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Methodology to calculate mooring and anchoring costs of floating offshore wind devices

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Abstract. The aim of this article is defining a methodology which allows us to evaluate the main mooring and anchoring costs of floating offshore wind farms. In this sense, costs of most important phases of life cycle will be analysed: manufacturing, installation, exploitation and dismantling. For this purpose several models will be defined taking into account the type of floating offshore wind platform (semisubmersible, Tensioned Leg Platform or spar), mooring disposition (transitional no tensioned, slack no tensioned, tensioned with 90º or tensioned with 45º), mooring material (chain, cable and synthetic fibre) and type of anchor (drag embedment anchor, suction pile, gravity anchor and plate anchor). Finally the proposed method will be applied to know mooring costs of a substructure located in the region of Galicia (North-West of Spain). Results show how each of these costs depend on the model considered, which help investors to decide what the best model is.

Key words

Marine renewable energy, floating offshore wind farm, mooring, anchoring, life cycle cost

1. Introduction

Offshore wind energy will be developed in next years in order to achieve European Union objectives [1]. However, there are places where depth is very high, so fixed offshore wind structures (monopile, tripod, etc.) cannot be installed. In this context, floating offshore energy will take part in offshore market.

However, one of the most important differences between fixed and floating substructures are mooring and anchoring systems.

In this sense, the aim of this article is defining a methodology which can evaluate the main life cycle mooring and anchoring costs of floating offshore wind farms. For this purpose several installation, preventive maintenance and decommissioning models will be considered.

2. Methodology

A. Introduction

The methodology used will be based on the life cycle phases of a product [2] [3]:

- Phase 1: definition.
- Phase 2: design.
- Phase 3: manufacturing.
- Phase 4: installation.
- Phase 5: exploitation.
- Phase 6: dismantling.

However, this article will reject definition and design cost because their importance is less than manufacturing, installation, exploitation and dismantling phases. Regarding this consideration, total cost of a mooring and anchoring system ($\boldsymbol{C_{ma}}$) will be as follows:

$$C_{ma} = C3_{ma} + C4_{ma} + C5_{ma} + C6_{ma} \quad (1)$$

B. Manufacturing

Manufacturing costs ($\boldsymbol{C3_{ma}}$) are calculated taking into account the cost in €/kg ($\boldsymbol{C_{kg}}$) [4] of mooring (p=1) [5] and anchoring (p=2) and their respective mass ($\boldsymbol{m_{ma}}$):

$$\boldsymbol{C3_{ma} = \sum_{p=1}^{p=2} m_{ma_p} \times C_{kg_p} \times LP_p} \quad (2)$$

In this sense, mooring and anchoring [6] devices will be dimensioned considering they are satisfying the requirements related to acting forces (wind [7], waves [8] and currents) [9] [10].

C. Installation

Regarding installation costs ($\boldsymbol{C4_{ma}}$) of mooring and anchoring, two different methodologies will be considered [11]. Method 1 employs a barge and a tugboat. Method 2 requires a specific vessel called AHV (Anchor Handling

Vehicle). Moreover, it should be noted that in the case of anchors, AHV vessel dropped directly anchor, completing the installation process. This technique avoids the use of subsea equipment, but makes difficult the placement of the anchor at the desired location. Furthermore, suction piles are cylindrical boxes which are embedded in seabed by suction. These are lowered to the seabed and then suction is applied by a valve, which is located at its top. This installation process requires the use of subsea pumps and, sometimes, divers.
Cost calculation for Method 1 is:

$$C4_{ma} = \left(C_b + C_{tb} + C_{DL} + C_{pd}\right) \times \left(\frac{N_{anchors}}{T_{instb}}\right) \quad (3)$$

Being:

- C_b: barge cost (€/day)
- C_{tb}: tugboat cost (€/day)
- C_{DL}: direct labour cost (€/day)
- C_{pd}: pumps and divers cost (€/day)
- $N_{anchors} = NWT \times LP$: number of anchors (anchors)
- T_{instb}: barge installation time (anchors/day)
- NWT: number of wind turbines (wind turbines)
- LP: number of mooring lines per platform (lines/platform)

On the other hand, cost calculation for Method 2 is:

$$C4_{ma} = \left(C_{AHV} + C_{DL} + C_{pd}\right) \times \left(\frac{N_{anchors}}{T_{instAHV}}\right) \quad (4)$$

Being:

- $\boldsymbol{C_{AHV}}$: AHV cost (€/day)
- $\boldsymbol{T_{instAHV}}$: AHV installation time (anchors/day)

D. Exploitation

According exploitation cost ($\boldsymbol{C5_{ma}}$), two different issues will be considered [12]: preventive maintenance ($\boldsymbol{C_{pm}}$) and corrective maintenance ($\boldsymbol{C_{cm}}$). Furthermore, we should take into consideration the fact that corrective costs will differ depending on the year of the life cycle ($\boldsymbol{N_{wf}}$), because there is a guarantee stage ($\boldsymbol{N_g}$):

$$C5_{ma} = \left(C_{pm} + C_{cm}\right) \times \left(N_{wf} - N_g\right) \quad (5)$$

The goal of preventive maintenance is to replace and renew components following an established programme: periodic inspections of equipment, cleaning, etc. All these specific tasks are defined by manufacturer manuals.

Costs of preventive maintenance are given by:

$$C_{pm} = CPM_{TRANSP} + \sum_{p=1}^{p=2} CPM_{MAT_p} + \sum_{p=1}^{p=2} CPM_{DL_p} \quad (6)$$

Being:

- CPM_{TRANSP}: cost of transport for preventive maintenance
- CPM_{MAT_p}: cost of materials for preventive maintenance
- CPM_{DL_p}: cost of direct labour for preventive maintenance

There are several preventive maintenance strategies:

- Onshore (without permanent accommodation): helicopter (M1), hiring Field Support Vessel (FSV) (M2) or buy a FSV (M3).
- Offshore (with permanent accommodation): buying FSV (M4).

On the other hand, the corrective maintenance is not programmed, taking place after the occurrence of a fault in the system. Therefore, it shall take into account the probability of failure of the component, as we can see in the following formulae [12]:

$$C_{cm} = \sum_{p=1}^{p=2} P_{f_p} \times \left(CCM_{DL_p} + CCM_{TRANSP_p} + CCM_{MAT_p}\right) \quad (7)$$

Being:

- P_{f_p}: failure probability
- CCM_{DL_p}: cost of direct labour for corrective maintenance
- CCM_{TRANSP_p}: cost of transport for corrective maintenance
- CCM_{MAT_p}: cost of materials for corrective maintenance

Failure probability will be calculated taking into account forces acting on the floating platform and the strength of the systems using Montecarlo Method [13].

E. Dismantling

The floating offshore wind farm must be dismantled and removed for repowering [14] or only ending the activity. Firstly, wind farm will be disassembled using specialized vessels. Once the material is onshore, it may be sold as junk, receiving income (which will be counted as negative cost), or deposited in some specific place, paying for it.
Therefore, the cost of dismantling ($\boldsymbol{C6_{ma}}$) is composed by the cost of decommissioning moorings and anchors ($\boldsymbol{C_d}$), the cost of cleaning the affected area ($\boldsymbol{C_c}$) and the cost of disposing the materials ($\boldsymbol{C_{dm}}$) [15]:

$$C6_{ma} = C_d + C_c + C_{dm} \quad (8)$$

3. Considered models

Three platforms will be considered: semisubmersible (Model A), Tensioned Leg Platform (TLP) (Model B) and spar (Model C). The number of lines per platform (LP) for each of these platforms is 6, 8 and 3 respectively [16]. Moreover, mooring disposition systems could be:

transitional no tensioned systems (1), slack no tensioned system (2), Tensioned Leg Platform (TLP) tensioned (90º) (3) or Taut Leg Buoy (TLB) tensioned (45º) (4), as we can see in Fig. 1:

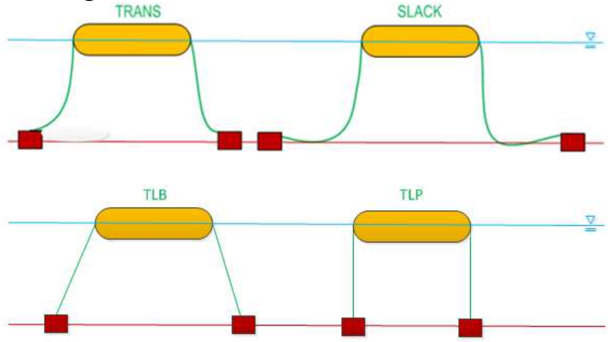

Fig. 1. Mooring models

Regarding mooring materials we will consider three cases: chain (Ch), cable (Ca) and synthetic fibre (polyester) (Fi). Moreover, cohesive (CS) and no cohesive soils (NCS) will be studied.

Finally and regarding anchoring, four different alternatives will be taken into account: drag embedment anchor (De) [17], suction pile (Sp) [18], gravity anchor (Ga) and plate anchor (Pa).

However, platform TLP with no tensioned mooring (slack or transitional) will be rejected, considering its own definition, which implies tension. Furthermore, drag embedment anchor does not allow vertical forces and plate anchor does not accept horizontal forces [19].

4. Results

Results have been obtained taking into account that floating offshore wind farm is located in Galicia (North-West of Spain), which will condition, through environmental forces applied, anchoring and mooring dimensions.

A. Manufacturing costs

As we can see in Table I, results for manufacturing costs of mooring indicate that most expensive mooring is Model B-tensioned (90º)-chain with a cost of 28,915,174 €. Moreover, the cheapest one is Model C-tensioned (45º)-fibre with a value of 505,867 €.

Table I. – Manufacturing mooring cost

$C3_{ma}$ p=1	MA1	MC1	MA2	MC2
Ch	11,183,421	5,733,466	13,749,525	6,938,776
Ca	-	-	-	-
Fi	-	-	-	-

$C3_{ma}$ p=1	MA3	MB3	MA4	MB4	MC4
Ch	4,611,443	28,915,174	6,289,137	6,378,234	1,856,525
Ca	1,155,554	-	1,575,958	2,179,478	549,800
Fi	1,018,181	-	1,388,606	1,737,944	505,867

Regarding anchoring, the cheapest anchor is plate anchor with costs between 793,800 for Model A and 2,721,600 € for Model B. On the other hand, the most expensive anchor is suction pile with values between 4,596,218 and 9,906,676 €.

Table II. – Manufacturing anchoring cost of no tensioned systems

	$C3_{ma}$ p=2	Type	MA1	MC1	MA2	MC2
Ch	CS	De	1,143,052	-	1,143,052	-
		Sp	-	-	-	-
		Ga	-	-	-	-
		Pa	-	-	-	-
	NCS	De	1,028,747	514,373	1,028,747	514,373
		Sp	-	-	-	-
		Ga	-	-	-	-
		Pa	-	-	-	-

Table III. – Manufacturing anchoring cost of tensioned systems

	$C3_{ma}$ p=2	MA3	MB3	MA4	MB4	MC4
Ch CS	De	-	-	-	-	-
	Sp	5,545,950	35,391,547	-	-	-
	Ga	-	-	-	-	-
	Pa	-	-	-	-	-
Ch NCS	De	-	-	-	-	-
	Sp	7,430,007	-	4,596,218	9,906,676	3,524,212
	Ga	-	-	-	-	-
	Pa	793,800	-	793,800	2,721,600	1,020,600
Ca CS	De	-	-	-	-	-
	Sp	5,545,950	-	-	-	-
	Ga	-	-	-	-	-
	Pa	-	-	-	-	-
Ca NCS	De	-	-	-	-	-
	Sp	7,430,007	-	4,922,251	12,040,477	4,309,675
	Ga	-	-	-	-	-
	Pa	793,800	-	793,800	2,721,600	1,020,600
Fi CS	De	-	-	-	-	-
	Sp	5,545,950	-	-	-	-
	Ga	-	-	-	-	-
	Pa	-	-	-	-	-
Fi NCS	De	-	-	-	-	-
	Sp	7,430,007	-	5,256,592	12,598,006	4,515,179
	Ga	-	-	-	-	-
	Pa	793,800	-	793,800	2,721,600	1,020,600

B. Installation costs

Installation costs depend on the type of anchor considered, because their installation method is different. In this sense, drag embedment anchors, gravity anchors and plate anchors do not need pumps and divers, so their cost will be less than suction piles, as we can see in Table IV and Table V.

Table IV. – Installation costs for drag embedment anchors, gravity anchors and plate anchors

$C4_{ma}$ (€)	MA	MB	MC
Method 1	1,497,636	1,996,848	748,818
Method 2	981,288	1,308,384	490,644

Table V. – Installation costs for suction piles

$C4_{ma}$ (€)	MA	MB	MC
Method 1	1,718,598	2,291,464	859,299
Method 2	1,075,986	1,434,648	537,993

Method 2 based on the use of AHV vessel is cheaper than Method 1, which combines barge and tugboat. In fact, the difference in terms of costs is around 600,000- 700,000 €.

C. Exploitation costs

According preventive maintenance, helicopter (M1) is the cheapest preventive maintenance system, with value of 388,266 €, as we can see in Table VI and Table VII. On the other hand, the most expensive maintenance method is one which involves buying a FSV vessel (M3), with values up to 1,235,275 €. This result depends a lot on the distance to shore.

Table VI. – Preventive maintenance costs for no tensioned platforms

C_{pm}	MA1	MC1	MA2	MC2
M1	388,266	388,266	388,266	388,266
M2	390,171	390,171	390,171	390,171
M3	1,235,275	1,235,275	1,235,275	1,235,275
M4	821,577	13,475,725	19,843,118	32,658,546

Table VII. – Preventive maintenance costs for tensioned platforms

C_{pm}	MA3	MB3	MA4	MB4	MC4
M1	388,266	388,266	388,266	388,266	388,266
M2	390,171	390,171	390,171	390,171	390,171
M3	1,235,275	1,235,275	1,235,275	1,235,275	1,235,275
M4	39,106,580	45,581,493	58,611,961	65,167,515	71,749,949

Otherwise, corrective maintenance costs related to mooring systems differ from 392.48 in Model A with transitional mooring to 125,997.50 € in Model C with slack mooring, as we can see in Table VIII:

Table VIII. – Corrective maintenance costs for no tensioned and tensioned platforms

C_{cm} p=1	MA1	MC1	MA2	MC2
Ch	392.48	125,997.50	392.48	125,997.50
Ca	-	-	-	-
Fi	-	-	-	-

C_{cm} p=1	MA3	MB3	MA4	MB4	MC4
Ch	-	-	-	99,787.35	10,511.28
Ca	-	-	-	51,022.19	33,559.59
Fi	-	-	625.85	29,454.77	28,149.93

On the other hand, most of corrective maintenance costs related to anchoring systems are too much reduced because the failure probability is low (high security coefficients have been considered). In fact, they have values from 955.40 to 48,946.54 €.

D. Dismantling costs

According dismantling, we have three different costs: decommissioning, cleaning and disposing materials.
Considering decommissioning, there are some differences in costs depend on the type of anchor used, as we can see in Table IX and Table X:

Table IX. – Decommisioning costs for drag embedment anchors, gravity anchors and plate anchors

$C4_{ma}$ (€)	MA	MB	MC
Method 1	898,582	1,198,109	449,291
Method 2	1,373,803	1,831,738	686,902

Table X. – Decommisioning costs for suction piles

$C4_{ma}$ (€)	MA	MB	MC
Method 1	515,579	687,439	257,790
Method 2	753,190	1,004,254	376,595

Moreover, cleaning costs will be 200,000 €, being common for the entire wind farm, and disposing materials cost is 213,239 €.

5. Conclusion

The phases of the life cycle cost of anchoring and mooring devices of a floating offshore wind farm have been taken into account: manufacturing, installation, exploitation and dismantling phases.
According results, synthetic fibre and plate anchor are, in economic terms, the best mooring and anchoring systems. On the other hand, considering installation process, most economic method is using an AHV vessel. However, in terms of dismantling using a cargo barge and a tugboat will be the best alternative.
Regarding maintenance, use helicopter of preventive purposes will be the best option.

This analysis of the life cycle costs of mooring and anchoring devices for floating offshore wind farms gives some ideas about what will be the future strategies in relation to floating systems.

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