Assessment methodology for impact of impulsive sound

Evaluation of available methods and action plan for the development of a methodology for application in the MSFD

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1 Introduction

1.1 Background and scope

In the last decades, numerous studies have shown that underwater sound could have a serious impact on marine life. As human activities at sea increased considerably, the generation of underwater sound also increased. TNO published an inventory of the existing knowledge on the underwater sound environment in 2009 and identified the most important anthropogenic sources of underwater sound (Ainslie et al. 2009):

- Shipping
- Sesimic surveys
- Piling
- Sonar
- Explosions

The European Marine Strategy Framework Directive (MSFD) aims at achieving or maintaining of a Good Environmental Status (GES) in European Seas. For the assessment of GES, 11 descriptors were defined among which the descriptor ‘Underwater Noise and other forms of energy (D11). At present, there are no quantitative targets for GES of the two sound indicators. A Task Group (TG) consisting of selected experts providing relevant experience was established for each of the qualitative descriptors. The TG Noise developed indicators for impulsive as well as ambient sound and drew up a guidance for the monitoring of sound (Dekeling et al. 2014). The Intersessional Correspondence Group Noise (ICG-Noise) of OSPAR elaborated on this and proposed a register for impulsive sound and a strategy for the monitoring of ambient sound. The impulsive noise register became operational in early 2016.

The purpose of the project, of which the present report is the first product, is to select a methodology for the risk assessment of the impact of impulsive sound on marine life and to fine-tune it in such a way that it can be applied in the 2018 MSFD assessment and the preceding OSPAR Intermediate Assessment (IA 2017). It is the next step in the evaluation of the data that are and will be brought together in the OSPAR Impulsive Noise Register. In this step, the impulsive sound data will be translated to the (potential) impact on relevant species. In a following step the results of the impact assessment should be evaluated. At which level is the impact negligible and what targets should be set to prevent the occurrence of unwanted effects? From targets set for impact on populations and/or ecosystems targets for impulsive sound can be derived (*e.g.* sound budgets). Figure 1-1 gives a schematic representation of these steps following the DPSIR framework (Kristensen, 2004)[1].

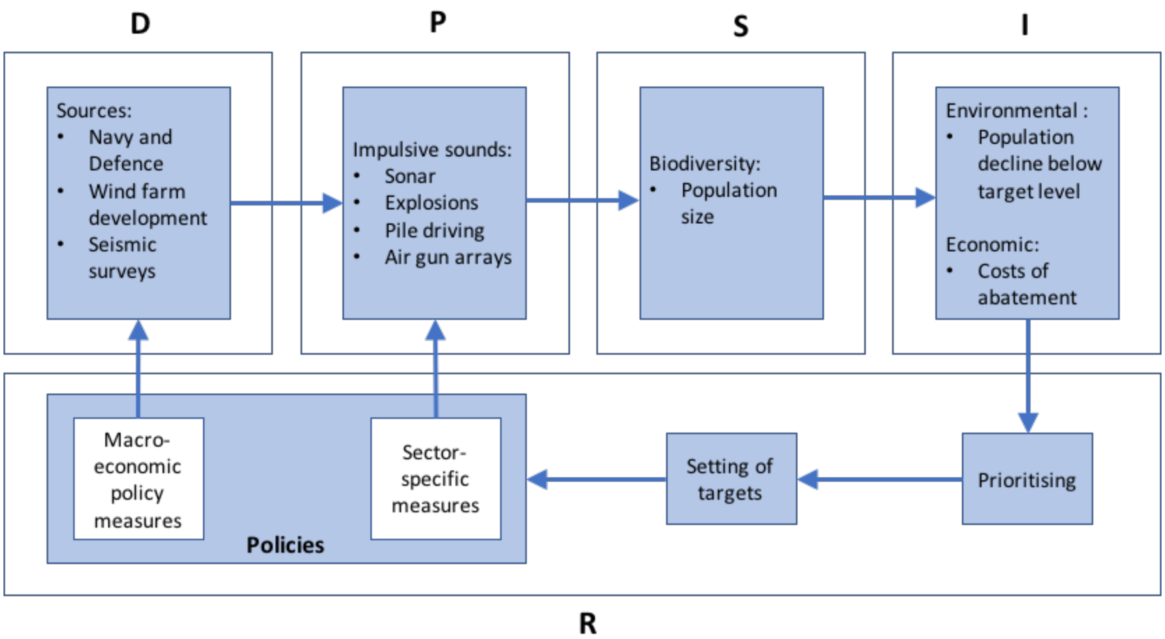

Figure 1-1 Integrated Environmental Assessment in the DPSIR framework applied to impulsive sound

[1] DPSIR is the abbreviation of Driving forces-Pressures-State-Impact-Response.

1.2 Outline of project and structure of report

The project consists of 4 phases that will be executed consecutively:

- Phase 1: Evaluation of available methods and work out an action plan for the next three phases;
- Phase 2: Development of a methodology for risk assessment;
- Phase 3: Application of the methodology in a MSFD assessment;
- Phase 4: Evaluation of effectiveness of potential MSFD targets (e.g. sound budgets).

This report is about the first part of the project: evaluation of available methods and work out an action plan for the next phases of the project. Chapter 2 describes the available methods in 2.1 (overview), 2.2 (methods without population modelling) and 2.3 (methods with population modelling) and evaluates them (2.4). These results are used for the description of the action plan for the next phases of the project in Chapter 3. Section 3.1 describes the steps to be taken to improve an existing methodology in such a way that it can be used in the context of the MSFD (phase 2) and section 3.2 describes the actions for the next two phases. The report finishes with a list of references (Chapter 4) and two annexes.

2 Frameworks for assessing impact of impulsive sound

2.1 Overview

In the last decade, several frameworks have been developed for assessing and/or quantifying the potential impact of anthropogenic (impulsive) sound on populations (NRC 2003, Thompson et al. 2013, New et al. 2014, Nabe Nielsen et al. 2014, King et al. 2015, Heinis et al. 2015, Maglio et al 2015). These frameworks differ in the way data are needed and in the precision of the outcome, but also in the way population consequences are estimated. Basically, three different approaches can be discerned, that will be described below:

- Mapping (§ 2.2)
- Frameworks using spatial distribution of sound and receptors (e.g. Interim-PCoD, § 2.3.1)
- Frameworks with agent-based modelling (§ 2.3.2)

2.2 Mapping of sound sources and receptors (no population modelling)

A first step in the risk assessment of underwater sound consists of a combination of sound source distributions (e.g. pulse block days or activity (Maglio et al 2015)) or modelled sound maps (based on propagation modelling) with distribution patterns of species. Comparable frameworks for assessing the cumulative effects of human activities, including the effects of impulsive sound, are the methods Harmony, Cumuleo and ODEM that were investigated by the OSPAR Accumulation working group (OSPAR Commission, 2015). All three methods use GIS-related input. The output is also GIS-related: a relative pressure per grid cell for a species, a habitat or a group of organisms. The three methods can focus on either just one species or on multiple species. In a map where pressure systems and ecosystem values are shown in layers, the overlaps may result in new insights. Like the methodology proposed by Maglio et al. (2015) these methods would appear be a useful way of viewing species and pressures in space. However, it is not possible to convert this information into descriptions of the impact on entire populations of non-stationary animals and / or ecosystems. Furthermore, if there is more information about one pressure than another, a biased picture may result. It is therefore necessary to look for alternative / complementary methods for the description of cumulative impact of multiple sources (and pressures). This involves assessing indicators of pressure (such as impulsive sound) and biodiversity (including the harbour porpoise) and it is also important to classify the pressure indicators based on relative importance.

It is concluded that these methods cannot be used to assess the impact of impulsive sounds on populations. They can, however, provide a first impression of areas where potential risks may occur.

2.3 Frameworks with population modelling

2.3.1 General

All frameworks for assessing the impact of (impulsive) sound on populations generally follow the steps in de the effect chain from sound source to population effects, that was described by the National Research Council of the United States, the PCAD model (NRC, 2005, Figure 2-1).

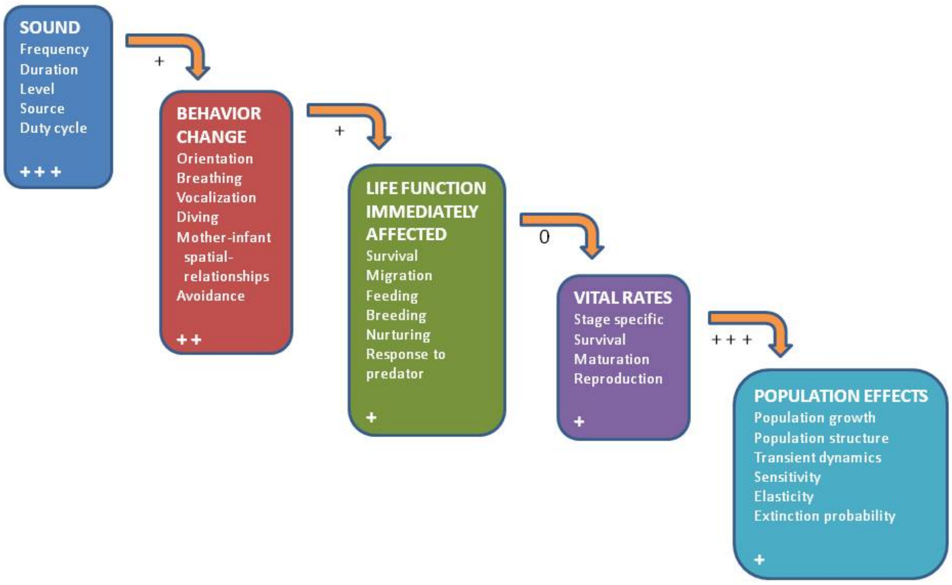

Figure 2-1 The *Population Consequences of Acoustic Disturbance* (PCAD) framework developed by the National Research Council's panel on the biologically significant effects of noise (after Figure 3.1 in NRC, 2005). The number of + signs provides an indication of the panel's estimate of the level of scientific knowledge about the connections between the boxes; 0 indicates that this knowledge is lacking.

The structure of the PCAD model was amended in a working group established by the US Office of Naval Research. Parameters were estimated on the basis of results from case studies looking at five species of marine mammal. During this process, the scope was also extended to include all possible forms of disturbance and the possible influence of the physiological effects of disturbance was also included. The amended model – the PCoD model (Population Consequences of Disturbance) – can be found in Figure 2-2 (see New et al. 2014 for details). It can be seen in the figure that disturbance can affect both the behaviour and the physiology of individuals and that changes in these factors can have a direct effect (an 'acute effect') on survival and reproduction (*vital rates*) in that individual or impact the individual indirectly by affecting health (this is a chronic effect).

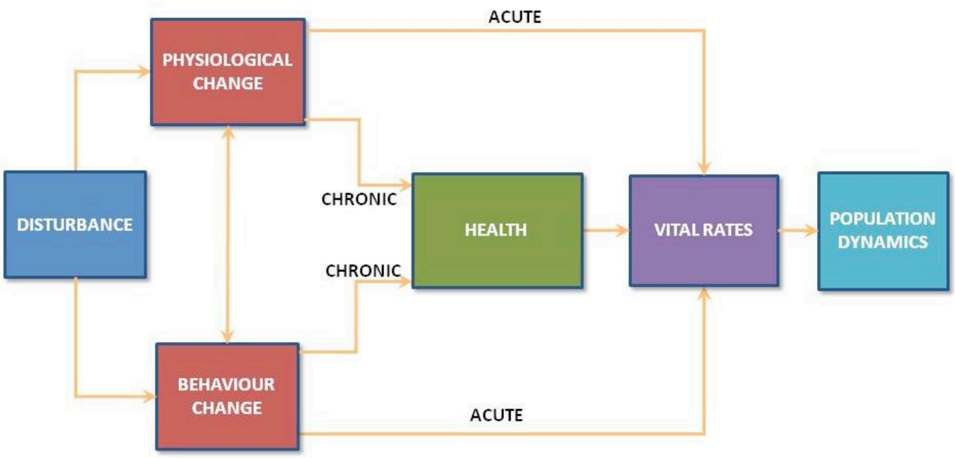

Figure 2-2 The PCoD framework for modelling the '*Population Consequences of Disturbance*' developed by the ONR PCAD working group (adapted after Figure 4 in New et al., 2014). The term *health* is used for all aspects of the internal condition of an individual that can affect the health of that individual. This may be, for example, the fat reserves or resistance to disease. *Vital rates* refer to all components of individual health (*probability of survival and producing offspring*, *growth rate*, and *offspring survival*).

Even though the PCoD model presented in Figure 2-2 is already a major simplification, it is not yet possible to make an estimate of all the required parameters for most marine species. This also applies to the species that are common indicators in the MFSD, such as the harbour porpoise and seals. The knowledge gaps relate primarily to the quantified effects of changes in behaviour and/or physiology, the knock-on effects on condition/health and the resulting probability of survival/reproduction (*vital rates*). Several practical solutions have been proposed to temporarily fill these gaps. The methodologies described until now differ in the way they translate sound exposure to individual survival and birth rate. How these methodologies work in practice is explained below in 2.3.2 and 2.3.3.

2.3.2 Frameworks using spatial distributions of (impulsive) sound and receptors (*e.g.* Interim PCoD)

The general approach of these frameworks involves the following elements:

1. Quantification of sound propagation
2. Determination of the areas affected by impulsive sound causing injury (PTS) and/or behavioural responses (species specific): threshold values and dose-response relationships
3. Define the duration of the activity (disturbance days)
4. Quantification of the number of affected animals by the activity per day (using, if possible season-specific, information on species distribution and densities)
5. Calculation of the total number of animal disturbance days (by multiplying the results of steps 3 and 4)
6. Assessment of the possible impact on the population by extrapolating the effect of the disturbance and/or injury to change in vital rates of the affected organisms.

For most species, there is little or no empirical evidence to quantify the relationship between behavioural or physiological change, as could be induced by impulsive sound, and fitness. This knowledge gap can be filled by expert judgment. Thompson et al. 2013 quantified the relationship between disturbance and/or injury induced by sound and vital rates of harbour seals through a series of informal discussions and workshops with research scientists and other stakeholders. Harwood et al (2014) developed an interim version of the PCoD framework by New et al. (2014). In this approach, presented in Figure 2-5, the parameters for the relationship between physiological and/or behavioural changes and the vital rates were obtained by bringing in experts to estimate them in a formalized *expert elicitation process* (Harwood et al. 2014; King et al. 2015). The principles of this process are summarised in the box below.

Intermezzo Expert elicitation

The Interim PCoD model establishes a quantitative relationship between the disturbance of behaviour and ‘vital rates’. That relationship was established by consulting experts in a formal 'expert elicitation’ process because of the lack of observational data. That process involved the use of a range of techniques to weight the experts' opinions independently and to provide a numerical estimate of the uncertainty in the relationship. See Harwood et al. (2014) for details.

In the implementation of the Interim PCoD model for the purposes of this study, ‘disturbance’ (in other words, ‘significant behavioural response’) was defined as a change in behaviour that can have an adverse effect on the probabilities of survival, reproduction and nurturing of offspring. This corresponds, in broad terms, to a score of 5 or higher on the 'behavioural response severity scale' for marine mammals in Southall et al. (2007).

A group of 13 international experts, who were selected on the basis of recent relevant publications, participated in the ‘expert elicitation’ process for harbour porpoises. They were asked to make estimates of the three parameters A, B and C for the relationship shown in Figure 2-3 between the number of disturbance days in a year and two specific dominant ‘vital rates’:

1. the survival probability for offspring (calves and juveniles);
2. the probability of adult females giving birth.

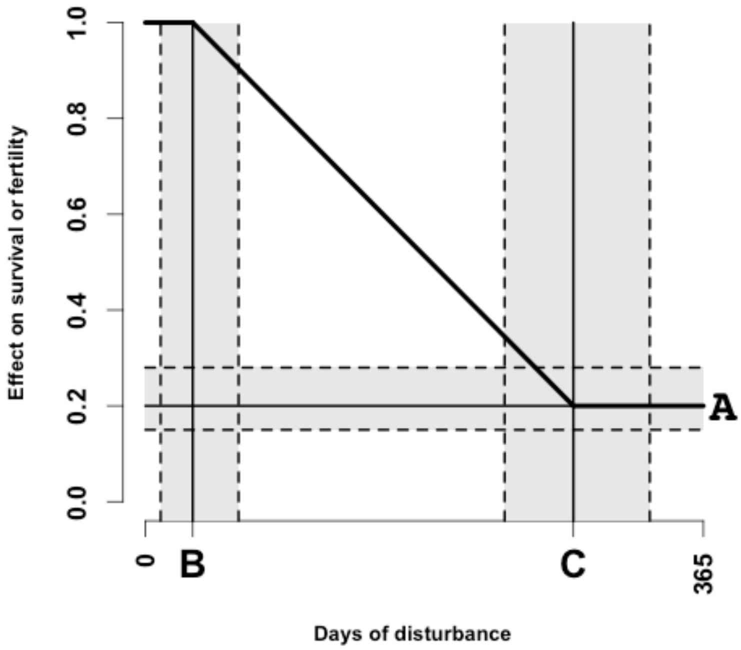

Figure 2-3 From [Harwood et al., 2014]: The hypothetical relationship between the number of days of disturbance experienced by an individual marine mammal and its effect on the probability of survival or fertility. A is the maximum effect of disturbance on this probability (in this case, the actual probability will be the population survival rate multiplied by 0.2), B is the number of days of disturbance an individual can tolerate before its survival or fertility is affected, and C is the number of days of disturbance required to cause the maximum effect. The shaded areas indicate the likely range around the best estimates of A, B and C provided by each expert.

The answers of the various experts, including an indication of the confidence interval, were combined to produce a two-dimensional probability distribution function, as shown in Figure 2-4.

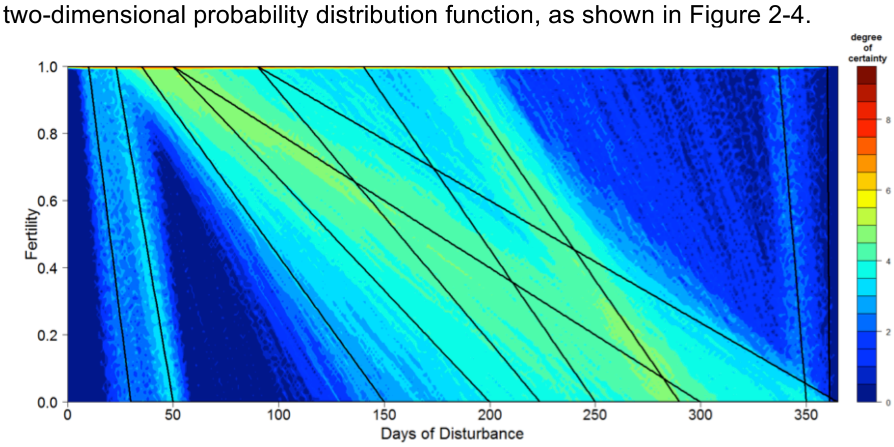

Figure 2-4From [Harwood et al., 2014]: Probability density function for the relationship between the number of days of disturbance experienced by an adult female harbour porpoise and the effect of that disturbance on her fertility. The black lines indicate the relationships suggested by individual experts. They are superimposed on a map that shows the overall support amongst the experts for combinations of values - 'hot' colours (reds and yellows) indicate combinations for which there was a lot of support, and 'cold' colours (various shades of blue) indicate combinations for which there was little or no support.

Given these probability distributions, a random 'virtual' expert opinion was derived for each simulation run in a stochastic population dynamic model that extrapolates the calculated number of disturbance days for individuals in ten age categories to 'vital rates' and demographic development (see also [Harwood et al., 2014]).

The *Interim PCoD framework* was developed in 2013 by SMRU Marine and the University of Saint Andrews to predict the possible effects on marine mammal populations resulting from disturbance, damage to hearing and collisions as a result of the construction and operation of offshore renewable energy structures (including wind energy). The framework and the associated software written in *R* (www.r-project.org) can be downloaded from the website of The Scottish Government (see www.smru.co.uk/pcod and www.scotland.gov.uk/Topics/marine/science/MSInteractive/Themes/pcod).

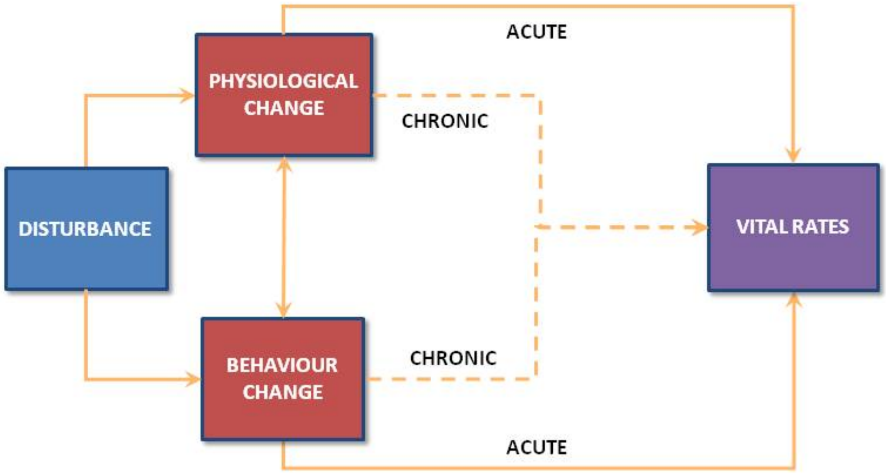

Figure 2-5 Simplified version of the PCoD framework from Figure 2-2 as applied in the Interim PCoD model. Due to the lack of empirical data about the effects of changes in physiology and behaviour on individual health, the links indicated by the dotted lines between the chronic effects of changes of this kind and *vital rates* were determined in an 'expert elicitation process' [Harwood et al. 2014]. The term *vital rates* here refer to all the components of individual health (*probabilities of survival and producing offspring*, *growth rate*, and *offspring survival*).

Frameworks incorporating Interim PCoD modelling or a comparable method were applied to a harbour seals (Thompson et al 2013) and harbour porpoises (King et al. 2015, Heinis et al 2015, Brandt et al 2016). In France, the Interim PCoD model will be used to predict the demographic impact of pile driving for the construction of a windfarm on the harbour porpoise population (Pettex, pers. comm.).

2.3.3 Frameworks with agent-based modelling (*e.g.* DEPONS)

Like in the frameworks described in 2.3.2, the modelling of impulsive sound fields form the starting point in frameworks using agent-based modelling. However, the consequences of the behavioural response of individual animals on energy levels are modelled more explicitly. Effects on the population emerge from the balance between reproduction and mortality, where mortality is influenced by individual animal's energy levels. The models focus on animals moving in a complex landscape, varying in space and time and estimate the impact of these variations (e.g. presence of sound sources) on their regular behaviour (e.g. foraging) and therefore, their energy levels. These models account for the effect of the extra energy expenditure by avoiding the sound source and the possible effect of moving away from a profitable foraging area and the time it takes to find a new good food patch. New et al. (2014) and Pirotta et al. (2014) worked this concept out for southern elephant seals and bottlenose dolphins, respectively. For the European waters, the DEPONS model (Disturbance Effects on the Harbour Porpoise Population in the North Sea) is more relevant (Nabe-Nielsen et al. 2014; van Beest et al. 2015). With this model, the impact of the presence of impulsive sound sources in a specific area on its harbour porpoise population is modelled by simulating the behavioural response of individual harbour porpoises to the impulsive sound(field)s. The DEPONS model version 1.1 is publically available since 24th April 2017 and can be downloaded via www.depons.au.dk.
The DEPONS model does not incorporate the potential impact of the effects on hearing on the population. However, Aarts et al. (2016) demonstrated by agent based-modelling how different movement strategies affect the number of individual harbour porpoises *Phocoena phocoena* receiving temporary or permanent hearing loss due to underwater detonations of recovered explosives (mostly WWII aerial bombs).

2.3.4 Conclusions

From 2.3.2 and 2.3.3 it can be concluded that two, principally different approaches exist for assessing the impact of disturbance by impulsive sound on populations of marine mammals. For the European seas, frameworks using either the Interim PCoD model or the DEPONS model are representative for these two approaches. In both approaches the modelling of sound propagation is the starting point. From that, sound fields can be determined based on assumed threshold values. The approaches differ in the way the behavioural responses are modelled. The Interim PCoD assumes that animals occurring in the area affected by impulsive sound are disturbed for some time (*e.g.* one day). From the number of animals disturbed times the number of days they are disturbed (animal disturbance days), the effects on vital rates are estimated with the results of the expert elicitation. These affected vital rates are the input for the population model. In the DEPONS model, it is assumed that animals move away from the sound source and as a result of that could lose energy because they can forage less effectively. The energy loss is translated into effects on vital rates, which are input to the population model. Both approaches rely on a series of assumptions filling in the existing knowledge gaps (see Appendix B). Some of these knowledge gaps could be remedied by experimental work in the near future, but for the filling in of others long-lasting and expensive experimental and field research is needed. It is, therefore, inevitable that for the time being the estimation of the impact of impulsive sound on populations will be based on various assumptions. Results of experimental work to come probably will not remedy all knowledge gaps, but can be used to reduce uncertainties and bandwidth of estimations.

2.4 Evaluation

A framework/methodology for assessing the impact of impulsive sounds on populations of marine organisms generally consists of the following steps:

1. Characterisation and quantification of the sound source, including propagation of the sound (location specific);
2. Determination of the size of the areas affected by impulsive sound causing injury (PTS) and/or behavioural responses (species specific): threshold values and dose-response relationships;
3. Define the duration of the activity;
4. Determine the number of animals affected taking the duration of the sound producing activity and variations in spatial and temporal distribution into account;
5. Assessment of the possible impact on the population by extrapolating the effect of the disturbance and/or injury to change in vital rates of the affected organisms.

It should be noted that the knowledge gaps for steps 1 – 4 are limited (although the bandwidth of estimations can be large, *e.g.* because of large natural variations). For the last step, the extent of uncertainties and knowledge gaps is larger, because for most species little is known about the relationship between disturbance and vital rates. The Interim PCoD model solved this problem by using a formalized expert elicitation. As far as is known, the Interim PCoD model is the only instrument currently operational that establishes a quantitative link between disturbance, *e.g.* by impulsive sound and consequences for populations of various species. That means that it is also the only instrument that can be used to determine the cumulative effects of disturbance by impulsive sounds of various sources. The DEPONS model also estimates the consequences of disturbance for a population, but is only operational for harbour porpoises in the North Sea (publically available since 24th April 2017). This model is, therefore, less flexible than the Interim PCoD model (see for Nabe-Nielsen & Harwood, 2016 for a comparison of the two models). Therefore, a methodology incorporating the Interim PCoD model for the quantification of the impact on populations appears to be the most logical. In the last 5 years, experience has been gained with the Interim PCoD model in several countries and it proved to generate results that can be understood well. It is also flexible and can be adapted relatively easy when new information becomes available.

To make a methodology generally applicable to all (impulsive) sound sources and species occurring in European seas covered by the MSFD, it should at least meet the following criteria:

- Quantification of impact of (impulsive) sound on (populations of) relevant marine organisms;
- The calculation should lead to results that can be interpreted easily, in such a way that comparison with targets is possible, for instance: “the yearly population decline should be less than 1%”;
- Applicable for a range of regions, marine organisms and pressures;
- Flexible in use (within boundaries) and in incorporating new knowledge;
- Transparent (explicability, probability of correct outcome);
- Unequivocal results, results not depending on executor;
- Open source (available for everyone);
- Relatively easy to use (good manual);
- Accepted in the scientific and OSPAR/MSFD community.

3 Action plan

3.1 Introduction

As explained before the purpose of the project is to develop a methodology to link the impulsive sound data in the impulsive noise register to effects on populations of relevant species and/or ecosystems. More specifically, the methodology should link sound data to criteria for assessing the GES of relevant biological indicators (*e.g.* populations of marine mammals). From the effects on these biological indicators and the evaluation of these effects (acceptable or not?) one could derive targets (or sound budgets) for maximum allowable sound levels by 'back calculating'.

This chapter contains an action plan for the development of a methodology meeting the criteria described in 2.4 (section 3.2), the application of the methodology in a MSFD assessment (section 3.3) and the evaluation of the effectiveness of potential targets resulting from the application the methodology (section 3.4).

3.2 Development of a methodology for assessing impact of impulsive sound

The focus of the first part of the project will be on the collecting of information and the identification of the adaptations needed to make the stepwise approach of which the general outline is described in 2.4 'MSFD-proof'.

3.2.1 Characterization and quantification of sound sources – Impulsive Noise Register

The first step in the methodology consists of the characterisation and quantification of the sound sources. The starting point for this is the Impulsive Noise Register, which has been developed for OSPAR by ICES to hold data on impulsive sound activities. The register accords with the guidelines from the European Union's (EU) Technical Group on Underwater Noise (adopted by OSPAR in 2014), and is maintained by ICES. This register was initially supported by OSPAR, and is now also used by HELCOM, and could similarly be used by other Regional Seas Conventions. This database collects the data from Contracting Parties in a standard format and in accordance with the data requirements for the OSPAR Impulsive Noise Indicator (OSPAR, 2014).

The definition of the OSPAR Impulsive Noise Indicator is (OSPAR, 2014):
Distribution in time and place of loud, low and mid frequency impulsive sounds – proportion of days and their distribution within a calendar year over areas of a determined surface, as well as their spatial distribution, in which anthropogenic sound sources exceed levels that are likely to entail significant impact on marine animals measured as Sound Exposure Level [SEL] (in dB re 1 μPa^{2}s) or as peak Sound Pressure Level [SPLpeak] (in dB re 1 μPa peak) at one metre, measured over the frequency band 10 Hz to 10 kHz.

In other words, the Indicator records the number of days within a specified spatial unit in which anthropogenic impulsive sound occurred in a specific calendar year. Only sound sources above a specified intensity level are included. These levels are detailed in the technical specification of the Impulsive Noise Indicator (OSPAR, 2014). This spatiotemporal unit of assessment is termed Pulse Block Day (PBD). The spatial unit used in this assessment is the ICES statistical sub-rectangle (hereafter ICES sub-block), which is defined in a standard way throughout the OSPAR region, and provides detailed resolution at the regional sea scale.

Impulsive sound sources that were reported in the Impulsive Noise Register for 2015 are:

- Sonar and acoustic deterrents
- Airgun arrays
- Underwater explosions
- Pile driving

Figure 3-1 shows a visualisation of the distribution of Pulse Block Days during 2015, based on the currently available data in the OSPAR Impulsive Noise Registry. This visualisation represents a partial assessment, since data were not available for all activities and Contracting Parties in this initial year of assessment

(2015). The visualisation maps show impulsive sound sources are distributed across the OSPAR Maritime Area, indicating levels of activity.

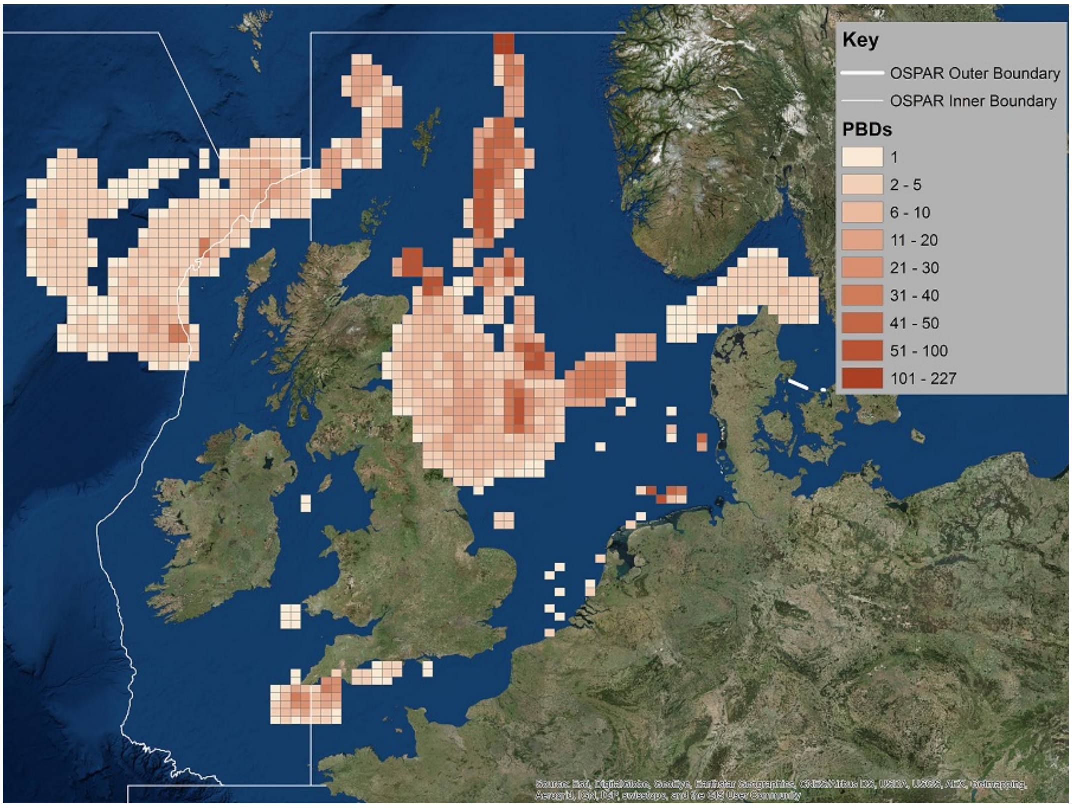

Figure 3-1 Total pulse block days reported for 2015 (from OSPAR, 2016)

3.2.2 From a pressure indicator to an impact indicator – disturbance days

The spatial distribution of impulsive sound sources, as recorded in the Impulsive Noise Register is now used as a pressure indicator in the upcoming Intermediate Assessment by OSPAR in 2017 (OSPAR, 2016). The present indicator, describing Pulse Block Days provides a broad overview of noise generating activities. During the development of the indicator it was assumed that this was the maximum achievable in this MSFD cycle and that not enough information would be available to develop a more advanced impact indicator However, knowledge has increased rapidly over the last years and new methods to assess impacts have been developed. This may enable to work towards a more advanced methodology in which not only the pressure but also the impact of impulsive noise on marine life can, to some extent, be assessed. This would be in line with the TG Noise advice on including a (proxy) of source level of activities in the register, so that not only an overview of the number of activities would be available, but also better information about the actual amount of sound generated (see Dekeling et al. 2014). The data recorded in the register would enable member states to estimate the size of the area affected by anthropogenic impulsive noise sources. Using information on response thresholds for relevant species, the actual area where effects could occur could be estimated.

The question remains on how the pressure indicator can best be translated into impact indicators, that more directly relate to the intensity of the disturbance and thus to the potential effects on marine organisms. To investigate this, Rijkswaterstaat commissioned TNO to explore how the impulsive noise register could be used to model the underwater sound field and the disturbance of marine mammals accumulated over multiple sound sources and sound types (von Benda-Beckmann et al. 2017).

The objective of this study was to assess how the impulsive noise register can be used to estimate the area disturbed by impulsive noise. This was achieved by calculating sound fields for all impulsive sound sources included in the Impulsive Noise Register for a selected period, and convert these, using generic impact thresholds, to count the number of disturbance days for each geographical. This approach is a first step making the method proposed by The Netherlands for assessing impulsive noise (Heinis et al. 2015) suitable for application in the MSFD.

To explore the possibilities for deriving maps from the impulsive noise register that can inform impact indicators, assumptions needed to be made about the source properties, sound propagation, and type of impact expected from the impulsive sound. The general approach adopted in this exploratory study was to apply simplified models for the sound production and propagation, to identify how information contained in the noise register can be used, and what type of output could be generated. Once this information path has been established, more sophisticated modelling approaches can be applied, as needed or desired for different applications or users.

A disturbance map was generated for the period 2015 (last accessed 16-11-2016) using the impulsive noise register as input (Figure 3-2), see von Benda-Beckmann et al. (2017) for the assumptions on sources and propagation. This map includes the contributions of source types in all noise categories. Due to the explicit modelling of the sound generated by each noise categories (‘low’, through ‘very high’), their contributions can be accumulated consistently. Due to the simplifications made in this process, the results should be considered illustrative rather than quantitative at this stage.

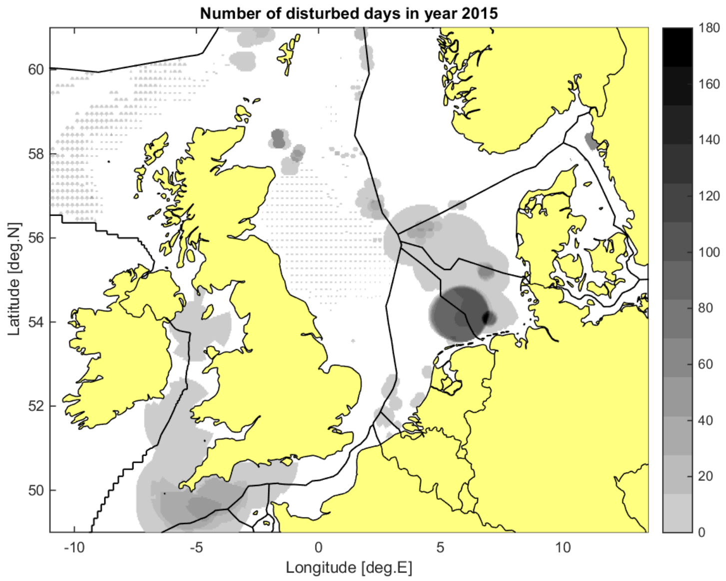

Figure 3-2 Example of a disturbance map generated with the Impulsive Noise Register generated for the year 2015 (last accessed 16-11-2016). The greyscale indicates the number of days in which an area is disturbed (i.e. levels of sound exceed the disturbance threshold, which is source specific) accumulated over all sources for a one year period.

Several important observations can be made from Figure 3-2. There is a large spread in affected areas, clearly showing how different in size the affected areas are for different sources. Different sources can disturb areas that are (much) larger or smaller than the ICES sub-grids, on which the source distribution in the OSPAR intermediate assessment for 2017 is based (compare Figure 3-1 with Figure 3-2). The distribution of sources will therefore not directly reflect the areas that are affected by sound, and the ICES sub-grid is *not conservative* in terms of estimated affected area (although it may be for some source types, such as surveys with small airgun sources).

The information contained in the disturbance maps can be further compressed into indicators for specific regions of interest. Regions of interest made for specific locations (e.g. whole North Sea, specific management units, Natura-2000 areas, etc). Two example indicators are provided here for illustration purposes.

The total concept of the ‘area disturbance days’ is a concept similar to Pulse Block Days used in the current impulsive noise register. Figure 3-3 shows the total number of area disturbance days, which was computed by summing the total number of days of disturbance, multiplied by the cell size over all cells for the 2015 period. Figure 3-3 shows the cumulative sum over all source types and areas in the impulsive noise register, and breaks it down by the contribution of each source type and noise category. It is interesting to note that activities in different noise categories (‘low’ pile driving vs ‘high’ explosions) can lead to a comparable contribution in terms of the total number of area disturbance days. Note also that the sum of the total area disturbance days for the individual source exceeds the cumulative total area disturbance days, which is due to the fact that the cumulative part accounts for spatio-temporal overlap of different sound sources. Another possibility to visualize the data, is to consider the total area that is disturbed by a certain number of days per year (see von Benda-Beckmann et al. 2017).

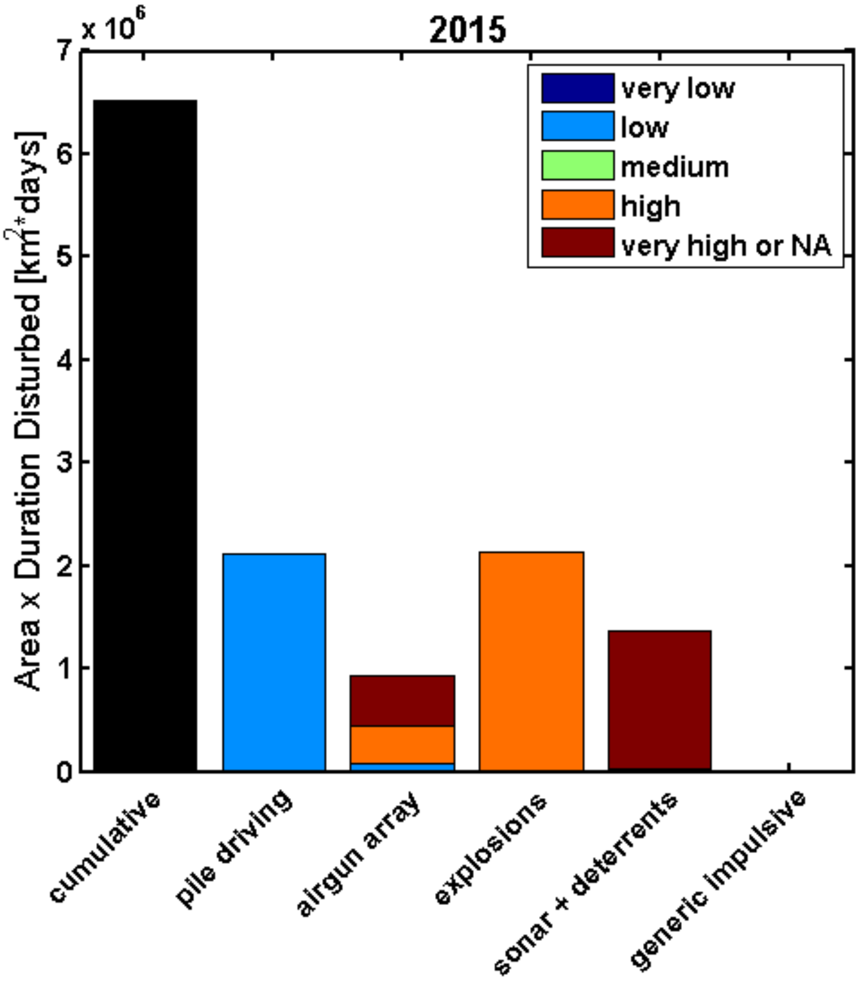

Figure 3-3 Distribution of disturbance days (area × days of activity) by source type and noise category (colours), summarizing the relative contributions of all sources to the total disturbance. This example includes the contributions from all activities reported in the impulsive noise register, as shown in Figure 3-2.

The study by von Benda-Beckman et al. (2017) provides examples of how the data that are currently contained in the Impulsive Noise Register can be used for the development of an impact indicator, such as area disturbance days. The study intends to stimulate discussion and highlight current strengths and shortfalls in data-detail.

3.2.3 General outline for the assessment methodology

For the further development of a robust and 'MSFD-proof' methodology to assess the impact of impulsive sound on marine life, information on various topics should be brought together. Although the general stepwise approach for different sound source types and species does not differ, the characteristics of the sound sources and sensitivities of species to impulsive sound do.

For the process of the Environmental Impact Assessments (EIA) for licensing offshore wind farms, The Netherlands applied and further developed the general framework for the assessment of effects on marine life (Heinis et al. 2015). The focus was on assessing the effects of pile-driving on the harbour porpoise population of the North Sea. This framework currently being the most detailed one, it will be the starting point for the methodology to be developed. It consists of a step-by-step procedure to quantify the cumulative effects on marine mammals of Impulsive Sounds produced by several initiatives. The approach developed in the Netherlands is well suited for use in the context of the MSFD for the following reasons:

- The approach makes it possible to determine the cumulative effects that multiple activities generating impulsive sound have on indicators for biodiversity, in this case the harbour porpoise population in the North Sea;
- In the stepwise approach, each step is clearly distinguishable and there is a clear description for each step of which methods are used;
- As a result, the requirements for the input data are also clear, including the importance of detailed records of impulsive sound;
- The approach is flexible. The calculations can be performed for larger or smaller areas and different population sizes. In addition, the calculations in each step can be made more precise if new information becomes available.

The procedure to determine the effects on the harbour porpoise population in the North Sea is:

Step 1: Quantification of sound propagation
In this step, the sound propagation is calculated with a (validated) numerical model thereby using information about the sound source (*e.g.* piling energy), bathymetry, bed characteristics (grain-size distribution) and the wind. In the Netherlands, the AQUARIUS sound-propagation model developed by TNO was used. However, any other model would do if it is representative for the average conditions of the location(s) of interest. Also, a simplified approach to full acoustic modelling can be chosen, *e.g.* an open and easy to use library of propagation distances based on type of activity and source specifications.

Step 2: Determination of the area affected by sound: effect parameters and threshold values

- Choose relevant effect type, e.g. PTS, TTS or disturbance / avoidance behaviour
- Use species specific threshold values for the effect type chosen, based on available data from controlled experiments and / or field studies. In the Netherlands, the calculations assume a threshold value for disturbance of harbour porpoises of SEL_1 = 140 dB re 1 μPa^2s (unweighted). This is the effect type that is considered to be indicative for effects on the population (see Annex A).
- Determine the size of the affected area, based on threshold values and sound propagation from step 1.

Step 3: Quantification of the number of affected animals

- Collect information on species distribution and densities based on data from surveys and determine seasonal variation. Based on the results of aerial surveys on the Dutch Continental Shelf, Geelhoed et al. (2011, 2014) calculated for three seasons (spring, summer and autumn/winter) average densities in areas A, B, C and D (see Figuur 3-4 for area boundaries).
- Calculate the number of affected animals by multiplying the affected area from step 2 with the average density.

Step 4: Calculation of the number of animal disturbance days

- Multiply the number of animals disturbed by the activity (result from step 3) with the duration of the activity in days (impulse days)[2].

Step 5: Assessment of the possible impact on the population

- Extrapolation of the effects on individuals determined in step 3 to effects on the population by means of population dynamic modelling. Values for population parameters such as population size and demographic rates (survival rate, fertility, etc.) are derived from the literature.

In the approach for the EIAs, The Netherlands used the Interim PCoD model (Harwood et al., 2013, 2014), considering that this model was the best available model for the specific purpose that was published in open literature at the time.

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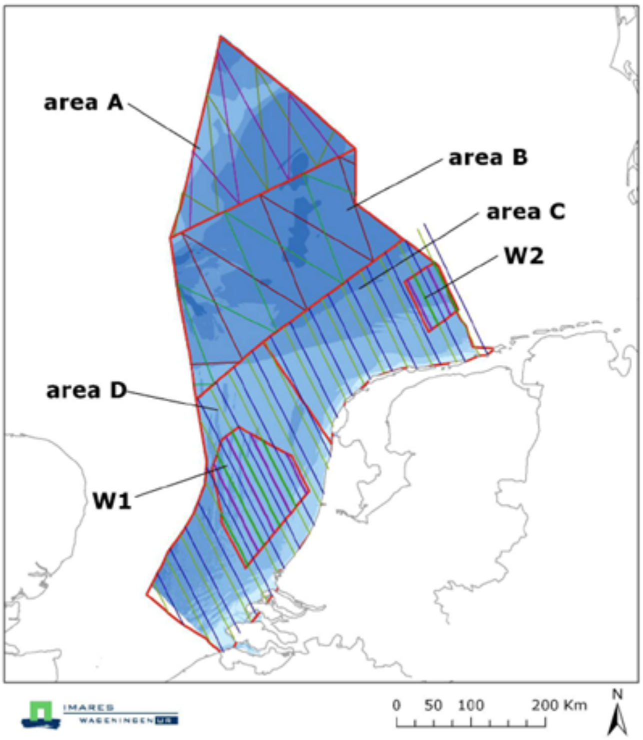
[2] The length of time that the behaviour of an individual is affected by a disturbance event is a critical parameter in the Interim PCoD model. The total number of animal disturbance days is calculated by multiplying the number of animals that may be disturbed on one day by the duration of the disturbance. No unequivocal picture has yet emerged from the information available at present about the duration of the disturbance (see also Heinis et al. 2015). However, the model results have proven to be relatively sensitive to the selected values (8, 24 and 48 hours). In the Dutch framework that is used for windfarm licensing, it is assumed that piling for one turbine foundation disturbs harbour porpoises or seals for one day (24 h = 1 impulse day). In practice, driving a single pile takes between 1 and 4 hours at most. Recent results from monitoring harbour porpoises during construction of the GEMINI windfarm suggest that the behaviour of harbour porpoises is 'back to normal' within 5-6 hours after termination of the piling.

Step 6: Cumulative effects assessment by multiple projects / impulsive sound sources

- Calculation of the cumulative exposure of harbour porpoises as result of multiple activities producing I-UWS (per year and over a period of several years).

The Interim PCoD model assumes that the population will not recover from an effect, in other words a fall as a result of the activities, after the activities end. Year-on-year effects therefore accumulate.

Knowledge gaps have been identified for each step in the approach. An overview of these knowledge gaps and a discussion of how, and how soon, they can be remedied can be found in Annex B.



Figuur 3-4 Chart after Geelhoed et al. (2011) of the DCS showing areas A (Dogger Bank), B (Offshore), C (Friesian Front) and D (Brown Bank). W1 and W2 show the areas relevant for wind energy at the time. The lines represent the transects flown and the colours represent the various surveys.

3.2.4 Actions needed for upgrading the methodology for MSFD

1. Inventory

To make the Dutch stepwise approach suitable for application in the MSFD, the following information should be brought together and incorporated in a new framework that is more broadly applicable than the present one:

- Check on the suitability of information on the impulsive sound sources in the Impulsive Noise Register for application in an impact assessment (see von Benda-Beckmann et al. 2017);
- Characteristics of activity types generating impulsive sound present in the MSFD-region (*e.g.* source levels, duration of activity, moving or static sound source, area where activity takes place);
- Description of dominant effect types per source type (*e.g.* temporary habitat-loss for marine mammals by pile-driving and seismic surveys, hearing damage in marine mammals by explosions);
- List of relevant biodiversity indicators that are susceptible to effects of impulsive sound and GES-criteria for these criteria;
- Derive of- and/or decide on threshold values for effects of impulsive sounds for each species and source (frequency weighting, yes or no, see also annex B);
- Specify information needed on distribution patterns of relevant species and if possible make it accessible (where to find?);

- Information on progress state of knowledge gaps listed in Annex B; knowledge increases rapidly by results of monitoring in relation to offshore windfarms as well as experimental work. Special attention should be paid to increased knowledge on the actual length of time the behaviour is disturbed (see also footnote 2) and the energetics of species of interest.

2. Working out a methodology for various species(groups) and sound sources
The inventory will yield insight into the amount of information available for each species(group) and sound source and the knowledge gaps that still exist. It is not likely that for all species(groups) enough information will be available to fill in all the steps needed to make a full assessment. In this phase of the project, a choice could be made to focus on the developing of a full framework for the species of which the population(s) is/are most sensitive to the effects of impulsive sounds at sea.

3. Recommendations for filling knowledge gaps
As noticed before, knowledge is increasing rapidly, but for some species less than others. An inventory should be made if this lack of insight could hamper assessing the GES for species or species(groups). In other words, could for these species(groups) the reaching or maintaining of the GES be hampered by the effects of activities at sea that generate impulsive sound? It is, therefore, also important to get an idea of the extent to which a specific knowledge gap could influence the result of the final assessment.

4. Presentation of the methodology to scientists and OSPAR/MSFD community
The results of this phase of the project, a concept 'cookbook' like methodology for assessing the impact of impulsive sound on marine organisms, will be presented and discussed in an international workshop. Representatives of the OSPAR/MSFD community as well as scientists and regulators should be invited.

3.3 Application of the methodology in a MSFD assessment and targets

The next two phase are yet not worked out in detail as the extent to which they can be executed largely depends on the results of the preceding phase. Activities that will be performed are:

- Pilot in which the adapted methodology will be applied in the context of the MSFD using the – preferably more detailed[3] – data recorded in the Impulsive Noise Register;
- Assessment of the relative impact of different impulsive sound sources and cumulative effects
- Thorough evaluation of the results in an international setting (workshops with scientists and regulators) and presentation in the OSPAR/MSFD community;
- Investigate the possibilities of deriving targets for impulsive sound based on the results of the (pilot) impact assessment and make a proposal for the best way to go forward.

[3] See 3.2.2 and von Benda-Beckmann et al. (2017)

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ANNEX A PARAMETERS FOR CALCULATING EFFECTS OF IMPUSLSIVE SOUND BY PILE-DRIVING AND AIRGUN ARRAYS

Relevant parameters for calculating the effects of on populations (from: Heinis et al. 2015)

It is assumed that effects on behaviour (disturbance / avoidance) by impulsive sound generated by pile driving and airgun arrays are indicative of the effects on populations.
The effects of TTS will have no, or only a negligible, effect at the population level because:

- The TTS onset contours calculated for previous appropriate assessments are much smaller than the maximum avoidance contours, which means that the number of harbour porpoises with hearing that is temporarily affected is also smaller than the number of harbour porpoises disturbed.
- On condition that mitigation steps are taken to prevent PTS (see below), the hearing of all the harbour porpoises that may be affected will recover in full (in the vast majority of animals within a few hours after leaving the area affected or after piling ceases).
- The effect distances for TTS in reality are likely to be much smaller than those calculated until now. That is because the threshold value adopted for 'TTS onset' in harbour porpoises is based on the results of the experimental exposure of harbour porpoises to airgun sound by Lucke et al. (2009). This is the sound dose (SEL_{cum}) at which a temporary increase in the hearing threshold of 6 dB is measured (in other words, hearing is 6 dB less sensitive). However, it has emerged from the results of recent research by SEAMARCO that, with recorded piling sound, a minor TTS of 2.3 – 4 dB can be observed in harbour porpoises at a SEL_{cum} of 180 dB re 1 $\mu Pa^2 s$ [Kastelein et al., 2014]. This value is significantly higher than the threshold value for SEL_{cum} of 164 dB re 1 $\mu Pa^2 s$ assumed in the calculations.
- The frequencies at which TTS can occur in harbour porpoises after exposure to piling sound are not in the frequency range that is important for finding prey using echo location. Indeed, in the case of a harbour porpoise exposed to recorded piling sound, it was found that the shift was limited to a relatively small band of low frequencies [Kastelein et al., 2014]. A statistically significant TTS was found only at frequencies of 4 kHz and 8 kHz, and not at the higher measured frequencies (16 kHz and 125 GHz, the echo-location frequency) and the lower frequency (2 kHz). It is striking that, at the frequencies where most of the sound energy of the delivered piling sound is located, namely the 600 – 800 Hz frequency band, there is no TTS. These observations are important for the assessment of the ecological relevance of a predicted hearing threshold shift. A temporary shift in the low-frequency range of the hearing spectrum is probably much less relevant for harbour porpoises in terms of foraging than it is in the high-frequency range. High-frequency sounds of about 125 kHz and the audibility of those sounds are essential in this species for locating prey (using echo location).

As for the possible effects of PTS, it has been assumed that the effects will be prevented by mitigation measures. At present, this is safeguarded by means of a regulation in the existing permits. It emerges from the calculations made for various wind farms that the distance at which harbour porpoises could suffer PTS is relatively small. This means that the effect can probably be prevented with a 'soft start' for piling and an 'acoustic deterrent device' (ADD).[4] This will drive harbour porpoises away to a distance outside the PTS contour line. The PTS distances continue to fall when sound standards are used.

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[4] Because ADDs and piling do not produce sound in the same frequencies, the possibility of cumulative effects on hearing is negligible.

ANNEX B KNOWLEDGE GAPS IN DUTCH APPROACH TO IMPACT ASSESSMENT OF IMPULSIVE SOUND AND THE HARBOUR PORPOISE

1. Quantifying sound propagation, validation of models based on results of measurements at Luchterduinen and Gemini

Status:
Piling: The knowledge gap is almost certain to be remedied in the short term. The necessary data for validation are available and the process of improvement is ongoing. The initial results for piling are expected in January 2016. There are not yet any plans for any changes to the model if the monitoring data prove to be very different from the model values. The result of the model validation will be published.

Seismic surveys: A workshop will be organised in July 2016 to compare models for seismic sound. It is expected that the same propagation models can be used, at least in part, as for piling sound. However, at larger distances, the model now available in the Netherlands underestimates the sound levels. A correction is required. The capacity to address this problem is limited. However, the data are available.

For the purposes of international comparison, there should not be too many differences between how different countries model sound propagation. A recent international comparison of piling sound models showed that the model results do not vary a great deal when looking at a single idealised scenario. The piling sound models will be validated using measurement results from recent projects (ENECO Luchterduinen and Gemini) in the coming months.

The effects of pingers or other *Acoustic Deterrent Devices* (habitat loss) and explosives (effects on hearing) have not yet been included in the cumulative effects assessment. The Ministry of Infrastructure and the Environment does not expect significant habitat loss as a result of pingers. How accumulation works in the case of explosives is still unclear; in any case, the aim is to prevent damage to hearing in marine organisms. The focus for the short term is on powerful sources - piling, seismic surveying and sonar (sonar is a minor source in the North Sea but it is relevant at the OSPAR scale). In the long term, the inclusion of all the sources in a cumulative effects assessment (including pingers and explosives) would be valuable.

2. Threshold values for disturbance and duration of disturbance: results of Gemini studies

The threshold value for disturbance: a harbour porpoise is disturbed when it is in an area where this threshold value is exceeded. The duration of the disturbance is the value that is used for the length of time a harbour porpoise's normal behaviour is affected.

Piling:
Ideally, the threshold value should be tested in realistic field conditions. The current threshold of SEL_1 = 140 dB re 1 $\mu Pa^2 s$ is a compromise between the results of field studies and results in controlled (and silent) experimental conditions. The value would appear to be realistic and there is little potential for improvement. It is good enough for use in OSPAR. Germany uses similar values (140-144 dB). In the long term, the threshold value could be made slightly more specific.
The duration of the disturbance is highly dependent on where a species (in this case, the harbour porpoise) is located at the time of the disturbance, for example whether it is near the sound source or not. The only way to really learn more about this area is to tag animals. However, the Interim PCoD model is sensitive to the duration of the disturbance. The calculations are based on a disturbance duration of 24 hours; this is probably a conservative assumption. A better, more realistic estimate is required here that also does justice to the fact that animals on the outer edge of a disturbed area are less severely affected than animals closer to the sound source. However, this knowledge gap cannot be remedied in the short term. In addition, there are probably individual differences in behaviour and differences between species (such as harbour porpoises and seals). Motivation also plays a role: an animal that is disturbed in a rich foraging area will be more likely to return than when there is ample prey outside the area disturbed by the sound. Additional targeted research (such as surveys before, during and after piling) may help to state duration in a more nuanced way than just a single day. However, a generally applicable solution is not expected in the short term.

Seismic surveys: There are still quite a lot of uncertainties in this area (and so a lot of knowledge is still required). A good qualitative study by Thompson (2013) showed that the level of the threshold value is similar to that for piling - other values may be slightly higher (*Short-term disturbance by a commercial two-dimensional seismic survey does not lead to long-term displacement of harbour porpoises).* There are more uncertainties relating to disturbance duration because of the nature of the seismic sound source: impulsive sounds are produced by a moving sound source for a relatively long period of time. The question of when animals return to an area after disturbance by seismic sound remains unanswered. At the same time, this question is perhaps less relevant: when there is a continuous disturbance, an area will be 'closed' for (approximately) two months and whether a harbour porpoise returns after 4 hours, 24 hours, or three days makes little difference in terms of the overall impact. The situation will be different if the disturbance lasts for weeks but there are no indications that this is the case.

3. Threshold values for hearing threshold shifts

Piling: The pulse interval (interval between piling strikes) is important.

The threshold value used for cumulative exposure to impulsive sound may be too low for PTS. Even if no action is taken, it is not very likely that animals will suffer PTS as result of piling or seismic surveys. PTS can be completely prevented if the appropriate steps are taken. There are relevant regulations in the Netherlands for both seismic surveys and piling. The issue of PTS has therefore not been addressed further. A more precise determination of the threshold value for PTS after exposure (cumulative or otherwise) to impulsive sound is not a priority.

The clearing of ordnance (a particular problem in the southern part of the North Sea) involves a major risk of permanent damage to animals' hearing. It may be possible to prevent these effects by using acoustic deterrent devices. New procedures are being designed for this purpose.

4. Frequency weighting

Currently, the impact assessment of impulsive sound on marine mammals is based on broadband, unweighted sound exposure levels. However, like in humans, the hearing sensitivity of marine mammals varies with the frequency of the sounds. Recent publications show the importance of taking frequency dependent sensitivity into account when assessing the impact of sound (Tougaard et al. 2015; Houser et al. 2017). In the United States, frequency weighting is already advised to assess the risk of inducing TTS or PTS in marine mammals (NMFS, 2016). If some form of frequency weighting would be applied to the received sound levels – which appears to be a sensible thing to do – the thresholds values for disturbance and TTS/PTS should also be adjusted.

5. Quantification of the number of disturbed animals: density estimates include large confidence intervals

The number of disturbed animals is estimated on the basis of density estimates by IMARES. As part of the DEPONS project, Dutch survey data have been combined with Danish, Belgian, German and British data. Models have been used to produce density estimates for three periods in the year. The estimates tell us something about the past but they provide only a limited indication of the future. The number of harbour porpoises off the Dutch coast proved to be unexpectedly low in the spring of 2015. On the basis of observations from previous years, it was assumed that harbour porpoise density off the Dutch coast would actually be relatively high in the spring. The factors that determine the location of the animals at any given time (the 'drivers') are still largely unknown. A long data series is still needed. This knowledge gap cannot be remedied in the short term.

6. Size of vulnerable subpopulation

The *vulnerable subpopulation* is that part of the total population that may be affected by the impulsive sound during the activity. The size of the vulnerable subpopulation provides an indication of the level of site fidelity in the animals most disturbed by impulsive sound. The smallest possible subpopulation consists of the animals located inside the disturbance contour during the activity, and the largest could be the entire population of the southern North Sea. Not a lot is known about the possible site fidelity of harbour porpoises. However, knowledge in this area is being acquired rapidly as part of the DEPONS project, which monitors tagged animals. The 'Assessment framework ecology and accumulation of effects' works with a specific subpopulation size, but with almost no justification. However, decisions made in this respect affect the model results (compare scenarios 1, 5 and 6 in Tables 3-4 of Heinis & de Jong, 2015). One way to remedy this knowledge gap would be to tag large numbers of harbour porpoises. This is not feasible in the short term.
A question about this option should be included in any new expert elicitation process.

7. The extrapolation of sound disturbance from individual animals to the effects on survival and reproductive success

The main knowledge gaps are to be found in the field of the extrapolation of the disturbance of individuals by sound to the effects on the health/condition of those individual animals, and the consequences for survival and reproduction. In the Interim PCoD model, this knowledge gap is filled in by using expert estimates of the relationship between disturbance and vital rates in a formal expert elicitation process (see Intermezzo in Section 2.3.2). At present, the Interim PCoD model is the most widely used instrument for determining population effects. However, the “Interim” status of the model shows that there are reservations. Some of them could be resolved if more quantitative information were to be available about the relationship between disturbance and the health/condition of individual animals (of various ages). This would make possible the application of a ‘full PCoD model’ (see Figure 2-2).

In the process of developing an assessment framework for windfarm licensing, a number of knowledge gaps relating to this step in the effect calculations were identified for harbour porpoises:

- Effect of disturbance on feeding and energy expenditure (‘time-budget’ analysis) This issue is more important for harbour porpoises than for other marine mammals because they are smaller and have to eat regularly to maintain their weight. That makes them relatively sensitive to disturbance because of the implications for feeding. This involves questions such as: at what level of disturbance will a disturbed animal use more energy than an undisturbed animal, at what level of disturbance does an animal stop foraging, does the animal become used to the source of disturbance, how long can an animal manage without food, in what conditions (including the amount of time spent without feeding, available food supplies) can a food shortage be remedied without there being a substantial effect on survival chances, and how is that related to the time of the year?
- Habitat suitability It is not yet entirely clear in the case of harbour porpoises whether or, if so, why the areas where the highest population densities are seen (at specific moments) are the most suitable habitats. Are the survival chances of harbour porpoises that are driven out of an area of this kind actually adversely affected (see previous point)? To what extent are seasonal variations in population levels linked to variations in the availability of food supplies?
- Mother-calf combination Can the sensitivity of pairings of mothers and calves to disturbance by comparison with solitary animals be affected by the masking of communications by piling sound?

Much more data are available for harbour and grey seals than for harbour porpoises. That includes both population estimates and knowledge about the movements of individual animals. In combination with experimental data about the energetic costs of changes in behaviour (see, for example, Rosen et al., 2007; Sparling & Fedak, 2004; Sparling et al., 2007), it is thought that the effect on the population could be estimated by combining an agent-based model (see, for example, Nabe-Nielsen et al., 2014) with a Dynamic Energy Budget.

8. Interim PCoD assumptions for population development and demographic parameters

An example of a critical assumption made by the Interim PCoD model is that

- the harbour porpoise population is stable and
- changes in the population do not depend on the density (and are therefore not linked to carrying capacity).

The consequence of these assumptions for the model outcomes is that a population, once there is an effect, in other words a decline as a result of an activity, will not recover after the termination of that activity. This is not realistic unless the calculations indicate that the population declines quickly to such an extent that it can no longer recover.

Ultimately, it would be desirable for those parts of the Interim PCoD model which are addressed using expert elicitation to remedy missing knowledge/uncertainties to include firm knowledge. It would be advisable to develop parameters in this area and to work towards a knowledge-based approach. It is essential, if the method is to be accepted, to be able to make an estimate in the short term of whether the assessment of the effects is realistic and of whether they are being structurally under- or overestimated. This area is should be the focus of attention during any new expert elicitation.

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