A new strategic framework to structure Cumulative Impact Assessment (CIA)

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Abstract—**In order to alleviate climate change consequences, UK governments are pioneering offshore energy developments with increasing commitment. The North Sea is a dynamic ecosystem with strong bottom-up/top-down natural and anthropogenic drivers facing rapid climate change impacts. Therefore, to ensure the compatibility of such large-scale developments with nature conservation obligations, cumulative effects need to be evaluated through cumulative impact assessments (CIA). However, by excluding climate change impacts, CIA lacks spatio-temporal appropriate baselines linking ecosystem components (e.g. physical indicators) to population dynamics which leads to uncertain predictions at populations levels. This study presents an overview of a framework for CIA using a holistic and pragmatic ecosystem approach based on spatio-temporal Bayesian network in order to identify pressure pathways, keystone components, ecosystem connectivity and resilience as well as population-level changes. We will also present potential fine-scale environmental monitoring solutions and data sources generated at MRED (Marine Renewable Energy Developments) site levels. Finally, we will discuss the usefulness of the two components that make up this framework: a database and an application of standardised shared tools that will pave the way to more transparent and multi-disciplinary collaborations. This framework will provide a multi-dimensional decision-making toolkit that would also lead towards more efficient SEAs (Strategic Environmental Assessment) as well as providing the ability to embed the CIAs of projects into regional and multinational schemes**.

Keywords—**Bayesian network, climate change, cumulative effects, database, ecosystem approach, marine renewable energies, online application.**

I. INTRODUCTION

TO mitigate climate change consequences, the UK government committed to increase the UK's offshore wind capacity from 8.5 GW today to 30 GW by 2030, delivering 1-2 GW of new offshore wind per year [1]. The North Sea is a dynamic ecosystem with strong bottom-up/top-down natural and anthropogenic drivers facing rapid climate change impacts [2]–[4]. As species are redistributed at a rapid pace across longitudes and latitudes and therefore moving through administrative boundaries, ecosystem baselines are temporally and spatially shifting [5]–[7]. As an example, fish have already shifted their distributions at a rate averaging 70 km per decade and these shifts are expected to continue if not to accelerate [7]–[9]. [10] predicted a redistribution of population interactions at a scale of 75 km up to 164 km for prey species (e.g. sandeels and herrings) and top predators (e.g. birds and marine mammals) respectively in the North Sea by 2050. To ensure the compatibility of projected large-scale marine renewable energy developments (MRED) with nature conservation obligations, the intended capacities need to be carefully planned and implemented to avoid unacceptable levels of environmental harm and therefore cumulative effects need to be assessed [11]. The Cumulative Impact Assessment (CIA) is currently required under both the Strategic Environmental Assessment (SEA) (Directive 2001/42/EC) and the amended Environmental Impact Assessment (EIA) (Directive 2014/52/EU).

Recently, the overall uncertainty due to data used to predict cumulative impacts led to project refusals (e.g.

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Docking Shoal during Round 2) based on the precautionary principle [11], [12].

EIA and post-consent conditions are not designed to answer larger-scale ecosystem changes. The licensing conditions, EIA and post-consent processes presently lack accuracy in assessing population and ecosystem changes at local to ecosystem spatio-temporal scales [13]–[15]. Furthermore, EIA scoping processes tend to over-simplify ecosystem complexities and neglect climate change ecosystem baselines by excluding hydrology and primary producer components influencing higher trophic level distributions [11], [16]–[19].

MRED developments are thought to have several effects on marine populations and ecosystems, although the extent to which these are biologically significant remains uncertain [20]. Impacts on seabirds are often cited as a key concern, with the main effects being collision mortality, displacement from key foraging areas and barrier effects leading to increased costs to movements such as commuting or migration [21]. Marine mammals and some fish may be impacted by noises generated during construction, operation or decomissioning activities [22]–[24].

Although the significance of such effects at population scales is difficult to acertain, evidence is becoming clearer that MREDs do affect birds, marine mammals as well as fish and the scale of effect, when considering multiple MREDs across a region, can be considerable [21]–[23], [25]. In addition to detrimental impacts, MREDs may have positive effects, for example by creating reef effects and the exclusion of fisheries may provide the opportunity for improved functionality of ecosystems that may have the potential to provide greater foraging opportunities for birds and mammals [26]–[28].These potential direct and indirect effects combined ultimately exacerbates uncertainties regarding climate change and MRED impacts on ecosystem shifts from primary producers up to colony and population levels, which in turn lead to a lack of efficient compensatory measures [29]–[31].

Even though the deployment of MRED aims to reduce CO_2 emissions, their combined impacts with climate change need to be understood [32] As they stand, SEA and EIA procedures struggle to identify interconnectivity between pressures and across ecosystem components which trigger mismatches and high uncertainties amongst spatial scales [33]–[35]. This leads to an uncertain eco-systemic assessment with limited opportunities for improving the understanding of impacts at ecosystem scales to inform the next leasing round [36]–[38]. The tools currently available are insufficient to reach broader ambitions to implement an ecosystem approach in order to manage marine waters [31].

Scotland has initiated more strategic and holistic data samplings as well as the integration of fisheries activities in order to better assess potential displacements. Since 2015 the Forth and Tay regional advisory group (FTRAG Group 2015) and the Moray Firth regional advisory group (MFRAG Group 2015) act as mechanisms for developers in these regions to pool resources, and work collaboratively with government, NGOs and SNCBs (Statutory Nature Conservation Bodies), in order to prioritise and progress strategic research areas. Such groups enable monitoring and feedback into EIA and can act as a template for undertaking strategic research to inform future developments, but have not, so far, led to research at the ecosystem scale. The need for developing consistent CIA methodologies and shared tools based on a collaboration between regulators, stakeholders and developers has been identified as crucial to assess the impact of marine industries such as MREDs [12], [39].

Addressing this requires an inclusive, holistic and pragmatic inter-disciplinary approach linking academic research, policymakers, industries, licensing groups and public engagements [17], [39]. Our research aims to build a bottom-up/top-down ecosystem-based approach using a habitat risk assessment dynamic Bayesian network (HRA-DBN).

This will integrate climate change oceanic drivers and MRED effects as well as other anthropogenic activities (e.g. fisheries) and explore potential fine-scale environmental monitoring solutions integrating innovative as well as existing methods used at MRED sites. Finally, we will discuss how already available databases and online web applications could be enhanced and used by MRED industries, stakeholders, decision-making bodies, NGOs and broader stakeholders of interests (e.g. general public).

II. HABITAT RISK ASSESSMENT DYNAMIC BAYESIAN NETWORK (HRA-DBN)

Tools such as iPCoD (interim Population Consequences of Disturbance), DEPONS (Disturbance effects on the harbour porpoise population of the North Sea) and SeaBord are used to predict if a project or an activity will affect populations [40]–[42]. SeaBord has been designed to predict the barrier and displacement effects at bird populations levels. DEPONS focuses on the effects of noise exposure on harbour porpoise populations [41]. Although iPCoD also aims to predict the effect of noise on marine populations, it can be used for fish, seabirds or marine mammals [40] Although those three models are used during the licensing process, they do not include the effects of multiple stressors as well as interconnections and feedback loops between ecosystem components and pressures [40], [42].

In France and Australia, advanced ecosystem-based management, as well as a modelling framework that includes multiple stressors and MREDs, have been produced [43], [44]. However, these approaches are not data-driven and remain based on expert opinion.

The Habitat Risk Assessment (HRA) model is one of the InVEST (Integrated Valuation of Ecosystem Services and Trade-offs) models created by Stanford University (Natural Capital Project). The HRA model quantifies the cumulative risks on habitats affected by multiple stressors induced by multiple ocean-uses and assesses the consequences on ecosystem service deliveries [45]. The cumulative risk is calculated according to exposures and their consequences in order to estimate the probability of disturbance. The risk is defined by multiple criteria, such as spatial and temporal overlaps between habitats and activities [46]. Different management scenarios can also be incorporated into the HRA model (e.g. one stressor vs multiple stressors management) so as to explore their efficiency towards stressor mitigation as well as meeting the ecosystem-based marine spatial planning requirements [45], [47], [48].

Score attributions and data quality criteria are both based on expert elicitations and user experiences. This constrains the extent to which uncertainty can be accurately quantified [46]. Due to the range of interpretations and views amongst users, expert knowledge may lead to overconfidence and thus introduce biases, or inaccurate estimations of model sensitivity when used to parameterise the model [45], [46], [49]. Expert elicitations may also tend to underestimate the multiple relationships and ecological processes behind ecosystem dynamics compounding uncertainties [49].

Dynamic Bayesian Networks (DBN) are flexible approaches. The term "dynamic" refers to modelling time series and interaction changes over time. Such models also allow the inclusion of different data sources (e.g. experimental data, statistical or simulation models, and elicited expert opinions) in order to spatially and temporally assess eco-systemic shifts and indicators at local to regional scales in high uncertainty contexts [49]. DBN links between habitats and species are purely data-driven and account for uncertainty without relying on expert elicitations [50]. Trifonova et al. (*under review*) used DBN in order to explore the spatial dynamics of mobile species over a 30 years time serie during the summer periods as well as to identify key indicators of ecosystem linkages and climate change at a UK regional North Sea scale.

Coupling the outputs of habitat and specie distributions under climate change and different MRED scenarios with the DBN created by Trifonova et al. (*under review*) would thus enhance the robustness of the HRA model [46], [49], [50].

As a result, it would produce a North Sea habitat ecosystem risk approach from local, regional and national boundaries frameworks based on physical/biological indicators and predicting marine population shifts under the mixed influence of climate and MRED industries.

The Habitat Risk Assessment Dynamic Bayesian network (HRA-DBN) will be structured with key ecosystem indicators as well as natural (e.g. climate change) and anthropogenic (e.g MRED or fisheries activities) spatially-explicit pressures.

By linking functional habitat variations (e.g. physical indicators) to trophic interactions and indicators, this model will identify key ecosystem components as well as their ability to confer ecosystem resilience [51], [52]. It will also be overlaid with anthropogenic activities (e.g. fisheries including fish catches and vessel monitoring systems data), other activities (e.g. shipping and oil and gas activities) as well as MPAs (Marine Protected Area). The HRA-DBN will also incorporate already built or planned MRED installations based on production goals, array footprints, the number of turbines as well as potential innovations (e.g. type of pile or shape of arrays). The flexibility of the HRA will enable us to consider various phases of MRED life cycle (from operational to decommissioning), while incorporating developments of structures innovation (e.g.floating wind), potentially triggering different impacts. Thus, the model will calculate the cumulative vulnerability generated by several stressors for each habitat or trophic key ecosystem component and facilitate the identification as well as the testing of innovative compensatory measures. Ultimately, the HRA-DBN will integrate physical/biological indicators associated with climate change and upper trophic levels affected by MRED in order to assess and predict ecosystem and population trade-offs and future distributions. This will help to identify potential mitigation and compensatory measures at correct spatio-temporal scales to maximise future ecosystem value and functioning in order to enhance marine spatial planning processes [17], [47], [48].

Mapping tools, (e.g. ArcGIS) are commonly used by the MRED industry to explore resource power predictions or support location decisions [53], [54]. Therefore, the model output will include maps and GIS shapefiles to illustrate the ecosystem risk scores triggered by the cumulative effects of MRED and climate change as well as their repercussions on keystone ecosystem components and biodiversity hotspots.

In the longer run, the HRA-DBN could also be implemented with power prediction models such as turbine optimisation or cable layout models, also known as micro-siting tools. For example, offshore wind farms energy production losses largely result from wind turbine wake effects.

Efforts are therefore made to understand this phenomenon [54], [55] and power prediction models explore the trade-offs between wind resources, energy production and investments based on individual turbine positions and array configurations [54]–[57].

However, due to climate change, wind resource predictions present uncertainties ranging between 0.5% for a ten-year prediction to 2% for a twenty-five year one, respectively [54]. [55] predicted wake effects and energy production based on windfarm layouts and showed that the error of power predictions could be reduced by initialising their model using prior chosen values as used in DBN.

Applying an HRA-DBN approach such as the one described here would reduce and concentrate monitoring efforts by targeting keystone trophic levels (those linked to highest degrees of change on the whole ecosystem). Combining the present holistic approach to CIA processes could pave the way towards transboundary standardisations of samplings and data requirements as well as addressing the need for representative and comparable data [2], [15].

III. A SHARED MONITORING EFFORT

Although Bayesian models are known to perform accurate predictions, even with small sample sizes, their structures can be optimised based on data learning processes, but doing this requires large data sets and data scarcity is often a limiting factor [49]. Additionally, increasing sampling effort of relevant environmental gradients and updating datasets are often recommended to characterise heterogeneous habitats and species which have a wide dispersal range, or are rare or difficult to observe [52].

Large data sets and fine-scale ones are also needed to validate and relate regional habitat risk scores to habitat conditions (e.g. fragmentation) [45], [46]. Therefore, strengthening monitoring programs and updating data are advocated not only to validate both the stability and the structure of the DBN-HRA, but to also improve risk assessment predictions in order to test the effects of fine and large-scale drivers [45], [46], [52].

Data collected to support MRED project EIA stages aims to quantify the abundance and distribution of mobile marine vertebrates that are using MRED sites at a fine scale, however, it is not designed to provide information regarding changes in movement patterns [17]. Better integration of environmental monitoring at MRED site-levels is needed that would include measures of habitat variables that can be used as indicators in order to predict where animals will be displaced once large-scale arrays are in place.

This could be achieved by using seabed autonomous sonar platforms, UAVs (Unmanned Aerial Vehicles) and analysing ROV (Remotely Operated Vehicles) data from an environmental perspective [17], [58], [59].

The Danish experience conducted in the Nysted and Horns Rev site showed that the T-POD system for recording the underwater sound production of porpoises could be used for studying marine mammal behavioural responses[60], [61]. On the same sites 'TADS' or 'thermal animal detection systems' have been efficient for measuring bird collisions[62].An important point is that the engineering community also needs to monitor fine-scale environmental variables on and around MRED devices. For example, to predict power production and monitor windfarm performances, turbines are equipped with anemometers recording windspeed and direction at m/s scales [55], [63]. Boat surveys for EIA purposes can provide high-resolution data, but they do not normally collect continuous and simultaneous data over an entire 14-day tidal cycle that will cover the changes in physical tidal resources as well as those in fish, mammal and seabird foraging behaviours [64], [65].

Although surface instruments (e.g. buoys) or floating plateform scans can be useful in some areas, in high-energy MRED sites they lack stability when measuring the entire water column and surveying animal interactions with the seabed [59]. Using multiple acoustic sensors autonomous seabed upward-facing sonar platforms such as FLOWBEC (Flow and Benthic Ecology 4D) would allow the continuous and simultaneous high-resolution monitoring of physical resources, habitat features and wildlife interactions [59], [66], [67].

FLOWBEC is equipped with onboard batteries and data storage providing a continuous recording of a 14-day spring/neap tidal cycle and enabling measurements to be taken near marine energy structures as well as in locations free of such devices [59]. [66], by analysing measurements recorded by the FLOWBEC mounted ADV (Acoustic Doppler Velocimeter), showed significant flow modifications and a reduced velocity in the tidal turbine wake. [67] created an algorithm to extract and analyse acoustic data recorded by FLOWBEC and demonstrated that dive profiles (e.g. seabirds), depth preferences, predator-prey interactions, and animal movements were correlated to hydrodynamic modifications driven by marine renewable energy devices.

Drones, also known as UAVs, are increasingly used to collect spatial and temporal high-resolution data to assess coastal ocean processes, habitats and species [68], [69].

[70] used UAV transects above tidal energy sites over several tidal cycles in order to assess physical scales and mechanisms driving predators hotspots occurrences around energy extraction sites. Therefore, surveying MRED sites using UAV would contribute to assess the micro-sitting of devices as well as monitoring above water wildlife interactions with anthropogenic structures and habitat uses. However, weather variables (e.g. cloud cover or sea state) influence animal detection and their presence or behaviour might be influenced by disturbance from UAV flights [69]. Some governments also apply regulatory restrictions on aerial drone uses, slowing the adoption of these devices[68].

Therefore the use of UAVs requires learning good practices in order to accurately monitor species' habitat uses and hotspot locations in MRED context [69]. Worldwide, offshore oil and gas industries and MRED use ROVs for prospecting seabeds, surveying drilling operations, ensuring maintenance and repairing structures [58]. [58] demonstrated that analysing routine ROV surveys contributed to better understanding marine megafauna (e.g. marine mammals and sharks) interactions with underwater anthropogenic structures. However, industrial ROV surveys are access restricted due to their commercially sensitive status and lack of environmental survey designs, thus making robust statistical analysis difficult [58].

A monitoring system combining FLOWBEC and drones, with ROV surveys would allow assessing species habitats uses and prey-predator interactions at a high- resolution scale above and below water. Monitoring the water column to predict phytoplankton bloom could also be done using gliders and other autonomous underwater vehicles providing subsurface variables supplementing satellite data [38].This would also ensure survey reproducibility in order to generate comparable datasets across sites and the simultaneous recording of biological and physics data to better understand fine-scale ecosystem responses towards MRED sites and climate change [17]. Integrating MRED site collected data, EIA and regional SEA data into the HRA-DBN would contribute to assessing and predicting contrasting or synergistic impacts between climate change and energy extractions based on appropriate thresholds from a fine-scale ecosystem up to a transboundary one over the next 50 years [10], [17].

Achieving high-resolution simultaneous and continuous environmental monitoring as well as data sharing at MRED site-level requires cultural changes [17], [71].

Collaborations between industries, scientists and regulators should be encouraged in order to allow more robust and synchronised monitoring efforts between the MRED sectors and ocean monitoring communities [58], [71]. This could be done via shared fundings linking academics, stakeholders and MRED industries [71]. Enhancing multi-disciplinary collaborative work could also be nudged by the use of standardised shared tools to centralise and access data as well as HRA-DBN model outputs [17].

IV. TOOL CREATION: DATABASE AND APPLICATION

There is currently no centralised UK-wide pathway for accessing data and information across the various stakeholders involved in the CIA process and MRED or other marine industries [11], [72]. A comprehensive overview of available data can be thwarted by factors such as turn-over between the different industry teams (e.g. building-phase teams, life-time/maintenance teams and decommissioning teams), commercial sensitivity concerns, and lack of a common format/framework to ensure comparability and compatibility across datasets [11], [73].

Creating a common UK-wide online database and tool able to provide the required information in a consistent format whilst keeping commercially sensitive information "hidden", could (if the uptakes were high) lead to streamlined consistent and transparent CIAs. This would ideally also be able to integrate data across sectors by encouraging wide stakeholders involvement (e.g. including fisheries, by integrating data related to their activities at the beginning of the SEA and CIA processes [30], [74]–[76]. Such an approach should be based on a shared open-access centre, merging existing data at local to global scales across space and time [77].

A. *MEDIN (Marine Environmental Data and Information Network): An MRED opportunity*

The German government created MARLIN [2] (Marine Life Investigator), a powerful large scale/high-resolution web portal combining data from lower trophic levels (e.g. benthic invertebrates) and demersal fish, up to top predators, such as seabirds and marine mammals from EIA and research-based monitorings. This holistic tool has contributed to improve monitoring and sharpen scientifically based marine spatial management [78]. The UK launched MEDIN [3], an open access collaborative metadata portal in April 2008. Today MEDIN compiles 14,000 UK marine datasets from a range of UK commercial sectors, governmental agencies, stakeholders and academics (MEDIN).

Although, MARLIN and MEDIN are sharing similar objectives, in the UK some sectors remain reluctant to share their data via MEDIN, arguing that releasing commercially sensitive data could either advantage other companies or could lead to misinterpretations by other data users [79]–[81]. Addressing both concerns could be done by anonymisation or embargo periods regarding data releasing and by dedicated, skilled employees to portal data management, funded by contributing sectors [80], Additionally, RESCORE[4] in France, and MarenData[5] in the EU are two databases gathering environmental, engineering, and performance types of data, resolving the embargo of sensitive data and sharing of resultsTherefore, following the RESCORE and MarenData confidentially frameworks and following the example of using the MARLIN framework within MEDIN would create a holistic and pragmatic shared database from a local to a national scale, for the CIA.

B. *Create an App*

In order to make sure the data is easily accessible and usable by industries, regulators, statutory advisors and other stakeholders, a solution would be to create a visual tool that would take the form of an Application. This Application could be a map summarising in the simplest way possible, the holistic and pragmatic ecosystem-based approach. It could consist of three layers. The first would be based on the HRA-DBN model with the key ecosystem drivers and spatially explicit risks.

The second would incorporate planned MRED installations based on the production goal, the shape of the array, the number of turbines, as well as other potential innovations. A rapid gain to current required CIA modelling could be linked to receptor-specific (seabird and marine mammals) static models for collision risks (Scot

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[2] https://www.geoseaportal.de/

[3] https://medin.org.uk/

[4] https://rescore.france-energies-marines.org/

[5] https://marendata.b2clogin.com/

Gov 2018) and combined collision and displacement effects (CEH 2019) to this second layer of the Application. This would maximise the efficiency gains for industries in using a central repository framework ensuring they can meet their various existing legislative requirements and/or receptor-specific impacts as required by current CIA processes. The evolution of the HRA-DBN would include dynamic spatial and temporal ecosystem aspects such as climate change, collisions and displacements interacting between the first and second layers. Finally, the last layer would output the habitat risk assessment scores (including receptor-specific components). The Application would also include scientific fact cards explaining the consequences of the risks and the current state of research regarding the zone(s) or the ecosystem component(s), which most contribute to the high score.

This Application could theoretically be divided into different levels of complexity according to the different groups of user requirements (e.g. MRED engineers, regulators, academics as well as the general public).

As part of the design phases for both a database and application, extensive and carefully targeted stakeholder engagement would be crucial to ensure both buy-in and eventual uptake. Clarity would be required on aspects such as ownership (of the data contained within the tool as well as the overall application), quality assurance and maintenance of database, and ultimate responsibilities for the tool, analyses and data contained within it.

Without early engagement and evidence that these wider considerations had been addressed, there is a high risk the tool would fail due to lack of uptake or confidence in it's inputs and outputs [82], [83]. In the long run, both our tools could potentially complement the range of decision support scenarios presented here. [48].

V. CONCLUSION

Creating a common online database and an Application encapsulating an HRA-DBN model ecosystem-based approach with all the MRED phases from project initiation up to the final phases (e.g. decommissioning) and other anthropogenic pressures could greatly improve the ecosystem outcomes of CIA processes, improve the accessibility of holistic approaches to CIA and facilitate transparent and consistent communications between different industry working groups, stakeholders and decision-making bodies, academics and other interested parties [76]. Additionally, it would better integrate various stakeholders (e.g. fisheries) to the sustainable development of MRED industries by integrating data related to their activities (e.g. catches and important fishing grounds) at the roots of the CIA processes [30], [74]–[76]. This multi-disciplinary research would provide a decision-making tool embedding a more strategic CIA into individual projects from local to ecosystem scales and could do so in marine environments globally. This would contribute to an MRED/climate change-proof ecosystem-based marine spatial management supporting sustainable use of our seas.

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