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Vulnerability and spatial competition: The case of fisheries and offshore wind projects

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Abstract :

Professional fishing activities are subject to spatial pressures. The cohabitation between a traditional fishing activity and development of the offshore wind energy industry raises questions about space sharing and rules of use. This paper proposes to adapt the vulnerability methodology developed to deal with global threats of climate change to this example of local, non-climatic change using the case study of a floating wind turbine project between Groix and Belle-Île (France). To understand and compare the potential impact of the different artisanal fishing activities, the method aims to conceptualize vulnerability with the identification of social, economic, and environmental key pressures and address them in a composite index. Although the smallest fishing units appear to be the most vulnerable, this effect is associated with a high sensitivity to the area near the coast. This research also highlights the importance of transparency and clarity during the construction of the composite index to avoid misinterpretation. This case study supports the relevance of applying the vulnerability method on a local scale to facilitate dialogue between stakeholders and reduce negotiation costs.

Highlights

► Adaptation of the vulnerability assessment to a new local stressor (offshore wind farm) ► Fishing fleets have a distinct degree of vulnerability. ► Despite the limits, the plasticity of the method offers a wide range of applications.

Keywords : Vulnerability, Socio-Economic Impact, Heterogeneity, Fishery, Offshore Wind Farm

1. Introduction

Growing concerns about energy security and climate change have led the expansion of sustainable technologies in our oceans (Alexander et al., 2013). In line with EU Directive 2009/28/EC, the number of offshore projects – particularly offshore wind farms – is increasing. Marine systems are, however, already subject to strong environmental (global warming, increases in invasive species), economic (growing numbers of regulations, development of offshore aquaculture), and social (increase in competition between stakeholders) pressures (Bennett et al., 2014). Thus, the development of renewable energy at sea places additional stress on socio-ecological systems, especially traditional fishing communities (Christie et al., 2014).

Numerous studies have focused on the optimal location for offshore wind farms, considering socio-economic and ecological aspects (Punt et al., 2009; Mackinson et al., 2006; Tien and van der Hammen, 2015), the acceptability of projects according to the types of compensation envisaged (Kermagoret et al., 2016), or the perception of risks and benefits (Klain et al., 2018; Silva et al., 2019). To date, little attention has been paid to assessing the socio-economic effects of wind farms on traditional fishing activities, considering the heterogeneity of fishing communities. Fisheries are often composed of fleets with different physical (Alban and Boncoeur, 2004), economic (Jardine et al., 2020), natural (Morgan, 2016), human (Guyader et al., 2013) and social (Rosas et al., 2014) dimensions. It is, therefore, essential to assess the socioeconomic impact of changes on heterogenous fishing activities subject to spatial competition with a holistic point of view (Jardine et al., 2020).

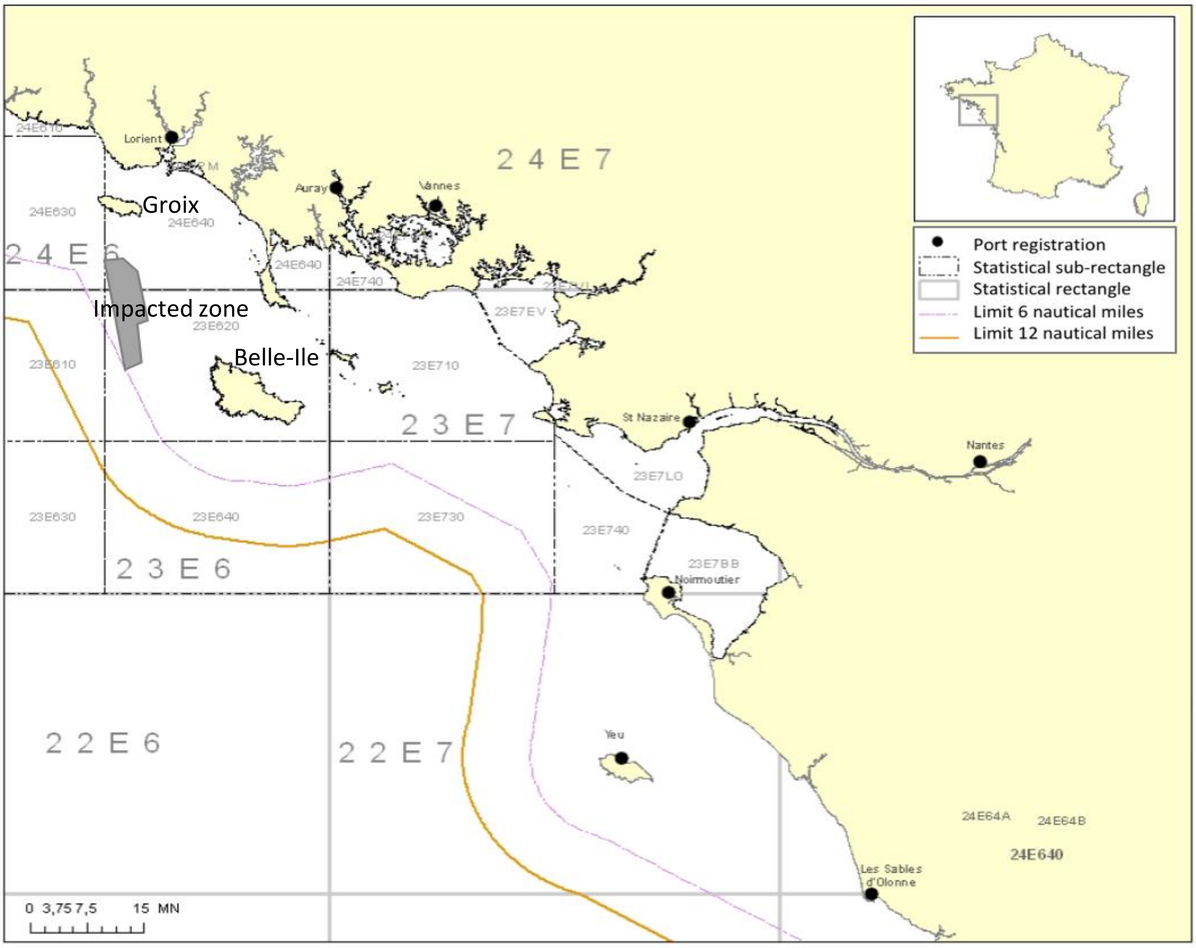
The problems of competition for space between an old activity and a new one that has entered its system (Loiseau et al., 2012) can be considered with the method of vulnerability. Initially defined as 'the extent to which the components of a system are sensitive to or unable to cope with the harmful effects of a stress factor' (IPCC, 2007), this analysis makes it possible to clarify the cause-effect relationships on stakeholders of a change in the socio-ecosystem (Turner et al., 2003). This method is generally applied to climate change-related pressures on coastal communities (Comte et al., 2019). In the present paper, we adapt this method at a local scale. Using the example of the offshore floating wind farm project between Groix and Belle-Île (France), this paper seeks to identify the key pressures and threats to traditional fishing activity in the area within a defined framework. The aim of this research is to compare and explain which fishing activities are more likely to be vulnerable by the wind farm project. First, a description of the impacted area and the threatened fishing fleets is done. Second, conceptualization of vulnerability is adapted at a local scale. Third, a composite index is built to obtain vulnerability scores with a scenario-based approach.

2. The case study of spatial competition

A vulnerability assessment was made on the project for the future floating offshore wind farm located between the islands Groix and Belle-Île on the French Atlantic coast. Located 22 km off the coast, the study area will contain three wind turbines lined up on a seabed of soft sediment at 55 to 70 metres depth (Fig. 1).

As the offshore wind farm is not yet installed, a vulnerability projection based on previous data and exposure suggestions can provide insight into the potential vulnerability. In 2018, 52 fishing vessels visited the area, making total landings of 420 tonnes with a current value of two million euros (Ifremer, 2020).

Fig. 1. Map showing the geographic position of the impacted zone (in grey)



Sources: Ifremer – SIH/AAMP

The community studied is represented by the fishers exploiting commercial stocks in the wind farm project. They engage in fishing activities that are heterogeneous from technical, environmental, and human perspectives (Carvalho et al., 2011). Therefore, a typology of fishing fleets is defined.

The segmentation used in this article is similar to the European framework used in reports on the economic performance of European fleets, according to 'the intersection of vessel length and fishing technique’ (passive or active) (European Commission, 2019) (Table 1). The heterogeneity is partly mitigated by differentiating between vessels under 12 and over 12 metres in length and the *métiers*, defined as the combinations of target species, fishing area and catch technique (Tingley et al., 2003).

Table 1. Fleets present in the impacted area in 2018.

		Size of vessels	
		< 12 metres	≥ 12 metres
Fishing Technique	Lines, traps, nets	Fleet 1 18 vessels (35%)	N/A[a] 2 vessels
	Trawls, dredges, seines	Fleet 2[b] 21 vessels (40%)	Fleet 3 13 vessels (25%)

[a] This fleet has a population of fewer than three vessels. For confidentiality reasons, this fleet was not analysed.

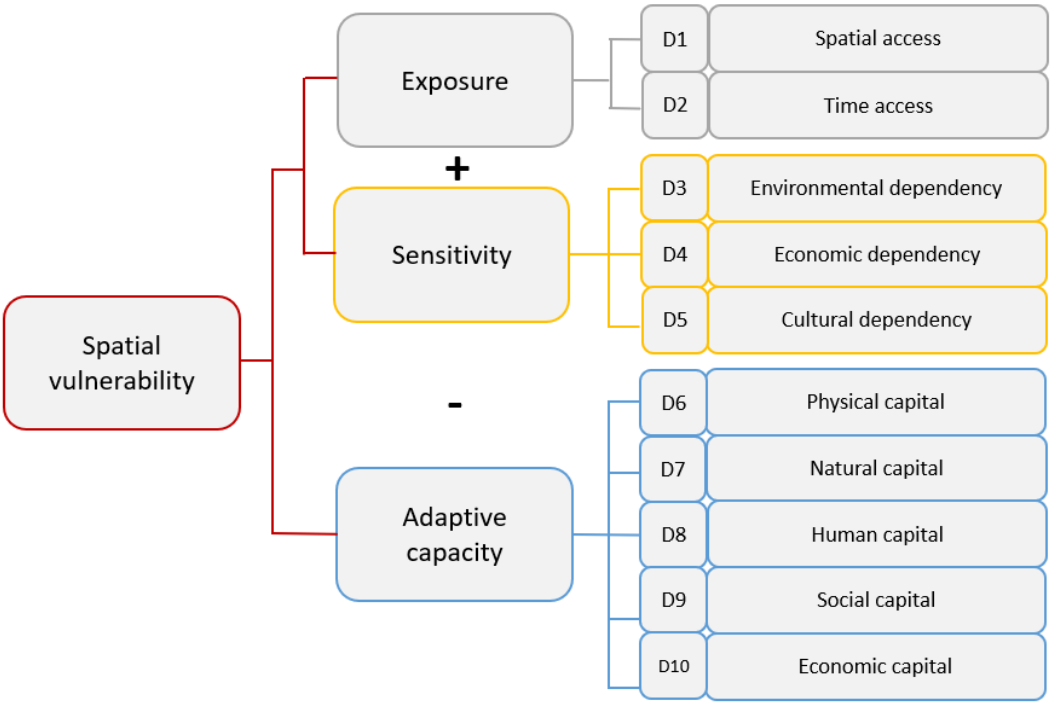
[b] Fleet 2 can use lines, traps or nets as complementary activities.

Source: Ifremer, 2020

3. Conceptualization of vulnerability in the case of spatial competition

Vulnerability is defined within the framework of socio-ecological systems (Holling 2001, 2013), incorporating three interlocking layers: Dimensions, Domains, and Indicators. First, vulnerability is measured according to three generic dimensions: exposure, sensitivity, and adaptive capacity (IPCC, 2007). For each dimension, domains are defined (Fig. 2). Domains reflect the different characteristics most relevant for the study (O'Brien et al., 2013). The definition of these domains comes from empirical and theoretical literature searches and supplemented by a series of ten interviews with ship owners, conducted in February and March 2020. The domains are then represented by one or several indicators. The indicators were primarily obtained from Ifremer, the French Institute of Marine Research (https://sih.ifremer.fr/) and aims to represent all the important processes generating vulnerability in the defined framework (Hinkel, 2011) (Table 2).

Fig. 2. Dimensions and domains (D1–D10) defining the spatial vulnerability of fishers regarding the implementation of an offshore wind farm.



Source: adapted from IPCC (2007) and Adger (2006)

3.1 Definition of exposure

Exposure is the first dimension to assess vulnerability. It is defined as 'the nature and degree to which a system experiences environmental or socio-political stress' (Adger, 2006). The development of offshore wind farm projects makes fishing activities vulnerable to reductions in exploitation area (Chen and Lopez-Carr, 2015). Thus, competition for the maritime space between traditional fishing and the emergence of new uses such as wind farms can lead to a decrease in income and welfare of fishers.

In contrast to environmental impacts linked to climate change, the degree of exposure caused by a reduction in space can be modified by public authorities and the designers of offshore wind farms. This is done through access regulations applied to an area, which may vary from one project to another (Christie et al., 2014; Blyth-Skyrme, 2011). Access to the area may or may not be authorized depending on (1) the characteristics of the environment, (2) the fishing technique used, and (3) the development stages of the project (McClanahan, 2010; Cohen and Foale, 2013). For example, some access to the area is prohibited during the construction phase at sea, but will be opened for some fishing techniques after construction (Roach et al., 2018). The degree of exposure is therefore multi-dimensional where vessels can either have Spatial Access (D1) represented by one indicator (spatial closure) and Temporal Access (D2) represented by one indicator (temporal closure). Because the fishing location is based on fishers' strategies and management rules, scenarios are suggested in the results section according to modification on the degree of exposure in terms of spatial and time closure.

3.2 Definition of sensitivity

Sensitivity was defined as "the degree of coastal region's society's dependence on marine fisheries" (Chen et al., 2015). Communities with a high dependence on resources and area will likely be more sensitive to the implementation of new projects (Marshall et al., 2017). Resource dependence is a concept initially described from an economic point of view with financial dependence on the area (Stanford et al., 2013). Sensitivity is high when the share of turnover derived from the impact zone is significant (Jardine et al., 2020). However, dependence on resources is not only a question of income, particularly as Europe financial support can be provided to accompany any measure causing a reduction in fishing opportunities. Dependency considers the relationship between fishers and resources (Tidball and Stedman, 2013), including (1) the consideration of the potential unique ecosystem and biodiversity in the target area. Closing a valuable area (with high diversity, high biomass, or valuable species) constraints the fishers in their activity (Gray et al., 2016), (2) the consideration of 'attachment to space' and 'sense of place' (Perry et al., 2014; Stedman, 2002). These cultural notions in relation to fishing habits are stronger in a space where fishing has a long history. This dependence on environmental, cultural, and economic resources is linked to the specific characteristics of a marine ecosystem. The choice of a site at sea should consider the physical properties of the environment for the new industry that is being established, and the financial and cultural dependence manifested by the present activities of the fishing fleets. Environmental (D3) dependency represented by the species richness in the area, economic (D4) dependency represented by the income in the area and cultural (D5) dependencies represented by the frequentation of the area and the fishing habit are therefore the three areas of sensitivity, which is a complementary dimension to exposure (Fig. 2). Together, they encompass the potential negative impacts of area closures.

3.3 Definition of adaptive capacity

Fishers have an adaptive capacity that counterbalances the potential impacts determined by the first two dimensions (IPCC, 2007). Adaptive capacity highlights the ability of the community to maintain its level of well-being, income, and cultural attachment in the face of spatial competition. The concept of opportunity cost is one approach to explore adaptive capacity (Smith et al., 2010). Opportunity cost defines the alternatives offered to fishers in terms of income. A high opportunity cost reflects opportunities to move to other fisheries. However, if this cost is low, fishers have few alternatives and will seek to maintain their activities in the same area, through negotiation or strong opposition to the project. Much of the work on fisheries is based on this concept of opportunity cost (Valcic, 2009; Smith, 2002). The difficulty when using this measure is to incorporate non-market elements, independent of the operating costs of a fishery and the expected revenues. Attachment to the profession practiced, to the species sought and, more generally, to all the elements forming social capital, reinforce the feeling of dependence on the area exploited. This is comparable to a low opportunity cost or, as Smith et al. (2010) put this, 'a strong emotional attachment to fishing has the same qualitative effect as a low non-fishery wage'.

Adaptive capacity is divided into five areas: physical capital, natural capital, human capital, social capital, and economic capital (Chen and Lopez-Carr, 2015; Adger, 2006). The physical capital (D6) covers the characteristics of fishing vessels, with the age of the vessel (in years). A complementary measure of physical capital is based on a combination of length (in meters), engine power (in kW) and tonnage (m^3) expressed in log (Nostbakken et al., 2011; Kirkley et al., 2002).

The natural capital (D7) highlights the diversity of fishing activities in the area studied, D7 is represented by two indicators: total number of *métiers*, and diversity of species caught. Human capital (D8) includes the components of the labour factor (Becker, 1975) with two indicators: the age of the fishers and the crew size. Social capital (D9) should allow the avoidance or resolution of conflicts between actors sharing the same space. This domain is represented through vessels registered in the same fishing port, meaning the members from a local community (Holland et al., 2013). Economic capital (D10) refers to an accounting interpretation of the performance of fishing enterprises (European Commission, 2019; National Marine Fisheries Service, 2018). D10 is represented by the annual turnover weighted by the boat characteristics.

Table 2. Description of selected indicators used for vulnerability and offshore wind farm impacts assessment of the fisheries

	Domains	Indicators	Year	Construction of the indicators	Rational / Explanation
D1	Spatial access*	I1	-	Proportion of area accessible to fishing vessel. (in %)	Reduction of fishing area affect income and well-being
D2	Time access*	I2	-	Proportion of the temporal closure accessible to fishing vessel. (in %)	Reduction of fishing time affect the income and well-being
D3	Environmental dependency	I3	2018	Number of species caught in the future wind farm area divided by the total number of species caught in a year. (in %)	Fleets are more sensitive when the diversity of catch observed in the area regarding the total catch needs to be low for low sensitivity
D4	Economic dependency	I4	2018	Annual sales (turnover) made from the area divided by the annual total turnover. (in %)	The income currently made in the area will be lost because the access to the area is restricted in space and time.
D5	Cultural dependency	I5	2018	Frequentation rate of the area by the number of months of activity declared. (in %)	The more frequently (time) they fish in the area the more dependent they are.
		I6	2011 to 2020	Number of years the fishing vessel operated in the area between 2011 and 2020 (in years)	The longer they fish in the area (in years) the harder it will be to change the fishing area
D6	Physical capital	I7	2018	Age of the vessel (in years)	The age of capital is often used as a proxy for the state of capital. The oldest vessels are the least efficient and potentially the least mobile (Guyader and Daurès, 2005).
		I8	2018	Combination of length, engine power and tonnage, transformed into a logarithm (for simplicity of values).	A vessel with a high engine power, length, and storage capacity are more likely to adapt
D7	Natural capital	I9	2018	Number of métiers declared in a year in general (in métier/years)	A high diversity of métiers reflects how fishers can shift target species for both short and long term. The use of these different tools makes it possible to diversify these catches and fish in other area.
		I10	2018	Number of species caught in a year in general (all area included) (in species/years)	The number of species catch gives a hit if they can shift form on species to another. (Guyader et al. 2013) A broader portfolio of target species makes the operators less vulnerable in principle (Aguilera et al., 2015; Morgan, 2016).
D8	Human capital	I11	2018	Age of the boat owner (in years)	The young captains are going to face longer the wind farm making them more vulnerable.
		I12	2018	Crew size (fishers/boat)	The captains have in charge more fishers and it may be more difficult to keep the full effective.
D9	Social capital	I13	2018	Number of vessels from the same fleet per harbor (in vessels/harbor)	Vessels belonging to the same harbour community facilitates exchanges through involvement in the same cooperative and the use of the same partners for the local fish market or technical assistance.
D10	Economic capital	I14	2018	General annual turnover divided by the indicator boat characteristics (D6). (in euros)	It refers to an accounting interpretation of the performance of fishing enterprises (European Commission, 2019; National Marine Fisheries Service, 2018).

* Indicators defined by the index developer (the other indicators are provided by Ifremer)

4. Composite index construction

A composite index aims to aggregate several individual indicators to provide a synthetic measure of a complex, multidimensional system. Based on the method of Hahn et al. (2009), the construction of the composite index is done in several steps: (1) standardization of data, (2) average of indicators by domain, (3) definition of weights, (4) aggregation of dimensions and (5) construction of scenarios (Baptista, 2014; Mazziotta and Pareto, 2013). The description of the method is presented in annex 1.

Step 1: As the selected indicators have different units (Table 3), a normalization of the data is carried out based on the Min-Max method (OECD, 2008). This universal normalization technique provides data with a similar range allowing the data to be placed on a scale of 0 to 1 using the following conversion:

$$Y_{X_f} = (X_f - X_{min})/(X_{max} - X_{min})$$

The standard indicator, Y_{X_f}, is calculated from the averaged in indicator X of the fleet f . X_{min} and X_{max} are the minimum and maximum values possible of the sample including the vessel of the three fleets. For percentage the scale ranges from the minimum X_{min}=0% to the maximum X_{max}=100%. Table 2 shows the descriptive statistics of the indicators grouped by domain. Averages are given in absolute or relative values with specific units (%, years, log, euro, number) and in normalized values ($\overline{\mathrm{X}}$ norm.) according to step 2 of the method.

Table 3: Indicators selected, $\bar{X}$ = average, CV = coefficient of variation, $\bar{X}$ norm. = average

					Fleet 1		**Fleet 2**		**Fleet 3**	
	Domains	**Indicators**	**Min**	**Max**	$\bar{X}$ ***cv***	$\bar{X}$ **norm.**	$\bar{X}$ ***cv***	$\bar{X}$ **norm.**	$\bar{X}$ ***cv***	$\bar{X}$ **norm.**
D1	Spatial access	I1	0	100	100 *0*	1	100 *0*	1	100 *0*	1
D2	Time access	I2	0	100	100 *0*	1	100 *0*	1	100 *0*	1
D3	Environmental dependency	I3	0	100	92.15 *0.14*	0.92	51.65 *0.69*	0.51	84.03 *0.11*	0.84
D4	Economic dependency	I4	0	100	71.26 *0.42a*	0.71	13.75 *1.56*	0.14	2.82 *0.65*	0.03
D5	Cultural dependency	I5	0	100	56.92 *0.46*	0.56	29.98 *0.62*	0.29	3.24 *0.68*	0.02
		I6	1	9	5.56 *0.60*	0.57	5.19 *0.50*	0.52	5.15 *0.59*	0.52
D6	Physical capital	I7	0	48	24.22 *0.48*	0.50	33.95 *0.21*	0.71	26.00 *0.45*	0.54
		I8	7.1	9.7	7.70 *0.05*	0.20	8.04 *0.04*	0.33	9.23 *0.03*	0.80
D7	Natural capital	I9	1	8	4.11 *0.42*	0.44	5.00 *0.35*	0.57	2.15 *0.26*	0.16
		I10	5	70	25.00 *0.44*	0.31	34.57 *0.50*	0.45	50.85 *0.11*	0.71
D8	Human capital	I11	29	80	50.06 *0.20*	0.41	42,52 *0.24*	0.27	46.15 *0.06*	0.34
		I12	1	4,89	1.45 *0.42*	0.12	1.81 *0.27*	0.21	4.03 *0.09*	0.78
D9	Social capital	I13	1	17	9.78 *0.76*	0.55	7.48 *0.93*	0.40	13.00 *0*	0.75
D10	Economic capital	I14	3830	80900	16432 *0.70*	0.16	16546 *0.60*	0.16	64642 *0.16*	0.79

Source: original work of the present study

Step 2: Each domain (D1 to D10) can be calculated from one or two standardised indicators. To measure the domain for each fleet (Domain_f), the average of all indicators included for each domain is done, using the sum of the standardized indicators ($Y_{i,f}$) divided by the number of indicators per domain (n).

$$\text{Domain}_f = \frac{\sum_{i=1}^{n} Y_{X_f i}}{n}$$

Step 3: A different weight can be assigned per domain. In the example presented, the same weighting is assigned, considering that all domains contribute equally to a particular dimension (Baptista, 2014). This approach aims to keep the domains on a similar basis, with a weight of 1 (Tate, 2012).

Step 4: The value of each domain is integrated into one of the three dimensions for each fleet, using both additive and multiplicative aggregation (Tate, 2012). The literature on composite index construction methods discusses the unpredicted erroneous interpretations when only one combination is selected (OECD, 2008; Greco et al., 2019; Blancas et al., 2013). For example, the Cobb-Douglas production function is based on a multiplicative combination of variables to demonstrate the returns to scale -increasing, constant, or decreasing-. In other contexts, where the concept of returns to scale is not required, the additive form is often used. Models of performance between production units, as the DEA - Data Envelopment Analysis – (Le Floc'h et Mardle, 2006), are frequently based on additive forms of the selected factors. We select the two forms of construction of the vulnerability index, additive and multiplicative, at the level of each domain. The results show that differences between the domains can be significant, but they compensate each other to give a close reading of the composite vulnerability index.

Additive aggregation: $DV_f = \frac{\sum_{x=1}^{k}(Domain_f \times Weight_{d,f})}{\sum_{x=1}^{k} Weight_{d,f}}$

Multiplicative aggregation: $DV_f = 1 - \prod_{x=1}^{k}((1 - \ Domain_f) \times Weight_{d,f})$

Each measure of the dimension DV =Exposure or Sensitivity, or Adaptive capacity for each fleet, *f*, results from the sum of the weighted domain score divided by the sum of the domain weights. The final step combines the three-dimension scores

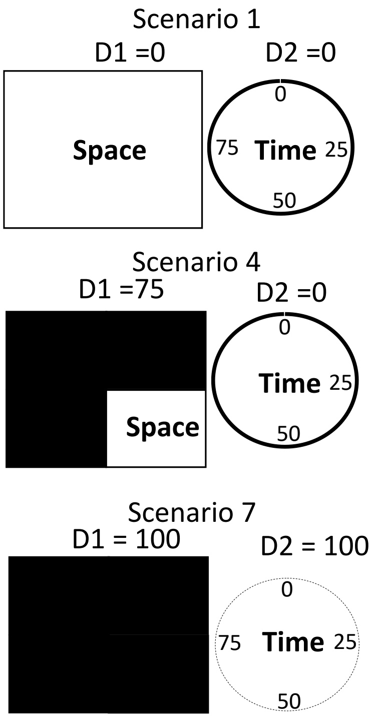
$$Vulnerability_f = \frac{\left[\left(Exposure_f + \ \text{Sensitivity}_f - \ \text{Adaptive capacity}_f\right) + 1\right]}{3}$$

This equation gives a spatial vulnerability score for each fleet between 0 and 1. The extreme situations are 1 for exposure and sensitivity and 0 for adaptive capacity, resulting in the highest level of vulnerability (=1). On the opposite, a value equal to 0 for exposure and sensitivity and 1 for the adaptive capacity gives a vulnerability score of 0.

Step 5: The management of fisheries during the construction and operation of the wind farm can follow a multitude of cases (Fig. 3). The public authorities may allow continued activity in all areas without time limits. Scenario 1 provides for this first limit case (D1=0 and D2=0), even though the construction phase necessarily prevents vessels from operating nearby for safety reasons. This scenario (1) represents the residual vulnerability – the vulnerability the fleet have even if they can access the area - The other extreme scenario prohibits any operation in the vicinity of the area all year round. Scenario 7 (initial scenario) simulates this situation, which is close to the creation of a marine protected area (D1=100 and D2=100), with no or greatly reduced fishing opportunities (Kriegl et al., 2021; Sala and Giakoumi, 2018). Between these two limited cases, management authorities have several options. We propose a set of three simulations (scenarios 2 to 4) with no fishing time limit (D2=0) and a graduated area closure. In scenario 2, 25% of the area is closed (D1=25). Half of the areas are closed in scenario 3 (D1=50). Finally, three out of four areas are not available in scenario 4 (D1=75). In scenarios

5 and 6, boats can use half the space (D1=50) or only one out of four areas (D1=75) half of the time (D2=50). Other possibilities are possible, without significantly changing the vulnerability results.

Fig. 3. Scenario for fisheries management in the impacted area



5. Results

The vulnerability scores provide a first measure that ranks the three fleets. The construction of scenarios provides a better perspective of the impacts on the vulnerability of the fleets, by varying the exposure dimension, and the use of two aggregation methods offers a critical result of the methodology.

5.1 Vulnerability scores – initial scenario

Exposure to the impacts generated by the construction of the wind farm requires a total ban on access to fisheries located within the construction zone (scenario 7). With equal exposure for all fishers (exposure = 100), vulnerability depends only on the dimension of sensitivity mitigated by the dimension of adaptive capacity (Table 4).

Under the assumption of the additive form, fleet 1 has the highest score ($V_{f1=0.80}$), showing these vessels are the most vulnerable, followed by fleet 2 ($V_{f2=0.66}$) and fleet 3 ($V_{f3=0.58}$). This hierarchy is in line with a basic assumption that small vessels are highly vulnerable due to their lower mobility, and thus lower ability, to shift their fishing effort to other areas.

The multiplicative form offers a different reading as fleet 2 ($V_{f2=0,61}$) is less vulnerable than fleet 3 ($V_{f3=0,63}$) with a small difference. We note that the vulnerability score of fleets 1 and 2 is reduced when the dimensions are expressed in a multiplicative combination, except for fleet 3 as its score increased. Indeed, the sensitivity index and the adaptive capacity index reach higher values under a multiplicative combination. However, the increase in adaptive capacity is too low (the maximum value is reached) for fleet 3 to counteract the sensitivity.

The first lesson in the comparison of the two results, additive, and multiplicative forms, concerns the lower scores for the adaptive capacity when the additive form is used. This adaptive capacity is based on a multi-criteria approach to capital, based on five attributes – physical, natural, human, social, economic –.

Table 4. Vulnerability score with exposure, sensitivity, and adaptive capacity per fleet in additive and multiplicative forms – scenario 1 (D1=0, D2=0).

	Fleet 1		Fleet 2		Fleet 3	
Scores	*additive*	*multiplicative*	*additive*	*multiplicative*	*additive*	*multiplicative*
Vulnerability (between 0 and 1)	0.80	0.70	0.66	0.61	0.58	0.63
Exposure	1	1	1	1	1	1
Sensitivity	0.73	0.99	0.35	0.75	0.38	0.88
Adaptive capacity	0.34	0.89	0.37	0.91	0.64	1

5.2 Vulnerability scores under various fisheries management

Fisheries management scenarios become operational at the end of the wind farm construction phase. While the initial scenario of no fishing is a possibility, the demands of fishers for access to their fishing grounds must be expected. The exposure dimension therefore no longer has a unitary value, depending on the decisions on fisheries management. The approach is similar to marine protected areas methods developed by McCay and Jones (2011) and McClanahan (2010).

Without multiplying the alternatives, in complement to the initial scenario, seven cases are presented (Table 5). Each scenario is represented by two values going from 0 to 100 without distinction between the fleet (see Fig. 3).

Table 5: Vulnerability score of the different fleets under different scenarios; $V_{add.}$ for Vulnerability score in the additive form and $V_{mul.}$ for Vulnerability score in the multiplicative form

	Exposure		Fleet 1		Fleet 2		Fleet 3	
Scenarios	**D1 (space)**	**D2 (time)**	$V_{add.}$	$V_{mul.}$	$V_{add.}$	$V_{mul.}$	$V_{add.}$	$V_{mul.}$
Scenario 1 - Residual	0	0	0.46	0.37	0.33	0.28	0.25	0.30
Scenario 2	25	0	0.51	0.45	0.37	0.36	0.29	0.38
Scenario 3	50	0	0.55	0.53	0.41	0.45	0.33	0.46
Scenario 4	75	0	0.59	0.62	0.45	0.53	0.37	0.55
Scenario 5	50	50	0.63	0.62	0.49	0.53	0.41	0.55
Scenario 6	75	50	0.67	0.66	0.54	0.57	0.45	0.59
Scenario 7 - Initial	100	100	0.80	0.70	0.66	0.61	0.58	0.63

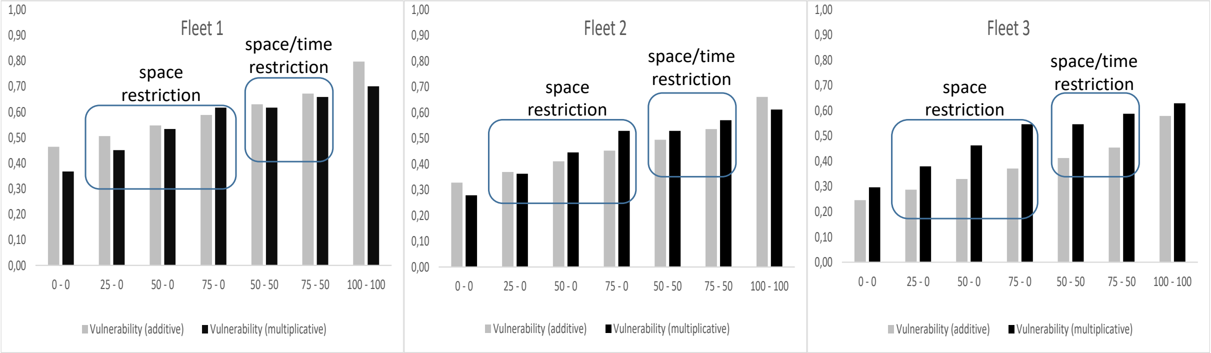
The construction of the different scenarios shows that when the exposition increases the vulnerability increase. Scenario 1 represents the residual vulnerability variate between 0.46 and 0.28.

The most common aggregation method used in the construction of a composite index for vulnerability assessment is additive (Tonmoy et al., 2014). To test our composite index, we compare both methods, additive, and multiplicative aggregation (Fig 4)).

The difference between the two calculation methods is the hierarchy between fleets. The additive approach indicates that fleet 1 is the most vulnerable, followed by fleet 2 and then fleet 3. The multiplicative approach confirms that fleet 1 is the most vulnerable, followed by fleet 3. In both cases, the differences in the vulnerability score are constant, whatever the scenario. However, a second difference between the two calculation approaches can be observed when measuring the differences. In the additive form, the vulnerability score of Fleet 1 is increased by 0.14 compared to Fleet 2. Fleet 2 has a higher score of 0.08 compared to Fleet 3. With the multiplicative form, the difference between fleets 2 and 3 is small (a difference of 0.02, stronger for fleet 3).

Scenario 4 and 5 display same scores in the multiplicative form with the same exposure [(1-(1-0,75)*(1-0) ⇔ 1-(1-0,5)*(1-0,5)]. From the point of view of the implementation of management measures, the two scenarios cannot be considered equivalent. In the first case, fleets are allowed to fish without time limits but in only one out of four areas. In the second scenario, fleets are allowed to fish in two out of four areas but only half of the time.

Fig. 4: Vulnerability score under different scenarios using two aggregation method



5. General discussion

Vulnerability score

All vessels are vulnerable to the establishment of an offshore wind farm at different degrees and the different scenarios show us an increase in vulnerability as exposure increases. Scenarios also show us that the vessels present a residual vulnerability even though the exposure is zero. This is explained by a high sensitivity to the ability to adapt. It is the difference in vulnerability scores that allows us to understand the different aspects of the socio-ecosystem that need to be improved to reduce vulnerability. Vulnerability is not a comparison tool but more of a discussion tool (Hinkel, 2011). Below, the three fleets will be unpacked to better understand their vulnerabilities.

Fleet 1 is more likely to be vulnerable due to a high sensitivity marked by resource dependence (see table 3), partly explained by the location of the impacted area. Indeed, this zone is located close to the coast. The coastal zone is used by fishers employing a wide variety of techniques, mainly low-energy intensive ones (Guyader et al., 2013). For highly dependent fishers, a reduction in the space exploited is a threat to their income (Van de Geer et al., 2013). Social consequences can also occur through a loss of cultural attachment (Marshall et al., 2017). These concepts are difficult to measure but are essential to consider during the negotiation phases to ensure the acceptability of such a project (Kermagoret et al., 2016). The preservation of fishing activities close to the impact zone is based on a high adaptive capacity, defined by the five domains, all linked to a form of capital (Morgan, 2016). The low levels of the physical and economic capital of coastal vessels are a limit to diversification, reducing the opportunity cost (Smith et al., 2010).

Fleet 2 is similar to fleet 1 but with lower economic dependence if the additive form is used. Domains related to forms of capital are distributed differently. In fleet 2, natural capital is based on the greatest number of *métiers* for a wide range of exploited species (intermediate between fleet 1, with the lowest number of species, and fleet 3) (Aguilera et al., 2015). These two small-scale fleets have a lower vulnerability as soon as the access is open to the area. The major issue for decision-makers is the selected criteria for separating small-scale and large-scale vessels. However, the multiplicative form makes the dividing line between small-scale and large-scale fisheries more complex as fleet 2 appears less vulnerable than fleet 3.

In our case study, fleet 3 uses active gears (trawling, dredging, or seining techniques). The issue of banning a technique causing strong negative impacts on the ecosystem is plausible (Kraan et al., 2020). Fleet 2 and fleet 3 have the lowest vulnerability due to weak economic dependence. The hierarchical process is inverted according to the additive or multiplicative method, but the results are very close in both cases. Its activities in the impact zone are marginal in economic terms. The site selected for the installation of floating wind turbines is located within the coastal strip, i.e., less than 20 nautical miles from the coastline, offering a sheltered area under bad weather conditions. Oriented towards mass production, fleet 3 depends on specific infrastructure in harbours (Harte et al., 2010). All vessels of fleet 3 belong to the same fishing harbour (D4, social capital). This concentration within a single harbour community facilitates the exchange of information (Rosas et al., 2014). On the one hand, even its low adaptive capacity is sufficient for this fleet to compensate for the expected losses of an area closure in the coastal strip, it can, in principle, seize other fishing opportunities (Gray et al., 2016). On the other hand, its vulnerability may increase if the study considers the impacts on the ecosystem. This is therefore a possible improvement to the vulnerability method by introducing an indicator estimating the negative impact of fishing gear on the ecosystem (sediment, fauna, flora, by-catches, accidental catches).

Limitations

The emergence of competition for space between fishing activities and offshore wind farms has led to the exploration of the interactions using the vulnerability method. Adaptation of the method at a local scale requires the definition of the study context (Baptista, 2014; Chen and Lopez-Carr, 2015; Comte et al., 2019). For example, too holistic a definition of the system could be confusing and lead to few applicable results (O'Brien et al., 2004). Therefore, only one pressure was considered here, that of competition for space inside the wind farm area, although other impact factors are also perceived as threats to fishers' activities (climate change, Brexit negotiations, marine pollution, market competition, health crises, etc.) (Bennett et al., 2014).

The question of the effectiveness of the method overtime should be addressed. Indeed, unlike conventional indicators such as the Human Development Index (HDI), the vulnerability score represents a possible future. Raoux et al. (2017) show that the conditions of access to the area in time and space by professional fishers have effects not measurable *ex-ante*, on the biomass and its ecosystem. The vulnerability score does not consider the value of the resources around the study area in case of the movement of fleets. The partial or total closure of fishing areas is sometimes equated with the creation of Marine Protected Areas, with an expected positive effect on the abundance of the resource. A potential benefit can only be expected after the construction phase of an offshore wind farm has been completed (Punt et al., 2009). To account for the effects obtained following the implementation of a wind farm, the vulnerability assessment will need to be updated regularly.

The vulnerability assessment is based on the construction of a composite index resulting from the prior identification of impacts and adaptive capacity. The selected indicators and a specific weight must be adapted to the issues raised by the fishers in interviews before the project is implemented (Islam et al., 2014). In the most favourable case of the existence of databases on threatened communities, the choice of indicators should be based on their relevance rather than their availability (Barnett et al., 2008). This justifies the creation of domains informed by a single indicator. In this study equal weights are assigned. However, Engle (2011) shows that indicators do not contribute equally to vulnerability and empirically derived weights should be used. More interaction with stakeholders using interviews needs to be done to attenuate this parameter.

The comparison between the two-aggregation method shows limits in the construction of the composite index if only one combination (additive or multiplicative) is used (Fig. 4). The issue with arithmetic and geometric mean approaches is that they assume a monotonic/ linear relationship between indicator and vulnerability and thus disregard potential nonlinearities and thresholds in this relationship (Tonmoy et al., 2014).

Due to the presented limit of the method, it is important to understand that vulnerability is a theoretical concept based on a composite index that cannot be measured in the same way as a mass of an object or an income obtain at the end of the month (OECD, 2008). To avoid misinterpretation, it is fundamental to not only base the discussion on the vulnerability score itself but alsothe score of dimensions and domains (Hinkel, 2011).

5.3 Advantages and application of the method

Applying the vulnerability assessment method to a local scale offers many advantages. It offers high flexibility of implementation at a low cost, subject to access to pre-existing databases. Used as a communication tool for discussion between stakeholders at each stage of the project, the local vulnerability assessment produces a single score based on three dimensions, the degrees of exposure, sensitivity, and adaptive capacity as a mitigation factor (Thiault et al., 2019; O'Brien et al., 2004).

Without putting this approach in competition with spatial optimisation models, one of the advantages of the vulnerability assessment is the place given to indicators relating to non-market values. The cultural attachment manifested by fishers is collected in at least three areas of the model: cultural dependence (through the number of years of activity in the area), human capital as a factor measuring experience, and social capital being equated with harbour communities.

The vulnerability assessment allows constructions of scenarios (O'Brien et al. 2004; Hahn et al 2009). The choice of scenarios depends on the objectives of the management (Blyth-Skyrme, 2011) and the aim of the community (in a social and economic aspect) regarding this area based on discussion with stakeholders, considering environmental and technological developments (Hinkel, 2011). Indeed, offshore wind farm projects are subject to technological breakthroughs that may modify the initial format by the number of machines installed. The area of occupation may vary overtime before the final decision on location is made. Environmental factors are also subject to other pressure factors that can change the stakes for fishers. The recommendation resulting from this research concerns an updated measure of vulnerability at each key moment of the negotiation stage to favour the social acceptance of a wind-energy project, often described as a threat to the sustainability of traditional fishing activities.

6. Conclusion

This research focuses on adapting the vulnerability method, often applied to climatic impact factors, to a question of spatial cohabitation in the coastal strip. The context chosen was that of spatial competition between a traditional activity, the exploitation of living marine resources by fishers, and the development of a new industry, marine renewable energy at sea. As its purpose is to reduce the costs of negotiations between stakeholders in a marine area that has multiple uses (fisheries, wind or tidal turbine sites, aquaculture basins, species conservation sites, recreational uses, etc.) the vulnerability assessment deserves to be widely applied to different situations of this kind.

The paper follows the method of composite index construction using two approaches, additive and multiplicative. The results focus on the vulnerability score by comparing the initial scenario with no fishing area and fishing time limits with scenarios of activity limitation in space and time. A future step is collaborative research with fishers and all stakeholders concerned by the impact area, indicating the limits of the method if only one form of calculation (additive or multiplicative) is preferred.

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Appendix A: Calculation of the Human capital, domain of the dimension adaptive capacity for the composite index assessing vulnerability of fishing activity regarding the implementation of a future offshore wind farm.

		Mean fleet1	Min value for study population	Max value for study population	Standardized value for fleet 1	Human capital component value for fleet 1
D8	Age of fishers	50.06	29	80	0.41	0.26
D8	Crew size	1.45	1	4.89	0.12	

Step 1: (repeat for all indicators): $Y_{X_f} = (X_f - X_{min})/(X_{max} - X_{min})$, example: $Y_{age\ of\ fisher,fleet1} = \frac{(50.06-29)}{(80-29)} = 0.41$

Step 2: (repeat for all domain): $\mathrm{Domain}_f = \frac{\sum_{i=1}^{n} Y_{X_{fi}}}{n}$, example: $\text{Human capital}_{fleet1} = \frac{(0.41+0.12)}{2} = 0.26$

Step 3: (repeat for all dimension)

using additive aggregation $DV_f = \frac{\sum_{x=1}^{k}(Domain_f \times Weight_{d,f})}{\sum_{x=1}^{k} Weight_{d,f}}$,

example $Adaptive\ capacity_{fleet1} = \frac{(0.35\times1)+(0.38\times1)+(0.26\times1)+(0.55\times1)+(0.16\times1)}{1+1+1+1+1} = 0.34$

using multiplicative aggregation: $DV_f = 1 - \prod_{x=1}^{k}((1 - Domain_f) \times Weight_{d,f})$
example $Adaptive\ capacity_{fleet1} = 1 - ((1-0.35)\times 1) \times ((1-0.38)\times 1) \times ((1-0.26)\times 1) \times ((1-0.55)\times 1) \times ((1-0.16)\times 1)$

Step 4: (repeat for all fleet): $Vulnerability_f = \frac{[(Exposure_f + \text{Sensitivity}_f - \text{Adaptive capacity}_f)+1]}{3}$,

Example using the result of the additive aggregation

$Vulnerability_{fleet1} = \frac{[(1+0.73-0.34)+1]}{3} = 0.80$