AQUO
Achieve QUieter Oceans by shipping noise footprint reduction
FP7 - Collaborative Project n°314227

WP 5: Guidelines to reduce ship noise footprint

T5.5
Synthesis of recommendations.
“Underwater Noise Footprint of Shipping: The “Practical Guide”

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SUMMARY

To reach the goal of the Marine Strategy Framework Directive (MSFD), EU Member States are committed to achieving and maintaining a “Good Environmental Status” (GES) for their respective maritime areas by 2020. This commitment aims at ensuring marine biodiversity and limiting anthropogenic pollution into the oceans. Identified as one of the pollutants, consistent with Descriptor 11 of the MSFD and work carried out by the Task Group (TG) Noise, continuous noise from shipping is especially addressed here.

However, there is at present no regulation that limits underwater noise related to shipping or any design requirement for the reduction of radiated noise levels from ships. Consequently, there is a risk of degradation of the environmental status in some European areas, due to underwater noise and its impact on marine life, with negative outcomes for biodiversity and population numbers.

In that context, the European Commission launched, in 2011, the theme [SST.2012.1.1-1.] “Assessment and mitigation of noise impacts of the maritime transport on the marine environment” (coordinated topic within the framework of the “Ocean of Tomorrow”) within the Seventh Framework Program.

This theme resulted in the start of the AQUO project (N°314227), in October 2012, which ran for a 3-year duration. The present document is the deliverable D5.8 of the AQUO project: Synthesis of recommendations – Underwater Noise Footprint of Shipping: The “Practical Guide”. It should be noted that another collaborative project, SONIC (N°314394), addressed the same EU call. It was required by the European Commission that the two projects collaborate with each other to ensure consistent conclusions, as far as possible, resulting in a common document [30].

It has to be noted also that, beyond the initial description of work on which the AQUO project was structured, an extensive dissemination of results at scientific events was done, and that the continuous exchanges with AQUO’s End-users and with other maritime industry stakeholders brought additional requirements that were addressed and covered as far as possible.

In Chapter 2 of the present document, the methodology defined within the AQUO project to address underwater noise in relation to shipping and its impact on marine life is presented. The purpose of the methodology is to take into account all the key components from the receiver (marine fauna representatives) to the emitter (the ship as a noise source) through the following key steps:

- Noise footprint assessment tool development;
- Development of a model for underwater radiated noise (URN) from ships, taking into consideration the variety of commercial ships and corresponding characteristics;
- Consolidation and validation of propagation models with on-site long-term measurements;
- Definition of acoustic sensitivity criteria for dedicated species;
- Application of the methodology to several maritime areas of interest;
- Proof of concept and reproducibility of the Ocean Shipping Noise Footprint.

Once the Noise Footprint Assessment Model has been implemented and calibrated for a maritime area of interest, it is possible to run different scenarios to test different possible mitigation measures, in order to estimate their efficiency. Thanks to that process, the
conclusions and recommendation arising from the AQUO Project can be justified on the basis of rigorous scientific and technical means.

AQUO was organized into five interconnected technical work packages (WP):

- **WP1 Noise footprint assessment model**: this WP aimed to develop and validate an underwater noise footprint assessment tool. This tool has been used intensively in WP5 to determine the efficiency of the different solutions.
- **WP2 Noise sources**: this WP focused on ship noise sources with a specific focus on propeller noise prediction, including cavitation effects and vibro-acoustic interaction with the hull.
- **WP3 Measurements**: the main objective of WP3 was to develop adequate noise measurement and analysis methods to provide reliable data.
- **WP4 Sensitivity of marine life**: this WP was dedicated to bioacoustics for European representative marine species. Its main objective was to provide initial criteria for the assessment of the shipping noise impact on marine life.
- **WP5 Guidelines to reduce ship noise footprint**: in this WP, guidelines to improve the design of ships were described as well as operational and maintenance considerations. Different solutions were assessed regarding ship URN reduction, fuel efficiency and impact on marine life.

The AQUO Project didn’t consist of only a juxtaposition of miscellaneous technical tasks. Its methodology and organization was targeting the search for practical solutions, taking into account the complexity of the topic in relation to marine life. For that purpose, the AQUO Consortium was composed of a multi-disciplinary team. All the technical tasks have been completed, with the main results summarized in Chapter 3 of the present document. The project resulted in more than 20 deliverables, most of them being publicly available through the website [www.aquo.eu](http://www.aquo.eu).

Chapter 4 is dedicated to the results of WP5, regarding the search for and the assessment of the efficiency of mitigation solutions. The solutions considered are split as follows:

- Solutions applicable at the level of a particular vessel through design;
- Solutions applicable for existing vessels, in relation to operational setting and maintenance;
- Mitigation measures at the level of a maritime area, through ship traffic control.

The next step consisted of assessing the efficiency of the different mitigation measures to select the most appropriate ones. For that purpose, the different results and modelling tools developed in the AQUO project were used, along with three goals:

- Reducing ship underwater noise source level;
- Studying the effect on fuel efficiency;
- Assessing the impact on marine life, using the noise footprint assessment model developed in WP1, through simulations in different maritime test areas.

The main conclusions and recommendations are listed in Chapter 5.
Regarding the main conclusions.

- It was shown that using the AQUO "Ocean Noise Footprint Assessment Model", it is technically possible to monitor in real time the underwater noise in a maritime area of interest, given knowledge of the ship traffic and physical characteristics of the area. However, the tool must be calibrated, or its validity checked, using direct in-situ long term recording of underwater noise. Furthermore, it is possible to implement bio-acoustic criteria to evaluate the risk on marine life (provided the criteria are available for the species of interest). The output of the tool can be used by the managers of the maritime area to reduce the impact on marine life, if mitigation measures are applied. The most efficient solutions result in an overall reduction of the intrinsic URN (underwater radiated noise) levels of the ships in the area. An example of such a solution would be the imposing of noise limits, such as those proposed by classification societies in their voluntary class notations.

- Regarding the reduction of ship URN, AQUO project studies have shown that significant reductions can be achieved (more than 6 dB) in some cases. To select the relevant technical solutions, reduction of both machinery noise and propeller noise should be addressed in a consistent way, without reducing fuel efficiency. Indeed, a case-by-case study to determine the dominant noise sources should be carried out, as the matter is highly dependent on ship type and operational profile. In order to be effective and to limit the impact on cost, it is important to perform the URN reduction studies at the initial ship design stage.

Regarding the main recommendations.

- Considering the fact that the actual implementation of noise control solutions for the reduction of ship URN will take time and that the mitigation solutions agreed by the shipping industry are not mandatory, it seems more relevant to enforce the control of underwater noise in European maritime areas of interest regarding marine life through management of shipping. As stated previously, the effect of this can be evaluated using the Ocean Noise Footprint Assessment Model. As a consequence, possible traffic restrictions applied to the noisiest vessels could become an incentive to ship owners and the industry to make actual improvements to the URN of future vessels.

- As for today, it is not foreseeable to impose URN limits in all waters: Marine Protected Areas appear to be appropriate candidates. Several member states have already properly identified these within their own waters, together with the species of interest that inhabit these regions.

- As a consequence, pilot projects should be launched as soon as possible, including initial actions such as establishing noise baselines in different areas. Therefore, the main recommendation targeting policy makers is the monitoring and (if possible) the control of underwater noise in some sensitive European maritime areas especially during periods of the year that are determined to be biologically critical.

- Regarding the shipping industry, it is obvious that the current status of the fleet with regards to the control of ship URN is at a starting point. Nevertheless, new ship designs will gain by including, in the specifications, minimising URN. As for today, it appears to be costly to apply voluntary regulatory notation in anticipation of future requirements. However, it was shown in the project that, several technical solutions (overall propulsion plant settings, extended use of diesel-electric engines, controlled pitch propeller optimized curves, resilient mountings, propeller and hull cleaning, etc.) are efficient not only for reducing URN but also for reducing on-board noise and vibrations, and fuel consumption, leading to additional benefits for the ship owner. Further, including underwater noise control at the earliest stage of ship design limits the required development, building and maintenance costs.
Also, since the underwater noise remains a new topic for the vast majority of the current fleet, an extended database for ship URN is to be set up to refine noise source characterizations. It is expected that the International Organisation for Standardization (ISO) will publish internationally agreed standards for the measurement procedures of ship URN.

Another important recommendation targeting the scientific community is to increase the research effort regarding underwater bio-acoustics. Indeed, despite the effort carried out in recent years, so far, there is still a lack of reliable and accurate criteria for the sensitivity to sound of endangered marine species.
1. Introduction

1.1. Context and needs

To reach the goals set in the Marine Strategy Framework Directive (MSFD) the EU Member States are committed to achieve and maintain the “Good Environmental Status” (GES) of their respective maritime areas by 2020 [30], [32], [33]. This commitment aims to ensure the marine biodiversity and limit the anthropogenic pollution into the Oceans.

Identified as one of the pollutants, in consistency with the Descriptor 11 of the MSFD and the work carried out by the Task Group (TG) Noise [34], [35], [36], the continuous noise from shipping is especially addressed here. In addition to the TG Noise and the scientific community, several stakeholders and organizations have acknowledged the need to give more importance on underwater noise issues and its impact on marine life, giving way to several recent actions:

- Regarding standardization, ISO/TC43 for instance is in a finalization stage of its work on vessel underwater radiated noise (URN) measurement standards [44] and terminology [45] but only the ANSI/ASA standard [72] has been published.
- Several studies have addressed the reduction of underwater noise from shipping [39], [40]. The IMO (International Maritime Organization) has published non-mandatory guidelines for mitigation of underwater noise from commercial vessels in relationship with protection of marine life [38], and the ISO TC8 is also working on the topic.

However, there is at present no regulation imposing limitation on underwater noise related to shipping or any design requirements for the reduction of radiated noise levels from ships, except in the case of fishery research vessels [37]. A previous FP7 European project, SILENV, defined a “green label” for silent vessels [41]. On the side of the classification societies, DNV-GL has introduced a rule note for underwater radiated noise of different categories of ships [42], and more recently Bureau Veritas defined two grades (“URN BV controlled” and “URN BV advanced”) for commercial vessels [43].

In summary, considering the expected increase in worldwide ship traffic, the time needed for the commercial fleet to be renewed, and the fact that the reduction of underwater noise is not mandatory, there is a risk of degradation of the environmental status in some European areas due to shipping underwater radiated noise and its impact on marine life, with negative consequences on biodiversity and numbers.

In that context, the European Commission launched in 2011 the theme [SST.2012.1.1-1.] “Assessment and mitigation of noise impacts of the maritime transport on the marine environment” (coordinated topic within the framework of the “Ocean of Tomorrow”) within the Seventh Framework Program.

This resulted in the start of the AQUO project (N° 314227) in October 2012 for a 3 year duration. The AQUO project was built by a consortium of 13 partners including those from the ship industry, specialized companies, a classification society, research centres and academics (Figure 1-1). It represents 8 European countries. Its main objective was to provide policy makers with practical guidelines, in order to mitigate the underwater noise impacts of shipping on marine life. Those guidelines are based on solutions regarding ship design, including propeller and cavitation noise and solutions related to shipping control and regulation.
It should be noted that another collaborative project, called “Suppression Of Underwater Noise Induced by Cavitation” (SONIC, project N°3143 94), addressed the same EU call, and that it was required by the European Commission that the two projects collaborate with each other in order to ensure consistent conclusions, as far as possible.

Both AQUO and SONIC projects have been completed. The results, which are in most cases publicly available through the respective websites [1] and [27], correspond to different reports, references [2] to [24] for AQUO Project, and references [28] to [29] for SONIC Project. At the end of the projects, a “Common Guidelines” document has been also published [30], in addition to the present document AQUO D5.8, which corresponds to the synthesis of the AQUO Project.

It has to be noted that, beyond the initial description of work on which the AQUO project was structured, an extensive dissemination of results at scientific events (references [46] to [71]) was done. The continuous exchanges with AQUO’s End-users and with other maritime industry stakeholders brought additional requirements that had to be addressed and covered as far as possible [25], [26].

1.2. Objectives of the present document

The main objective is to provide the regulators and stakeholders of the maritime domain with practical solutions to fulfil the MSFD requirements with regards to the underwater continuous noise from shipping and its impact on marine life, outlining the specific AQUO Project methodology. The significant knowledge gaps on how to assess the effect of shipping noise on the marine underwater environment and its fauna have motivated the methodology developed within AQUO, described in section 2. Indeed, in order to address the topic, there is a need for covering aspects like: the characterisation of ships as noise sources, traffic models to get a synthesis of the global shipping pollution, physical characteristics of the area of interest, animal population of the area and sensitivity to sound of the marine species of interest, as shown on Figure 1-2:
These guidelines are the final synthesis of the work carried out within AQUO.
- In section 2, an overview of the methodology followed during the project is given, including a presentation of the Ocean Noise Footprint Assessment Model.
- In section 3, the main technical results from the different AQUO project work packages and tasks are summarized.
- In section 4, a comprehensive list of possible mitigation measures is introduced, then analysed through different criteria. The assessment of the impact on marine life is done using the Ocean Noise Footprint Assessment Model coupled to bio-acoustic criteria, highlighting the most efficient ones.
- Section 5 concludes on the final recommendations and the suggestion for the way ahead. A list of future research needs is also given and detailed in the Annex.

2. AQUO’s methodology

2.1. General approach

The “Ocean Underwater Noise Footprint” for anthropogenic activity is defined as:
“The representation of the noise level arising from maritime activities that affects a portion of the sea. It includes the description of the noise sources and the propagation of the sound in the ocean environment that can be represented as a noise map, without frequency weighing. It can be used to assess the effect or impact of anthropogenic sound on marine life, using suitable indicators.”

The Ocean Shipping Noise Footprint is then the same concept concerning shipping noise specifically.

The purpose of the methodology is to take into account all the key components from the receiver (marine fauna representatives) to the emitter (the ship as a noise source) throughout the following key steps:
- Noise footprint assessment tool development
- Ship underwater radiated noise models development, considering the variety of commercial ships and corresponding characteristics
• Consolidation and validation of propagation models with on-site long-term measurements
• Definition of acoustic sensitivity criteria for dedicated species
• Deployment of the methodology on several maritime areas of interest
• Proof of concept and reproducibility of the Ocean Shipping Noise Footprint

Once the Noise Footprint Assessment Model has been implemented and calibrated for a maritime area of interest, it is possible to run different scenarios to test different possible mitigation measures, and estimate their efficiency. Thanks to that process, the conclusions and recommendation arising from the AQUO Project can be justified on the basis of rigorous scientific and technical means.

This overall approach is summarized in the Figure 2-1 below:

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**2.2. Organization of the AQUO Project**

AQUO Project didn’t consist of only a juxtaposition of miscellaneous technical tasks, but its methodology and organization was targeting the search for practical solutions taking into account the complexity of the topic, in relationship with marine life. For that purpose, the AQUO Consortium is composed of a multi-disciplinary team.

In addition to the two work packages dedicated to management and dissemination/exploitation, the project was organized into five interdependent technical work packages, illustrated in Figure 2-2.
2.3. Implementation of the methodology to address the impact on marine life of underwater noise due to shipping

2.3.1. Principle and assets

The method allowing the determination of ocean shipping noise footprints is detailed in reports [6] and [24], and some elements have also been presented at different conferences [50], [59], [60], [63]. The corresponding tool, Quonops© can operate in real-time or with recorded data. It produces series of instantaneous acoustic field data in order to derive statistical trend for a frequency band of interest (for example the third octave 125 Hz) and for different temporal metrics (6h, daily, weekly, etc.). To do so, Quonops© is connected to different data sharing platforms in order to integrate at each instant the bathymetry, the AIS traffic in the large area, the temperature, the salinity, the significant wave height and the in-situ measurement (Figure 2-3).

Three areas (Figure 4-2) were selected for AQUO’s studies: OBSEA (Mediterranean Sea, close to Barcelona), ANTARES (Mediterranean Sea, offshore Toulon) and USHANT (Atlantic Ocean, Offshore Brittany).

A specific procedure to calibrate the noise fields was implemented in the tool and tested on data from the OBSEA observatory, where the LIDO system (Listening to the Deep Ocean Environment developed by LAB-UPC) provides acoustic data that are recorded continuously. Dedicated algorithms including five month data (from March to July 2014) and identification of natural noise led to overall uncertainties of 1.5 dB for natural noise and 3.8 dB for anthropogenic noise.

Real oceanographic environment and real ship traffic data were used to assess the noise in the three areas. The reference periods used for this study were:

- December 2014, representative of a winter situation regarding sound speed profile;
- June 2015, representative of a spring/summer situation.
To account for the variability, stochasticity and uncertainties of key physical and environmental parameters, a statistical approach is adopted. This approach, illustrated in Figure 2-4, has the advantage of capturing the sensitivity of the noise maps to the variability of both ocean environment and shipping traffic. On the left is a representation of the predicted noise map at a given instant, with superimposition of locations of ships using AIS data. On the top right, the noise level in a given frequency band at a given observation point (identified by the red arrow) is represented along time (several hours). Not surprisingly, a sharp increase of noise appears at some instants, corresponding to the passage of vessels near the observation point.

As shown on the bottom left of Figure 2-4, percentiles have been used to represent the statistical noise in each area. A percentile corresponds to the proportion of time and space for which the noise exceeds a given level at a specific position and during the period of time of interest.
2.3.2. The marine fauna as receivers

The results obtained within AQUO do not presume to give an exhaustive solution to this problem but illustrate the applicability and reproducibility of this complete assessment. The assumptions under which the simulations are run reflect the case-by-case mandatory consideration of the problem. Some examples of needed inputs to be provided are:

- Regarding the fauna: species of interest and potential impact
- Regarding the area: geographical situation and associated governance and environment properties
- Regarding the traffic: scheme of traffic and corresponding control and type of ships sailing the area

A receiver-based approach implies that the focus is to be made on species of interest. A generic approach, as illustrated in the Figure 2-6, was followed with regards to the Natura2000 database to select the areas of interest.
Another key element is the availability of bio-acoustic criteria. Biologist and bio-acousticians involved in the project converged on a global methodological approach based on the concept of zones of influence (see Figure 2-7) to derive bio-acoustic criteria.

This concept has been applied within AQUO for three species from different taxa:
- Harbour porpoise (*Phocoena phocoena*) [18], in representation of marine mammals,
- Atlantic cod (*Gadus morhua*) [17], in representation of fishes, and
- Common cuttlefish (*Sepia officinalis*) [19], in representation of marine invertebrates.

The application of the concept on these species was done through scenarios of masking (for cod and porpoise) and behavioural reaction (for Atlantic cod). For the cuttlefish the hearing impairment was investigated.

The risk of masking cannot be assessed in a generic way. In order to demonstrate the applicability of the methodology, two scenarios (see Figure 2-8) were implemented to assess masking:
- Masking of communication signal used by male cod during spawning assuming an average distance between the female and male cod to evaluate the risk of masking of this signal from shipping noise.
- Masking of killer whale predator sounds located at some distance from a Harbour Porpoise.

![Image](image_url)

**Figure 2-8:** Left: Scenario used to evaluate the masking of spawning cod sounds from shipping noise. Right: Scenario used to evaluate the masking of killer whale (predator) calls from shipping noise.

As a result, the corresponding risk (combination of species and type of impact in a given area) can be calculated and reported as a map (see example on Figure 2-9). This approach was applied for the assessment of mitigation measures in Task 5.4 [24]

![Image](image_url)

**Figure 2-9:** Risk assessment example: map of Atlantic cod spawning communication masking (20m from the surface) and potential behavioural reaction toward shipping noise in June 2014 in Ushant area [24]
2.4. Methodology for the assessment of the efficiency of noise footprint mitigation solutions

The first step is to establish a list for possible practical solutions and mitigations measures [21]. These can be split into three different types:

- Reduction of underwater noise emissions of the individual vessels through improved design,
- Reduction of underwater noise emissions of the individual vessels through adapted operational settings or improved maintenance,
- Reduction of noise footprint at the level of a maritime area through ship traffic management.

It should be noted that the first category is applicable to new designs only (and possibly retrofit of existing vessels for some solutions) while the two other ones can be applied to the existing fleet.

The next step consists of assessing the efficiency of the different mitigation measures in order to select the most appropriate ones. For that purpose, the different results and modelling tools developed in AQUO project were used, along with three goals, as shown in Figure 2-10:

- reducing ship underwater noise source level [22],
- studying the effect on fuel efficiency [23],
- assessing the impact on marine life, using the noise footprint assessment model developed in WP1, through simulations in different test maritime areas [24].

![Use of the noise footprint assessment model](image)

Figure 2-10: Process followed in the AQUO Project for the search and the assessment of practical solutions and mitigation measures
3. Summary of AQUO Project results

3.1. WP1 – Noise footprint assessment model

The main objective of this work package was to define, build and validate an operational tool able to predict the footprint of anthropogenic noise of shipping activities, by implementing the methodology described in section 2 of the present document. The work package benefitted from the use of Quonops®, a global ocean noise prediction platform developed and operated by Quiet-Oceans, and from the use of real-time feeds of audio stream provided by LIDO (UPC) observatories and interface. This tool was used in WP5 to determine the efficiency of different solutions with regards to the spreading of radiated anthropogenic noise in the ocean and to the impact on marine life. This work package was a key element to address the needs for transport policy and environmental risk assessment.

The different tasks in work package 1 were the following:

- Task 1.1.1 “Needs and policies” (report [2] and paper [51]): The first task established a map of all the maritime areas where there are already recommendations and rules regarding underwater noise impact. Information on the legal and institutional conditions on which European marine areas in general were/are/will be managed and implemented have been gathered. Good practices have been identified in order to adequately define the needs. A cross-analysis of the conjunction of intense ship traffic and presence of sensitive marine species has resulted in maps allowing the identification of priority areas of interest in European waters.

- Task 1.1.2 “Definition of noise footprint” (report [3]): This study includes a literature review, focusing on papers or documents related to underwater noise due to shipping and impact on marine life. Then, a discussion is carried out using parallel considerations with airborne noise environmental issues and with the assessment of sonar detection performance. In the last part, this report proposes the definition of noise footprint adopted by the AQUO Project and clarifies the use of noise maps and statistical indicators.

- Task 1.2 “Scenarios for noise footprint assessment” (report [4]):
  - A scenario, in relation to the noise footprint assessment model, is defined by the maritime area of interest and sensor locations, the period of the year and the weather conditions, the topology and physical characteristics of sea bottom, the underwater acoustics parameters (natural ambient noise, speed of sound and density in water with respect to depth and range), the ship traffic (type of ships, ship spatial and time distribution, ship routes and speeds...), and the ship characteristics (underwater radiated noise with respect to speed).
  - Two types of scenarios were retained to numerically simulate noise footprint: The first type is devoted to the validation of the footprint assessment model in Task 1.5 of the AQUO Project. In that case, ship traffic and type is not controlled but will be registered using AIS information. The second type is devoted to the determination of the efficiency of noise mitigation measures (such as reduction of intrinsic radiated noise of ships, introduction of ship speed limitations, modification of ship routes...), in the scope of Task 5.4 of AQUO Project.
  - Based on the analysis of their interest regarding both ship traffic and marine life, three test areas were selected for modelling in the Quonops® tool: OBSEA (Mediterranean Sea, close to Barcelona), ANTARES (Mediterranean Sea, offshore Toulon), USHANT (Atlantic Ocean, Offshore Brittany).

- Task 1.3 “Development of noise footprint assessment model” (report [5]): This task is devoted to the implementation of the methodology in Quonops®, a global ocean noise
prediction platform by Quiet-Oceans. The research effort of the project has led to the delivery of an operational footprint assessment tool, which include real-time access to acoustic data stream for calibration. In the scope of the AQUO Project this tool has allowed continuous mapping of shipping and natural noise across three areas within European waters. This innovative operational service for ocean noise footprint assessment, which has been calibrated using in-situ underwater noise data provided by the LIDO interface, is now fully operational for the AQUO project WP5 research in order to evaluate the efficiency of a series of mitigation solutions, and also constitutes a decision aid tool for policy makers.

- Task 1.4 “Validation of the noise footprint assessment model” (report [6] and papers [59], [60], [63] and [68]): The objective of this task is to validate the implementation of real-time soundscape modelling. To achieve this, the modelling performed by Quonops® has been compared to measured data from in-situ measurements, and to alternative modelling software suites developed by UNIGE and FOI. The test maritime area is close to the OBSEA platform, an underwater observatory deployed by UPC near Barcelona (Spain). The oceanographic equipment is composed of a buoy and underwater measuring systems, including a hydrophone. Data was recorded during the period from March to July 2014, including the ship traffic through AIS information. The good comparison between the results allows the validation at this stage.

### 3.2. WP2 – Noise sources

The main objectives of this work package are:

- to characterise the underwater noise emissions of the ship, providing input data for the noise footprint model (developed in WP1 and used in WP5),
- to validate and/or improve models and methods to predict underwater noise radiated by the propeller, including cavitation effects, and interactions with ship hull (wake, vibro-acoustic response).

In particular, efforts are focussed on the improvement of the knowledge of cavitation noise phenomena and in the development of predictive models for the propeller noise radiation (including validation with measurements). Such predictive models include the assessment of the efficiency of the propeller with the technical solutions proposed to limit the noise radiation. These models and the results of the studies have also been used in WP5 to assess the effectiveness of different technical solutions to reduce ship URN, and consequently noise footprint in the underwater environment.

The different tasks in work package 2 were the following:

- Task 2.1 – Derivation of underwater radiated noise patterns (report [7] and papers [55] and [57]). The main objective here was to define improved parametric models, representing the level of URN of a ship according to ship type, size, speed and frequency. These models were used in the AQUO Project for the determination of noise maps though implementation in the “Ocean Shipping Noise Footprint Assessment Model”. The method is based on the concept that the global URN of a ship can be decomposed into three noise components (machinery, propeller, and cavitation), each component having a characteristic URN pattern with respect to frequency and speed. This study has allowed significant improvements in comparison to previously available models. However, the uncertainty for a particular vessel can be large due to the variability of ship design within a category. Also, there is still a lack of well documented experimental data available in the literature.
• Task 2.2 – Predictive theoretical models for propeller URN (report [8] and paper [54]). In this task different predictive methods for radiated noise from propellers, including the hydrodynamic interaction with the hull, have been evaluated, using numerical modelling by different AQUO Partners (UNIGE, SSPA, CEHIPAR, and University of Strathclyde). The prediction of the underwater radiated noise from a propeller (cavitation or not) using numerical tools is a difficult task due to the complexity of the phenomena involved. The main studies have focussed on two case studies: a large research vessel (CTO) and a coastal tanker (SSPA), as input data and experimental results in model and full scale are available. Different numerical methods were used to carry out simulations on the various aspects:
  o Velocity fields to the propeller: RANS coupled with unsteady potential flow method, SHIPFLOW RANS code, k-ε RANS turbulence model with multiple reference frames, Finite volume RANS solver;
  o Behaviour of non-cavitating propeller (pressure field): Non-linear BEM + LES (OpenFOAM environment), Self-propulsion condition imposed in the RANS code
  o Acoustic radiation (non cavitating): Full-scale URANS model coupled with the FWH (Flowcs-Williams Hawkings) analogy, Far-field propagation using FWH;
  o Behaviour of cavitating propeller: Unsteady panel method coupled with viscous flow prediction of the ship wake
  o Acoustic radiation (cavitating): Helmholtz integral method flow solver combined with Zwart’s cavitation model.

• Task 2.3 – Experimental investigation in model scale (report [9] and papers [48], [52], [54], [56] and [69]): the results of the experimental campaigns in model scale carried out at the different facilities of CEHIPAR, SSPA and UNIGE are presented and discussed. In consistency with Task 2.2, the studies have focused on the same case studies, thus allowing a numerical-experimental comparison. Furthermore, it was possible to compare with each other the results obtained in different facilities in model scale, as well as to compare them with full-scale sea trials data. This activity is of great interest since rather limited data is available in open literature, especially regarding radiated noise measurements. The experiments carried out included:
  o In the UNIGE cavitation tunnel: Propeller characteristics curves cavitation characterization, pressure fluctuations, radiated noise, propeller flow (LDV)
  o In the SSPA water tunnel, propeller forces, pressure pulses, radiated noise, the propeller model scale being placed behind a model scale of the ship hull
  o In the CEHIPAR cavitation tunnel: Observation of cavitation, pressure fluctuations, flow speed (LDV)
  o In the CEHIPAR towing tank: Resistance, open water tests, self-propulsion, wake survey test (PIV), underwater radiated noise measurements

• Task 2.4 – Propeller-hull vibro-acoustic interaction (report [10] and papers [49], [58], and [70]): The objective is the numerical prediction of the contribution of the vibro-acoustic response of ship structure excited by the propeller in the total underwater radiated noise (URN) of a ship. Two vessels measured at sea in AQUO WP3 are modelled (a coastal tanker and a small research vessel, using two types of methods, according to the frequency range of validity: the finite elements method with or without boundary elements, the SEA method, and hybrid methods. Most of numerical studies in this work were carried out using commercial software. It is found in general that the numerical modelling fits experimental data in a satisfactory way. However, the modelling of the loads and the estimation of their magnitude is decisive to predict accurately the vibro-acoustic behaviour of the ship. Therefore, experimental data are necessary to carry out this kind of study.

• Task 2.5 – Synthesis – impact of propeller noise on global URN (report [11] and papers [64], [65] and [70]): The main objective of this task was to look for a synthesis of all the
contributions into a total ship radiated noise. For that purpose the different models developed in the previous tasks were exploited. The results of the analysis show that at low speeds, machinery noise dominates whereas propeller noise without cavitation is not very relevant. At higher speeds, in the case of a cavitating propeller, cavitation noise dominates, especially at medium and high frequencies. However, even in this case, machinery noise is still relevant in the low frequency range. Therefore, it is expected that both propeller and machinery noise should be reduced to obtain significant improvements on the total underwater radiated noise of a ship.

### 3.3. WP3 – Measurements

The objective is twofold:

- collecting dedicated and accurate experimental data focused on feeding and validating the modelling activities of the project and the improvement solutions proposed for mitigating the Noise Footprint of ships,
- developing new tools, equipment or techniques regarding ship underwater radiated noise, and the measurement of underwater radiated noise related to shipping.

The different tasks completed are summarized below:

- **Task 3.1- Proposal for a European standard measurement method for ship URN (report [12] and papers [47] and [67]):** This study has allowed detailed investigation of the effect of different key parameters on the uncertainty and repeatability of URN measurement of ships, both in deep and shallow waters. One of the most important parameters is the accurate determination of sensors locations and the estimate of sound propagation loss. A new procedure has been defined, split into two grades and with two variants for deep and shallow waters. The results of the study prove that the needs expressed for accuracy and repeatability can be fulfilled. Furthermore, the method was used successfully to carry out sea trials on different vessels in the scope of Task 3.2. It is thought that the work carried out here is a significant contribution to the improvement of ship URN measurement techniques, which can be used to build a new standard or to contribute to the work done in the scope of the international standardization organizations.

- **Task 3.2 - On-site measurements – Experimental data for identification and quantification of cavitation noise and other sources (report [13] and papers [49], [53], [58] and [65]:** In this study, measurements have been carried out on six different vessels: three research vessels (two tested by TSI and one larger vessel tested by CTO), one small fishing vessel (tested by TSI), one coastal tanker (tested by SSPA), and one commercial ferry (tested by TSI). In addition to the measurement of radiated noise under different operational conditions, the experimental campaigns included measurements of on-board vibrations. For two of the vessels, there was also a direct observation of cavitation and measurement of pressure fluctuations in the vicinity of the propeller.

- **Task 3.3 - Development and test of an on-board system for automatic detection of cavitation (report [14]):** The feasibility of a low-cost system has been addressed. The system is based on the use of accelerometer(s) located on the hull close to the propeller(s), able to automatically identify cavitation effects after real-time processing. The satisfactory agreement between the results provided with the system and the cavitation visual records shows the feasibility of implementing a low cost system to detect cavitation in real time. In practice, this means that if the ship is sailing in a noise sensitive area, getting the information provided by the system could help the crew to
take the decision to change speed or the propeller settings, when applicable, to have less cavitation, and hence less underwater radiated noise (URN), thus mitigating the potential impacts on marine fauna.

- Task 3.4 - Long-term in-situ real-time measurements of ambient underwater noise, with simultaneous record of AIS data (report [15]): The overall objective was to allow relevant underwater noise data in relation with marine life and ship traffic to be obtained. Four generations of autonomous buoys, with different features or upgrades, were developed during the project and tested successfully in different maritime areas. These, along with the corresponding software are described in the report. The buoys are capable of the following functions:
  - Continuous hydrophone acquisition for several hours,
  - Real-time data transmission over 3G,
  - Satellite alert when 3G is not available,
  - Optional WiFi transmission when a ship is in the vicinity,
  - Measurement of environmental parameters through CTD probe,
  - Registration of shipping traffic through AIS,
  - Registration of buoy position through GPS

3.4. WP4 – Sensitivity of marine life

The main objective of WP4 is to provide an assessment of the impact of shipping noise on marine life and an input to WP1 and WP5 to develop predictive models and solutions to reduce the underwater noise footprint. Indeed, the output of WP4 represents key information to define the needs and consequently to allow the assessment of the associated noise mitigation measures. Within that scope, bio-acoustic experiments were conducted on different representative marine species including fish, invertebrates and marine mammals. Measures were taken to fulfill ethical issues regarding experiments with animals and approved by an external expert.

The different tasks in work package 4 were the following:

- Task 4.1 - Identification and characterization of noise sensitive areas (report [16] and paper [51]): In this task, we used the current legislation and definitions from IMO, the Habitat Directive, the Bird Directive, and Natura2000 as well as the database from Natura2000 to build the distribution map of sensitive species to noise. Then, using the AIS database at EU waters level, we also plotted ship density as an additional layer to define the criteria to be used to select representative marine areas of interest for the AQUO Project. The information collected helped to define the scenarios to be used for the AQUO noise footprint assessment model developed in WP1 (see Task 1.3).

- Task 4.2 – Noise sensitivity of marine life
  - Sub-Task 4.2.1. - Displacement effects of ship noise on fish population (report [17] and paper [61]): This experiment studied the long term behavioural reaction by wild cod to ship noise and describes the character and scale of the reaction. This study took place on the Swedish west coast with a small local cod population equipped with acoustic tags. For the ship noise disturbance, a Swedish Coast Guard ship was used. In general, the observed reactions in terms of horizontal swimming were smaller than expected and what the study was designed for. However, the scale of reaction will not lead to an increase in energy consumption due to the disturbance. This study was able to track fish with good accuracy. This is one of the first studies of its kind that tracked free swimming fish over a long period of time around an acoustic disturbance event.
  - Sub-Task 4.2.2. - Masking effects of shipping noise on harbour porpoises (report [18]): This study on the masking effect of ship noise on hearing in harbour
porpoises’ consisted of a series of auditory measurements in some individuals held at two facilities in the Netherlands. Their hearing sensitivity was first tested in an un-masked situation by measuring auditory brainstem responses to repeated acoustic stimulation. Subsequently, these measurements were repeated in the presence of red noise, resembling the acoustic underwater signature of ships. The results show that ship noise has the potential to mask the auditory perception of harbour porpoises over the entire frequency range tested in this study. Furthermore, the conclusions of this study recommend that, by contrast to the MSFD criteria focusing only low frequencies, that higher frequency ranges should also be considered.

- Sub-Task 4.2.3. - Tolerance of cephalopods to low frequency ship radiated noise (report [19] and paper [62]): Offshore noise exposure comparative experiments on common cuttlefish were conducted, in similar conditions as during laboratory studies, in terms of sound characteristics, received levels and time exposure. Particle motion measurements were also conducted both in laboratory conditions, as well as at the same locations and depths where the individuals were exposed at sea. Scanning electron microscopy revealed similar injuries in the inner structure of the statocysts, as those found in cuttlefish in previous experiments.

- Task 4.3 – Criteria for bioacoustic sensitivity of maritime areas (report [20]): In this task, it is first described how the different zones of influence, for the marine life to its whole, can be expressed. Then, thanks to the joint work of acousticians and biologists, more details are given, establishing the key links between acoustic levels and effective impact. The focus is hereafter made on three species representing different representative species of European maritime areas (Harbour porpoise, Atlantic cod, and Common cuttlefish).

### 3.5. WP5 – Guidelines

The objective of this work package was to provide support to policy makers, to meet the requirements of the Marine Strategy Framework Directive (MSFD). The “Practical Guide” provided by the AQUO consortium is the present document.

The different tasks completed are:
- **Task 5.1** - Comprehensive listing of possible improvement solutions and mitigation measures (report [21]): see section 4.1 of the present document
- **Task 5.2** – Effectiveness of solutions to reduce ship URN (report [22] and papers [64], [66], [69], and [70]): see section 4.2 of the present document
- **Task 5.3** – Impact of solutions on fuel efficiency (report [23] and paper [66]): see section 4.2 of the present document
- **Task 5.4** – Effectiveness of solutions to reduce noise impact on marine life (report [24]): see section 4.3 of the present document
- **Task 5.5** – Synthesis of recommendations, corresponding to the present document
4. Assessment of the efficiency of solutions and mitigation measures

4.1. List of possible solutions

We considered different solutions or mitigation measures, which were detailed in the report [21]. They are split as follows:

- Solutions applicable at the level of a particular vessel through design,
- Solutions applicable for existing vessels, in relation with operational setting and maintenance,
- Mitigation measures at the level of a maritime area, through ship traffic control.

Solutions applicable at the level of a particular vessel through design

Note that solutions identified with (*) may be considered at retrofit.

- Solutions regarding the ship design at the global architecture level:
  - Choice of type of engine (use of diesel electric propulsion, gas turbine...)
  - Choice of solution at propulsion level (type of propeller, podded propulsion, water-jet propulsion...)
  - Reduction of Turn Per Knot (TPK = ratio between shaft rpm and ship speed in knots)
  - Optimization of hull design

- Dedicated noise reduction solutions for machinery:
  - Systematic use of efficient elastic mountings for the most noisy equipment items
  - Acoustic enclosure for equipment items with strong airborne noise radiation
  - Use of active noise control systems (*)

- Dedicated noise reduction solution for propeller:
  - Propeller blade design optimization (*)
  - Use of non-conventional propellers (*)
  - Use of wake conditioning devices (*)

- Dedicated structural solutions to reduce underwater radiated noise:
  - Modification of hull (hull girder spacing, hull thickness, double hull)
  - Use of lightweight materials
  - Structural damping (*)

- Other innovative noise reduction solutions through design:
  - Hull bubble curtains for the hull and/or the propeller (*)
  - External hull acoustic decoupling coatings (special materials) (*)

Solutions applicable for existing vessels:

- Solutions regarding ship operation:
  - Speed reduction
  - Optimisation of propulsive system parameters settings
  - Appropriate management of dynamic positioning

- Solutions regarding ship maintenance:
  - Propeller and hull cleaning
  - Proper maintenance of noise and vibration issues (balancing, status of machinery items, elastic mounts and other noise and vibration insulation devices).
Mitigation measures at the level of a maritime area, through ship traffic control:

- Mitigation measures applied to individual ships (already known to be noisy)
  - Radiated noise reduction of each ship (assuming that each noisy vessel has been improved through design changes)
  - Imposing a limit value for URN to all ships present in the area
  - Speed reduction (or change)
  - Track change

- Mitigation measures applied globally to ship traffic
  - Traffic concentration or dilution
  - Optimization of distance between vessels
  - Vessel type separation scheme
  - Exploiting local geographical features (fostering sailing in shallow or deep waters, island area preference...).

### 4.2. Assessment of solutions at the level of a vessel

As previously explained and illustrated, part of the mitigation solutions are linked to the efforts that could be made at the level of each individual vessel either through design changes (for new vessels), either through optimization of operational parameters or improved maintenance (for existing vessels). These solutions have been reviewed in detail in report [21] and their efficiency is determined, quantitatively as much as possible, using different predictive models or from expertise. The results for reduction of underwater radiated noise and effect on fuel efficiency are detailed in reports [22] and [23], respectively. Indeed, the application of technical solutions for the reduction of ship underwater radiated noise are more likely to be applied by ship owners and ship builders if they are also beneficial for fuel efficiency (or at least neutral).

The following Table 1 summarizes these outcomes.

The expected noise reduction of these solutions are differentiated by frequency ranges (here “low frequency” corresponds typically to lower than 100 Hz, “medium frequency” between 100 Hz and 1000 Hz, and “high frequency” above). Regarding the efficiency, the dark green colour means that a significant reduction of radiated noise level (RNL) is expected (typically more than 3 dB), the light green colour means a small improvement, and the yellow colour means no significant evolution. In the different solutions analysed here, no cases were found associated to a significant risk of degradation of RNL.

The expected effect of fuel efficiency is shown by the green colour if fuel efficiency is improved, the yellow colour if no significant effect (or in case it is difficult to conclude in general), and the orange colour in case of fuel efficiency degradation.

The second column in the table is in relationship with the applicability: “NB” for new ship buildings, “RF” for retrofit, and “IS” for a ship in service.
<table>
<thead>
<tr>
<th>Mitigation measure</th>
<th>Applicability</th>
<th>Underwater Rad. Noise</th>
<th>Fuel efficiency</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type of engine</strong></td>
<td>NB</td>
<td>Low freq.</td>
<td>Med. Freq.</td>
<td>High freq.</td>
</tr>
<tr>
<td><strong>Diesel-electric propulsion</strong></td>
<td>NB</td>
<td>Low freq.</td>
<td>Med. Freq.</td>
<td>High freq.</td>
</tr>
<tr>
<td><strong>Podded propulsion</strong></td>
<td>NB</td>
<td>Low freq.</td>
<td>Med. Freq.</td>
<td>High freq.</td>
</tr>
<tr>
<td><strong>Reduction of TPK (turn per knots)</strong></td>
<td>NB</td>
<td>Low freq.</td>
<td>Med. Freq.</td>
<td>High freq.</td>
</tr>
<tr>
<td><strong>Elastic mountings</strong></td>
<td>NB/RF</td>
<td>Low freq.</td>
<td>Med. Freq.</td>
<td>High freq.</td>
</tr>
<tr>
<td><strong>Increase of the stiffness of machinery foundation</strong></td>
<td>NB/RF</td>
<td>Low freq.</td>
<td>Med. Freq.</td>
<td>High freq.</td>
</tr>
<tr>
<td><strong>Structural solutions (hull girder spacing, hull thickness, double hull)</strong></td>
<td>NB</td>
<td>Low freq.</td>
<td>Med. Freq.</td>
<td>High freq.</td>
</tr>
<tr>
<td><strong>Structural damping</strong></td>
<td>NB/RF</td>
<td>Low freq.</td>
<td>Med. Freq.</td>
<td>High freq.</td>
</tr>
<tr>
<td><strong>Bubble curtain (propeller)</strong></td>
<td>NB/RF</td>
<td>Low freq.</td>
<td>Med. Freq.</td>
<td>High freq.</td>
</tr>
<tr>
<td><strong>Improved propeller</strong></td>
<td>NB/RF</td>
<td>Low freq.</td>
<td>Med. Freq.</td>
<td>High freq.</td>
</tr>
<tr>
<td><strong>Non-conventional propellers</strong></td>
<td>NB/RF</td>
<td>Low freq.</td>
<td>Med. Freq.</td>
<td>High freq.</td>
</tr>
<tr>
<td><strong>Optimized ship handling</strong></td>
<td>IS</td>
<td>Low freq.</td>
<td>Med. Freq.</td>
<td>High freq.</td>
</tr>
</tbody>
</table>
Table 1: Effect of mitigation measures on ship URN – Assessment using the results of [22] and [23]. Dark green: more than 3dB reduction, light green: small URN reduction improvement, yellow: no significant URN reduction. Orange: Fuel efficiency degradation.

In summary, reductions of RNL of more than 6 dB can be achieved but this should be done by combining different noise control measures in a consistent way, generally considering both propeller noise and machinery noise. When only one noise source on a ship is treated, the overall effect on the underwater radiated noise of the whole ship may be insufficient. The reason is that the radiated noise of a ship is composed of the superposition of several noise sources, from machinery, propeller and hydrodynamic interaction with the hull. Then, it would be necessary to combine different ship noise control measures in a consistent way. As an example, Figure 4-1 taken from reference [22] shows the improvement obtained by combining improvement of machinery vibration insulation and an improved propeller. In practice, a case by case analysis is necessary, taking into account the type of the ship and the operating conditions.

Figure 4-1: Assessment of reduction of RNL in some frequency bands using combined mitigation solutions (elastic mounts, enclosures, improved propeller)
When designing and building new ships, it is important to perform the URN reduction studies at the initial design stage. If not, the late noise control measures will be expensive and/or ineffective. In the case of retrofit, some noise control measures such as the use of improved propellers, the integration of damping materials or external acoustic coatings, may be relatively easy to implement. For others, related to modifications of structure or the installation of elastic mountings, it is more difficult and may prove unfeasible depending of the ship initial design. The use of bubble curtains seems to be a relatively efficient solution (about 6 dB reduction for the whole ship RNL), but requires the installation of additional machinery equipment.

In the case of existing vessels, the importance of proper maintenance and hull/propeller cleaning is confirmed. In all cases, the reduction of ship speed is expected to reduce significantly RNL except in the case of ships equipped with CPP working at reduced speed. In the latter case, a large reduction of RNL can be obtained by running at optimum pitch instead of constant RPM but this requires in general a modification to the propulsion system.

### 4.3. Assessment of mitigation measures area at ship traffic level in a maritime area

As already presented previously, the assessment of mitigation measures applicable through ship traffic control can be done by the assessment of the impact on statistical noise maps of the impact on marine life, using the AQUO Ocean Shipping Noise Assessment Tool derived from Quonops®. The results reported here are detailed in the report [24]. This section is organized as follows:

- A summary of the reduction scenario is presented;
- A description of the assessment of two particular URN reduction solutions on noise reduction and associated effects on Atlantic Cod and Harbour Porpoises is proposed.

#### 4.3.1. Reduction Scenarios assessed

In order to assess the efficiency of different mitigations related to ship traffic control, three test areas were selected to run different scenarios [4], [24]. The joint effort between Quiet-Oceans (Brest, France) and the Laboratoris d’Aplicacions Bioacustiques, Technical University of Catalonia, BarcelonaTech (UPC, Spain) who have merged their real-time noise measurement, analysis and modelling capabilities, means that continuous noise monitoring and noise mapping were achieved for three areas as illustrated in Figure 4-2:

- OBSEA and ANTARES in the Mediterranean Sea,
- USHANT in the Atlantic Ocean.
The simulated scenarios [6] are defined based on the actual reference maritime and oceanographic situations. The impacts of the mitigation solutions (each one corresponding to a different scenario) on the underwater noise are assessed as the difference between the actual and the modified noise fields in the 125 Hz 1/3 octave band. The results are summarized in Table 2. Detailed results of the simulations are reported in a comprehensive report [24].

The large diversity of scenarios has been implemented which covers:

- Individual URN reduction for specific categories of vessels which systematically leads to global and cumulative reduction at basin scale; the scenario where all vessels fulfil the BV URN advanced limit [43] shows major benefits;
- Traffic regulation scenarios are based on a local organization of the stream of vessel in Traffic Separation Schemes (TSS). Both scenarios have shown a significant reduction of the cumulative noise at the cost of a specific traffic management that could be operated, for example, by MRCC (Maritime Rescue Coordination Centres);
- Speed limitation scenarios are efficient only when both following conditions are satisfied: (a) a significant proportion of the vessels in the regulated area are navigating at speeds that largely exceed the speed limit; (b) the regulated area is not polluted by the noise generated outside the regulated area. It has to be noted that simulation algorithms have been built with the constraint of keeping the same number of ships within the period studied;
- Spatial planning of the traffic consists on encouraging the vessels of specific categories to follow specific routes. The noise distribution is likely to be very significantly modified, some places incurring noise increases whereas other places significant noise reduction. The local characteristics of the environment (bathymetry, bottom type, etc.) play an essential role in the magnitude of the effect.

The generalization of the results is not always straightforward. However, the worldwide applicability of this approach and the associated tools give the opportunity to model and assess most of scenarios of different nature, and evaluate the effect on most species. As explicitly done with the scenario run within AQUO, the bio-acoustics criteria should be clearly identified, quantified and associated to critical scenarios for the considered species.
### Scenario type | Mitigation measure | Maritime area | Global Noise Reduction (noise map indicator) | Comments |
---|---|---|---|---|
**URN reduction** | Reduction of ship URN noise (technical solutions) | USHANT and ANTARES | Significant reduction in all area | Could be achieved with combined noise control solutions (see example on Figure 4-1) |
| BV URN-controlled vessels limits | USHANT | Significant reduction in all area | |
| BV URN-advanced vessels limits | USHANT | Large reduction in all area | |
**Traffic regulation** | Grouping by 3 vessel-packets while transiting | USHANT | Significant reduction in all area | Achievable through the supervision of MRCC (Maritime Rescue Coordination Centres) |
| Insuring minimal distance of 10km between individual vessels while transiting | USHANT | Significant reduction in all area | Achievable through the supervision of MRCC (Maritime Rescue Coordination Centres) |
**Speed limitation** | Speed limited to 13 knots for all vessels in the MPA only | USHANT | No significant gain | Reduction is masked by the commercial traffic occurring offshore |
| Speed limited to 13 knots for all vessels in the full area | ANTARES | Significant reduction in all area | |
**Spatial planning** | Fostering deep waters | OBSEA | Reductions and increases across the area | |
| Fostering shallow waters | OBSEA | Reductions and increases across the area | |
| Traffic Separation Scheme translated 10km offshore | USHANT | Reductions and increases across the area | |

Table 2: Summary of the mitigation measures whose efficiency has been evaluated through simulated scenarios in different maritime areas. Light green colour indicates a significant reduction; dark green indicates high reduction; grey colour indicates that noise is reduced in some areas, and increased in other areas. Yellow colour indicates no significant gain.

### 4.3.2. Assessment of the effect regarding marine life

Risks for masking and for behavioural reaction can be derived from the noise footprint assessment tool. There is a need to define a suitable indicator to quantify the effect of solutions at basin scale. As an indicator, we suggest the use of percentage of surface of the ocean that is affected in the reference situation and not affected any more in the regulated situation.
Table 3 reports the benefits of the reduction and mitigation solutions for each scenario for the Atlantic Cod and Harbour Porpoises criteria when applicable. Masking and behavioural risk were evaluated. The benefits in terms of reduction of the impacted surface range from not significant when the reduction is only a few percent, to outstanding when the reduction exceeds 20%. Interestingly, some solution can have large benefits to reduce behavioural risks but no significant effect on masking. On the other hand, some other solutions are significantly effective for both behavioural and masking risks.

<table>
<thead>
<tr>
<th>Scenario type</th>
<th>Mitigation measure</th>
<th>Maritime area</th>
<th>Reduction of Risk from Baseline Situation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Masking Predator Call for Harbour Porpoise</td>
</tr>
<tr>
<td>URN reduction</td>
<td>Reduction of ship URN noise (technical solutions)</td>
<td>USHANT</td>
<td>Not evaluated</td>
</tr>
<tr>
<td></td>
<td>BV URN-controlled vessels limit</td>
<td>USHANT</td>
<td>-1%</td>
</tr>
<tr>
<td></td>
<td>BV URN-advanced vessels limits</td>
<td>USHANT</td>
<td>-22%</td>
</tr>
<tr>
<td>Traffic regulation</td>
<td>Grouping by 3 vessel-packets while transiting</td>
<td>USHANT</td>
<td>Not evaluated</td>
</tr>
<tr>
<td></td>
<td>Insuring minimal distance of 10km between individual vessels while transiting</td>
<td>USHANT</td>
<td>-2%</td>
</tr>
<tr>
<td>Speed limitation</td>
<td>Speed limited to 13 knots for all vessels in the MPA only</td>
<td>USHANT</td>
<td>-2%</td>
</tr>
<tr>
<td></td>
<td>Speed limited to 13 knots for all vessels in the full area</td>
<td>ANTARES</td>
<td>Not applicable</td>
</tr>
<tr>
<td>Spatial planning</td>
<td>Fostering deep waters</td>
<td>OBSEA</td>
<td>Not applicable</td>
</tr>
<tr>
<td></td>
<td>Fostering shallow waters</td>
<td>OBSEA</td>
<td>Not applicable</td>
</tr>
<tr>
<td></td>
<td>Traffic Separation Scheme translated 10km offshore</td>
<td>USHANT</td>
<td>Not evaluated</td>
</tr>
</tbody>
</table>

Table 3: Evaluation of the benefits of the reduction solutions at 125Hz on the marine fauna using a surface reduction indicator. Assessment is not applicable when species are not present in the area. Not significant benefits are coloured in blue. Significant benefits are displayed in light green. Outstanding benefits are coloured in dark green.
4.3.3. Example

In the following example, the focus is on a particular scenario (global URN reduction through improved ship design, in the USHANT area [24]), in order to provide a more detailed presentation of the methodology and results.

One output of this scenario simulation is given in the Figure 4-3. This noise map represents the corresponding gain in terms of underwater noise for the whole Ushant area. The structure of these noise maps and especially of the colour scale is explained in detail in [24].

![Figure 4-3: Gain of the reduction of URN through design improvement observed 25% of the time in June 2015 at 125Hz in Ushant area (offshore Brest, France in the Atlantic)](image)

Throughout this example, it is demonstrated that the area manager is able to assess quantitatively, in terms of noise what the benefits are in terms of underwater noise, spatially and temporally. Indeed with the assessment tool, it is possible to present the gain of the “reduction of URN through design improvement” observed 25% of the time in June 2015, in the 125Hz 1/3 octave band in an area for instance.

It can be observed that an overall gain of between 3 and 6 dB is expected in most areas, especially in deep waters. In shallow areas, a gain up to 3 dB is predicted. Interestingly, this solution is able to reduce the anthropogenic noise to levels below what is inferred to be environmental noise, and let the environmental noise dominates (light blue areas).

The added-value of this powerful quantitative assessment tool is enhanced as it includes the impact on the marine fauna. As an example, under the assumptions previously explained (paragraph 4.3.2), the impact maps, before and after this scenario where ship URN is reduced thanks to design improvement, are given in Figure 4-4. In this figure, the benefits are presented for the whole area and within the limits of the Marine Protected Area Parc Naturel Marin d'Iroise".
The effectiveness of this reduction measure on both masking and behavioural reactions is mainly noticeable in the shallow water areas. One relevant metric for the protected area manager is also the impacted area in surface unit (absolute or relative). The criterion to evaluate the impact foreseen and the benefits of a given solution would then rely on a surface threshold. For instance, for this particular case study, the reduction counted in terms of surface of impacted area is about 10% for both masking and behavioural risks.
5. Recommendations and way ahead

5.1. Main conclusions

The main conclusions are the following:

- Using an “Ocean Noise Footprint Assessment Model”, it is technically possible to monitor in real time the underwater noise in a maritime area of interest, given the knowledge of the ship traffic and physical characteristics of the area. However, the tool must be calibrated, or its validity checked, using direct in-situ long term recording of underwater noise. Furthermore, it is possible to implement bio-acoustic criteria to evaluate the impact on marine life (provided that the criteria are available for the species of interest).

- The managers of the maritime area can use the output of the tool to assess the reduction of impact on marine life obtained by applying mitigation measures. The mitigation measures could consist of regulating the ship traffic in the area. However, the results show that solutions based on ship traffic management on the existing fleet, such as reduction of speed or track changes have relatively small effect.

- The most effective solutions consist of a global reduction of the intrinsic URN (underwater radiated noise) levels of the ships in the area, for example by imposing a noise limit. This can be achieved
  - For existing ships, through appropriate operational settings and proper maintenance. However, the noise reduction is expected to be insufficient to fulfil the noise limits.
  - For new ship buildings, through improved design.

- Regarding the reduction of ship URN:
  - The AQUO Project studies have shown that it is possible to significantly reduce the URN, by more than 6 dB.
  - To select the relevant technical solutions, a case-by-case study of the possible reduction of both machinery noise and propeller noise should be addressed in a consistent way, without reducing fuel efficiency. Indeed, a case-by-case study to determine the dominant noise sources should be carried out, as the matter highly depends on ship type and operational use.
  - In order to be effective and to limit the impact on cost, it is important to perform the URN reduction studies at the initial ship design stage.

As a complement to these main conclusions, a list of AQUO exploitable results is given in the Annex, and more detailed statements can be found in the Common AQUO-SONIC Guidelines document [30].
5.2. Recommendations

Considering the fact that the actual implementation of noise control solutions for the reduction of ship URN will take time and that the mitigation solutions agreed by the shipping industry are not mandatory, it seems more relevant to enforce the control of underwater noise in European maritime areas of interest for marine life through the management of the shipping. As stated previously the effect of this can be evaluated using the Ocean Shipping Noise Footprint Assessment Model. As a consequence, possible traffic restrictions applied to the noisiest vessels could act as an incentive to ship owners and ship industry for the actual improvement of the URN of future vessels.

The use and deployment of AQUO’s methodology is proposed at short notice since the timeline is as follows (recalling the Article 5 §2. of the Marine Strategy Framework Directive):

“Member States sharing a marine region or sub-region shall cooperate to ensure that, within each marine region or sub-region, the measures required to achieve the objectives of this Directive, in particular the different elements of the marine strategies referred to in points (a) and (b), are coherent and coordinated across the marine region or sub-region concerned, in accordance with the following plan of action for which Member States concerned endeavour to follow a common approach:

[…]  
(b) Programme of measures:
(i) Development, by 2015 at the latest, of a programme of measures designed to achieve or maintain good environmental status, in accordance with Article 13(1), (2) and (3);
(ii) Entry into operation of the programme provided for in point (i), by 2016 at the latest, in accordance with Article 13(10).”

At present it is not foreseeable to impose limits in all waters, and therefore Marine Protected Areas appear to be suitable candidates. Several member states have properly identified these, together with the species of interest that inhabit these regions.

Pilot projects should be launched as soon as possible, including initial actions such as establishing baselines. Therefore, the main recommendation targeting policy makers is the monitoring and possibly the control of underwater noise in some sensitive European maritime areas during some key periods of the year. The actual implementation (to be carried out by each Member State) could include:

- Establishing the list of maritime areas and times of the year considered as critical
- For each selected area, defining noise limits (e.g. in the form of statistical indicators) in relation with sensitive marine fauna present in the area
- Identifying possible restrictions to be applied to ships which with excessive URN
- Ship traffic managing by the authorities in these protected areas to control the area taking into account underwater noise.

It is noted that, in the present implementation, the AIS system does not cover some classes of vehicles (for instance, small watercrafts, ships below 300GT and fishing vessels are not necessarily provided with this system or may turn it off occasionally). Furthermore, the data actually stored in the system do not include parameters that would improve the accuracy of predictive models (such as: actual draft of the vessel, operating and propulsive conditions). For the above reasons, an extension of the use and/or the scope of the system is highly supported.
Regarding the shipping industry, it is obvious that the current status of the fleet with regards to underwater noise considerations is at a starting point. Nevertheless, new buildings will gain by including in the specifications such requirements. As for today it appears at a costly regulatory anticipation but the point is that, technically, several solutions (Overall propulsion plant settings, extended use of diesel-electric engines, controlled pitch propeller optimized curves, resilient mountings, propeller and hull cleaning, etc.) are efficient not only for underwater radiation of the noise but as well for on-board noise and vibrations and fuel consumption. Including this underwater noise aspect at the earliest stage of the design ensure to limit the studies, building and maintenance costs.

Also, since the underwater noise remains a new topic for a wide majority of the current fleet, an extended database for ship URN is to be set-up to refine noise source characterizations. It is expected that the ISO will publish internationally agreed standards for the measurement procedures of ship URN.

Regarding the technical solutions at ship design level, targeting shipbuilding industry, the main recommendations are the following:

- **Solutions for new designs which can be proposed readily:**
  - Use diesel electric propulsion for ship types where it is applicable and relevant regarding operational use.,
  - Propulsion architecture using 4-str main engines: systematic use of elastic mounts with adequate design of foundations, and reduction of shaft rpm,
  - Propulsion architecture using heavy 2-str engines: reduction of noise and vibration by design improvement of the equipment itself,
  - Optimization of propeller for URN while keeping fuel efficiency.

- **Solutions for new designs to be confirmed by more studies:**
  - Air bubble injection systems in the vicinity of the propellers
  - Use of advanced propellers (for example ducted propellers)
  - Silent dynamic positioning systems

- **Solutions which can be applied to existing vessels:**
  - Define a « quiet operating situation » by acting on propulsion plant settings
  - Require proper maintenance (verify that the propeller is not damaged and cleaning the hull and the propeller)
  - Meanwhile, alternate systems such as on-board systems for monitoring propeller cavitation (using local accelerations or pressure measurements) should be promoted.

Another important recommendation targeting the scientific community is to increase the research effort on underwater bioacoustics. Indeed, despite the effort carried out in the recent years, as there is still a lack of reliable and accurate data to characterize the sensitivity to sound of endangered marine species.
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[5] AQUO D1.4 - Noise footprint assessment model, 2015 (Confidential)
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[62] Michel André, Sound Pressure and particule motion effects on open-sea noise exposed cuttlefishes, Conference Oceanoise 2015, Vilanova i la Geltrú, Spain, 11-15 May 2015
[63] Thomas Folegot, Mike van der Schaar, Dominique Clorennec, Pierrick Brunet, Lancelot Six, Robert Chavanne, and Michel André, Monitoring Long Term Ocean Noise in European Waters, IEEE-MTS Oceans’15 Conference, Genoa, Italy, 19-21 May 2015


### Annex: List of exploitable results

<table>
<thead>
<tr>
<th>Type of result</th>
<th>Description of results (and lead partner)</th>
<th>Potential end-user/ relevant sector</th>
<th>Exploited by/Disseminated to (if applicable)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exploitable results for scientists</td>
<td>Improved models to represent underwater radiated noise levels (source levels) of different categories of vessels with respects to size and speed. <em>Lead Partner: DCNS.</em></td>
<td>Scientists (academics, ship industry and specialized companies)</td>
<td>AQUO reports R1.9 and D2.8</td>
</tr>
<tr>
<td>Exploitable results for scientists</td>
<td>Improvement of predictive methods of propeller noise, including cavitation effects and interaction with the hull, using numerical modelling, <em>Lead Partner: UNIGE.</em></td>
<td>Scientists (academics, ship industry and specialized companies)</td>
<td>AQUO report D2.3</td>
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<tr>
<td>Exploitable results for scientists</td>
<td>Improvement of predictive methods of propeller noise, including cavitation effects and interaction with the hull, using scale model experiments in laboratories, <em>Lead Partner: SSPA.</em></td>
<td>Scientists (academics, ship industry and specialized companies)</td>
<td>AQUO report D2.3</td>
</tr>
<tr>
<td>Exploitable results for scientists</td>
<td>Assessment of the sensitivity of different marine animals to underwater radiated sound (cod, harbour porpoise, cephalopods), and derivation of criteria. <em>Lead Partner: UPC.</em></td>
<td>Scientists (bio-acousticians)</td>
<td>AQUO reports D4.2, D4.3, D4.4, and D4.5</td>
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<tr>
<td>Exploitable results for scientists</td>
<td>Set-up and technique for measuring the noise of ship hull-propeller interaction at model scale in atmospheric towing tank. <em>Lead partner: CEHIPAR</em></td>
<td>Scientists (academic and ship industry, specialized companies)</td>
<td>AQUO report D2.4</td>
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<tr>
<td>Exploitable results for private sector</td>
<td>List of recommended mitigation measures for the reduction of underwater radiated noise of vessels for protection of marine life, while keeping fuel efficiency <em>Lead Partner: DCNS and SU.</em></td>
<td>Ship industry, IMO</td>
<td>AQUO reports R5.9, D5.3, D5.5 and D5.8</td>
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<td>Type of result</td>
<td>Description of results (and lead partner)</td>
<td>Potential end-user/ relevant sector</td>
<td>Exploited by/Disseminated to (if applicable)</td>
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<tr>
<td>Exploitable results for private sector</td>
<td>Method and algorithm for the automatic on-board detection of propeller cavitation of a vessel while sailing. Allows the crew to control propeller cavitation with the purpose to reduce ship underwater radiated noise. <em>Lead Partner: DCNS.</em></td>
<td>Ship industry and specialized companies</td>
<td>Planned conference</td>
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<td>Exploitable results for scientists and policies</td>
<td>Definition of the concept of “Ocean shipping noise footprint”, and associated indicators. <em>Lead Partner: Quiet-Oceans.</em></td>
<td>Scientists, policy makers.</td>
<td>AQUO reports D1.2 and D1.6</td>
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<td>Exploitable results for policies</td>
<td>Methodology for defining a regulation regarding the control of underwater noise due to shipping in a given maritime area for protection of marine life. <em>Lead Partner: Bureau Veritas.</em></td>
<td>Authorities (member states) in charge of the management of maritime areas and control of ship traffic, IMO.</td>
<td>AQUO report D5.8</td>
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<tr>
<td>Exploitable results for scientists and private sector</td>
<td>Ocean shipping noise footprint assessment tool: Method and tool for the assessment of the impact on marine life of underwater noise due to shipping in a maritime area. <em>Lead Partner: Quiet-Oceans.</em></td>
<td>Scientists and Private sector (specialized companies)</td>
<td>AQUO reports D1.2, D4.5, and D1.6</td>
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<tr>
<td>Exploitable results for scientists and private sector</td>
<td>The feasibility of prediction of ship underwater radiated noise due to internal machinery using computer vibro-acoustic softwares (FEM-BEM and SEA methods) has been demonstrated. <em>Lead Partner: TSI.</em></td>
<td>Scientists and Private sector (ship industry and specialized companies)</td>
<td>AQUO report D2.8</td>
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<tr>
<td>Exploitable results for private sector and policies</td>
<td>List of recommended mitigation measures for the reduction of underwater noise due to shipping in maritime areas for protection of marine life. <em>Lead Partner: Bureau Veritas.</em></td>
<td>Ship owners / Authorities (member states) in charge of the management of maritime areas and control of ship traffic.</td>
<td>AQUO reports R5.9, D5.7 and D5.8</td>
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<tr>
<td>Exploitable results for private sector and policies</td>
<td>Standard for the accurate measurement of ship underwater radiated noise (source level) of ships in deep and shallow waters. <em>Lead Partner: TSI.</em></td>
<td>Standardization committees, classification societies, ship industry, ship owners</td>
<td>AQUO report D3.1</td>
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<tr>
<td>Data</td>
<td>Experiments at sea: Underwater radiated noise levels of six different vessels (including two commercial vessels) and related on-board noise and vibration recordings. <em>Lead Partner: TSI.</em></td>
<td>Scientists, ship industry</td>
<td>AQUO report D3.3</td>
</tr>
<tr>
<td>Data</td>
<td>Experiments at sea: Direct observation of propeller cavitation, in relation to ship noise and vibration, for two vessels (one large research vessel and a coastal tanker). <em>Lead Partner: SSPA and CTO.</em></td>
<td>Scientists, ship industry</td>
<td>AQUO report D3.3 and D2.5</td>
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<tr>
<td>Data</td>
<td>Experiments at sea: Long term recording of underwater radiated noise, correlated to ship traffic, using an autonomous buoy. <em>Lead Partner: UPC.</em></td>
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