Connectivity of artificial structures in the North Sea – literature review and recommendations for future studies

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Flemming Thorbjørn Hansen, Aurelia Gabellini and Karen Edelvang

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1. Preface

This note is a status report on a study funded by a grant from the Danish Maritime Fund (Den Danske Martime Fond – DDMF) on request from the Danish Environmental Protection Agency.

The note analyzes the connectivity of artificial structures, and gives an overview of future tasks to be conducted. The report is structured and organized as a report with introductory and methodology sections thoroughly described.

Agent-based modelling simulations predicting the natural dispersal of pelagic life stages of marine non-indigenous species between hard substrate habitats in the North Sea, including man-made structures (MMS), have been conducted. They will serve to prepare for the following tasks:

- **Post processing** of agent-based model simulations to extract different types of metrics describing the connectivity between hard substrates in the North Sea.
- **Interpretation** and discussion of result.
- **Recommendations** on how the generated data can be applied in future risk assessment and studies.
2. Background

2.1 Intro
The North Sea is a shallow shelf sea with a soft sea bed comprising primarily of mud and sand including areas of man-made structures (MMS) such as rigs, pipelines, cables, renewable energy devices and shipwrecks. These structures offer hard substrate to sedentary organisms (Molen et al., 2018). In the North Sea there are approximately 1,350 oil and gas installations and over 4,000 wind turbines (Fowler et al. 2019). The number of wind turbines is estimated to triplicate by 2030 (Coolen et al. 2018).

The influence of artificial structures on the marine life in the North Sea has been studied in a number of projects in the past years. These studies were based on surveys (Coolen et al., 2016; Grecian et al., 2018; Schutter et al., 2019), computational modelling (Adams et al. 2014; Lynam et al. 2017; Thorpe 2012), and combined computational modelling with population genetic analysis (Dannheim et al. 2018; Coolen et al. 2020) or with remote operated underwater vehicles (ROV) images (e.g. Henry et al. 2018). Many studies focused on the impact of decommission of oil and gas platforms (e.g. Hyder et al. 2017; Tidbury et al. 2020), others tried to understand if man-made structures would enhance dispersal of marine sedentary species (stepping stone effect) (e.g. Dannheim et al. 2018; Coolen et al. 2020).

2.2 Man-made structures as marine habitats
Although MMS in the North Sea are numerous, they are patchily distributed and thus the hard surfaces of MMS have a relatively low areal coverage compared to other habitats. MMS may support different types of organisms and communities attached to or associated with hard substrate habitats, but because of their patchy locations, the likelihood that a species will be present on an individual site depends on multiple factors determined by the ability or chance of species to spread between sites.

These factors include e.g. the distance to other MMSs and to natural hard substrate habitats, the sea currents supporting the drift and migration of pelagic live stages, and the characteristics of the pelagic life stages themselves (~pelagic larvae duration, survival, numbers etc.). Other potential vectors of dispersal include shipping activities (where organisms can spread via ballast water or attached as fouling agents to the ship hulls), rafting (where organisms may attach to floating debris, seaweed and macroalgae), or via host organisms (such as fish, marine mammals or seabirds).

2.3 Literature review
2.3.1 Man-made structures in the North Sea
A number of studies have investigated the presence of species on MMS in the North Sea. Based on diving expeditions and maintenance of buoys, Coolen et al. (2016) compared the distribution of the invasive Caprella mutica and the native Caprella linearis in the southern North Sea on buoys, wrecks, and oil and gas platforms. Coolen et al. (2016) found that the invasive C. mutica occurred more frequently nearshore while the native C. linearis occurred offshore. Another study based on ROV videos in eight Dutch and nine Danish oil and gas platforms was carried out by Schutter et al. (2019), who investigated the effects of location and depth for oil and
gas platforms as artificial substrates. They found a significant clustering based on location: a southern cluster close to the Dutch shoreline, and a northern cluster near Denmark. They also found that communities close to the seafloor (maximum depth of 5 m) were characterized by higher species diversity (Schutter et al., 2019). They identified one invasive species *Mnemiopsis leidyi* (phylum Ctenophora) (Schutter et al., 2019).

Other studies analyzed the relationship between MMS and predators. A food web model of the North Sea ecosystem showed that the removal oil and gas platforms and pipelines may contribute to a decline in some groups of fish (rays and sand eels), and an increase in others (sharks, flatfish and roundfish) (Lynam et al., 2017). However, other structures such as wrecks and wind turbines may have a much larger impact than oil and gas structures on rays, sharks, sand eels, flatfish and roundfish (Lynam et al., 2017). Based on tagged data, Grecian et al. (2018) investigated the effect of oil and gas platforms on apex predators, and examined three species - grey seal, northern fulmar and harbour porpoise. They concluded that MMS have little or no effect in comparison to the spatial and temporal variability in the environmental conditions, with the exception of harbor porpoise, which showed a positive relation within 1 km of a pipeline or platform.

These above examples indicate that the occurrence and distribution of marine species on MMS are not randomly distributed, but must be subject to various forms of zonation. For sessile organisms including non-indigenous species (NIS) associated with hard substrate habitats, natural dispersal of pelagic life stages are considered a key mechanism determining these patterns of zonation.

### 2.3.2 Natural dispersal and connectivity

In the recent decade, a number of studies have addressed the connectivity between MMS in the North Sea using computational modelling of the dispersal of pelagic life stages of species associated with hard substrates. These studies use a combination of hydrodynamic modelling predicting ocean currents and agent-based modelling mimicking the drift and behaviour of pelagic life stages. The use of agent-based modelling is often referred to as individual-based models, biophysical models, particle tracking or Lagrangian models. Some of these studies have also presented results from population genetic analyses. The use of genetic metrics in population genetic theory aims at identifying genetic (~allelic) differences (or similarities) of populations and/or subpopulations of individual species and has been used in studies estimating dispersal distances and migration rates among marine organisms, as well as connectivity between marine populations (e.g. see: Hedgecock et al. 2007, Gagnaire et al. 2015). Using population genetic studies may provide the empirical evidence or indices for whether simulated patterns of larval dispersal and marine connectivity may or may not be reflected directly in population genetic structures.

The first article about biological connectivity of oil and gas platforms in the North Sea was published in 2012. Thorpe (2012) studied how tides affect the biological connectivity between platforms in the North Sea based on the M2 tidal flow estimation of Kwong et al (1997) and Davies and Kwong (2000). In this study, Thorpe (2012) considered the average tide and mean flow to observe if platforms are connected. He found that the southern North Sea platforms are tidally connected, mostly in groups of two to six platforms, while in the northern parts of the North Sea only two to three platforms are connected. Thorpe (2012) also found that the northern platforms are disconnected from those in the south.
2.3.3 The stepping-stone effect

Adams et al. (2014) studied marine renewable energy devices as stepping stones in the region around south-western Scotland using agent based modelling. They considered the baseline habitat for two generic species: one that is not limited by habitat type (and can live anywhere on the coastline), and one that inhabits specific hard substrate habitats (including ports and marinas). They defined novel habitats applied to a total of 312 wind turbine areas with foundations and scouring protections. They subsequently ran simulations with pelagic larvae duration of 1, 2, 4, 8, 16 and 28 days (with and without the novel habitats of the wind turbines). The aim was to investigate the proportion of particles successfully dispersing from each category of habitat (baseline or novel) to other habitats in order to provide an overview of the interaction between baseline and novel sites. Simulated agents were regarded as settled, when they were within 500 m of a habitat site. On the basis of these investigations, Adams et al (2014) concluded these structures creates new dispersal pathways allowing previously impossible northward dispersal.

Dannheim et al. (2018) investigated how wind farms in the southern parts of the North Sea may support stepping stone dispersal of marine species using an individual-based model, LAR-VAE&CO. The study included three species: the European flat oyster Ostrea edulis, the common limpet Patella vulgata, and the blue mussel Mytilus edulis, with pelagic larvae duration of 16 days, 20 days and 2 months respectively. They ran simulations to assess the retention and seeding potential between populations of different coastal origins, the potential of wind farms being colonized by coastal natural populations, and the potential connectivity between individual windfarms. The results showed that all wind farms would receive blue mussel larvae from the coastal habitats, while only the wind farms closest to the coast would receive oyster larvae, and eight wind farms out of nine would receive larvae from limpets.

The dispersal of larvae between windfarms identified both isolated and interconnected sites, depending on the pelagic larvae duration and showed a strong variability between years (Dannheim et al., 2018). The analysis also showed that species are potentially able to utilize windfarms for stepping stone dispersal, thus supporting larval settlement on windfarms that would otherwise not have been reached by dispersal directly from coastal habitats. Another important result from this study was that, it was “…not possible to validate the dispersal model outcomes with population genetic data from M. edulis to an acceptable level of confidence”, and “…Similarly, no patterns were detected from the population genetic analysis of P. vulgata”. This lack of coincidence between outcomes of the population genetic analyses and the larval dispersal modelling results was attributed to methodological issues related to the gene sequences analysed. The gene sequences “…proved unsuitable evaluation of connectivity patterns at the current scale”.

In a recent publication, Tidbury et al. (2020) assessed the impact of oil and gas decommission on the network of hard substrate in the entire North Sea. They modelled pelagic larvae dispersal of seven species commonly found settled on artificial hard substrates within North-Eastern Europe, including a non-indigenous species and a vulnerable species (C. fornicata and L. pertusa). The pelagic larval durations of the seven species varies between 21 and 200 days. Agent-based model simulations were conducted for 2001 to 2010 with a spatial resolution of approximately 5.5 km and vertically with 25 non-equidistant layers. Each grid cell of 15 x 15 km contained hard substrate, and MMS acted as spawning and settling sites (Tidbury et al., 2020).
They concluded that “a decommissioning scenario with full removal of oil and gas platforms results in a nearly 60% reduction in connectivity...” which could have “…negative implications for species’ distribution, gene flow and resilience following disturbance or exploitation of marine hard substrate communities”. Tidbury et al. (2020) also indicated that further modelling is required including other mechanisms such as the effect of supply ships.

Lastly, Coolen et al. (2020) used particle tracking modelling and population genetics analysis to investigate the stepping stone effect of MMS (platforms, windfarms, buoys and shipwrecks) for Blue Mussels, *Mytilus edulis*. In the model, particles were released on 1 March 2004 and 2005 in the top layer including a pelagic larval duration of 16 to 70 days for a total of 1,000,000 particles. The model indicated that locations with more than 85 km from the shore would be isolated from coastal communities; however, *Mytilus spp.* were found at all inspected locations, up to 181 km from the nearest coastline. Coolen et al. (2020) hypothesized that *M. edulis* on such distant platforms is explained by the presence of jack up rigs that are used near offshore installations. The genetic analyses did not find any clear structure among the populations, and isolation by distance did not show any increase in isolation with increasing distance.

2.3.4 Assessment

Some of the studies described above have focused on only one type of structure, a minor part of the North Sea, or only one species. The most complete study so far was done by Hyder et al. (2017) and published in Tidbury et al. (2020), and included shipwrecks, oil and gas platforms, buoys, wind farms, and natural hard substrates for the whole North Sea considering seven species.

An important lesson from the two studies including population genetic analysis (Dannheim et al. 2018, Coolen et al. 2020) is that patterns of marine connectivity for specific species are not necessarily detectable in population genetics. Whether this is mainly due to methodological constraints or to limitation in the larval dispersal modelling is currently not fully understood. It may be explained by missing important parameters such as mortality, vertical migration in the water column, or resolution issues of the hydrodynamic models or something else.

There is still a lack of knowledge related to the effect of all man-made structures in the whole North Sea, especially when considering the dispersal of the non-indigenous Species (NIS). The majority of the sessile NIS associated with hard substrates listed in the HELCOM/OSPAR target species list (jointbwmxemptions.org) have short pelagic larval durations of a few days to a few weeks. How man-made structures in the entire North Sea may support stepping stone dispersal of these species with short pelagic larval duration (PLD) have not yet been fully studied, and is therefore addressed in the current study. Furthermore, data on the actual distribution (absence or presence) of NIS on MMS in the North Sea as a whole is not available. Thus, while the modelling effort in this and previous studies may provide insight into potential dispersal patterns and barriers for NIS associated with hard substrates in the North Sea, the realized dispersal and succession of NIS *in situ* remains unknown and will need to be addressed in future studies.

Natural dispersal of pelagic larvae is driven by ocean currents, and supported by various biological traits of individual species. These include pelagic larval duration, larval survival, environmental tolerances, and the ability of larvae to actively detect and settle on suitable substrate; but they may also include shipping activities. The role of shipping activities for spreading NIS
between MMS in the North Sea remains unknown. A hypothesis may be that the chance of NIS being “transferred” from ships passing by will depend on the intensity of the shipping activity near the individual MSS. To test this hypothesis, a data basis has to be established aggregating all relevant data on shipping activities in the vicinity of MMS in the North Sea. Existing and future recordings of NIS found on or near MSS may ideally be statistically tested using the proximity of shipping activity as one of the explanatory variables. The mapping of shipping activity near MMS in the North Sea is also addressed in the current study.
3. Study scope

The scope of this study is to develop a data base to be used as a baseline for future risk assessments of decommissioning plans of man-made structures in the North Sea. This data base will present metrics for how individual, or groups, of MMS may serve as stepping stone for NIS based on analysis of the potential natural dispersal of pelagic live stages. The data base will also present metrics on the type and intensity of shipping activities in the vicinity of individual, or groups, of MMS.

The project will develop advice on how this type of information can be applied in future risk assessments of decommissioning plans and scenarios specifically addressing the risk of MMS facilitating stepping stone dispersal of NIS in the North Sea. The project will consist of 3 parts:

- **Part 1**: A systematic analysis of the potential larval dispersal and connectivity between MMS in the North Sea, specifically focusing on NIS associated with hard substrates and with short to intermediate pelagic larval durations (days to weeks).

- **Part 2**: An analysis of the proximity of MMS in the North Sea to various types of shipping activities.

- **Part 3**: Development of advice on how to apply this type of data in future risk assessment of decommissioning plans and scenarios.

While this study was specifically initiated to address the potential spread and introduction of MMS by NIS, the findings can be used as baseline for native species associated with hard substrates as well.

The term “decommissioning” is used in the report as a term referring to both total removal of an off-shore structure once the structure is no more in use, as well as partly removal and/or breakdown and deposition of the structure components at, or in the vicinity of, the site where the structure was originally installed. In any case the remaining structures or parts of structures, serve as hard substrate for biota.
4. Methodology

4.1 Study area
In the current study we have analysed the connectivity of hard substrates (MMS and natural hard substrate habitats) in the North Sea and Kattegat using a regular grid with a spatial resolution of 10 x 10 km (Figure 1). The spatial extent of the model area was set to an area covering the central parts of the North Sea. This area is somewhat smaller than the full extent of the Greater North Sea (e.g. according to OSPAR). Model boundaries were determined by the hydrodynamic model used for the larval dispersal modelling (see later). Hence, the model area does not cover the entire North Sea, because parts of the northern region are excluded. Skagerrak and Kattegat are included because of the importance of the Skagerrak gyre for conveying larvae from the southern and eastern parts of the North Sea towards natural hard substrates along the coastal regions of southern Norway.

Figure 1. Map of the study area (black outline) and the 10 km x 10 km grid (grey outline) used for analysing the connectivity between hard substrates of MMS and natural habitats in the North Sea. Blue colours show bathymetry (IOC, IHO, BODC 2003). Quadratic boxes is the division of the spatial extent into a 10x10 km grid used for data aggregation and analyses (see later).

4.2 Information on hard substrates
We extracted information on natural hard substrates, pipelines, oil and gas platforms and wind turbines from EMODnet (EMODnet 2020). Data on ship wrecks was available from the CEFAS website (Posen et al. 2018).
Table 1. Data sources for hard substrate categories.

<table>
<thead>
<tr>
<th>Category</th>
<th>Source</th>
<th>Updated date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural hard substrate</td>
<td>EMODnet</td>
<td>03-05-2019</td>
</tr>
<tr>
<td>Pipelines</td>
<td>EMODnet</td>
<td>20-12-2019</td>
</tr>
<tr>
<td>Oil and gas platforms</td>
<td>EMODnet</td>
<td>20-06-2016</td>
</tr>
<tr>
<td>Wind turbines</td>
<td>EMODnet</td>
<td>05-03-2020</td>
</tr>
<tr>
<td>Ship wrecks</td>
<td>CEFAS</td>
<td>07-08-2020</td>
</tr>
</tbody>
</table>

4.2.1 Natural hard substrates
The distribution of hard substrate was derived from data available under the European Marine Observation Data Network (EMODnet) Seabed Habitats project (http://www.emodnet-seabedhabitats.eu/), funded by the European Commission’s Directorate-General for Maritime Affairs and Fisheries (DG MARE). We considered only the seabed substrate category “Rock or other hard substrates”. We did not include the seabed substrate categories “mixed” sediment” and “coarse sediments”. Some of the habitats assigned to these two categories, especially where substrate originates from glacial deposits such as in the Danish parts of the North Sea may contain hard substrate surfaces such as scattered boulders and cobbles (e.g. see Edelvang et al. 2017). However, the coverage and extent of these hard substrates is unknown. The resulting areal coverage of natural hard substrates within study area was 3,228 km².

4.2.2 Oil and Gas platforms
A total of 1,904 platforms were included in the EMODNET data set, of which 957 platforms are located within the boundaries of our study area. The current status of the 957 platforms is given below in Table 1.

Table 2. Status on platforms in the model area.

<table>
<thead>
<tr>
<th>Status</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>In operation</td>
<td>805</td>
</tr>
<tr>
<td>Closed down</td>
<td>45</td>
</tr>
<tr>
<td>Decommissioned</td>
<td>63</td>
</tr>
<tr>
<td>Removed</td>
<td>1</td>
</tr>
<tr>
<td>Under construction</td>
<td>2</td>
</tr>
<tr>
<td>Derogation</td>
<td>1</td>
</tr>
<tr>
<td>Unknown</td>
<td>40</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>957</strong></td>
</tr>
</tbody>
</table>

Only platforms “in operation”, “closed down”, “Under construction” and “unknown” were included in this study, i.e. in total 892.
Different methods have been proposed by different studies to estimate the hard substrate surface areas of O&G off-shore platforms. Tidbury et al. (2020) calculated areas from buffers zones around each assigned structure relative to their respective tonnage:

- <10,000t: 100 m
- 10,000–100,000t 200 m
- >100,000t: 500 m

These buffer zones were based on “industry standards for typical safety exclusion zones around various types of offshore structures” (Tidbury et al. 2020), and thus, not on any estimation of the actual area of the hard substrate. A total surface area hard substrate based on this method for our study area is approximately 48 km².

Another methodology proposed by IMSA (2011a) was based on a “the external underwater surface area of a steel jacket like Brent Alpha or Brent Delta”. Here, four categories of platforms were classified based on the weight of the jacket of the platform (see Table 3 below).

Table 3. Platform categories based on jackets weight (according to OSPAR; IMSA 2011b). Table and caption from Imsa 2011a.

<table>
<thead>
<tr>
<th>Platform category</th>
<th>Weight (jacket)</th>
<th>Surface area jacket (in m² with platforms heights between brackets)</th>
<th>Number of platforms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete</td>
<td></td>
<td>43,000 – comparable to ultra large steel</td>
<td>21</td>
</tr>
<tr>
<td>Ultra large steel</td>
<td>&gt; 10,000 tons</td>
<td>43,000 (140 m)</td>
<td>41</td>
</tr>
<tr>
<td>Large steel</td>
<td>2000 – 10,000 tons</td>
<td>10,000 (70 m)</td>
<td>106</td>
</tr>
<tr>
<td>Small steel</td>
<td>0 – 2000 tons</td>
<td>2,500 (35 m)</td>
<td>343</td>
</tr>
</tbody>
</table>

Note: The surface areas of the jackets are approximations based on figures of ultra-large structures in the North Sea. These numbers give only rough indications and need to be revised if used for more detailed studies (in consultation with G. Picken).

This method does not include areal coverage of drill cutting piles below the platform (which may be highly contaminated), or any additional scouring protection if present. A total surface area of hard substrate based on this method for our study area is approximately 4.6 km². Thus, an order of magnitude less than the method proposed by Tidbury et al. 2018. For this study we apply the method proposed by ISMA 2011.

In order to translate platform weight into surface area according to Table 3, we use the weight of the sub-surface part of the platform as included in the EMODNET data set field “weight_sub”. For a number of platforms, no data exist on platform weight, and these platforms were assigned to the category of platforms less than 2,000 tons, corresponding to 194 platforms in total. The resulting areal coverage within the study area was 4.6 km².

4.2.3 Wind turbines
Data was based on EMODNET (2020) polygon layer and a point layer including the location of Danish wind farms (www.energistyrelsen.dk), both data sources with information on the number of turbines.
Tidbury et al. (2020) calculated the surface area off hard substrates around individual wind turbine by assuming a buffer zone of 50 m around each wind turbine, representing the safety zone for fishing vessels advised on KIS-ORCA. Another study by Glarou et al. (2020) refers to a typical radius of scour protection for individual wind turbines of up to 20 meters in the North Sea. The scour protection of future wind turbines expected in the Dutch part of the North Sea in outlooks for 2050 was assumed to be 2,000 m², which is equivalent to a 25 m radius around each turbine (Coolen et al. 2019). The differences in areal coverage based on the different assumptions are a factor of 6.25. In this study we used the 20 m scour protection radius around each turbine, resulting in a coverage of 5.0 km² in our study area.

4.2.4 Wrecks

Data on wrecks in the North Sea has been compiled by Tidbury et al. (2020) from data purchased from www.wrecksite.eu including 33,255 wreck registrations in the Greater North Sea (made available at CEFAS website (Posen et al. 2018) as hard substrate coverage in a 15x15 km grid). Tidbury et al. (2020) estimated hard substrate surface area coverage of ship wrecks in a similar way as they did for oil and gas installations, by applying the same buffers based on tonnage extended to include smaller vessel tonnages. The area of hard substrate was calculated assuming buffer zones around wreck positions according to tonnage of individual wrecks:

- <100t: 25m
- 100 -1 000: 50m
- 1,000 -10,000: 100m
- 10,000 -100,000: 200m
- > 100 000t: 500m

Tonnage in this case was based on adjustment of the original tonnage of the ship taking into account construction material specific decomposition rates and burial rates (for details see Tidbury et al. 2020). Based on these data, a surface area of app. 16 km² is estimated for wrecks within the Greater North Sea.

We compared these estimates on area coverage with another study by Zintzen (2007), who examined the biodiversity of ship wrecks in the Belgian parts of the North Sea. The mean estimated dimensions for shipwrecks in this study were 80.9 m in length and 11.4 m in width. "...The projected area of this mean wreck was 919.5 m² and its real surface was estimated to be between 3,677.8 m² and 6,436.2 m² ...". To compare these real surface areas with those of Tidbury, we assumed an 80.9 m ship to correspond to app. 6,000 tons based on a crude estimate calculated from length vs. tonnage observations of observed ships in operation in the Baltic Sea (Karasalo et al. 2017). For an 80 m wreck based on these assumptions, we found a discrepancy between Zintzen (2007) and Tidbury et al. (2018) of roughly a factor 6, corresponding to at surface area of wrecks in the greater North Sea of ca. 2.6 km².

Yet another study by IMSA (2011a) also looked at the hard substrates in the Greater North Sea. Their estimate on the surface area of wrecks was based on a survey by Krone and Shröder (2010) assuming an average of 1,200 m² for 64 wrecks examined in the German Bight. The total number of wrecks in the North Sea was estimated to between 25,000 and 45,000 based on national recordings of wrecks within the EEZs. The total surface area of wrecks was estimated to between 30 and 54 km².
Although there is a lot of uncertainty and variability related to these numbers, Tidbury et al. (2020) seems to be the most comprehensive study, and their estimates are to some extent in the same order magnitude as IMSA (2011) with a deviation of approximately a factor of 2. Thus, in this study we apply the data set available by CEFAS (Tidbury et al 2020, Posen et al. 2018) resulting in an area coverage of 13.3 km² in our study area.

4.2.5 Pipelines
The EMODNET data set includes the trajectories of pipelines in the North Sea with data e.g. on the current status of each pipeline (e.g. if it is active, not in use, decommissioned etc.), the pipe diameter and year of installation. For the current study we included pipelines with the status “Active”, “Not in use” or “Abandoned”. They include a total of 34,304 km of pipeline within the study area. Of the 34,304 km, 31,701 km of pipelines are assigned a pipe diameter (Table 4).

Table 4. Total length of Pipelines in the study area divided into categories of pipe diameters.

<table>
<thead>
<tr>
<th>Pipe diameter (cm)</th>
<th>Total length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 – 20</td>
<td>6,075</td>
</tr>
<tr>
<td>20 – 40</td>
<td>5,745</td>
</tr>
<tr>
<td>40 – 60</td>
<td>3,297</td>
</tr>
<tr>
<td>60 – 80</td>
<td>4,072</td>
</tr>
<tr>
<td>80 – 100</td>
<td>4,956</td>
</tr>
<tr>
<td>&gt;100</td>
<td>7,556</td>
</tr>
</tbody>
</table>

The mean diameter is ca. 60 cm, corresponding to a total hard surface area including only the surface perimeter of the pipeline of 59 km² (64 km²). Including all pipelines assuming 60 cm diameter for pipelines without data on diameter).

While some of the pipelines are placed directly on top of the seabed, others may be partly or totally buried in trenches (oil and gas UK, 2013; Lacey and Hayes, 2020). Others again may be covered with protection of various sorts including gravel depositions, or concrete mats (Lacey and Hayes 2020). Due to sediment transport and erosion processes, some buried or partly buried pipelines may be partly exposed over time (Fredsøe 2016). Both partly or fully exposed pipelines as well as various types of protections potentially serve as hard substrate for marine life.

We did not find information on the proportion of pipelines being buried in the North Sea, nor did we find any inventory of the coverage of different types of protection substrates.

- However, some indicative information exist for different countries regarding the trenching and burial of pipelines:

  - For Denmark for instance, according to the Danish Energy Authorities the majority of Danish pipelines have been buried ½ to 1 meter down in the seabed (DEA 2006).

  - For the Netherlands according to Noordzeeloket (www.noordzeeloket.nl) “cables (6000 km) and pipelines (ca. 4500 km) must be installed in such a way that they do not endanger or impede shipping and fishing. This means that they must be buried at sufficient depth to ensure safe fishing and navigation.”
In Belgium according to the Royal Belgian Institute of Natural Sciences pipelines in the Belgic parts of the North Sea constitutes 163 km of pipelines. Pipelines offshore are laid on the seabed, while “..closer to shore they are buried in the seabed, at a depth of 70 cm to 2 m, and are covered with a protective layer of gravel.” (https://odnature.naturalsciences.be/mumm/en/cables-pipelines/)

In UK, an old US EPA report from 1980 states that “all but one of the major pipelines in the north sea has been trenched and buried (Nothdurft 1980).”

For most parts of the North Sea, sand or muddy sediments are the dominating seabed substrates facilitating the burial of pipelines. By overlying the EMODNET polyline data set with the EMODNET seabed substrate polygon data set, we retrieved proportion of pipelines located within different substrate categories:

- 87% of all pipelines are located on sandy or muddy substrates;
- 13% are located on “coarse substrate” or “mixed sediment”;
- Only 6 km (<< 1%) of pipeline are located on “Rocks or other type of hard substrates”.

Hypothetically, older pipeline installations may have been installed at a time before national legislation required burial of pipelines. Data on year of installation is available for 1,477 (42%) of the pipeline trajectories in the EMODNET database, and 8% of these were installed prior to 1990.

Given the information we have collected, we conclude:

- We did not find any inventory on buried or exposed pipelines.
- However, “most” pipelines I the North Sea seems to be buried or partly buried.
- Sediment conditions in general support burial or trenching throughout the study area maybe with some exceptions on parts of the seabed consisting of mixed sediment or coarse substrates
- Total pipeline surface area estimated to approximately 64 km²
- Pipeline protection using e.g. concrete mats or gravel deposit are commonly used, however no information was found on where and to what extent these have been deployed in the North Sea.
- Only a minor proportion of 8% of the pipelines where installation year is known, are installed prior to 1990.

Due to the lack of data in the current study we will include all pipelines as hard substrate and assuming a mean diameter of 60 cm of pipelines where data are missing. Surface areas are calculated as the perimeter times the length of each pipe, and all areas of pipelines a summarized within each 10x10 km grid. We assume that 20% of all pipelines in all grids are fully exposed, i.e. the remaining 80% are fully buried. This corresponds to total area of hard substrate 12.9 km².
4.2.6 Area calculations
All calculated areas were assigned to the corresponding grid cells in the 10x10 km grid. Areas calculated based on data where each structure or group of structures is represented by a single x-y position. The entire area calculated for each position was assigned the grid cell the position is located within.

For areas calculated based on data where each structure or group of structures is represented by a line segment or a polygon, the calculated area was divided among overlapping grid cells proportional to the fraction of the length of the line segment or the fraction of the area of the polygon that falls within each of the overlapping grid cells.

For data on ship wrecks we used data on areal coverage already compiled by CEFAS into a 15x15 km grid for the North Seas. We resampled these areas into our 10x10 km grid using the method for assigning polygon associated areas to 10x10 km grid cells as described above. We excluded the 10x10 km grid cells where the centroid of grid cell lied outside the boundary of the HBM model used for the larval dispersal simulation, i.e. close to land boundaries, bays and inlets.

In the parts of the North Sea, Skagerrak and Kattegat included within this study, approximately 99% of hard substrates originates from natural hard substrates including “rocks and other hard substrates”. The MMS with the largest estimated areal coverage is “Ship wrecks” (0.41 %), “Pipelines” (0.39 %), “Wind turbines” (0.15 %), “Oil and Gas platforms” (0.14 %) (see Table 5).

<table>
<thead>
<tr>
<th></th>
<th>Area [km²]</th>
<th>Area [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total hard substrate coverage</td>
<td>3,263</td>
<td>100</td>
</tr>
<tr>
<td>Natural hard substrate</td>
<td>3,228</td>
<td>98.9</td>
</tr>
<tr>
<td>Pipelines</td>
<td>12.8</td>
<td>0.39</td>
</tr>
<tr>
<td>Oil and gas platforms</td>
<td>4.6</td>
<td>0.14</td>
</tr>
<tr>
<td>Wind turbines</td>
<td>5.0</td>
<td>0.15</td>
</tr>
<tr>
<td>Ship wrecks</td>
<td>13.3</td>
<td>0.41</td>
</tr>
</tbody>
</table>

4.3 Shipping activities
Vessel density data were extracted from EMODnet (EMODnet Human Activities: Vessel Density Map. Publication date 2019-03-11, Revision date 2019-12-16), where the following ship types are available and considered:

- All - All types
- 00 - Other
- 01 - Fishing
- 02 - Service
- 03 - Dredging or underwater ops
- 04 - Sailing
- 05 - Pleasure Craft
- 06 - High speed craft
- 07 - Tug and towing
Data is based on AIS (Automatic Identification System) data. We used the average vessel density for 2018. The data is available as raster data (1x1 km) on vessel intensity measured as hours/km²/month. We aggregated all data into our 10x10 km grids in grid cells with a coverage of hard substrate.

4.4 Larval dispersal modelling

4.4.1 Hydrodynamic data

Data on ocean current speed and direction, water temperature and salinity was extracted from a hydrographic dataset generated by the hydrodynamic model, HBM, for the North Sea, Skagerrak and Kattegat (Berg and Poulsen 2012, figure 2). The spatial resolution of the model is 5 nm in the North Sea and Skagerrak and 0.5 nm in the transitional areas between the North Sea and the Baltic Sea including the Kattegat. The vertical resolution is 50 and 52 layers respectively. We used data for 10 years from 2001 to 2010.

Figure 2. Model area of the HBM model divided into sub-domains with different model resolutions, see text (Berg and Poulsen 2013)
4.4.2 Agent Based Model

The simulation of larval dispersal was carried out using the agent-based modelling library (IBMlib) which is a freeware developed by DTU Aqua (Christensen, 2008; Christensen et al., in review). The IBMlib supports a number of larval behaviours and parameters important for predicting larval dispersal. The larval behaviour parameters and inputs used in the larval dispersal modelling for this study include:

- Pelagic larval duration
- Dispersal depth interval
- Spawning start and end
- Spawning and settling habitat
- Vertical dispersion
- Horizontal dispersion

During the larval dispersal simulation, IBMlib keeps track of start and end positions of each simulated larvae. The pelagic larval duration (PLD) represents the duration of the life stage (typically a larval stage) where the species drift freely in the water column and hence are subject to passive transport by ocean currents. At the end of the PLD, the larvae will then settle on the seabed. In this study we chose to focus on the PLD as the primary trait, and not consider specific species. We use a range of short and intermediate PLD values: 1, 3, 5, 10, 15, 20, 30, 50 and 100 days.

The beginning and end of spawning were set to 1 April to 30 September respectively. Dispersal depth during the PLD was set to between 0 – 40 meters to comply with general patterns in vertical distribution of pelagic larvae observed by Corell et al. (2012) in the Baltic Sea. To ensure a random distribution across this depth interval, we applied a constant vertical dispersion of 0.001 m²/s. Horizontal dispersion is included primarily to reflect the unresolved hydrodynamics of the hydrographic data at scales smaller than the spatial resolution of the model. The horizontal dispersion was set to 10 m²/s.

4.4.3 Simulation setup

200,000 agents were released each year and for each PLD randomly in all grid cells containing hard substrate. Agents were regarded as successfully settled if they settled in a cell with hard substrate. Agents were released from 1 April to 1 September.

The agents were not released proportional to the areal coverage of hard substrate of each 10x10 km grid. This is because areal coverage varies several orders of magnitude with some grids having a high (e.g. 50-100 %) coverage of natural hard substrates and other grids with very low (e.g. 0.001 - 1 %) coverage of hard substrate of various types of MMS. A proportional release of agents with coverage percentages, at the same time ensuring a sufficient statistical basis for analysing connectivity in a robust way, would require a very large number of agents in each simulation, which is not possible. Instead, we account for the coverage percentages as part of the connectivity analysis (i.e. the proceeding section).
4.5 Connectivity analysis

4.5.1 Connectivity matrices

The connectivity analyses were based on the same grid used for aggregating data on hard substrates and vessel intensities, i.e. the sub-division of the study area (Figure 1) into a regular grid of 100x85 cells corresponding to a spatial resolution of 10x10km. This grid is in this context referred to as the connectivity grid. Connectivity adjacency matrices were constructed from the larval dispersal modelling results comprising start and end positions of each agent, and counting the number of all pairwise connections between all grid cells in the connectivity grid. Only agents with at start and end position within grid cell including coverage of hard substrates were included.

The connectivity adjacency matrices with absolute numbers of connections for each year and for each PLD were lumped into one matrix for each PLD representing all years. Next, each entry in the connectivity matrix representing all years were adjusted to account for the areal coverage. This was done by multiplying the matrix entries representing the total number of connections between each pairwise locations with both the fraction of the area of the start position covered with hard substrate, and the fraction of the end position covered with hard substrates. Subsequently each of the adjusted matrices were translated into a connectivity probability matrix for each of the nine PLD.

While connectivity matrices representing the transition probability between sites can be referred to as the “potential” connectivity, the connectivity matrices representing the absolute numbers of agents connecting each pair of sites (here adjusted for areal coverage of hard substrate) can be referred to as the “realised” connectivity, similar to the definitions proposed by Watson et al. (2020). In our case realized connectivity is in fact the realized connectivity of an ideal distribution of a species where spawning are assumed proportional to the areal coverage of each hard substrate site, rather than the actual presence or density of a species as proposed by Watson et al. (2020).

4.5.2 Hydrographic regions

The term “Hydrographic region” was introduced by Rossi et al (2014) studying the connectivity patterns and dispersal barriers of pelagic life stages in the Mediterranean Sea. The term refers to marine regions where the connectivity within each region are high and where the connectivity to other regions are low. The outline of the regions depend on the hydrographic conditions during the pelagic life stage and the biological traits of the organisms, especially the pelagic larval duration. Other biological traits that may affect the outline of a hydrographic region include mortality, environmental tolerance thresholds (e.g. to temperature, salinity and oxygen), vertical positioning and migration in the water column etc. (Hansen and Christensen 2018).

In this study, hydrographic regions were delineated using cluster analysis using the clustering algorithm “Infomap” (Rosvall and Bergstrom, 2008) available in the R package “igraph” (Csárdi and Nepusz 2006). The Infomap algorithm is based on information theory principles and has been used previously in marine connectivity studies. These include e.g. the Mediterranean studying the oceanic connectivity between marine reserves (Rossi et al., 2014); in the North Sea studying the network of MPAs (Huserbråten et al. 2018); and in the Kattegat and eastern Baltic Sea analysing the risk of dispersal of marine non-indigenous species (Hansen and Christensen, 2018).
An example of a graphic representation of the delineation of hydrographic regions is shown in Figure 3.

Figure 3. Example of a graph plot representing the outline of hydrographic regions (i.e. clusters of 10x10 km grid cells) identified for a simulation of a PLD of 100 days for the period 2001-2010.

In Figure 3, the initial number of agents in the simulation is 2,000,000. The number of agents successfully settled within hard substrate habitats and included in the connectivity analysis is 798,661 (indicated in the lower left corner by “n”). The WITHIN region connectivity for each region is represented by node values (within circles), representing the percentage of agents with an initial position in each region that end up in the same region. The BETWEEN regions connectivity are indicated by arrows representing the direction of the connectivity and arrow thicknesses representing the relative magnitude of the connectivity (max thickness set to 17% after which it remains unchanged). Bars next to nodes represent the number of agents supporting the delineation of each individual region relative to the region with the largest number of agents. White areas represent areas outside the larval dispersal extend due to lack of suitable habitat and/or due to unfavourable salinity conditions exceeding the larval salinity tolerance limit during drift. Land areas are displayed in grey. Notice: The results are not adjusted for coverage percentages of hard substrates.

The hydrographic regions in the current study of MMS in the NS are used to identify clusters of MMS and natural hard substrate habitats, where pelagic larval stages of NIS are predicted to disperse between hard substrates within the region, and to locate dispersal barriers preventing dispersal to other regions. The hypothesis is that a NIS with a certain PLD, which is introduced or observed on a hard substrate site (MMS or natural hard substrate) in one region is more likely to spread to other sites within the same region than to any of neighbouring regions. The exchange of pelagic larval stages between regions is expected vary considerably and some regions may be strongly separated with no or very little exchange of simulated larvae. Boundaries between such regions are expected to act as dispersal barriers. The strength of the potential dispersal barriers, depend on the magnitude of the self-recruitment of the hydrographic regions and exchange of simulated larvae between them.
4.5.3 Connectivity metrics

From the connectivity matrices a number of metrics can be obtained which can be used to quantify the various aspects of connectivity both for individual 10x10 km grid cells with hard substrate coverage, and for the hydrographic regions identified using clustering techniques. Most of these metrics are derived from graph theory, which means that the connectivity matrices have to be translated into a graph. A graph consists of nodes and edges, where nodes in our case represent individual matrix entries and edges represent the connections between the nodes in terms of connectivity in absolute numbers or probabilities, in graph theory referred to as “weights”. By using graph theory it is possible to calculate metrics that can be used to e.g. identify nodes, or set of nodes, which are important for the connectivity in the network, i.e. in our case, the network of MMS and natural hard surfaces in the NS. The metrics considered for the current study are explained below.

Sources and sinks

Source and sink maps are quantitative (or relative) representations of all hard substrate areas with values (or colours) indicating the extent to which each 10x10 km grid cell serve as a source and sink of simulated agents to and from any other 10x10 km grid cell, respectively. The map representation does not have any information on the number of connections to other sites or where to the connection exists, or how far away. However, source and sink maps can give an indication of which MMS’s and/or natural habitats are the main receiver and/or donor areas of simulated larvae.

Degree

Degree is one out of numerous metrics derived from graph theory that can be extracted for each node (each 10x10 km grid cell in our case). The degree represent the number of connections to/from each node (Csárdi and Nepusz 2006) without considering the weight or strength of each connection. Thus, unweighted node degrees does not discriminate between strong or weak connections, i.e. connections represented by a high or low number of agents. In marine connectivity, high node degrees indicate populations that exchange propagules with many others nodes (Boulanger et al 2020).

The degree can be divided into in-degree and out-degree representing numbers of connections into or out of each node. As for source and sink maps the values does not have any information on where to the connections exist. For analysing connectivity of hard substrate surfaces of MMS’s and natural habitats in the North Sea degree can give use full information together with other metrics such as sink and source locations. As an example, a locations with high out-degree and identified as a major source location is a location with simulated larvae potentially reaching many connection in high numbers.

Weighted vertex degree

Another metric from graph theory is the weighted vertex (=node) degree, which is similar to degree, however, instead of counting the number of connections, this metric sums the edge weights of the adjacent edges for each node (Csárdi and Nepusz 2006). This means that nodes with few but strong node connections may attain similar or higher values than nodes with many but weak node connections. As for the degree, the weighted vertex degree can be divided into in-degree and out-degree representing weighted sum of connections into or out of each node.
As for source and sink maps the values does not have any information on where the connections exist. In the analyses of MMSs in the NS weighted vertex degree with high values will indicate either few but strong connections to other grid cells, or many but weaker connections.

**Betweeness centrality**
Betweeness centrality has been used in a number of marine studies to identify portions of sea that sustain the connectivity of whole marine networks (Costa et al. 2017). Betweenness centrality is a measure of the number of shortest paths between nodes in a network that passes through each node. The higher the value, the larger of number of shortest paths passing through a particular node. According to Costa et al. (2017) betweeness centrality can be calculated using an algorithm proposed by Brandes et al. (2001) and used in the Igraph r-package if connectivity probabilities between nodes (=edge weights) are reversed:

\[ d_{ij} = \log \left( \frac{1}{a_{ij}} \right) \]

where \( a_{ij} \) is the edge weight, or connectivity probability, from node \( i \) to node \( j \).

In the analysis of MMS in the NS, betweeness centrality can be used to identify areas of hard substrate in the NS, which are important for sustaining stepping stone dispersal of pelagic life stages between sites.

**Transitivity or cluster coefficient**
This is yet another metric from graph theory also sometimes referred to as “cluster coefficient” (Csárdi and Nepusz 2006). Transitivity measures the average fraction of pairs of neighbours of a node that are also neighbours of each other (Montoya and Sole 2002), i.e. so-called triangular connections. Here neighbours are nodes (or 10x10 km grids in our case) which a node is connected to. Transitivity can be calculated as “global” or “local” transitivity, and attain values between 0 and 1.

Local transitivity is calculated for each node as the fraction of connected neighbours. I.e. the chance that two randomly selected nodes already connected to the node of interest are also mutual connected, i.e. in a triangular connection.

In the analysis of MMS in the NS high values of local transitivity indicate that the connections to a MMS are also mutually well connected suggesting multiple pathways of stepping stone connections. In addition, if the MMS also have a high degree (number of connections) and high weighted vertex degree (strength of connections) then the MMS belongs to an extensive and well connected network. The global transitivity can be calculated as one value for each of the hydrographic regions identified using the Infomap clustering techniques and can be used as an indication of how well connected MSS and natural hard substrates are within the cluster.

**Minimum path length**
This metric calculates the shortest path between pairs of nodes either as minimum number of nodes connecting the nodes and/or the geodic distance (Csárdi and Nepusz 2006). The metric can be calculated for each node and the path length from this node to all nodes it is connected to. This way the metric will provide information on e.g. the average distance or step length to other nodes. In the analysis of MMS in the NS, the minimum path length describe how far or via how many steps each site are connected to other sites.
**Momentum**

A last metric of relevance which is not derived from graph theory, was suggested by Hansen et al. (2015). Here the momentum is calculated for each node or 10x10 km grid in our case and represent a combination of dispersal potential and dispersal distance extracted from the connectivity probability matrix and the connectivity grid respectively. The momentum is calculated as the sum of the products for the connectivity probabilities and the geodesic distances to each of the connected hard substrate sites. In the analysis of MMS in the NS, high values thus, is an indication that agents from hard substrate sites are dispersed widely with relatively high probability to many other hard substrate sites and far away.

**Summary of connectivity metrics**

The various types of metric described above each reflects a specific property of the network. Individual properties may have limited application on its own, while the combined information of multiple metrics can provide useful and more complete understanding of the type of connectivity characterizing a network of hard substrates and the individual hard substrate sites. E.g. complex networks in the real world are often sparsely connected, tightly clustered and with a relatively small diameter, which can be described by the respective indices of degree, cluster coefficient (=transitivity) and average minimum path length (Kininmonth et al 2009). Other examples are mentioned in the description of the individual metrics above.

Thus, the understanding on how individual MMS in the NS may contribute to the connectivity of pelagic life stages need to be addressed using a multivariate approach including different types of connectivity metrics as described above. Here we propose to include these multiple connectivity metrics as part of the baseline for connectivity of non-indigenous species between hard substrate surfaces in the North Sea.
5. Results

5.1 Hard substrate coverage
The total areal coverage of all types of hard substrates both from MMS’s and natural substrate (in %) is shown in Figure 4. Maps of the areal coverage for each type of hard substrate including oil and gas platforms, wind turbines, pipelines, wrecks and natural hard substrate habitats are given in Appendix 1. Hard substrate. Notice that the legend of areal coverage is not linear and covers 6 orders of magnitude. Values range from very low coverages of down to 0.0001 % in areas dominated by MMS in the offshore parts of the NS and up to more than 75 % in areas dominated by natural hard substrate habitats concentrated along the coastal areas of southern of Norway, Sweden and the UK.

![Figure 4. Percentage of the 10x10 km grid cells of the North Sea occupied by all the types of hard substrates.](image)

5.2 Shipping activity in the North Sea
The shipping activities in the North Sea in terms of average shipping intensity in hours/km²/month for 2018 for all types of vessels and aggregated into a grid covering the NS with grid resolution of 10 km, are shown in Figure 5. The shipping activities for each individual vessel type are shown in Appendix 2. Shipping activities in the vicinity of MSS and natural hard substrates are in general concentrated along the coastal regions of the North sea, with some exceptions in the central parts at the location of oil and gas installations primary associated with tanker and cargo vessel activities presumably during mooring, load and/or unload.
5.3 Connectivity analysis result

The results presented in this section will show results for one of the nine PLD scenarios for each connectivity analysis output and examples on how results can be interpreted. The rest of the outputs will be presented in appendices. For most of the connectivity metrics this work is not yet finalised. A full overview of the pending tasks will be presented in the status section in the end of the report.

5.3.1 Connectivity matrices

Connectivity matrices for each PLD covering the 10-year period 2001-2010 have been generated both based on absolute (raw) numbers of simulated agent connections, as absolute numbers adjusted to the areal coverage of hard substrate of each grid cell and as probabilities of transition between grid cells. Of the 2,297 grid cells associated with hard substrate from either MMS and/or natural hard substrates, 2,136 grid cells were included in the connectivity matrices representing in total 4,562,496 possible pairwise connections (represented by matrices with 2,136 rows and 2,136 columns). The 161 grid cells not included in the connectivity matrices were excluded because these grid cells lie outside the computational grid of the HBM model domain used for the agent-based modelling. The connectivity matrices are not presented here due to their sizes but are available upon request.

5.3.2 Hydrographic regions

Results from the hydrographic region delineation for the 100 days PLD are shown in Error! Reference source not found. and Error! Reference source not found.. In total, 10 hydrographic regions were found for the 100 days PLD scenario. In Error! Reference source not found., the connectivity between the 10 hydrographic regions are displayed using arrows representing the probability of an agent with a start position in one region ending up in one of the other regions.
Result for region delineation based on larval dispersal modelling results adjusted to areal coverage percentages of hard substrates. Arrows indicate the direction the connectivity and thickness of arrows indicate the magnitude of probability of an agent with a start position in one region will settle in another region. Numbers in circles represent the probability in pct of agents with a start position in that region will settle in the same region (=self-reproduction).

In Error! Reference source not found., the connectivity between the 10 regions are displayed using arrows representing the absolute numbers of connections between each region based on total counts of simulated agents adjusted to the areal coverage of hard substrate at the start and end postions. Results for region delineation based on larval dispersal modelling results adjusted to areal coverage percentages of hard substrates. Arrows indicate the direction the connectivity and thickness and colors of arrows indicate the relative magnitude of the absolute number of agents (adjusted to areal coverage – see methodology section for details) with a start position in one region that will settle in another region. Thicknesses and colors of arrows represent a logarithmic scale, log10. Numbers in circles represent the probability in pct of agents with a start position in that region will settle in the same region (=self-reproduction).

The two maps show different patterns and their interpretation supplements each other. E.g. the connectivity displayed as probabilities (Error! Reference source not found.) shows that the simulated larvae with a start position in any of the central and southern regions of the NS (red, orange, yellow and light green) and the Kattegat, will most likely end up in the natural hard substrate habitats along the south coast of Norway. However the “realised” connectivity in terms of absolute numbers of agent representing each pairwise connection (between regions) of e.g. between the central yellow region and the region along the south coast of Norway can potentially exchange an absolute number of agents of the same order of magnitude in both directions.

The difference in patterns is due to the large difference between regions in the number of agents that will successfully reach and settle in another region. The region along the south coast of Norway has large areal coverages of natural hard substrate, and hence a potential larval production, many orders of magnitude larger than the regions in the central parts of the NS primarily containing hard substrates for MMS. The oceanographic currents are oriented in a direction from the central and southern parts of the NS towards the Norwegian coast via Skagerrak, the large excess of potential larvae production along the Norwegian coast outweighs the much less frequent and less pronounced oceanographic currents connecting the south coast of Norway with the southern and central part of the NS.
Figure 6. Map of hydrographic region delineation considering 100 days pelagic larval duration for 2001-2010. Arrow thickness indicate the between regions connectivity as connectivity probability, see text for details.

Figure 7. Map of hydrographic region delineation considering 100 days PLD for 2001-2010. Arrow thickness indicate the between regions connectivity as the relative magnitude of the absolute number of agents of each connection, see text for details.

The presentations of the potential (Error! Reference source not found.) and realised (Error! Reference source not found.) connectivity between hydrographic regions for 100 days PLD
scenario include a large number of arrows. For other PLD scenarios with shorter PLD, the number of regions increase significantly and so the number of connections represented by arrows. For a better presentation an alternative map representation is proposed and shown in Figure 8 for the 3 days PLD scenarios showing the realised connectivity equivalent to Error! Reference source not found.. Results for region delineation based on larval dispersal modelling results adjusted to areal coverage percentages of hard substrates. Arrows indicate the direction the connectivity and colours of arrows indicate the relative magnitude of the absolute number of agents (adjusted to areal coverage – see methodology section for details) with a start position in one region that will settle in another region. Colors of arrows represent a logarithmic scale, log10.

Figure 8. Alternative Map representation of hydrographic region delineation here considering 3 days PLD for 2001-2010. Arrow colors indicate the relative magnitude of the absolute number of agents representing each connection, see text for details.

To visualize how the individual regions delineated from the 100 days PLD scenario correlates with start and end positions from three region, examples are plotted on top of the regions map (Figure 9).
Figure 9. Start (left) and end (right) positions of agents from individual regions (no.2, 4 and 6 from top to bottom) based on the 100 days PLD scenario. Notice that agent positions are based on simulations from 2010 (200 000 agents) while the hydrographic regions and transitivity values are based on all years 2001-2010 (2 000 000 agents).
The delineation of hydrographic regions and the analysis of the within and between regions connectivity both in terms of transition probability between regions and in terms of absolute numbers adjusted to areal coverage of hard substrate, give important insights into which areas are interconnected and where boundaries between regions may be efficient dispersal barriers. The latter is not easy to deduce from the maps presented here, and there is a need to develop procedures and methods for extracting and visualising dispersal barriers in a more simple way.

5.3.3 Degree
We calculated the number of connections (degree) for each hard substrate grid cells for the 100 days PLD scenario shown in figure 10. In general, the number of connections into (in-degree) hard substrate grid cells is highest in the western part of the NS, while the connections out of (out-degree) hard substrate grid cells is highest in the eastern parts of the North Sea. Both out- and in-degree decreases close to the shores. For the Danish sector of the North Sea, the number of connections is relatively high mostly represented by connections out towards other areas, while the number of connections from other areas into the Danish sector are more limited.

Figure 10. Degree as number of connections to/from each hard substrate grid cell. Each cell is 10x10 km. Based on connectivity matrix representing absolute numbers of simulated agent connections for 100 days PLD for 10 years (2001-2010). ALL: including both IN and OUT degree. IN: In-degree. OUT: Out degree.
5.3.4 Weighted vertex degree

We calculated the number of weighted connections (weighted vertex degree) for each hard substrate grid cell for the 100 days PLD scenario shown in Figure 11.

Taking into account the strength of the individual connections areas dominated with large areal coverage of natural hard substrates, the coastal areas of Norway, Sweden and the UK obtain the highest values. The large coverage of hard substrate in these area results in a large number of released larvae settling successfully on hard substrate and thus supports many and strong connections to neighbouring areas, contrary to areas where areal coverage of hard substrates is low and thus only can support a larval release many orders of magnitude smaller.

MMS Hotspots of outward connections apart from MSS close to major natural substrate areas are areas in the south-western parts of the NS and off the coastal areas of Germany and the Netherlands. MMS in the Danish parts of the NS have relatively low outward connection strengths to other MSS despite the otherwise large number of connection (degree in Figure 10). The same can be concluded for coastal areas along Belgium, The Netherlands and Germany. Many of the MMS in the central and northern parts of the northern half of the NS have intermediate connections strengths to other MSS.

When looking at the weighted connection into MMS’s, there are indications that the Danish part of the NS is a hotspot for receiving NIS with PLD 100 compared to MMS in the North Sea in general. Other potential hotspots apart from natural hard substrates are MMS west of southern Norway, along the east coast of Scotland close to the extensive areas of natural hard substrates and off the coastal areas of The Netherlands and Germany. MMS in the central parts of the NS north and south of Dogger have relatively low strength connections to other MMSs.
5.3.5 Transitivity

We calculated the transitivity, also known as the cluster coefficient, based on the 100 days PLD scenario using connectivity matrix representing absolute numbers of agents of each connection adjusted to the areal coverage of hard substrate (see methodology section for details). Transitivity was calculated for each hard substrate grid cell (local transitivity) and for each of the 10 hydrographic regions (global transitivity) identified using the Infomap clustering algorithm, Figure 12.

Transitivity measures the probability that the adjacent hard substrate grid cells of a grid cell are connected, and high values close to 1 is an indication that all or most of the areas connected to an area are also connected other areas in triangular units. The local transitivity is highest along the coastal areas in general and in a few parts of the western NS offshore indicating that these areas are more efficiently integrated in connected networks, compared to most of the MMS in the offshore parts of the NS, which have low transitivity values. Local transitivity in the Danish parts of the NS is in general relatively low, with only a little more than half of the connected areas sharing the connection with another area.

The global transitivity calculated for each hydrographic region considers only the connections within the region and ignores any other connections to areas in other regions. The results show the highest transitivity values are found for the region in the south – eastern parts of the NS including the Danish parts of the NS with values close to 1 indicating that MMSs within this region belongs to a highly integrated network, however, with weak connections. Only 3% of the agents successfully settling on hard substrates with a start position in this region ends up settling in the same region, see figure 6, due to the low areal coverage of hard surface in general (<0.1 pct). Thus, despite a high transitivity a relatively high spawning intensity may be required in order to effectuate some or more of the possible connection between MMS in this region.

Figure 11. Weighted vertex degree or strength as sum of edge weights of connections going OUT of (left) and INTO (right) each hard substrate grid cell calculated for the 100 days PLD scenarios. Calculations are based on the absolute numbers of agents of each connection adjusted for the areal coverage of hard substrate (see methodology section for details). Notice the scale is log10.
Figure 12. Calculated transitivity, also known as cluster coefficient, as a measure of the fraction of hard substrate grid cell connections, which are also connected among themselves (for details see the methodology section). Left: LOCAL transitivity type “Barrat” based on the 100 days PLD scenario. Right: GLOBAL transitivity calculated for each hydrographic regions.

The lowest values are found for the regions in the central parts of the NS, which also co-inside with MSS with low areal coverage, low self-recruitment, and low weighted vertex degree. The transitivity has not yet been calculated for the remaining 8 PLD scenarios.

5.3.6 Calculations still pending

In order to fill the spectre of possibilities for the analyses, a number of calculations has not been performed for the existing data set. These includes:

- Betweeness centrality
- Minimumum path length
- Momentum
- Primary source and sink areas
6. Status on the current study

6.1 Initial project deliverables
In the original project description, five deliverables were identified:

1. Mapping of man-made structures (MMS) and other natural hard substrate habitats in the North Sea based on existing data and standardized (Standardized in a way suitable for addressing the other project deliverables)

2. Production of connectivity matrices and maps showing the potential natural dispersal and connectivity between physical structures in the North Sea considering different durations of pelagic larvae stages (relevant for marine non-indigenous species)

3. Classification of areas with MMS in relation to natural dispersal and connectivity to other MMS and hard substrates in the North Sea

4. Classification of areas with MMS and their location relative to shipping activities and intensities in the North Sea.

5. Recommendations on how the results from the current study be applied for management purposes by the Danish EPA.

6.2 Status of the deliverables

Deliverable 1 – Mapping of MMS and natural hard substrates
This deliverable has been fully achieved. Existing data on MMS and natural hard substrates has been aggregated on a grid covering the North Sea, Skagerrak and Kattegat, with a 10 km spatial resolution. The areal coverage of individual types of MMS and hard natural substrates has been calculated based on a thorough literature review.

Deliverable 2 – Connectivity matrices and natural dispersal

- This deliverable is partly achieved. The larval dispersal simulations covering a 10 years period and including 9 different pelagic larval durations (PLD) from 1 day to 100 days is finalised, with a total of 2 000 000 simulated agent per PLD.

- The computation of connectivity matrices representing both absolute numbers of agents per connection adjusted to areal coverage of hard substrates and matrices representing these numbers as transition probabilities of each connection have been finalised.

- Hydrographic regions have been delineated for each PLD, and the connectivity between regions in terms of transition probabilities and absolute numbers of agents (adjusted to areal coverage of hard substrate) has been calculated.

- Results have been presented as preliminary maps for each PLD representing the 10 years period. The preliminary maps still need some development to improve the presentation and representation of the results. In Addition, procedures for how to extract and
visualize in a simple way the primary dispersal barriers between regions needs to developed.

- Additional connectivity matrices representing the connectivity probabilities of connections including not only the realized agent connections between hard substrates but also including the number of agents not successfully settled within hard substrate areas, have not yet been calculated. These matrices were intended to be used for delineating hydrographic regions and to evaluate any deviation in hydrographic regions delineation depending on the connectivity matrices used.

**Deliverable 3 – Classification of MMS according to natural dispersal**

This deliverable has been initiated. A literature study has been done identifying what type of connectivity metrics can be calculated for individual or areal units, of MMS and natural hard substrates. The result of this review suggests that a number of connectivity metrics needs to be calculated. It is not possible to represent connectivity of individual or groups of MMS or areas, to other MMS or areas with a single value. Marine connectivity and connectivity in complex networks in general can be described using many different metrics each representing unique characteristics of the network nodes, in our case hard substrate sites.

Examples of the connectivity metrics “degree”, “weighted vertex degree” and “transitivity” calculated for the 100 days PLD, have been presented in this report including examples on how the outputs can be interpreted. These metrics remains to be calculated for the 8 additional PLD scenarios, and the interpretation needs to be further developed. The additional connectivity metrics suggested in the methodology section have not yet been developed, and some technical issues remains to be solved, specifically regarding the calculation of betweeness centrality.

**Deliverable 4 – Classification of MMS according to shipping activities**

This deliverable is partly achieved. Maps of shipping intensity of individual vessel types have been aggregated in the grid covering the NS with a 10 km resolution. These maps are included in this report. Additional maps have been considered aggregating shipping intensity within a larger radius into each 10 km grid. Suggested radius is 25 km. These maps have not yet been created.

**Deliverable 5 – Recommendations**

This deliverable has not yet been initiated. The purpose of this deliverable was to develop procedures and recommendations for how to use the outputs from the current study for future studies and management questions. The recommendations was intended to be developed in dialog with the Danish EPA and other relevant authorities during a one-day workshop.
7. Bibliography


Coolen J W P, Lengkeek W, van der Have T, Bittner O, 2019. Upscaling positive effects of scour protection in offshore wind farms Quick scan of the potential to upscale positive effects of scour protection on benthic macrofauna and associated fish species. Wageningen University & Research report C008/19


IMSA 2011a. Ecosystems associated with North Sea oil and gas facilities and the impact of decommissioning options. With attention for local and regional effects. Background report phase 1 Living North Sea Initiative. IMSA Amsterdam.

IMSA 2011b. Decommissioning of North Sea oil and gas facilities: An introductory assessment of potential impacts, costs and opportunities, LiNSI background report Phase 1.


40 Connectivity of artificial structures in the North Sea


Oil and Gas UK, 2013. DECOMMISSIONING OF PIPELINES IN THE NORTH SEA REGION 2013. Available at www.oilandgasuk.co.uk


Appendix 1. Hard substrate

Figure 13. Percentage of the grid cell occupied by hard substrate sediment.

Figure 14. Percentage of the grid cell occupied by pipelines.
Figure 15. Percentage of the grid cell occupied by offshore platforms.

Figure 16. Percentage of the grid cell occupied by wind farms.
Figure 17. Percentage of the grid cell occupied by ship wrecks.
Appendix 2. Vessel intensity

Figure 18. 2018 average density for service vessels.
Figure 19. 2018 average density for sailing vessels.

Figure 20. 2018 average density for pleasure crafts.
Figure 21. 2018 average density for high speed craft.

Figure 22. 2018 average density for tug and towing vessels.
Figure 23. 2018 average density for passenger vessels.

Figure 24. 2018 average density for cargo vessels.
Figure 25. 2018 average density for tanker vessels.

Figure 26. 2018 average density for military and law enforcement vessels.
Figure 27. 2018 average density for unknown vessels.
Appendix 3. Hydrographic regions–connections as probabilities
Connectivity of artificial structures in the North Sea
Connectivity of artificial structures in the North Sea
Hydrographic regions – connections as absolute numbers adjusted to areal coverage of hard substrates
Connectivity of artificial structures in the North Sea
Connectivity of artificial structures in the North Sea
Connectivity of artificial structures in the North Sea
Appendix 4. Connectivity metrics

These results have been calculated for one PLD scenario, see results chapter.
- Degree (IN and OUT)
- Weighted vertex degree (IN and OUT)
- Transitivity (LOCAL and GLOBAL per hydrographic regions

These results have not yet been calculated.
- Betweeness centrality
- Minimum shortest path
- Momentum