BSH Cumulative Impact Study 2019

Comparative study of DEPONS and iPCoD

Bundesamt für Seeschifffahrt und Hydrographie

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Comparative Study of DEPONS and iPCoD

Prepared for	Bundesamt für Seeschifffahrt und Hydrographie
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CONTENTS

FIGURES

TABLES

1 Summary

Due to the increase in anthropogenic activities at sea, concern has been raised about the impact of the elevated noise generated by the activities on marine wildlife. In the North Sea, the harbour porpoise (*Phocoena phocoena*) makes up a high proportion of the marine mammals living in areas with planned activities.

Two model approaches have been developed to estimate the cumulative effects of noise generating activities at sea. As a top-down approach, the interim Population Consequence of Disturbance (iPCoD) model is a stage-based matrix model, where the user can specify the estimated number of disturbed animals per activity per day. Subsequently, the model will calculate the cumulative impact on the population, using a range of expert elicitation estimates of birth and mortality rates. In contrast, the second model approach, Disturbance Effects of Noise on the Harbour Porpoise Population in the North Sea (DEPONS), applies a bottom-up approach by using an individual-based model to assess the cumulative impacts. DEPONS models the behaviour of individual harbour porpoises, calibrated on telemetry and observational data from the North Sea. Subsequently, the impact is assessed by aggregating the impact distributed among the individuals.

While both models produce population size estimates and reflect changes in populations over time, there are fundamental differences between the two approaches. DEPONS is an agent-based model, where the behaviour of the individuals is modelled, and the population consequences are estimated as emergent properties of the model. DEPONS is spatially explicit, which means that population consequences can be resolved in space and time. The drawback of DEPONS is the lack of dynamic habitat preference predictions. In contrast, the iPCoD is a non-spatial explicit model, with population parameters being estimated by expert elicitation rather than empirical data. This means that the model is not specially adjusted for specific populations and will produce generic population consequence estimates.

In principle, both models are suited to estimate the cumulative impact of noise disturbances. The iPCoD is a relatively fast model, which facilitates the testing of multiple scenarios quickly, however the major driver of model estimates is expert elicitations rather than empirical data. The DEPONS has more detailed output and is calibrated according to empirical data but takes multiple days to execute a single model scenario simulation.

Both the iPCoD and the DEPONS model are risk-based models that are conceptually different and thus incompatible from the ‘habitat approach’ which is favoured by the BSH. Habitat models can be used to make limited tools such as iPCoD and DEPONS more precise. Yet, the best way to manage ecosystem impacts of aquatic noise is to apply the habitat approach in accordance with the German Schallschutzkonzept but expanded and informed by dynamic habitat- and agent-based modelling to identify value habitats.

2 Introduction

Over the past couple of decades, the North Sea has experienced a large increase in anthropogenic activities, such as shipping traffic and offshore construction (for example for offshore wind farms). At the same time, the evidence that the noise generated by the activities can affect the behaviour and distribution of marine mammals has increased as well (reviews by Thomsen *et al.*, 2006, 2011; Southall *et al.*, 2007; OSPAR, 2009). This means that, in addition to the direct effects of intense noises such as temporary (TTS) and permanent (PTS) noise-induced threshold shifts, noises can have indirect effects on marine mammal populations by temporarily displacing individuals from quality or critical habitats, which in turn can have effects on survival and reproduction (National Research Council, 2005).

Harbour porpoises constitute a large proportion of the marine mammals occupying the North Sea (Hammond *et al.*, 2013). Moreover, several studies show that harbour porpoises are especially sensitive to anthropogenic noise (Tougaard *et al.*, 2015). However, it is unknown to what extent the current and planned anthropogenic activities in the North Sea will affect the harbour porpoise population.

To investigate this question, two distinct models have been developed. First, the Disturbance Effects of Noise on the Harbour Porpoise Population in the North Sea (DEPONS) and second, the Interim Population Consequences of Disturbance (iPCoD). In this report we have described the assumptions and variables considered in each model and subsequently compared and evaluated the model output regarding conditions and side effects from constructions which the models can reproduce. Lastly, we have provided advice on the possible use of each model in a cumulative effect assessment of noise on the harbour porpoise in the North Sea.

3 DEPONS

The Disturbance Effects of Noise on the Harbour Porpoise Population in the North Sea (DEPONS) is an agent-based model (ABM, also sometimes referred to as IBM for individual-based model) (Grimm and Railsback, 2006), designed to model noise effects on a harbour porpoise population, by modelling the noise effect on individuals and subsequently aggregating the effects to population level. It builds on the work done by Nabe-Nielsen *et al* (Nabe-Nielsen *et al.*, 2014).

An ABM is a model that describes the autonomic behaviour and state of an individual. This also means that it is assumed that population changes can be estimated from the collective change in the individuals of the population.

In ABM, the movement of the agents is modelled using a Lagrangian object-oriented model which allows for the distinct modelling of an activity. This model is then coupled with a classic Eulerian framework which simulates the hydrodynamics of the aquatic system. The simulated agents within the model domain are capable of reacting to Eulerian gradients such as water temperature or flow velocities. It is thus possible to investigate potential effects of hydraulic and environmental cues on movement of aquatic organisms on a complex spatial scale over time.

Some ABM also allow for the definition of a sensory sphere around each agent that can potentially stretch across several Eulerian grid cells (Figure 3.1). The implementation of a sensory sphere enables the agent to detect the gradient of Eulerian variables and/or the presence of other Lagrangian agents (for example conspecifics) within the radius of its sensory sphere. The size of the sphere can be defined through a user-specified radius together with the angle of the agent’s field of view, meaning that, if needed, an agent can be specified to only sense variables ahead of its direction of orientation.

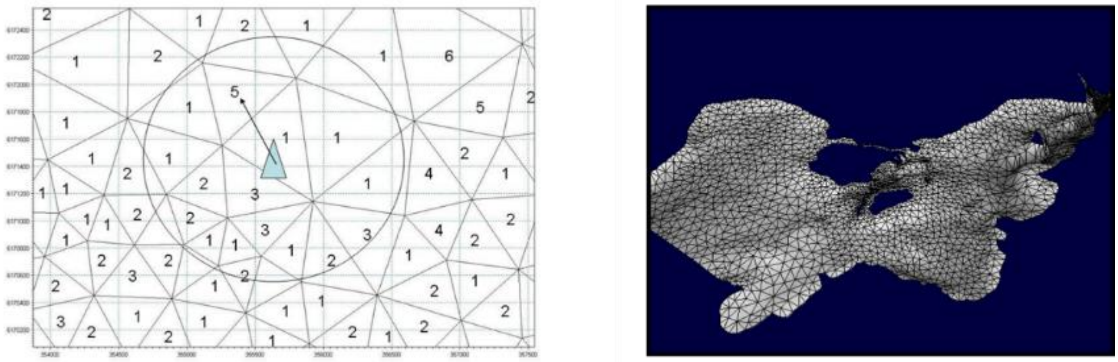

Figure 3.1 Example of an agent navigating grid cells in ECOlab by DHI software (Left: full HD model for an ocean basin. Right: details of the HD mesh. Agents in ABM lab can navigate in the same domain as the HD model, gathering information from the grid cell that the agent occupies the surrounding cells; however, the agent’s movements are not confined by the resolution of the grid cells).

A general ABM consists of a series of steps, wherein each agent makes a series of “decisions”. Agents are released into the domain and each agent attains the traits and states defined by the model. While the value of each trait, for example: the average swimming speed during foraging, will be different between the agents due to the stochastic selection processes defined in the ABM, they remain the same throughout the life of the agent. States, such as weight of the agent, distance travelled, etc., will change over the course of the agent’s life. Ultimately, decisions made by the agents are based on their traits, combined with external variables (for example noise) and internal states, which will result in a range of behaviours. This decision process of the agent takes place in the form of a decision tree where the yes/no answer leads to a new decision and when the end of the decision tree is reached, behaviours are executed, state variables are updated, and the process cycles to the next time step (further detail see Thomsen *et al.*, 2019).

And while it seems a valid assumption that the properties of a system are the sum of the properties of the individuals, it also proposes a major challenge for ecology modelling. As all individuals in a population are distinct from each other and foremost are inclined to increase their own fitness and not the fitness of the population (Grimm and Railsback, 2004), changes in the populations are not the sum of the properties of the individuals, but emerge from the interactions between the individual and the environment and the interplay with other individuals (Grimm and Railsback, 2004).

The DEPONS model operates in 30-minute time steps. In each time step, each modelled individual makes decisions on direction and speed of movement, based on the type of habitat occupied and level of noise exposure. By the end of each time step, the energetic status of the individuals is updated, and the probability of survival based on energy level is calculated. The model divides individuals into juveniles and adults. Adulthood is achieved after reaching the age of maturity (3.44 years). During lactation, some adults are labelled as “adults with calves”, determined by the birth rate of the population. The survival probability of calves is dependent on the energy status of the mother. The increase in number of juveniles in the population after the lactation period depends on the calve survival during lactation. The model also incorporates density dependence, with increases in mortality as a result of larger populations.

Basic assumptions of the model are:

- Population effects are the sum of the effects on individuals
- Modelled habitat quality reflects the potential for individuals to obtain food/energy
- Assumed relationship between energy level and survival
- Constant birth rates
- Assumes calve mortality only depends on energy level of mother
- Behaviour is constant in time and confer with the behaviour documented in literature/studies
- The distribution within a behavioural pattern is sufficiently consistent to be statistically described
- No environmental stochasticity
- Uncertainty can be estimated by repeated simulations of the same disturbance

Table 3.1 Key variables needed to be specified in the DEPONS model. Currently the model is calibrated for the North Sea and all parameters are based on scientific literature or experimental trials.

Variable Group	Parameter
Life-history	- Birth rate - Age of maturity - Start date of lactation - Lactation duration - Energy status and survival relationship
External disturbance	- Spatial distribution of disturbances - Timing of disturbances - Source strength
Movement and response	- 17 parameters defining movement in undisturbed waters. Already calibrated for North Sea harbour porpoise - 5 parameters for response to noise exposure. Already calibrated for North Sea harbour porpoise.
Energy consumption and availability	- Energy consumption in relation to water temperature and whether lactating or not - Spatial distribution of food availability

4 iPCoD

The Interim Population Consequences of Disturbance (iPCoD) is a stage-based matrix model, which models the change in population sizes in 1-year time steps. As a matrix model, the iPCoD starts with an initial population abundance, divided into life stages of the harbour porpoise. In the iPCoD, this is divided into calves, juveniles and adults. Through each cycle, the probability of staying in a stage, transition into a new stage or being removed from the population is calculated. Additionally, for the adults, the probability of giving birth to a female calf is also calculated. The probabilities largely depend on survival and birth rates, which can vary between years around a mean value. Variations are typically obtained by expert elicitation and are meant to reflect the environmental variations.

As this is a top-down population model, the proportion of the population or sub-population being disturbed by noise is calculated from an estimated number of animals likely to be disturbed each day. This number is provided by the user, either as expert elicitation or calculated as the number of animals likely to be located within a specific distance to a noise disturbance. At the end of an annual time step, the population at each stage is divided into classes of undisturbed, moderately disturbed or severely disturbed. Each class will be assigned independent survival and birth rates, which in turn affect the probability of remaining at the stage, transitioning into a new stage or dropping out of a stage. At the next time step, all stages are initially set to undisturbed.

Basic assumptions of the model are:

- All individuals have identical properties
- Densities in disturbed areas reflect “true” densities compared to overall population
- Individuals have no memory of disturbances from the previous period
- Animals do not show response movement to noise disturbances
- No density dependence, meaning that larger populations do not restrict population growth

Table 4.1 Key variables needed to be specified in the iPCoD model. Most parameters are estimated from expert elicitation.

Variable group	Parameter
Life-history	- Birth rate - Calf survival - Juvenile survival - Adult survival - Age of maturity
External disturbance	- Spatial distribution of disturbances - Timing of disturbances
Density estimates	- Expected number of animals predicted to be disturbed by 1 day of activity for each development - Uncertainty in expected number of animals disturbed - Population size
Relationship between life-history and disturbance	- Link between number of days disturbed and survival or birth rate (expert elicitation) - Inter-annual variation in birth rate and survival of juveniles and adults as a result of environmental variation (expert elicitation)

5 Comparison of model output

The DEPONSE and iPCoD were compared within the themes: Population dynamics, sound propagation and estimation of disturbance. The comparison was conducted by identifying the parts of each theme where the models differed.

An overview of key differences between the two models can be seen in Table 5.1.

Table 5.1 Key variables needed to be specified in the DEPONS model. Currently the model is calibrated for the North Sea and all parameters are based on scientific literature or experimental trials.

Output	DEPONS	iPCoD
Sound propagation	Spherical spreading incorporated into the model	AQUARIOUS
Level of noise exposure	Distance to the sound source per individual	Categorical, either disturbed or not disturbed.
Consequence of disturbance on survival and birth rate	Indirectly affected through effects on foraging efficiency, which can affect energetic levels	Relationship parametrized by expert elicitation, relating the number of days disturbed to birth rates and survival
Spatial distribution of noise	Spatially explicit, meaning that individuals outside noise range will not be affected	Not spatially explicit, but user defines the proportion of the population that is affected

Population dynamics

Both models produce a population size estimate over time and reflect population changes in time. The iPCoD produces annual population estimates, while the DEPONS produces daily population estimates. Both models can also discern the effects on population structures, where iPCoD predicts changes in the life-stage (calves, juveniles, adults) structure of the populations and DEPONS estimates changes in population age structure.

Sound characteristics and propagation

The DEPONS model operates with a sound model, using broad band spherical spreading to calculate the transmission loss. This essentially means that the model assumes that the sound propagates equally in all directions, independent of bottom substrate and the acoustical properties of water. This leads to a bias in the amount of noise which the individual agents receive. Conversantly, the IPCoD uses the AQUARIUS (TNO, 2019) sound propagation model as basis for the zone of disturbance for the pile driving events. However, iPCoD is not restricted to use this model, as the zones of disturbances are calculated prior to the application of iPCoD, and other sound propagation models can be used to estimate the zones of impact.

Common for both models is the use of broad band sounds, and essentially none of the models consider the frequency distribution. This incorporates a bias in the impact zone size, as harbour porpoises hear sound much better at the high end of the frequency distribution (e.g. above 10 kHz) compared to the lower end (e.g. < 10 kHz and especially < 1 kHz) where most energy of pile driving is located). This is also a relatively new approach to use, and within the last year we have at DHI only started coding our ABM models to be able to resolve frequencies to enable the inclusion of M-Weighting and sound loss at certain frequencies.

Estimation of disturbance

Each model quantifies the noise exposure level at the receiver. However, the DEPONS model quantifies the noise exposure level, based on relative distance of each individual to the sound source and the noise level of the sound source. The iPCoD model treats the repose to noise categorically, where individuals are either disturbed or not disturbed. The proportion of the population disturbed is estimated by combining the impact ranges derived from the applied sound propagation model with expected densities in the area. The applied thresholds of disturbance vs. non-disturbance are derived from expert elicitation. Thus, it is possible to include an assessment of the noise levels experienced by individuals from a noise source in the DEPONS, whereas this level of assessment cannot be made using iPCoD.

Cumulative impact assessment

Thus, while overall the two models can achieve the same goal of estimating the cumulative impact of noise disturbances on marine mammals, the DEPONS model can provide a wider range of model output and predictions than the iPCoD model, including estimation of spatial changes in distributions in relation to noise disturbances, along with estimations of energetic variations in time and space.

Chances and limitations

The iPCoD is a top-down population model that makes use of expert elicitations to parameterize disturbance estimates. The approach is considered to be “interim”, as the expert elicitations should be replaced with empirically derived values when and if they become available. However, due to the nature of the iPCoD model, it is a very flexible approach that can be adapted relatively quickly to new populations, as long as expert elicitation is present for the population. Subsequently the model can be improved by exchanging elicitations with empirical data. The iPCoD is also relatively fast, using 5-15 minutes for 500 replicate simulations of one scenario. Thus, the model can be used to quickly evaluate a large range of disturbance scenarios. One criticism of this model is that the method of expert elicitation is far from being a perfect tool when it comes to areas where knowledge is rather poor (Mosleh *et al.*, 1988; Morgan, 2014). In the case of PCAD, it seems questionable for example to ask about an expert opinion on issues such as transfer functions from behaviour to vital rates where knowledge is non-existent. Another criticism is that the model is ‘static’, i.e. response movement is not considered. Based on the available evidence with regard to porpoises and underwater sound (Thomsen *et al.*, 2006; Dähne *et al.*, 2013), this seems unrealistic.

The DEPONS is a bottom-up population model, where detailed knowledge on the behaviour of individuals yields information on emerging population consequences of disturbances. Thus, as the DEPONS is tailored to the North Sea harbour porpoise population, large quantities of data are needed to fit the model to other populations. However, for the North Sea population, it can produce a wide range of population consequence estimates, such as the degree of disturbance of individuals, the spatial extent of the disturbance and the population distribution consequence of the disturbance. The modelling time for DEPONS is longer than the iPCoD and will take 5-8 days for 10 replicate simulations of one scenario. One major criticism is that the DEPONS does not take the detailed dynamics of the habitat into account that might be governing the baseline movements of harbour porpoises in the first place (Skov and Thomsen, 2008; Skov *et al.*, 2014)

One of the key limitations of both models are the underlying assumptions driving the models. For the DEPONS, this includes a range of parameters in the model that are calibrated to enable the model to replicate patterns observed in real life. For the iPCoD, it is the parameters estimated through the expert elicitation process. While both models have setups to minimize the risk of errors, both approaches include a degree of assumptions that need to be verified from experimental work in order to prove the assumptions. This is also one of the areas where the two models differ in the application of the premises. While the pattern-oriented modelling can lead to the inclusion of wrong parameters or values, which simply indicates that the underlying processes are not (yet) completely understood, the approach should still lead to realistic overall behaviours. Conversantly, the expert elicitation does try to make predictions based on experience of the experts rather than on empirical data. This means that a shared experience between experts which is false will introduce biases into the model. Considering our assessment in the previous paragraph, expert elucidation appears to be a rather limited approach. A sensitivity analysis should be applied to any modelling attempt to quantify potential biases.

Potential of DEPONS and / or iPCoD to support the BSH's habitat approach

The habitat approach is based on the concept of 'lost' habitat, i.e. on the proportion of an area (which must be defined) where sound levels would lead to displacement due to avoidance behaviour of for example harbour porpoises. This concept is close to the initial concept of indicators for descriptor 11 for the Marine Strategy Framework Directive (MSFD). According to Tasker et al. (2010), the impulsive sound indicator 11.1. which is relevant here, was aimed at the management of sound impacts based on gaps in distribution caused by behavioural alterations after "loud" impulsive sounds. Conversantly, the approach by DEPONS and iPCoD might be classified as 'risk-based assessments', also applied in Environmental Impact Assessment's (EIAs) which aim to identify the proportion of affected individuals from a population (see Boyd *et al.*, 2008).

The above implies that the risk-based and habitat approach are mutually exclusive. Thus, it's not possible to use either DEPONS and / or iPCoD to support the habitat approach. It's also not meaningful to modify both systems to fit the habitat approach as the risk-based and habitat approach base their assessment on different 'units' (i.e. proportion of affected individuals vs. proportion of affected habitat).

A combination of DEPONS and iPCoD might be conceptualised insofar as both the risk-based approach and the habitat approach rely on best available information of marine life. Yet, even here the approaches differ on what is precisely required: According to the risk-based approach the management crucially relies on the most precise information on animal distribution to arrive at any sensible number of 'animal taken out of a population'. This, as we have seen in our review of DEPONS and iPCoD, has limitations. The habitat approach is less dependent on exact numbers of disturbed receptors and more focused on identifying 'important' and 'less important' habitats that might come with specific thresholds for GES (as % disturbance). An example for this is the German Schallschutzkonzept (see BMU, 2013). The analysis of habitat quality, which has been applied by DHI for several years, is exactly matching the requirements of the habitat approach as favoured by the BSH.

The inclusion of habitat models in both DEPONS and iPCoD is technically possible but also cumbersome to some degree. For example, as the iPCoD is non-spatial, habitat information will have to be translated into number of animals not disturbed in contrast to a scenario with no habitat protection, and the cumulative impact of scenarios with and without habitat protection can be compared. Habitat models can be introduced into DEPONS by modifying the underlying forage maps. As the forage maps act as an attractor to the modelled species, the maps could be altered to reflect the appointed high value areas in the habitat approach, by assuming that these areas will have a higher quality than the surrounding areas. Running DEPONS in this setup could illustrate if the high value areas will fulfil the purpose of aggregating the porpoises. The results could also be verified by comparing baseline simulations with surveys from existing protected areas. Other sound sources or factors driving the distribution could also be added to the DEPONS setup. However, while the approach is currently workable for the iPCoD, changing the DEPONS is more complex, due to the software setup of DEPONS. And in summary, applying habitat models to either iPCoD or DEPONS will do nothing to strengthen the habitat approach. It will just make clearly limited risk-based models slightly more precise.

The alternative for management of underwater noise for the MSFD would be to apply the habitat approach which is informed by dynamic habitat models and agent-based models to arrive at a meaningful picture of valuable habitats for indicator species such as the harbour porpoises. DHI has already made a start with harbour porpoises in a project for BSH (Skov *et al.*, 2014). There has also been progress in the application of the models. Conventionally, estimation of habitat quality and suitability has been conducted using top-down population modelling, where the presence of a species is linked to predictor variables, and the presence of the species in non-surveyed areas and times is predicted based on these models. Different levels of complexity are included in this modelling depending on the capabilities of the modelling parties. At DHI, we are currently combining dynamic predictor variables derived from our hydrodynamic modelling along with static variables from other sources, using General Additive Mixed models to predict the fluctuation in habitat quality over year and season. The advantages of the habitat models are that they are clearly derived from empirical observations. However, the predicted habitats derived from the models only imply areas which are suitable to the selected species, but do not infer the presence of the species, as barriers for species dispersal could be preventing the species from utilizing the habitats. Progress is being made to apply agent-based models to assess the usability of the habitats to test for potential barriers and other hindrances. This is currently done using the in-house models developed at DHI. Both the information derived from the habitat models and the ABM can be used to map habitats based on degree of importance for the indicator species. Based on these maps, and in accordance with the Schallschutzkonzept (BMU 2013), specific thresholds for GES (in % disturbed areas) can be set. These thresholds can be updated using new information and subsequent dynamic habitat and agent-based modelling following the 6 years reporting cycle of the MSFD.

6 Conclusion

In principle, both the iPCoD and the DEPONS are suited to estimate cumulative effects of noise disturbances. Both the stage-based matrix model approach used in iPCoD (Lefkovitch, 1965) and the individual-based model used in DEPONS (DeAngelis and Mooij, 2005; DeAngelis and Grimm, 2014) approach have been used in ecology for some time and represent two sides of ecological modelling. The iPCoD is a fast approach where some metrics are derived from expert elicitation, which can introduce biases in the estimations, but also offer fast simulation times. This allows for the assessment of multiple scenarios. In contrast, the DEPONS model is a slower and more comprehensive model, which supplies the user with a larger range of data. It allows for the derivation of spatially explicit information on the noise impact, and the proportion of animals affected is an emergent property of the model rather than an input. Yet, there are also some points of criticism both concerning iPCoD and DEPONS. iPCoD seems to be static, and expert elicitation could be a rather limited tool when knowledge is virtually non-existent as is the case with PCAD and marine mammals. DEPONS seems to be resting on a model simplification which means that marine mammal habitats never change. Thus, it’s unclear how realistic the baseline movement patterns of the porpoises are.

Both the iPCoD and the DEPONS model are risk-based models that are conceptually different and thus incompatible from the ‘habitat approach’ which is favoured by the BSH. Habitat models can be used to make limited tools such as iPCoD and DEPONS more precise. Yet, the best way to manage ecosystem impacts of aquatic noise is to apply the habitat approach in accordance with the German Schallschutzkonzept but expanded and informed by dynamic habitat- and agent-based modelling to identify value habitats.

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