masking-in-mammals/
[Accessed 12 September 2021].

The University of Rhode Island, 2021. *Ship Quieting Technologies.* [Online]
Available at: https://dosits.org/animals/effects-of-sound/moderate-or-eliminate-the-effects-of-human-activities/ship-quieting-technologies/
[Accessed 26 September 2021].

The University of Rhode Island, 2021. *Source Level.* [Online]
Available at: https://dosits.org/glossary/source-level/
[Accessed 25 September 2021].

Tladi, D., 2011. *Ocean Governance: A Fragmented Regulatory Framework.* [Online]
Available at: http://regardssurlaterre.com/en/ocean-governance-fragmented-regulatory-framework
[Accessed 17 September 2021].

Tougaard, J., Madsen, P. T. & Wahlberg, M., 2008. *UNDERWATER NOISE FROM CONSTRUCTION.* [Online]
Available at: http://www.marinebioacoustics.com/files/2008/Tougaard_et_al_2008.pdf
[Accessed 20 August 2021].

Trucco, A., n.d. *Emissione acustica ed elettromagnetica della nave - SEGNATURA ACUSTICA,* Genoa: DIBE – University of Genoa.

UNCTAD, 2020. *Maritime Transport Services and Infrastructure Supply.* [Online]
Available at: https://unctad.org/system/files/official-document/rmt2020ch2_en.pdf
[Accessed 20 August 2021].

University of Rhode Island, 2021. *Seismic Airguns.* [Online]
Available at: https://dosits.org/animals/effects-of-sound/anthropogenic-sources/seismic-airguns/
[Accessed 28 August 2021].

van Leeuwen, J. & Kern, K., 2021. *The External Dimension of European Union Marine Governance: Institutional Interplay between the EU and the International Maritime Organization.* [Online]
Available at:
https://watermark.silverchair.com/glep_a_00154.pdf?token=AQECAHi208BE49Ooan9kkhW_Ercy7Dm3ZL_9Cf3qfKAc485ysgAAAsIwggK-BgkqhkiG9w0BBwagggKvMIICqwIBADCCAqQGCSqGSIb3DQEHATAeBglghkgBZQMEAS4wEQQMLQxr1bCwrqRC9PfwAgEQgIICdfnHl5YbKBylRzNm-XSBnPaHIHenprLg9KDgzNKVCc
[Accessed 17 September 2021].

Wadden Sea World Heritage , 2021. *Richly Diverse.* [Online]
Available at: https://www.waddensea-worldheritage.org/richly-diverse
[Accessed 23 August 2021].

Wadden Sea World Heritage, 2021. *Naturally Unique.* [Online]
Available at: https://www.waddensea-worldheritage.org/naturally-unique
[Accessed 23 August 2021].

Wadden Sea World Heritage, 2021. *Naturally Unique.* [Online]
Available at: https://www.waddensea-worldheritage.org/naturally-unique
[Accessed 23 August 2021].

Wadden Sea World Heritage, 2021. *One Wadden Sea. One Global Heritage..* [Online]
Available at: https://www.waddensea-worldheritage.org/one-wadden-sea-one-global-heritage
[Accessed 23 August 2021].

Wadden Sea World Heritage, 2021. *Taking Shape.* [Online]
Available at: https://www.waddensea-worldheritage.org/taking-shape
[Accessed 23 August 2021].

Wadden Sea World Heritage, 2021. *Trilateral Wadden Sea Cooperation.* [Online]
Available at: https://www.waddensea-worldheritage.org/trilateral-wadden-sea-cooperation
[Accessed August 24 2021].

Weilgart, L., 2007. *A Brief Review of Known Effects of Noise on Marine Mammals.* [Online]
Available at: https://escholarship.org/uc/item/11m5g19h
[Accessed 12 September 2021].

Welch, C., Piekkari, R., Plakoyiannaki, E. & Paavilainen-Mantymaki, E., 2011. Theorising from case studies: Towards a pluralist future for international business research. *Journal of International Business Studies,* Volume 42, pp. 740-762.

Wisdom, J. & Creswell, J. W., 2013. *Mixed Methods: Integrating Quantitative and Qualitative Data Collection and Analysis While Studying Patient-Centered Medical Home Models.* [Online]
Available at: https://pcmh.ahrq.gov/page/mixed-methods-integrating-quantitative-and-qualitative-data-collection-and-analysis-while
[Accessed 18 September 2021].

Wisniewska, D. M. et al., 2018. High rates of vessel noise disrupt foraging in wild harbour porpoises (Phocoena phocoena). *Royal Societay Publishing.*

Woodward, A., 2019. *Insider.* [Online]
Available at: https://www.businessinsider.com/ocean-animals-that-went-extinct-species-threatened-2019-6?international=true&r=US&IR=T
[Accessed 27 September 2021].

WWF, 2021. *FOR WHALES, UNDERWATER NOISE IS POLLUTION TOO.* [Online]
Available at: https://wwf.ca/stories/for-whales-underwater-noise-is-pollution-too/
[Accessed 2 September 2021].

WWF, 2021. *WWF.* [Online]
Available at: https://www.wwf.nl/globalassets/pdf/nieuws/wwf-shipping-and-underwater-noise-report-2021.pdf
[Accessed 3 October 2021].

# Appendix

## Interviews

6 semi-structured interviews were carried out and the participants were chosen from three main categories: 2 economic actors, 2 ecological actors and 2 technical actors. With the aim of gaining a deep understanding of all the 3 sectors, the participants belonging to different categories received slightly different questions. Since the interviews could not be recorded, a summary of the interviews follows.

**Ecology and Biology:**

1. Is the issue of underwater noise pollution significant in your sector? If yes, why?
2. What are the effects of underwater noise pollution on marine mammals if there are any?
3. What are the species that are majorly affected by underwater noise pollution?
4. Do you know about projects or measures with the aim of reducing underwater noise pollution?
5. How would you limit underwater noise pollution?
6. What do you think about the lack of mandatory regulations regarding underwater noise pollution?

The interviewees of this category include an expert from The University of Veterinary Medicine Hannover which is active in projects that aim at observing and analysing marine mammals' behaviour when subject to noise. Based on some observations carried out, the interviewees argue that underwater noise pollution is a significant issue that must be faced quickly to avoid the fleeing and the extinction of certain species from certain areas. Some of their studies provide evidence showing the reactions of harbour porpoises and grey seals to underwater noise. The main effect of noise on marine mammals is masking. The loud noises emitted by ships interfere with the sounds emitted by the animals for example for echolocation, feeding and mating. In extreme cases, the noise can also affect the hearing capacities of the animals. The interviewees believe in the fact that the most feasible and efficient solution to reduce the problem is imposing speed restrictions. These would not only limit underwater noise emission but also reduce strike between ships and animals (that often involve whales). The interviewees strongly suggest that the research should focus on the behavioural reactions of animals and not only on the speed reduction, fuel consumption and noise emission. Indeed, behavioural changes provide the reason why speed limitation should be applied, and this provides the foundations for future policies. The interviewees suggest that future research and measures should involve limiting navigation areas making areas where vessels pass clearer for animals. They also suggest the future use of measuring stations to provide continuous recordings of shipping noise. The process is long, the impacts on animals must be observed and showed and only then ways to mitigate the effects can be developed.

**Technical**

1. Is the limitation of underwater noise pollution a priority in the engineering field?
2. What causes underwater noise pollution in ships?
3. Can you explain what happens when the propellor cavitates and why it must be avoided?
4. How would you limit underwater noise pollution?
5. Do you know about projects or measures with the aim of reducing underwater noise pollution?
6. What do you think about the lack of mandatory regulations regarding underwater noise pollution?

Some naval engineers were interviewed regarding the topic of underwater noise pollution. The awareness and significance of the issue of underwater noise is increasing. After accepting the presence of the issue, the University of Genova of Marine Engineering and Naval Architecture is carrying out experiments and doing research to understand what the main sources of noise emissions in ships are. The interviewees argue that the main source of noise is the cavitating propellor. Noise is generated also by the vibrations of machines present on the ship which are radiated through the hull and in the ocean. In addition, they are aware of projects and solutions that could be applied to limit cavitation. However, many of these would be costly and would require the substitution of the whole propellor system. Solutions to cavitation would not only limit underwater noise emission but in the long term would limit the total costs. A cavitating propellor damages the propellor itself which in the long run must be substituted resulting in extremely high costs. Investing in maintenance and in innovative solutions to reduce cavitation would reduce the overall total costs. The interviewees also argue that another way of tackling the issue of underwater noise would be imposing speed limitations. This solution would be the most efficient since it is immediately possible and applicable to all ships. In addition, depending on the specific fuel oil consumption of the engine present on the ship, a reduction in speed would require less fuel consumption, resulting also in this case in an overall cost reduction. Moreover, the University of Genova is an active member of the AQUO project which aims to find solutions to mitigate the issue of underwater noise reduction. The interviewees argue that imposing mandatory regulations its challenging especially if they involve changes to the propulsive systems. In this case the measures could only be applicable only to new ships and this would not be sufficient to limit the issue.

**Shipping and Economics**

1. Is the limitation of underwater noise pollution a priority in the shipping field?
2. Do you know about projects or measures with the aim of reducing underwater noise pollution?
3. How would you limit underwater noise pollution?
4. What would be the pros and cons of imposing regulations to limit underwater noise pollution
5. How would you think the various parties involved would react to mandatory regulations on shipping activities to reduce underwater noise?
6. What do you think about the lack of mandatory regulations regarding underwater noise pollution?

The shipping sector is aware of the potential problems caused by underwater noise pollution. Currently, it is not one of the main priorities. Indeed, the parties' attention at the moment is focused on the reduction of GHGs emissions. Their priority is reaching the goal set by IMO of the 50% reduction in GHGs emissions by 2050. Regarding the projects concerning underwater noise pollution they are aware of the IMO guidelines published in 2014, but since it does not impose mandatory regulations and no target has been set it is still early to establish when these will actually be applied. In other words, no mitigations measures to reduce underwater noise pollution are currently being applied. Regarding possible future measures to limit the issue 3 main arguments came up: routes restrictions, technical solutions concerning the hull and propellor of ships and, speed limitations. The most feasible solution would be speed limitations, but the various stakeholders would be subject to various costs, some of them are: trips would require more time so, in the long term more ships would be required; inventory, monitoring and operational costs would increase; the logistical chains involved in the whole transportation systems should adjust. If not mandatory, introducing these measures would go against the main parties' interests. For this reason, more research and policies should be developed in order to offer benefits, and not only cost, for the parties that are willing to apply these measures. The lack in regulations is justified by the absence of results demonstrating the impacts of underwater noise pollution. The interviewees argue that there is not enough evidence demonstrating lethal or significant impacts on marine mammals that would justify the presence of mandatory regulations.