ASSESSING THE VALIDITY OF NAVIGATION RISK ASSESSMENTS: A STUDY OF OFFSHORE WIND FARMS IN THE UK

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DECLARATION OF CONFLICTS OF INTEREST

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ABSTRACT

The developments of offshore wind farms can place increased pressures on conflicting marine users, particularly in already crowded waterways. Risk analysis of potential hazard scenarios are conducted by developers and regulators in the form of Navigation Risk Assessments which seek to identify, measure and mitigate impacts through data collection, consultation, modelling and risk assessment. These activities have inherent uncertainties and limitations which are rarely discussed and have the potential to undermine the value and credibility of the risk assessment. To evaluate the accuracy of Navigation Risk Assessments, their predictions are compared with the historical incident record of accidents involving wind farms. This review identifies significant methodological limitations and sources of uncertainty endemic in the Navigation Risk Assessment process which results in an over-estimation of risk. These include a lack of inclusion of historical evidence, issues during elicitation of expert judgment and methodological limitations of both quantitative risk models and the underlying risk assessment. Based on our evaluation, future research directions are highlighted to support decision makers on marine spatial planning by increasing the robustness of Navigation Risk Assessments.

KEYWORDS

Navigation Risk Assessment, Navigation Safety, Maritime Risk Assessment, Offshore Wind Farms

1 INTRODUCTION

Offshore Wind Farms (OWFs) have the potential to impose a significant negative impact to the environment and other marine users if not properly managed (DECC, 2011). The construction of an obstacle in otherwise navigable waters presents a potential allision (contact) risk to passing vessels which could result in pollution, significant damage to the turbine and vessel, and loss of life (MCA, 2021a). Furthermore, collision hazards are created by offsetting shipping, such as the creation of choke points or converging shipping lanes. In addition, OWFs can impact radar coverage, change wind and tidal patterns or increase transit time for essential shipping routes and ferry services. These impacts all need to be considered in detail before an OWF is constructed, and where necessary, identify mitigation measures to reduce the impacts to acceptable levels.

OWFs are becoming an increasingly common feature of the marine environment. In 2008, there was a total global capacity of OWFs of less than 1GW. By the end of 2020, this had increased to 35GW, with more than 6GW installed annually between 2019 and 2020 (GWEC, 2021). Targets to increase renewable generation could see more than 300 GW required in Europe alone by 2050, greatly increasing the number of offshore turbines. The United Kingdom (UK) has the most developed offshore wind infrastructure of any country in the world. In 2020, the UK had 3,000 turbines operating or under construction across almost 48 OWFs with a combined grid connection of 10.4GW, 30% of the global total (Crown Estate, 2021). Whilst the UK is the world leader in offshore wind energy production, during 2020 new turbines were being installed throughout Europe, China, South Korea and the United States. In China alone, 3GW of new capacity was added in 2020, more than any other country and 50% of the global increase (GWEC, 2021). Managing the safety of these developments, and mitigating their impact on maritime safety, is a complex task for navigation authorities (van Hoof et al. 2020).

There is therefore an inherent challenge in maintaining the safety and efficiency of global shipping and the need for greater renewable energy generation. To make informed, evidence-based, and reliable decisions on the safety of new developments, decision makers rely on the outputs of risk analyses and safety studies. Various methodologies have been proposed by researchers in the academic literature to advance these techniques. This might include marine spatial planning studies to deconflict OWFs with other key maritime activities (Castro-Santos et al. 2020; Diaz and Soares, 2020; Abramic et al. 2021; Obane et al. 2021). However, such studies typically consider shipping and navigation impacts at a high-level amongst many other constraints. Alternatively, the use of more quantitative risk modelling techniques using vessel traffic analysis or expert judgement (Christiansen et al. 2001; Mehdi et al. 2019; Yu et al. 2020a) can be used to better quantify the risks of any proposed development on maritime navigation.

Within the context of the UK, every OWF proposal is required to prepare and submit a Navigation Risk Assessment (NRA) as part of the Environmental Impact Assessment (EIA). The NRA should seek to identify, assess and if necessary, propose mitigations to ensure that the OWF does not have a significant impact on shipping and navigation receptors. There is significant inherent uncertainty around predicting these impacts; how will vessels respond to an offshore development, which routes will they take, will there be changes in the types and numbers of vessels in the area and will this result in more accidents? NRAs attempt to gauge the significance of any impacts through data analysis, modelling, consultation and structured risk assessments. Therefore, as in many other high consequence industries such as nuclear or oil and gas, the NRA process combines both an analytical, quantitative assessment of risk and a deliberative, collaborative exercise involving stakeholders and decision makers (Aven and Zio, 2011).

Ultimately, NRAs should be judged by whether they accurately characterise the risk of a development, their validity (Aven and Heide, 2009). Many authors have drawn attention to limitations in risk assessments more generally (Aven and Zio, 2011), including both EIAs (Tennoy et al. 2006; Lees et al. 2016) and maritime risk analyses specifically (Skjong and Wentworth, 2001; Yang et al. 2008; Goerlandt and Kujala, 2014; Sun et al. 2018; Rawson and Brito, 2021). Mehdi et al. (2018) draw attention to the potential negative impacts of poorly calibrated NRAs for OWFs; increasing risks to vessels or increasing costs to developers. Uncertainties are inevitable in the context of maritime safety impacts of OWFs (van Hoof et al. 2020), aleatory uncertainty due to the inherent randomness of the system itself and epistemic uncertainty due to a lack of knowledge of the system (Knapp and Hoorn, 2017).

One method to consider the validity of a risk assessment is through a “reality check”, whereby the risk analysis is compared with the operating experience of the corresponding system (Goerlandt et al. 2017). Whilst reality checks can be applied to other contexts, NRAs for OWFs pose an interesting case study due to inherent challenges in making accurate predictions. Firstly, such developments are relatively novel and therefore there is little historical evidence from which to calibrate risk predictions (Presencia and Shafiee, 2018; Mehdi et al. 2018; Yu et al. 2020a; Cevasco et al. 2021). In the context of OWF component failures, some recent work has noted that there is a significant discrepancy between risk analysis outputs and reference values that undermines effective decision making (Cevasco et al. 2021). Secondly, the environment in which they are constructed is a complex and dynamic system with numerous interacting stakeholders such as commercial, fishing and recreational users, each of which would be impacted differently. Thirdly, the degree of impact is highly site specific, with each project having different sizes, depths of water and traffic profiles.

Several important contributions are made within this paper. Firstly, to address the aforementioned gaps in our knowledge of historical accidents in OWFs (Presencia and Shafiee, 2018; Yu et al. 2020a), a systematic analysis of historical incident data within the UK is performed, characterising the types and trends of accidents. Secondly, given the operating profile of UK projects, the annual incident rate per project is estimated, providing quantifiable metrics for decision makers in planning the requirements for mitigation measures. Thirdly, by aggregating accident predictions contained within NRAs for UK projects, the predictive accuracy of these NRAs against the historical incident record can be compared, clearly identifying the degree to which they accurately characterise the risk. Finally, from this several insights are discussed on the specific techniques and limitations in OWF risk analysis that can be used to improve the accuracy of future studies and better contribute to the safe and sustainable development of OWFs.

The paper is laid out as follows. Section 2 describes the principal literature on maritime risk analysis for OWFs and validity issues of safety studies. Section 3 outlines the methodologies and datasets utilised within this study. Section 4 describes the results of both the historical accident analysis and benchmarking with NRAs. Section 5 includes the discussion which draws out several insights into the NRA process which could be improved, before conclusions are drawn in Section 6.

2 LITERATURE REVIEW

Within the United Kingdom, the National Policy Statement (NPS) for Renewable Energy Infrastructure (DECC, 2011) recognises that OWFs will inevitably have some impact to navigation. The NPS states that no consent should be given for "applications which pose unacceptable risks to navigational safety after all possible mitigation measures have been considered" (DECC, 2011: 53). To demonstrate this, each applicant is required to undertake an NRA in accordance with the guidance produced by the Maritime and Coastguard Authority (MCA), namely Marine Guidance Note (MGN) 654 (MCA, 2021b). In addition, the Methodology for Assessing the Marine Navigational Safety and Emergency Response Risk for OREIs (MCA, 2021a) describes some methodological approaches to achieving this.

The underlying principle of these is following the International Maritime Organisation's (IMO) Formal Safety Assessment (FSA) methodology (IMO, 2018), which is the most prevalent structure for maritime risk assessment within the industry (Montewka et al. 2014). The IMO's FSA methodology consists of five key stages; identifying hazards, assessing the risks, identifying appropriate risk mitigation measures, undertaking a cost benefit assessment and, finally, presenting recommendations. The FSA recommends that the "characterization of hazards and risks should be both qualitative and quantitative, and both descriptive and mathematical, consistent with the available data" (IMO, 2018:5). In the absence of available datasets, "expert judgement, physical models, simulations and analytical models may be used to achieve valuable results" (IMO, 2018:6).

Therefore, as with EIAs more generally (Glasson et al. 1999), an NRA is a predictive exercise which seeks to identify, measure and mitigate any risks or impacts to the safety of navigation as a result of the OWF (Mehdi et al. 2018). A key challenge relates to the sparsity of historical data of relevant accidents (Mehdi et al. 2018; Yu et al. 2020a). Therefore, it is common for quantitative tools and qualitative expert judgement to be utilised to assess the likelihood and consequence of these impacts. Significant work has sought to develop quantitative risk models to assess maritime risk (Li et al. 2012; Lim et al. 2018; Kulkarni et al. 2020). These include the development of dynamic traffic simulations (Fujii and Tanaka, 1975), aggregated geometric models (Pedersen, 1995) and Bayesian Networks (Hanninen, 2014) amongst many others (OpenRisk, 2018). Many of these approaches have been adopted by researchers to assess the specific risks of OWFs (Mehdi et al. 2018).

Mehdi et al. (2019) develop a dynamic risk model that accounts for the manoeuvrability characteristics of vessels to identify interactions between vessels and turbine structures. Often a combination of modelling and expert input is used, such as the assessment of the risks associated with the US Atlantic development of OWFs undertaken by Copping et al. (2016). Yu et al. (2020a) constructs a Bayesian Network utilising data from the Automatic Identification System (AIS) that is sensitive to the movement characteristics and risk profiles around OWFs. This is expanded upon in Yu et al. (2021) to integrate a geometric collision model and tested using a case study at Burbo Bank OWF. Mou et al. (2021) utilise fault trees to assess numerous risks to OWFs, including collision risks with vessels. To assess the consequence of impacts between vessels and turbines, finite element analysis has been utilised (Dai et al. 2013; Moulas et al. 2017). These models can produce more quantitative and evidence-based metrics than other methods might allow.

In each of these approaches, the models are subject to key areas of uncertainty. Firstly, there is uncertainty of how vessel navigation will change as a result of a new OWF. Some studies have sought to address this gap by analysing the experience at constructed OWFs to better predict the impacts of future OWFs, such as passing distances and distributions. For example, Rawson and Rogers (2015) compare the change in traffic flows in the Thames Estuary, whilst Yu et al. (2020b) focus their analysis in Chinese waters. Secondly, the validity of the underlying quantitative models has been questioned by several researchers. Results from collision modelling methodologies have been shown to vary depending on which model is utilised (Goerlandt and Kujala, 2014) and to have weak correlations in some cases (Rawson and Brito, 2021). Others have questioned the underlying assumptions in maritime risk models (Mazaheri et al. 2014; Altan, 2019). Furthermore, it is difficult to assess the validity of the underlying models and their applicability to OWFs given the sparsity of historical accident data.

Given these limitations, subjective data is utilised in risk evaluation (Yu et al. 2020a) and within an industry context, the majority of decision making is reliant on expert judgement (Munim et al. 2020). The National Policy Statement (DECC, 2021) and MCA guidance documents (MCA, 2021b) give significant weight to the views of stakeholders on the impacts of OWFs and encourage consultation through the risk assessment process. Significant work in the social sciences has demonstrated how experts can be subject to bias and heuristics which might impact the accuracy of their judgements (Tversky and Kahneman, 1971; Slovic et al. 1979; Kahneman et al. 1982; Tetlock, 2005; Rae and Alexander, 2017).

The challenges introduced through limitations in modelling and expert judgement are not unique to OWFs and have been widely explored in the literature on the IMO’s FSA process (Skjong and Wentworth, 2001; Yang et al. 2008; Sun et al. 2018). More broadly, several authors have drawn attention to limitations in probability-based risk assessments (Aven and Zio, 2011) and attention to uncertainties in EIAs specifically (Tennoy et al. 2006; Lees et al. 2016). It has often been concluded that EIAs present much greater confidence in their predictions than can be reasonably warranted from the methodologies employed (Tennoy et al. 2006; Duncan, 2008). More generally, EIA’s have been criticised by the scope of their assessment, the quality of research and their level of transparency (Fairweather, 1994). Whilst some have proposed frameworks through which to evaluate EIAs (Lee et al. 1999; Fenner-Crisp and Dellarco, 2016), there has been little attention to maritime risk assessments, and NRAs for OWFs specifically. Furthermore, several authors have noted that maritime risk assessments rarely reflect the inherent uncertainties within their studies, arising from input data, parameter estimates and modelling methodologies (Knapp and Hoorn, 2017).

This paper addresses these shortcomings by developing a framework for a reality check (Goerlandt et al. 2017) of the predictions made by NRAs within the UK against the historical incident record. From this, the validity of previous NRAs can be assessed, shortcomings identified and methods to address them proposed.

3 METHODOLOGY AND DATA

3.1 APPROACH

A multistage methodology was developed that is summarised in Figure 1. Firstly, a search was conducted for NRAs published in the public domain for OWFs in the UK waters (see Section 3.2). Secondly, numerous incident databases were searched for incidents relating to OWFs within the UK (see Section 3.4). In both cases, the hazards were identified which related directly to the offshore wind farm, either occurring within the spatial boundaries of the site or involving project vessels. The resulting datasets were analysed to derive the expected frequencies and the actual frequencies of incident occurrence per project and nationally, which has been compared. Each of these methodological steps is expanded upon in the following sections.

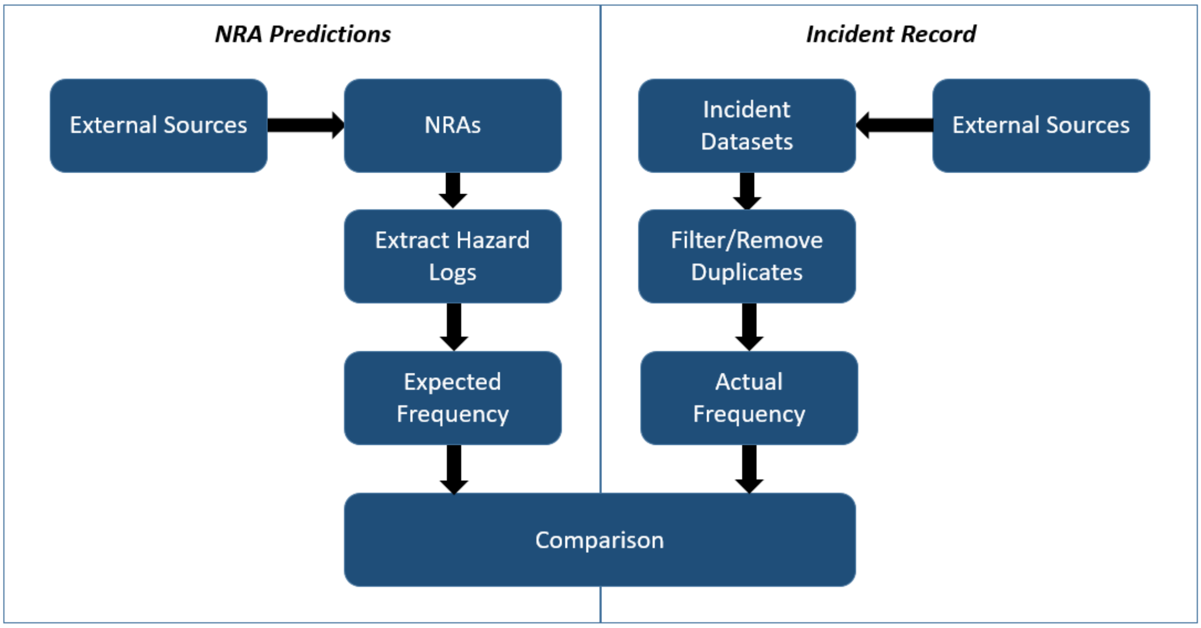

Figure 1: Methodological Approach.

3.2 IDENTIFYING NRAS

A survey was conducted of NRAs of OWFs in the UK Exclusive Economic Zone (EEZ) published between 2002 and 2019. A systematic search was undertaken from three principal data sources which are described in Table 1.

Table 1: NRA sources

Source	Description
National Infrastructure Planning Portal	For projects exceeding thresholds as per the Planning Act 2008, the portal provides application documents for ongoing or recently submitted projects (https://infrastructure.planninginspectorate.gov.uk/).
Marine Data Exchange	The Marine Data Exchange (MDE) is a system that The Crown Estate has developed to store, manage and disseminate offshore survey data for offshore developments (https://www.marinedataexchange.co.uk/).
Web Searches	For other projects, some developers host application documents on the respective project websites. Each project was searched for using a web search engine to identify any NRAs in the public domain.

Of 54 projects identified, NRAs were available for 26 of them (shown in Figure 2). Of these 26, 14 are fully operational, one is under construction, five have been consented but not constructed, four will shortly be submitted or are currently being examined by the Planning Inspectorate and two have been cancelled either due to financial reasons or were refused planning permission. Three commercial consultancies accounted for all of the reviewed NRAs, namely Anatec (19), Marine and Risk Consultants Ltd (Marico) (5) and Strategic Marine Services (SMS) (2).

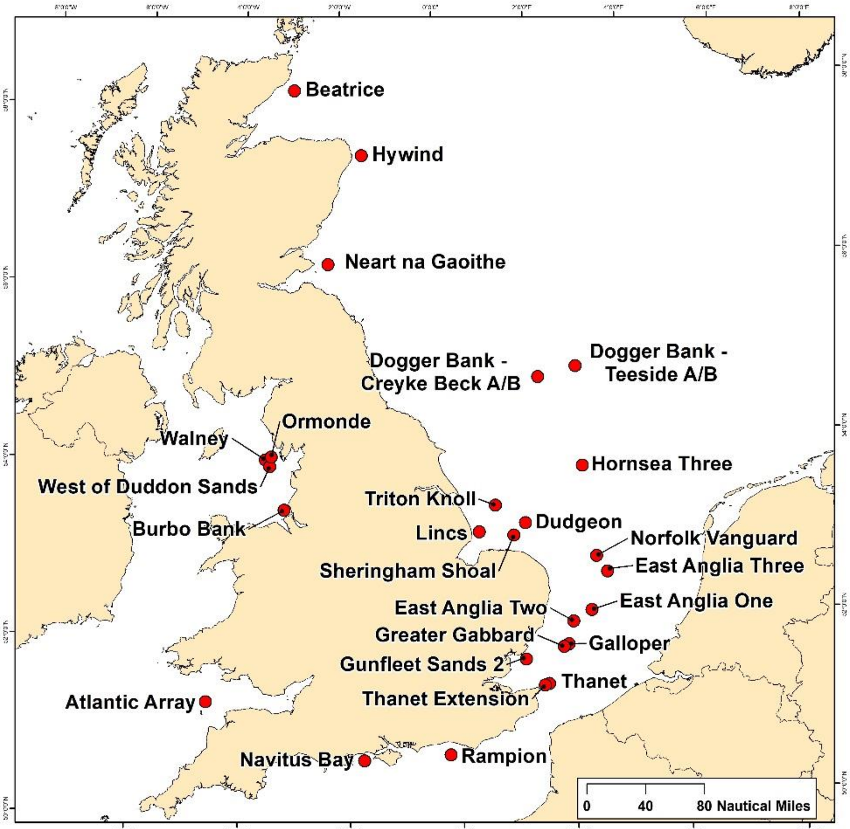

Figure 2: Locations of Reviewed Wind Farms.

3.3 DERIVING HAZARD LIKELIHOOD PREDICTIONS

To meet guidance documents (MCA, 2021a; 2021b) each NRA is required to produce a structured hazard log that provides likelihood and consequence values for each hazard. The hazard log synthesises all aspects of the study and enables judgement of the significance of different hazards, and whether the risks are Tolerable or additional mitigation is required. Therefore, for every NRA the predicted likelihood of different accident events occurring can be derived.

Table 2 shows a representative hazard log with each row corresponding to an identified hazard, with the description, causes and likely consequences of that hazard provided. Finally, numerical values are provided for the consequence and likelihoods, using a set of criteria provided. An example of frequency criteria is provided in Table 3, with both qualitative and quantitative descriptions given.

Table 2: Example Hazard Log.

Risk No.	Hazard	Risk Description	Most Likely			Worst Credible			Average Risk Score	Mitigation Measures
			Probability	Consequence	Risk Score	Probability	Consequence	Risk Score		
1	Collision	Ship collides with another vessel.	5	3	15	2	5	10	12.5	Pilotage, VTS, TSS, Buoyage etc.
2	Allision	Ship strikes turbine.	5	2	10	2	5	10	10	Pilotage, VTS, TSS, Buoyage etc.

Table 3: Likelihood Criteria used in Thanet Extension NRA (Marico Marine, 2018).

Score	Definition
1	Remote/Negligible (<1 per 1,000 years)
2	Unlikely (1 per 100-1,000 years)
3	Possible (1 per 100 years)
4	Likely (1 per 10 years)
5	Frequent (1 yearly)

It is notable that all NRAs utilise a categorical value for hazard likelihood (Table 3) and therefore each score presents a range of values which might be interpreted differently by stakeholders (Ang and Buttery, 1997). For example, an assigned score of 3 must range from the minimum probability of score 4 to the maximum probability of score 2 (1 in 10 years to 1 in 100 years). In order to capture this range, three probabilities are extracted, a high interpretation (0.01), a low interpretation (0.1) and a mid-interpretation (0.05). This reflects multiple interpretations of the hazard that might be considered by the risk assessors and stakeholders. Furthermore, as in Table 2 the hazard log provides a "most likely" and a "worst credible" description of the hazard. To derive a single likelihood score value, both return periods are combined as non-mutually exclusive events, such that P(A or B) = P(A) + P(B) – P(A and B). By way of example, for a hypothetical hazard entitled "Fishing Vessel Allision with Turbine", the probabilities can be extracted as below in Table 4. This was repeated for each hazard and then the scores aggregated into different hazard categories.

Table 4: Hazard probability extraction process

Category	Given Value	Description from Matrix	Interpretation (P/Yr)
Most likely	4	1 per 1 to 1 in 10 years	High = 1.0 Mid = 0.5 Low = 0.1
Worst Credible	3	1 per 10 to 1 per 100 years	High = 0.1 Mid = 0.05 Low = 0.01
		Total	High = 1.0 Mid = 0.525 Low = 0.109

3.4 HISTORICAL INCIDENTS

No database exists specifically of navigation incidents involving OWFs, and the authors are not aware of any previously published work that includes such a database. Therefore, five principal sources of incident data were reviewed, including official UK accident databases and secondary sources (Table 5). Where possible, the date, accident type, vessel types, relevant project site and incident narrative were retained. Whilst it is likely that minor incidents are under-represented (Hassel et al. 2011; Qu et al. 2012), the authors believe this is the most comprehensive dataset on UK navigational incidents in OWFs. Given the various time extents of the datasets, the subsequent analysis is limited to the years 2010-2019. Each record was manually checked to ensure that duplicate values between databases were identified and removed.

To determine the relevant incidents in the Marine Accident Investigation Branch (MAIB) and Royal National Lifeboat Institution (RNLI) databases, a two-stage process was undertaken. Firstly, a keyword search was conducted on the vessel types and narrative description to include only wind farm service vessels and mentions of wind turbines. Secondly, the locations of the navigational accidents were plotted and compared to the locations of offshore wind farms, with a manual review of the descriptions of each adjacent incident. Thereby, only relevant incidents associated with the project were retained.

Table 5: Incident Data sources

Source	Description	Years
MAIB Database	The MAIB database obtained under FoI request was searched to identify all incidents involving windfarm service vessels, or whose description mentions wind turbines or named OWFs.	2010-2019
MAIB Report 23/2013	MAIB Accident Report 23/2013 contains details on previous incidents involving wind turbines.	2009-2012

Source	Description	Years
RNLI	No description is available however Wind Farm Support Vessel (WFSVs) is contained as a vessel type.	2008-2019
Anatec (2018)	The NRA for the Hornsea Three OWF contains a description of previous historical incidents in the UK. However, this data is anonymised.	2005-2016
Web Searches	Internet searches related to “offshore wind farms” OR “wind turbines” AND “collision” OR “contact/allision” OR “grounding”.	2000-2019

Unfortunately, as the incident data is anonymised, in some cases it is not possible to make definitive conclusions about which incidents related to which specific individual projects. This is principally due to OWFs often located near to one another and sharing Operation and Maintenance (O&M) bases, therefore incidents involving maintenance vessels that occur on route or in ports could be related to multiple possible projects. We would naturally except the risk profile to differ between projects, located in different environments with different traffic profiles, yet we cannot fully reflect this and therefore derive national per project averages in these cases. In addition, this means that we cannot easily differentiate between whether a project was under construction or operational at the time of the incident in many cases, which may have different risk profiles.

3.5 COMPARING PREDICTED AND EMPIRICAL HAZARD LIKELIHOODS

The NRA hazard predictions and historical incident record can be compared in multiple ways. Firstly, directly comparing the predicted and observed incident rates for different hazard types and vessel types enables the calculation of the relative ratio between the two hazard probabilities. Secondly, the locations of historical incidents can be reviewed to identify spatial trends. Thirdly, the incident rates can be modelled as random (stochastic) events by assuming their occurrence follows a Poisson process where the events are independent of each other. Where the Poisson process has a constant failure/incident rate, expressed by the parameter λ, it is then called a homogeneous Poisson process (HPP). These assumptions states that the failure rate is independent of time without any accelerating or decelerating tendency, hence λ has a constant rate. Equation 1 describes a Poisson random variable where λ is the number of events occurring during a fixed time interval and i is the number of events occurring. Such distributions have been routinely used for flood frequencies (WMO, 1989), road accidents (Nicholson and Wong, 1993) or offshore accidents such as fires (Halim et al 2021).

$$P(x=i)=e^{-\lambda}\frac{\lambda^{i}}{i!} \tag{1}$$

This enables us to better visualise the distributions of NRA predictions and historical incident records across different hazard types. Further, we can demonstrate the range in interpretations that a categorical frequency scale entails.

4 RESULTS

The results of the analysis described below include the historical incident record, the NRA predictions and comparison between them.

4.1 HISTORICAL INCIDENT ANALYSIS

In total, 69 incidents were identified which consisted of 6 collisions between vessels, 29 allisions of a vessel with a fixed structure, 21 groundings and 13 near misses. Figure 3 shows the temporal distribution of these events, indicating that the number of incidents increased between 2011 and 2014. This may also be due to the greatly increased number of projects under construction and operational during this period (Crown Estate, 2021) which increases the likelihood of an incident.

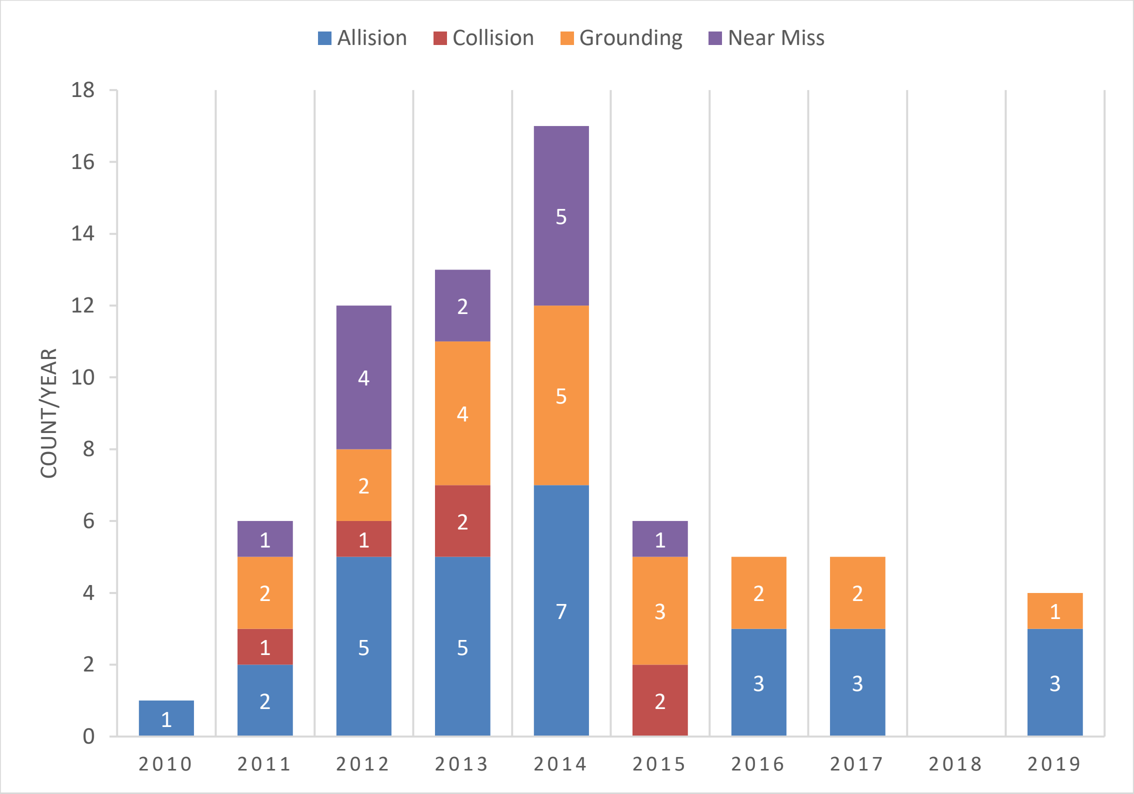

Figure 3: Incident types and count per year.

Incidents have also been categorised by location, with 36% occurring within the array area, 20% occurring in waters outside of the array area and 43% occurring within ports, typically the O&M base for a project. Figure 4 shows the location of all navigational accidents around constructed OWFs in the UK. The majority of accidents have been concentrated in inshore waterways such as harbours and port approaches. Figure 4 shows three regions in the UK which have significant OWF developments: the Irish Sea, Thames Estuary and the Wash Estuary. In general, there have been few historical accidents either at or adjacent to these development sites. Of these, the majority are construction or maintenance vessels colliding with each other or project structures. Where the data extent includes pre and post construction, the spatial analysis does not identify any statistically significant increase in historical accidents adjacent to the project sites following their construction.

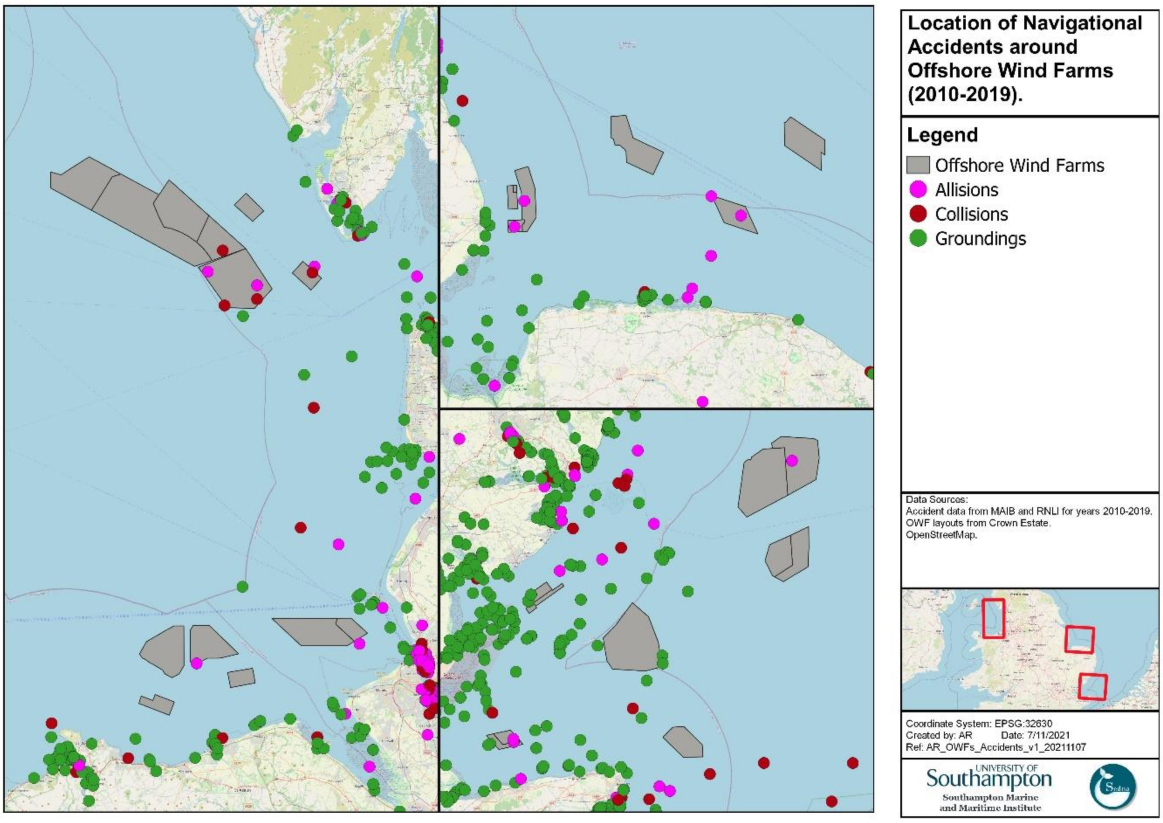

Figure 4: Location of Incidents around OWFs.

Figure 5 shows the activities around Sheringham Shoal OWF from AIS data and the historical incident record. Three allisions have been recorded within the footprint of the wind farm, involving Wind Farm Support Vessels (WFSVs) contacting turbines. In addition, groundings and collisions have been recorded in the entrance to Wells-Next-The-Sea where the O&M base is located. Importantly, no other incidents involving other vessel types were recorded adjacent to this site since construction begun in 2010.

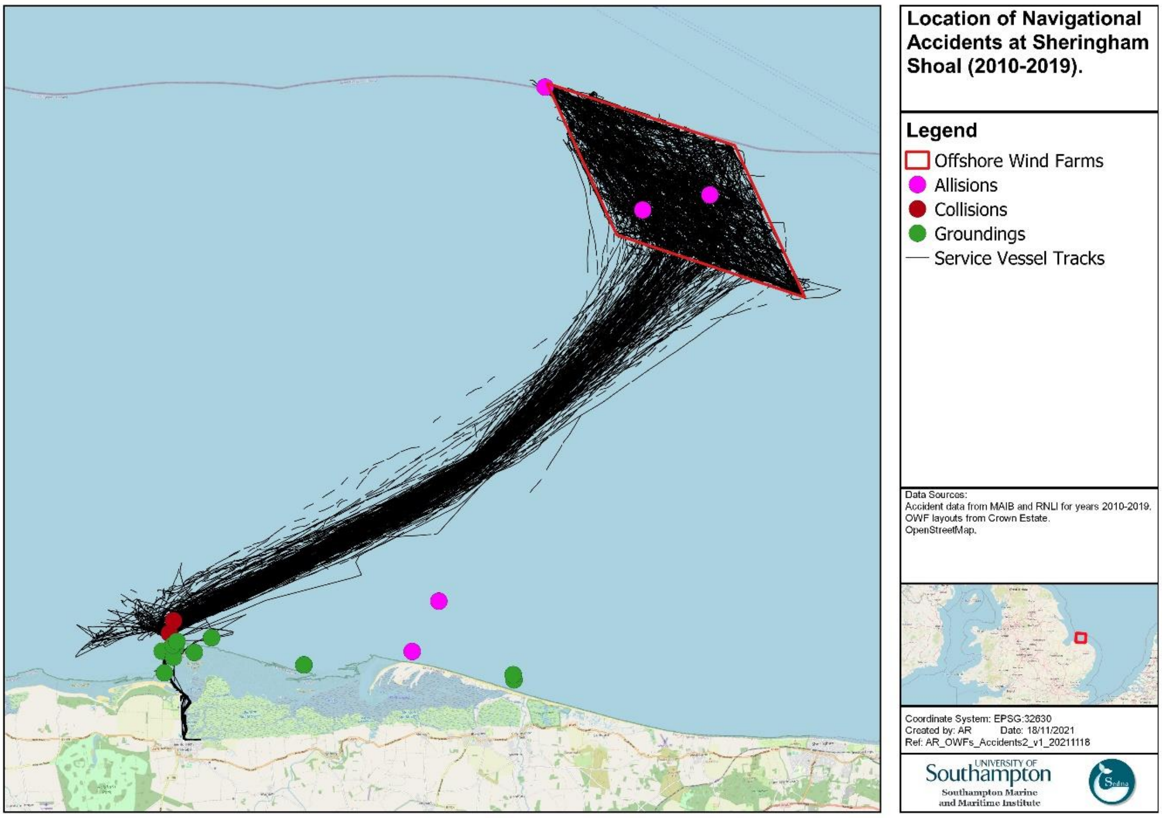

Figure 5: Tracks and Incidents at Sheringham Shoal OWF.

Table 6 shows the number of incidents by type, noting that collisions and near misses necessarily involve two vessels per incident. 82% of all incidents involve WFSVs, accounting for 93% of allisions and 100% of groundings. As these vessels are the most frequent type operating in close proximity to a project, this result is unsurprising. Every grounding involved a WFSV on route between an O&M base and a project site. Allisions account for approximately half the recorded incidents, the majority of which are WFSVs coming alongside turbines within the array area. Few allisions are recorded by a non-project vessel, however, anecdotally there have been more allisions involving fishing and recreational vessels which are unreported.

Table 6: Incidents by Vessel Type.

Vessel	Allision	Collision	Grounding	Near Miss	Total
WFSV	27	9	21	15	72
Fishing	2	0	0	2	4
Recreational	0	2	0	4	6
Other	0	1	0	5	6

The aforementioned analysis shows absolute numbers of incidents, but to determine the relative frequency of occurrence it is necessary to calculate an incident rate (Bye and Almklov, 2019). To achieve this, a list of 38 projects were identified and their approximate dates of construction and commissioning identified. From this, it can be determined that between 2010 and 2019, there have been cumulatively 45.4 years of construction activities in the UK sector, and a further 226.8 years of operational activity. From this, the average incident rate per year of activity can be estimated and is shown in Table 7.

Where the information was available, 50% of incidents occurred for operational projects and 50% occurred for projects under construction. Given the significant greater exposure of operational projects, this suggests that incidents are proportionally more likely to occur during construction periods. Some of the historical incidents have involved partially constructed or marked turbines which are difficult to identify (MAIB, 2013). Furthermore, the activities necessary during construction are far more frequent than operationally, necessitating more vessels navigating between turbines and coming alongside. Allisions are approximately three times more likely to occur per year of construction than year of operation.

Table 7: Incident Rates.

Incident Type	N	Rate	Return Period
Collision	6	0.022	45.4
Grounding	21	0.077	13.0
Near Miss	13	0.048	20.9
Total Allision	29	0.107	9.4
WFSV Allisions	27	0.099	10.1
Fishing Allisions	2	0.007	136.9
Total	43	0.254	3.9

4.2 NRA PREDICTION ANALYSIS

Of the 26 NRAs identified, the hazard logs were extractable for 18 of them (69%). The hazard likelihood scores for allisions and collisions were extracted and aggregated to produce the predictions per project, a summary of which is shown in Figure 6 for the mid-value interpretation. On average, allisions are seen as more likely compared to collisions, largely due to WFSV’s, with fishing vessels and commercial vessels less likely to have such an incident respectively. It should be noted that there are some significant outliers in the results, the Thanet OWF Extension for example estimates 8 allisions per year and is therefore outside the bounds of Figure 6. Of the NRAs analysed, the Thanet Extension was one of the few projects which was denied consent due to navigation safety issues and therefore this predicted high-risk score is perhaps an accurate reflection of the high underlying risk of the project.

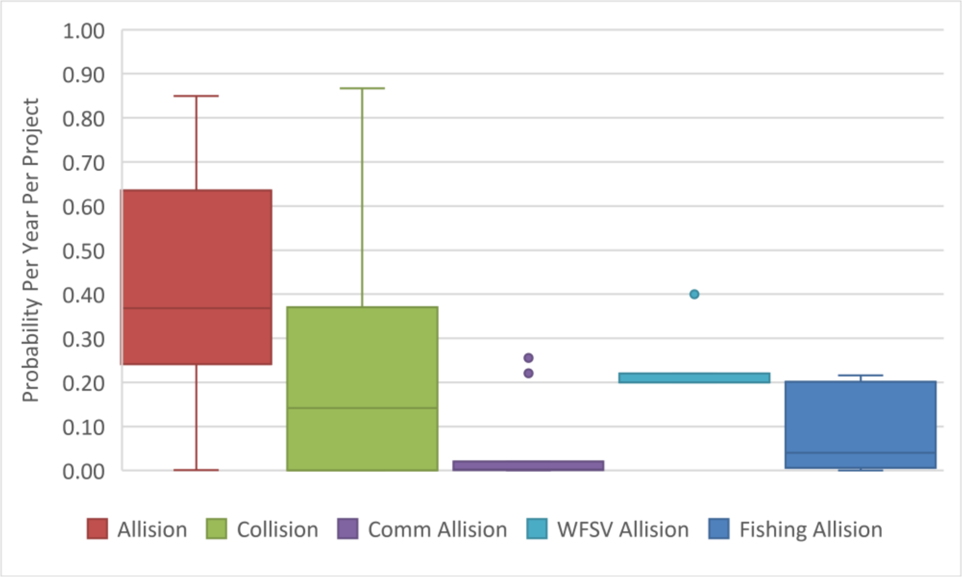

Figure 6: Comparison of hazard likelihood scores (Mid categorical interpretation).

4.3 BENCHMARKING OF RISK ASSESSMENT AND INCIDENTS

Table 8 compares the aggregated probabilities from the NRAs with the calculated incident rates. Each row indicates the predicted probability of occurrence of that hazard during the operational phase of the NRAs and the incident rates for the relevant hazard type. Based on the median predicted likelihood across the 18 NRA hazard logs reviewed, the approximate national incident frequency with 38 projects can be derived. Utilising the hazard probabilities and incident rates fit to a Poisson distribution, we can plot and compare distribution densities for different incident types (Figure 7). They show the significant range in probabilities that can be obtained by different interpretations of the likelihood values used in the assessment.

The results show a significant overestimate of hazard occurrence for every category. For example, the median allision expected frequency is between 1.77 and 0.19 incidents per project year. By contrast, the historical incident record suggests that the actual rate is between 4.85x10^{-2} and 1.07x10^{-1}, accounting for uncertainties in which phase of a project historical incidents had occurred. This suggests that allisions are being estimated at between 1.7 and 16.7 times more likely in the NRA than the incident rate would suggest. Scaled across the 38 OWFs, we would expect between 7 and 67 allisions every year, when the historical incident record shows an average of 2.9.

These differences are more significant if we consider vessel types. Fishing vessels are scored between 2.8 and 29.4 times more likely, albeit there is likely underreporting for these vessel types within the incident data (see Section 3.4). For WFSVs, this difference is less pronounced but still significant with between a 1.0 and 10.1-fold difference. Of particular note are commercial ship collisions with wind turbines which have not occurred within the UK, estimated at between 1.1x10^{-3} and 1.0x10^{-1} per project per year, and as such we should expect between 0.3 and 27 incidents to have occurred during the 272 years of exposure.

Table 8: Comparison of Values.

		Median from NRAs	Total from 18 Projects	Projection with 38 projects	Total Incident Rate	Ratio Incidents: NRA
Allisions	High	1.77E+00	43.89	67.42	9.21E-02	16.65
	Mid	3.68E-01	12.22	13.99		3.46
	Low	1.85E-01	4.67	7.04		1.74
Collisions	High	7.40E-01	48.10	28.12	1.67E-02	33.57
	Mid	1.42E-01	19.09	5.39		6.43
	Low	7.09E-02	5.13	2.70		3.22
Fishing Allisions	High	2.16E-01	16.94	8.21	4.18E-03	29.40
	Mid	4.04E-02	6.51	1.53		5.50
	Low	2.02E-02	1.80	0.77		2.75
Comm Allisions	High	1.01E-01	5.56	3.83	0.00E+00	N/A
	Mid	2.20E-03	1.05	0.08		N/A
	Low	1.10E-03	0.53	0.04		N/A
WFSV Allisions	High	1.00E+00	17.37	38.00	8.79E-02	10.08
	Mid	2.00E-01	3.48	7.61		2.02
	Low	1.00E-01	1.74	3.80		1.01

It is of note that the most well calibrated incident type are allisions involving WFSVs, with a low distribution of predictions (Figure 6). This much higher confidence and accuracy might reflect that this is the most frequent hazard type, and therefore there is the most historical data for which to calibrate risk predictions.

Whilst we have chosen to use a median risk assessment score in this assessment in order to account for outliers, were the mean hazard likelihood used, the predicted risk scores would be far greater. Allision likelihood, for example, has a mean to median ration of between 1.4 and 1.8. For allisions involving WFSVs this is less at 1.16 whilst for commercial vessel allisions, this ranges from 3.1 up to 26.6. This difference is significant, reflecting high risk scores assigned to commercial allisions in some of the NRAs.

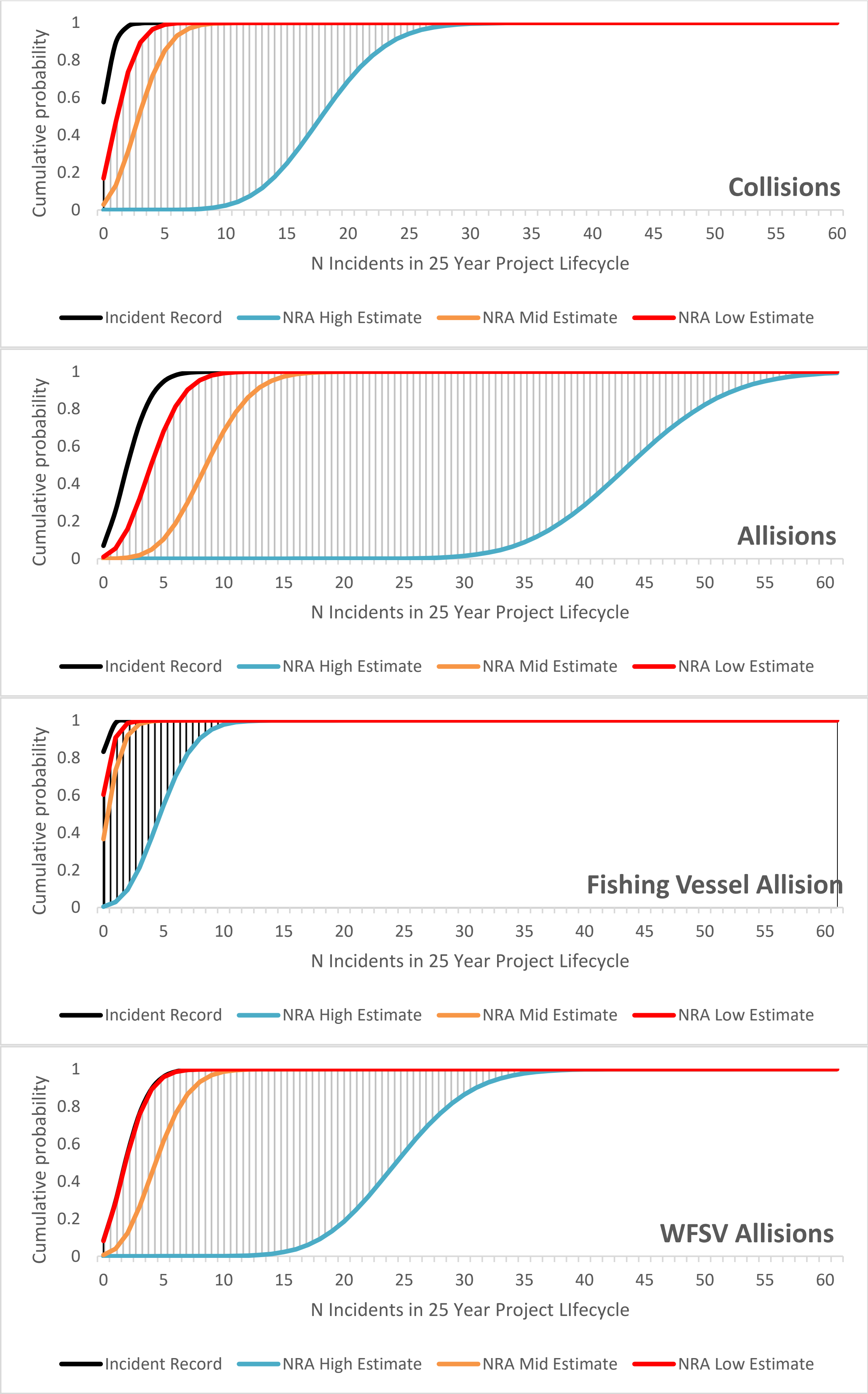

Figure 7: Comparison of NRA and Incident Cumulative Distributions.

5 DISCUSSION

The results of the analysis indicate that navigation accidents at OWFs in the UK are rare, typically involving project service vessels. Furthermore, the predicted frequency at which they occur greatly exceeds the actual frequency, suggesting that NRAs are poorly calibrated. The majority of NRAs purport to follow the guidance of the IMO's (2018) Formal Safety Assessment (Mehdi et al. 2018), in common with wider maritime risk studies (Montewka et al. 2014). Therefore, to better understand some of the reasons as to why this discrepancy could occur and how these challenges might be addressed, each stage of the FSA is discussed within this section.

5.1 FSA STAGE 1: IDENTIFICATION OF HAZARDS

The NRA should initially identify a list of hazards and associated scenarios specific to the problem under review (IMO, 2018). Whilst to some extent the regulatory guidance dictates some of these decisions, these choices have an inevitable impact upon the resulting hazard scores. Firstly, the choice of study area size and resultant absolute risk scores are correlated; larger study areas inherently will have a greater risk than a smaller study area. Furthermore, where risk scores are comparative between baseline and future case, larger study areas will exhibit a relatively smaller increase than if the study area were more local to the development; as more vessels, routes and hazards are included in the scope even if not necessarily impacted by the development. Therefore, it is important that the study areas and assumptions of an NRA are agreed between regulators, stakeholders and the applicant at the outset.

Secondly, the choice of hazard definitions varies significant between the assessments. An incident would involve a combination of vessel type, area, accident type or wind farm stage (construction or operation) and therefore many permutations are possible. One NRA might consider a hazard entitled "Powered vessel collides with turbine", whereas another might consider "Commercial vessel collides with turbine during construction". As a result, the number of hazards varies between 13 and 850 across the NRAs reviewed, with hazards decomposed into smaller more manageable problems, but there is mixed evidence as to whether this improves or detracts from the accuracy of the forecasts (Rae and Alexander, 2017).

Thirdly, NRAs must assess the risks throughout the project lifespan, of approximately 25 years. In all NRAs reviewed, only one future case scenario is assessed and therefore the parameters that define this would have a significant bearing on the overall results. Decisions are required as to the likely passing distance ships would pass from the boundary of an OWF given other navigational constraints. Within the literature a range of values have been proposed of between 0.5nm and 2nm (Rawson and Rogers, 2015; Yu et al. 2020b). Assuming a closer passing distance in the future case might result in a greater perceived risk. Furthermore, risks during this period would change due to increased traffic volume and this too needs to be accounted for. In almost all the NRAs, a 10% uplift in traffic is estimated without supporting evidence, suggesting that this is convention and not necessarily reflective of expert forecasts. Furthermore, routes taken by vessels is also impacted by other developments, with cumulative and in-combination effects of multiple projects having a significant impact upon the validity of NRA predictions. These assumptions should be better tested within the context of the NRAs.

5.2 FSA STAGE 2: RISK ANALYSIS

Having identified scenarios and hazards, the NRAs then undertake a detailed assessment of the likelihood and consequences of accidents at the project sites. All NRAs reviewed included two principal inputs into risk analysis, risk modelling and expert judgment, which are considered in turn.

5.2.1 The Role of Models and Modelling in NRAs

The FSA guidance promotes the use of evidence based and quantitative risk models (IMO, 2018), and these methods have been adopted by OWF NRAs. The implication is that the use of models promotes a scientific, rigorous and evidence-based approach to the assessment, ensuring conclusions are robust. Reviews of maritime risk models within the literature (Lim et al. 2018; Kulkarni et al. 2020) have shown the breadth and capabilities of such methods. Within industry, several reviews have shown that consultancies performing NRAs have adopted some of these methods (Ellis et al. 2008; OpenRisk, 2018). Of the 26 NRAs reviewed, only three did not present some form of quantitative risk modelling, and there is no explicit requirement within the guidance as to which tools should be utilised (MCA, 2021a). The review identified that route modelling to assess potential contact risk (for example following Pedersen, 1995) and domain modelling to assess potential collision risk (for example following Fujii and Tanaka, 1975) using AIS data are the most common.

Yet, the reviewed NRAs implemented different interpretations and assumptions of these models that inevitably influences resultant risk scores. Whilst comparisons are rare, the Thanet Extension was assessed by two consultancies using domain analysis (Marico Marine, 2018; Anatec, 2019), resulting in a significant difference in collision risk increases of 50% and 2.2%. Such a conclusion was also demonstrated by Goerlandt and Kujala (2014) who demonstrated a lack of inter-methodological reliability. A challenge with EIAs more generally (Tennoy et al. 2006; Duncan 2008) and NRAs specifically is the ability to validate the model results, given model assumptions and limitations. It is common for consultancies to employ proprietary algorithms which can be largely described as “black box”, with commercial sensitivity as to the specific methodologies and values employed (Psaraftis, 2012). Furthermore, the onus is on the developer or consultant to self-declare the validation of their model (MCA, 2021a) and therefore it becomes impossible for either the regulator or stakeholders to fully assess the accuracy and uncertainties inherent within them. Interviews conducted with regulators by Mehdi et al. (2018) contradicts this assertion, suggesting that some regulators believe that these models are sufficiently transparent, but there is insufficient detail within the NRAs reviewed to support this. Whilst some earlier work has suggested that historical incidents could be used for validation, such as previous groundings (Christiansen et al. 2001), this review has shown there is an insufficient historical incident record for this purpose. Other models have been proposed which are tailored to OWFs (Mehdi et al 2019; Yu et al. 2021) and therefore may be better able to capture these risks. However, these have not received significant industry uptake.

To complement risk models, several NRAs rely on realistic and immersive full-bridge ship simulation to test specific challenges related to that project. Such an approach is advantageous over computer models as it is transparent and enables the human element and decision making of the ships masters to be tested. However, there is significant cost, both financially and the requirement for suitable and experienced personnel to spend large amounts of time at the simulator. Therefore, it would not be practical to run all permutations of weather, vessel type, participants and traffic conditions and therefore a sample is required. For example, simulation was used to test the feasibility of continued pilotage operations in a constricted waterway with the development in place (Marico Marine, 2019). 159 pilot transfers during seven days of simulations with nine independent pilots across a range of conditions and vessel types were conducted (Marico Marine, 2019). Such an approach might provide a more tangible and stakeholder led method to model the impacts of OWFs.

5.2.2 Eliciting Expert Judgements in NRAs

Given the uncertainties and challenges associated with maritime risk modelling (Yu et al. 2020a), expert judgement is often the principal input to maritime risk assessments (Munim et al. 2020). This is typical of decision making for potentially large consequence outcomes, whereby the deliberative group exercise allows the inclusion of non-modelled issues (Aven and Zio, 2011). Given the relative scarcity of relevant data, experts might provide accurate forecasts as they have access to privileged industry information, have significant domain knowledge or might be generally better forecasters (Rae and Alexander, 2017). The term expert is ambiguous (O'Hagan, 2006; Rae and Alexander, 2017) but might suggest persons with significant knowledge of a subject. Expertise in NRAs is provided by the consultants, regulators, fishermen, recreational users, ports, and other local stakeholders within the area of the project. Many of the NRAs report the use of stakeholder consultation of hazard workshops to score the risks and produce the hazard logs. Whilst there are several structured and reliable methods for undertaking this (O'Hagan, 2006), there is very little documentary evidence as to how this process was achieved. Given the lack of historical evidence on maritime risk for OWFs this paper has highlighted, expert judgement may be most necessary but also most questionable for several reasons (Rae and Alexander, 2017).

Firstly, experts are subject to biases and heuristics which might make their predictions inaccurate and overconfident (Tversky and Kahneman; 1971; Slovic et al. 1979; Adams, 1995; Rae and Alexander, 2017). More generally, biases and heuristics, such as anchoring, representativeness and availability naturally influence human decision making (Kahneman et al. 1982; Kahneman, 2011). Furthermore, Tetlock (2005) showed that many experts have limited predictive accuracy, albeit this is a result in their style of reasoning rather than their expertise per se. Secondly, these judgements are undermined by a lack of historical data, a reference class, against which to calibrate the accuracy of their predictions (Rae and Alexander, 2017). Base case neglect and the unfamiliarity with OWFs for local stakeholders in some cases can make quantifying the associated risks of OWFs challenging. Thirdly, the NRA process is undermined by a lack of feedback. As with other EIA contexts (Duncan, 2008), NRAs are not routinely audited or monitored post-consent and therefore the accuracy of either the assumptions or the predictions is not reviewed. This might result in poor practice and inaccurate assumptions propagating through NRAs as navigation safety does not enable verifiable, timely and unambiguous feedback.

Methodologically, the reliance of NRAs on hazard logs and risk matrices has several inherent weaknesses (Cox, 2008; Hubbard, 2009; Kontovas and Psaraftis, 2009). These include problems defining the categories, inability to reflect uncertainty and mapping continuous variables to a discrete two-dimensional grid. Others have shown that the use of categorical or descriptive measures of probability can be interpreted very differently. For example, within the NRAs “Probable” is used to describe events that occur between once in one year and once in ten years, by contrast Renooki and Witteman (1999) derived “Probable” as and 85% chance and Ang and Buttery (1997) defined it as a 10% chance. Two experts could therefore interpret the risks very differently but utilise similar languages to describe it.

Whilst there are limitations and challenges with including expert judgement, the expertise of stakeholders is essential in OWF NRAs where there is little historical data. Therefore, structured methods developed to better train and elicit judgements should be more widely utilised and better documented within NRAs (Szwed et al. 2006; O’Hagan et al. 2006). Others have demonstrated how expert judgement could be better included within maritime risk models such as through Bayesian Networks. For example, Yu et al. (2021) combine a quantitative risk model and a Bayesian Network for an OWF, arguing that this approach provides empirical evidence that is sensitive to the environment and navigational practices of the area.

5.3 FSA STAGE 3 & 4: RISK CONTROL OPTIONS AND COST BENEFIT

To address high risk hazards, risk control measures should be identified and the costs and benefits of each assessed to determine their contribution in reducing risk (IMO, 2018). Within this review, it was noted that not a single NRA presented any cost-benefit analysis. Risk control measures were presented and recommended such as the use of Aids to Navigation, establishing safety zones, routeing measures or re-design of the OWF layout. Each of these controls is potentially of significant cost to the project, yet these are not quantified and conclusions on their requirement is entirely qualitative. There is significant scope to improve the quality of the NRAs by determining an appropriate methodology for presenting cost benefit assessment. The IMO's (2018) FSA guidance documents do present such methodologies based on the principals of Cost of Averting a Fatality. It is a significant failing of NRAs that the risk control measures are not properly justified.

5.4 FSA STAGE 5: RECOMMENDATIONS FOR DECISION MAKING

Finally, having assessed the risks and identified risk control measures, the results should be presented to the relevant decision makers in an auditable and traceable manner (IMO, 2018). Principally, an NRA's underlying purpose is to inform decision makers on the degree of risk associated with a project, whether that risk is tolerable and what risk control measures are required. Within this context, several deficiencies have been noted which might undermine the validity of this approach.

Firstly, there is no clear guidance with NRAs as to what constitutes an acceptable impact to navigation for use by decision makers (Kontovas and Psaraftis, 2009; Psaraftis, 2010). The FSA Guidelines contain an appendix discussing measures and tolerability of risk but explicitly state that it is not intended to provide prescriptive thresholds (IMO, 2018). References are, however, made to guidelines produced by the UK's Health and Safety Executive (HSE) which provide societal risk bounds for loss of life at $1x10^{-3}$ to a crew member per year. Others have argued that a per trip measure of risk acceptability is both a more relevant and practical measure (Psaraftis, 2010). Three of the NRAs attempted to use quantitative risk criteria in the form of fatality probabilities to benchmark the results with published ALARP figures, but most used broader definitions of ALARP using qualitative judgements. This is in contrast to regulations adopted in other European countries where specified quantitative thresholds of risk acceptability are made (Ellis et al. 2008; Mehdi et al. 2018). In Germany, a working group has deemed that the total risk should not be more than 1 in 100 years (Mehdi et al. 2018). It could be argued that these limits are relatively strict when compared to existing incident rates elsewhere in the country, particularly if the incidents are minor in nature.

Secondly, within the UK there is no structured baseline NRA against which the OWF impacts can be benchmarked. Whilst it could be assumed that the underlying risk around a proposed project site is acceptable, or navigation authorities would be implemented further risk controls, the lack of an accepted baseline makes it challenging for different groups to agree on the additional impacts of the OWF. Furthermore, the acceptability thresholds dictate that the impacts of OWFs would need to be significant to be judged intolerable. Between 2015-2019 there were an average of seven fatalities from all causes on merchant vessels in UK waters (MAIB, 2019). Acceptability criteria in many NRAs breach intolerable levels at one fatality between once in ten and once in 100 years (Anatec, 2018; Marico Marine, 2018), significantly more frequent than would be expected from a single area.

Thirdly, in only three of the 26 NRAs reviewed, were the risk assessment results presented cumulatively. The acceptability of an individual hazard is judged against predefined criteria, yet the total risk of the project is assessed only qualitatively. By increasing the number of hazards, the risk scores could be manipulated to ensure they meet acceptable thresholds where they are assessed individually only. Conversely, risk aggregation itself has limitations in potentially hiding high risks to sub-sections of the overall system (Bjornsen and Aven, 2019). More generally, previous research has shown that risk matrices inherently cluster scores in the mid-range of values (Hubbard, 2009).

Fourthly, the review identified that NRAs do not specifically or adequately discuss the uncertainties inherent in their assessments, a common criticism of maritime risk assessments more generally (Goerlandt and Montewka, 2015). For example, single values of likelihood and consequence are presented and therefore uncertainties are not communicated to decision makers (Hoorn and Knapp, 2015). One method used by two NRAs was to increase the likelihood scores for hazards where there was greater uncertainty, taking a more precautionary approach. Confidence intervals or probability distributions could be developed from expert judgement (O'Hagan et al. 2006) or data but the low number of incidents necessitate a wide range of values (Aven and Heide, 2009). Furthermore, a Bayesian approach to risk analysis has been argued as more suitable due to better reflecting uncertainties (Hanninen, 2014), inclusion of a greater number of inputs (Baksh et al. 2018), integration of risk controls (Mazaheri et al. 2016) and being more applicable in situations with scare data (Aven and Zio, 2011).

Finally, the results of this analysis identify that NRAs overestimate the risk, but NRAs typically do not consider the impacts of OWFs on reducing risk. For example, OWF turbines could act as safe havens in an emergency or act as landmarks during search and rescue. Furthermore, an OWF on a shallow bank might reduce the risk of grounding as they are far more visible. WFSVs have on a number of occasions been the first responders to an incident, potentially preventing loss of life. There seems to be no mechanism through which NRAs present this argument that should be taken into account by decision makers.

6 CONCLUSION

OWFs are major infrastructure developments which could have significant impacts on the safety of navigation for all marine users. NRAs are important studies to ensure that any significant risks are identified, accurately characterised and appropriate risk control measures put in place. Failure to accurately calibrate NRAs can result in potentially dangerous developments from being awarded consent, onerous and costly mitigation measures or projects being rejected unnecessarily (Mehdi et al. 2018).

This work provides a detailed analysis of the types and frequencies of maritime accidents at OWFs and compare the predictions made within NRAs against them. The results clearly identify that NRAs overestimate the risk of navigational accidents, given the historical incident record, particularly for incidents involving large commercial shipping. Several potential contributing factors are identified including the study design, methods of expert elicitation, challenges with maritime risk modelling and representation of uncertainty. Given these limitations, the conclusions drawn by NRAs could be easily contested by drawing attention to assumptions and uncertainties that influence the resultant risk scores.

The academic literature has promoted several methodological approaches which can help address these gaps. Recent advances in risk models tailored to OWFs and more structured methods of garnering expert elicitation are used in other disciplines but not routinely for OWF NRAs. Furthermore, there is an absence of any significant consideration of the cost benefits of risk control options. Similarly, presenting uncertainty in risk assessment is important to improve transparency with decision makers. The benefits of advances in these methodologies will not only support the safe expansion of OWFs but serve to improve the quality of analysis and the evidence base for other offshore developments. As there is increasing pressure on already crowded waters, the development of a robust and evidence-based approach to marine spatial planning will promote coexistence of different marine activities and improve safety at sea.

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