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Research paper

A decision making strategy for cost-effective anchoring and mooring design in floating offshore wind systems

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ABSTRACT

Site-specific stationkeeping system optimization is regarded as essential to reduce costs and enhance floating offshore wind turbine power production. However, the selection and design of the anchor system is often overlooked. This study proposes a flexible decision-making strategy to select the most cost-effective anchor at early wind farm design stages, based on a minimum set of input data (seabed type, anchor load angle, and basic mooring line properties) and a bottom-up cost estimation approach. From these parameters, the methodology derives a plausible anchor type, size, and cost. The strategy provides consistent and reasonable size and cost estimates when applied to literature case studies. A review of technical solutions, unit costs, and installation procedures unifies fragmented information from scientific literature and commercial examples. The proposed design method is straightforward to integrate with technological advancements and economic evaluations, and could be extended to other floating offshore applications. Compared to existing alternatives, the proposed strategy relies on a minimal set of input parameters and provides a quantitative basis for selecting the best-performing anchor. It also contributes to advancing stationkeeping system design, cost estimation, and life cycle assessment studies, by enabling selection of more realistic anchor systems without relying solely on designer experience.

1. Introduction

Wind has established itself as the largest variable renewable electricity source as of 2024 (International Energy Agency, IEA). However, the estimated levelized cost of energy (LCOE) of floating offshore wind farms currently exceeds 0.2 USD/kWh, *i.e.* approximately four times higher than that of bottom-fixed offshore wind turbines (International Renewable Energy Agency, IRENA). A major reduction in the LCOE is expected to come from the increased scale of future wind farms, more efficient planning of operational expenditures (OPEX), and reduced foundation costs. To date, neither research nor industry have converged to a single, optimal design of the floater and its stationkeeping system. In fact, it has been shown that site-specific selection and optimization of the system can significantly reduce costs and enhance power production (West et al., 2021).

The design of optimal mooring lines and anchors for a floating offshore wind turbine (FOWT) aims to guarantee the system's survivability and safety in all exciting conditions, while minimizing the system cost. Reference mooring systems have been defined for certain floaters or case studies (Allen et al., 2020; Catapult, 2024), but site-specific optimization is required to maximize profitability, accounting for factors such as the platform dynamic response, the sea depth, and the seabed type. Although anchors are a crucial component and can significantly affect operation planning, they are often overlooked at the initial design stages of a project or summarily addressed in mooring design, cost estimation, and life cycle assessment (LCA) studies (West et al., 2021; Myhr et al., 2014; Xu et al., 2021; Castro-Santos et al., 2018; Maienza et al., 2020). For instance, anchors can account for up to 26% of the total mooring system cost (Maienza et al., 2020), making them a component to be properly considered in the overall budget. However, the design of the anchoring system is inherently coupled with the configuration of the mooring lines and associated equipment, thus requiring a fully integrated analysis of the mooring layout. For example, certain mooring configurations may impose predominantly vertical loads on the anchors, thereby limiting the applicability of specific anchor types. Furthermore, seabed conditions significantly influence anchor selection, as different soil types impose constraints on the installation method and holding capacity of each anchor type. Recent studies on torpedo anchors (Wang et al., 2023; Hossain et al., 2015) and suction anchors (Xiao et al., 2020) have shown that anchor embedment and holding

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Abbreviations

AHTS	anchor handling tug supply (vessel)
AHV	anchor handling vessel
BU	bottom-up (approach)
CAPEX	capital expenditures
CSV	construction support vessel
DEA	drag embedded anchor
DECEX	decommissioning expenditures
DP	driven pile
DrP	drilled pile
DWA	deadweight anchor
FOWT	floating offshore wind turbine
HMPE	high modulus polyethylene
I&C	installation and commissioning
KPI	key performance indicators
LCA	life cycle assessment
LCOE	levelized cost of energy
MBL	minimum breaking load
O&G	oil and gas
O&M	operation and maintenance
P&F	purchase and fabrication
OPEX	operational expenditures
ROV	remotely operated vehicle
SA	suction anchor
SEPLA	self-embedding plate anchor
TD	top-down (approach)
TLP	tension leg platform
TRL	technology readiness level
UHC	ultimate holding capacity
VLA	vertical load anchor
WEC	wave energy converter

capacity are highly sensitive to installation processes, soil layering, and installation-induced remoulding and strain softening. Experimental and numerical investigations demonstrate that dynamic penetration behavior, consolidation effects, and load inclination can substantially alter anchor performance, particularly in layered soils and calcareous sediments, and that installation effects alone may reduce short-term capacity by more than 40%. These findings motivate the development of structured, conservative anchor selection frameworks for preliminary assessments. Even in preliminary assessments, neglecting the interdependence between anchors, mooring lines, and seabed characteristics can lead to technically unfeasible solutions and inaccurate cost estimations. Such simplifications may undermine the reliability of the design process, particularly if tailored cost functions and design constraints are not properly incorporated (Xu et al., 2021; Campanile et al., 2018; Díaz and Soares, 2023). To overcome this problem, Cerfontaine et al. critically analyzed a variety of suitable anchors for FOWT applications, with varying performance-cost characteristics, and they discussed future developments (Cerfontaine et al., 2023). In most cases, the selection of an anchor and its design are only addressed qualitatively, being mostly based on the personal experience of the designer (ORE Catapult and ARUP, 2024; Ma et al., 2019). Moreover, there is currently no established method for selecting an anchor during the early stages of offshore wind farm design. This study proposes a complete cost estimation and decision making strategy to select the anchor type through a bottom-up (BU) approach. In one of the most recent reviews on mooring costs, Giglio et al. (2023) proposed a bottom-up (BU) costing strategy tailored to wave energy converter (WEC) applications. However, the methodology is general enough to be applicable to any offshore floating system, thus appealing to a broader audience. Despite its versatility, the strategy proposed in this work relies on a minimal set of input data, including seabed type, load orientation, and unit costs of components and equipment to estimate capital expenditures (CAPEX).

To address the presented challenges, this study aims to contribute to the current state-of-the-art through the following:

- Present a comprehensive overview of the state of the art, including updated cost estimation functions for mooring systems covering lines, anchors, and associated installation costs. The objective is twofold: to develop a tailored cost estimation database and to critically assess the limitations of existing studies. Additionally, an analysis of currently developing and permitted offshore wind farms is included to provide an industry-based perspective.
- Propose a straightforward methodology for anchoring system design, incorporating preliminary sizing techniques and contextualizing the approach for an audience beyond floating wind turbine systems, thereby broadening its applicability to other offshore floating technologies.

This new, flexible strategy is defined as an easy-to-follow guide to select the anchor alternative with the best techno-economic performance, during feasibility, preliminary front-end engineering design pre-FEED, and basic design stages. A major challenge was the collection of suitable technological solutions, including detailed installation procedures, and the definition of a coherent set of unit costs, as information was generally fragmented, not updated, and partially missing in the available literature. The present work offers an accurate review of marine anchors and cost functions that unifies scientific knowledge and reflects commercial examples.

The rest of the paper is organized as follows: Section 2 defines the nomenclature and key characteristics of mooring lines and anchors to establish a common framework and facilitate understanding of the rest of the paper; Section 3 presents the background for this study to depict the state-of-the-art in terms of mooring line and anchor design, cost estimation methods, and commercial examples; Section 4 illustrates the BU approach for cost estimation; Section 5 then explains in detail the decision making strategy; finally, Section 6 discusses the application of the proposed strategy to literature case studies to highlight its effectiveness in improving the quality of results and to identify the most promising solutions or issues that should be addressed in the near future. The proposed strategy is able to select a realistic anchor, and the differences in the estimated anchor size suggest that it is of primary importance to increase the accuracy of LCOE and LCA studies.

2. Mooring and anchoring systems

Before presenting a detailed analysis of the state of the art, this section provides a brief overview of the main components of mooring systems. The elements responsible for maintaining the floating structure near its intended installation coordinates, within limits defined by operational and safety requirements, constitute the stationkeeping system. Under this definition, mooring lines, anchors, and functional equipment are included, as schematically illustrated in Fig. 1. The functional components include buoys and buoyancy modules, clump weights, connectors, chain stoppers, tensioners, and tension reductioners, among others. However, due to the limited information available in the literature and the relatively minor influence of these operational elements on overall cost and design, they are not considered in this study. Readers seeking further detail may refer to the functional components cost functions analyzed in Giglio et al. (2023).

While design and modeling methodologies do not represent a main contribution within this study, these are an essential pre-requisite in the BU cost estimation approach (see West et al., 2021; Ghigo et al., 2022 for examples of design methodologies). Accordingly, a procedure to estimate the diameter and mass of mooring lines is proposed in Section 4.1, while anchor design techniques compatible with the proposed methodology are reported in the supplementary material.

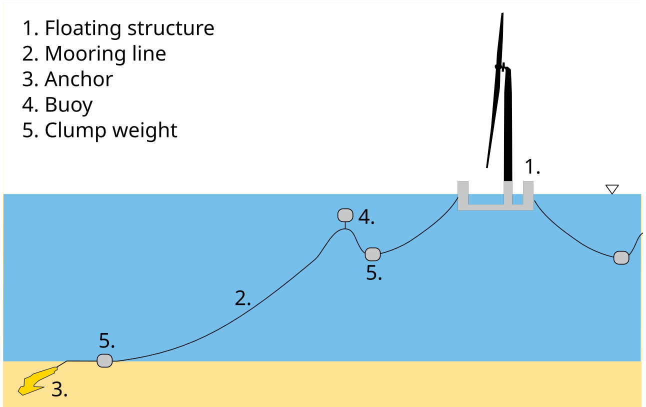

Fig. 1. Reference mooring configuration for the purpose of this study (elements not to scale).

2.1. Mooring lines

Mooring lines are tension elements that connect the floater to its anchors. The number of lines per floater depends on its design and on safety and structural evaluations, but it might differ from the number of anchors per floater. For instance, multiple mooring lines might link the same floater fairlead and anchor for a tension leg platform (TLP) to sustain significant forces (Uzunoglu and Guedes Soares, 2019), if commercially available lines lack sufficient diameter to handle the loads, or as a redundancy measure to improve safety (DNV, 2024).

According to how restoring forces are transmitted to the floater, mooring systems are classified as catenary, taut, and semi-taut [1]. Lines can be composed of the following section types:

- Chains can be studlink or studless, the former being typically heavier, having a higher drag coefficient, and exhibiting superior fatigue resistance (Giglio et al., 2023). Common mooring chain grades include R3, K3, R3S, R4, and R5 (Corewind, 2020).
- Synthetic fiber ropes encompass a variety of polymers, such as nylon, polyester, and high modulus polyethylene (HMPE), and they are currently the prevalent choice for FOWT projects, as it will be shown in Section 3 in Table 2. Polyester and nylon were selected in this study due to the availability of both cost metrics and material properties in the literature (Giglio et al., 2023).
- Steel wire ropes are sometimes more prone to damage and corrosion (Corewind, 2020), but they are valued for their favorable properties, including a relatively lower mass at the same minimum breaking load (MBL) compared to chains (Myhr et al., 2014). These ropes represent a promising alternative for TLPs (Boo et al., 2024), for which multiple lines could be used to achieve the required stiffness and sustain the very high loads involved.

Some oil & gas (O&G) TLPs utilize rigid tendon systems, composed of hollow steel cylinder sections. While there are a few examples of similar designs in FOWT-related literature (Koh et al., 2016; Vijay et al., 2018; Rui et al., 2024), the unavailability of commercial data precludes their inclusion in this work.

2.2. Anchors

Anchors secure floating structures to the seabed, acting as individual structures subject to both the mean and dynamic components of the loads transmitted through mooring lines. Anchors can fit into three main categories: plate anchors, pile anchors, and gravity anchors (Cerfontaine et al., 2023). However, the preliminary selection targeted in this study requires a more specific list of solutions, *i.e.* drag embedded anchors (DEA), vertical load anchors (VLA), suction anchors (SA), driven piles (DP), drilled piles (DrP), and deadweight anchors (DWA) [2]. Fig. 2 provides a visual summary of this list.

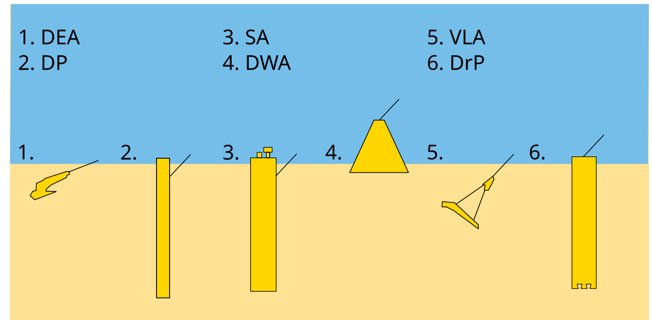

Fig. 2. Anchor alternatives considered in this study (not to scale).

The selection of these anchors is based on their use in existing FOWT projects, detailed in Section 3 and Table 2, as well as their technology readiness level (TRL) (ORE Catapult and ARUP, 2024; European Commission, 2014). As discussed in Section 5, this set of anchors provides solutions suitable for most proposed FOWT floater designs, accommodating various soil conditions and load orientations.

DEAs are steel plate anchors, typically composed of a fluke and a shank. Their holding capacity is generated by soil resistance above or in front of the anchor, relying on horizontal load transfer from the mooring line. These systems are installed by dragging along the seabed, enabling partial or full penetration. A tension proof confirms successful installation. DEAs, which cannot resist vertical loads, are the most commonly used anchor type in FOWT projects, as shown in Table 2.

VLAs are plate anchors designed for greater seabed penetration than DEAs. They are well-suited for taut and semi-taut mooring configurations where uplift forces exceed DEA capacity. VLAs often feature a releasable shank that repositions after embedment, allowing the load to act perpendicularly to the fluke.

SAs consist of steel or concrete open-ended hollow cylinders. Soil friction and the soil plug inside the cylinder generate vertical holding capacity, while horizontal capacity results from lateral soil resistance. After partial embedment through their own weight, installation is completed by pumping water out of the caisson, activating pumps through remotely operated vehicles (ROVs).

DPs are slender, steel pile anchors whose holding capacity is achieved through soil friction and lateral soil resistance. These anchors are installed using hammers or vibrating machinery, which are lowered to the seabed during installation and can be removed once the pile is in place. An upending frame can be used to move them from an horizontal position on deck to a vertical one for installation.

DrPs are hollow cylindrical anchors, either open-ended or closed. Their holding capacity is provided by skin friction and lateral soil resistance. For rock seabeds, load transfer mechanisms differ significantly (Bañuelos-García et al., 2021; del Estado, 2008), requiring different design methodologies or new geometries (Cerfontaine et al., 2021). They are installed into pre-drilled holes, with or without grouting (Cerfontaine et al., 2023), requiring specialized equipment.

DWAs are heavy concrete or steel anchors that may incorporate shear keys for enhanced friction. Other designs, such as ballasted floating

[1] For a more detailed overview of the mooring layout with the associated characteristics, the interested reader is referred to Jiang (2025), Davidson and Ringwood (2017).

[2] The term "deadweight anchor" has been chosen over "gravity anchor" to avoid potential confusion with gravity-installed anchors, such as torpedo anchors. This distinction is intended to enhance clarity, and adopting this terminology in future studies is recommended.

devices submerged during installation and/or integrated with the substructure, also exist (ORE Catapult and ARUP, 2024; Uzunoglu et al., 2025). Their holding capacity derives from their significant mass, with additional frictional contribution from the seabed. Installation is limited by crane capacity.

Proper anchor sizing, in terms of geometrical dimensions and mass, should account for both cyclic and static loads (ISO, 2013; API, 2024) and consider the interconnected safety of mooring lines and anchors (de Mécanique des Sols et, 2024). In the absence of detailed soil description, site-specific sizing based on static conditions is assumed sufficient, with design procedures provided in the supplementary material.

2.2.1. Innovative anchor designs

Innovative anchor designs have been developed to reduce costs and grant access to previously unsuitable locations. While they often exhibit low TRL and they lack standardized sizing procedures, they represent promising alternatives for future applications. Below is an overview of some notable innovations (ORE Catapult and ARUP, 2024; Cerfontaine et al., 2020; Zhang et al., 2024; Raaj et al., 2023):

- Screw piles are hybrid anchors combining shaft resistance and soil engagement with the screw surface. Their use is restricted to penetrable soils, and large-scale applications are currently undocumented.
- Torpedo anchors are gravity-installed anchors deployed by free-fall from a significant height. These systems require soft seabeds for penetration and sufficient water depth for free-fall installation.
- Micropiles are a group of small-diameter piles held together by a framework and combining soil mobilization. These anchors offer easier transportation and installation compared to large-scale piles.
- Self-embedding plate anchors (SEPLA) are plate anchors installed using a hollow cylinder that embeds the plate into the soil, increasing installation accuracy compared to DEAs and VLAs. The driver cylinder is then retrieved for reuse.
- Innovative rock anchors: Rock-based seabeds pose unique challenges due to the need for specialized equipment and difficulty in modeling soil-anchor interactions. Examples include the self-drilling rock anchors for aquaculture proposed by Cerfontaine et al. (2021).

3. Literature review

Having outlined the range of mooring and anchoring solutions applicable to FOWTs and their main design characteristics, it is necessary to examine how these components have been addressed in previous research. The literature review that follows positions the proposed taxonomy within the broader context of mooring and anchoring studies, highlighting how existing works handle component selection, sizing, and cost evaluation. This step serves to identify current limitations and to motivate the development of the decision-making and cost-modelling framework presented in the following sections.

In reviewing existing research, it becomes evident that anchor selection for FOWTs has received limited dedicated attention. ORE Catapult reviewed qualitative decision criteria (ORE Catapult and ARUP, 2024), while Ma et al. focused on the anchor design process (Ma et al., 2024). Both examples, however, lack a clear strategy to guide the reader in making an unbiased decision on the anchor type to employ based on well-defined key performance indicators (KPI). Moreover, these methods focus exclusively on anchor suitability, and require extensive site-specific information.

The lack of a standardized anchor selection strategy is felt across offshore wind literature. While mooring configurations are frequently analyzed, cost estimation methodologies or studies focusing on economic KPIs often neglect detailed anchoring considerations or treat the mooring–anchor system using simplified or generic assumptions. Reference floater designs, *e.g.* Allen et al. (2020), are often adopted, with mooring systems subsequently adapted in a simplified manner, without full consideration of the target location, metocean conditions, or economic parameters. This standard practice does not ensure that the same performance can be achieved or that the design is correctly re-scaled. Arbitrary selection of mooring lines and anchors without a representative cost-modeling framework could lead to the unreasonable results affecting both the final cost of the system and the mooring lines and anchor performance.

Diaz and Guedes-Soares proposed a cost and financial evaluation model for offshore wind farms (Díaz and Soares, 2023). The optimal floater for a given site is chosen among reference configurations, characterizing mooring lines by their material and associating a single anchor type to each floater. Component costs are scaled by water depth, number of lines, and anchors, but the authors omit proper line scaling criteria that would ensure an optimal behavior of the FOWT under local metocean conditions. Mooring and anchor installation operations are also grouped with platform and turbine installation costs, reducing the method's flexibility.

Myhr et al. estimated the LCOE for different FOWT floaters, each with an associated mooring and anchoring system (Myhr et al., 2014). However, limiting assumptions on costs and on component scaling, *e.g.*, not adjusting chain line diameter when adapting the system to a different water depth, could affect a proper comparison as well as extension of the results to other floater concepts.

In the context of a broad cost estimation framework for offshore wind farms (Castro-Santos, 2013), Castro-Santos et al. published a deep-water installation cost model (Castro-Santos et al., 2018). Fundamental operations are distinguished, but costs and vessel requirements and times can not be employed in a more generic framework and some operations, like hook-up, are omitted.

Giglio et al. proposed a BU approach for WECs, linking costs to component geometry and mass (Giglio et al., 2023). In a top-down (TD) approach, costs are a percentage of the total cost or a function of rated power. In a BU approach, each component is designed to meet operational requirements, and its cost is estimated as fabrication cost, normally based on mass or length, and installation costs, which are the sum of the costs of each installation step. Despite scale differences between WECs and FOWTs, the BU approach allows flexible, detailed cost estimation that can support the selection of the anchor type, provided all cost elements are carefully considered. This approach could be significantly effective in a mooring optimization framework.

For example, West et al. optimized taut mooring systems through a multi-objective genetic algorithm minimizing component cost and footprint (West et al., 2021). However, the way loads are transmitted through the line and the load angle at the anchor fairlead is ignored, undoubtedly affecting the anchor size and cost. Similarly, Xu et al. optimized FOWT mooring systems in shallow waters (Xu et al., 2021). While DEAs are considered for catenary systems and SAs for taut systems, the anchor design and cost are constant, resulting in a non load-dependent function. Campanile et al. also chose the anchor size a priori when optimizing the FOWT mooring system in intermediate and deep water depths (Campanile et al., 2018). The pre-selection of anchors in these studies also ignores factors such as soil characteristics and installation requirements, often relying on industrial examples.

Anchor selection studies clarify the relevance of these factors, but in turn they do not address mooring design. Recently, Cerfontaine et al. discussed state-of-the-art and future development of FOWT anchors (Cerfontaine et al., 2023). They combined geotechnical and installation requirements, highlighting applicability limits for a variety of anchors. However, suggested design strategies require a detailed knowledge of the seabed. CoreWind's review of FOWT state-of-the-art mooring and anchor designs also provides a good overview (Corewind, 2020). However, their cost estimation lacks details and sizing procedures only give an order of magnitude of the relationship between holding capacity and anchor mass.

A clear representation of the fragmented state of the literature is given in Table 1. References are categorized based on seven characteristics: publication year, which is important for monetary values; the mooring and anchor columns indicate whether these components are explicitly considered at any stage and list which anchor alternatives were considered, as defined in Section 2; the costs column specifies which components are included - Purchase and Fabrication (P&F), Installation and Commissioning (I&C), and Operation and Maintenance (O&M) - following Section 4; the time and vessel columns indicate whether installation time and vessel type are considered, as they are key parameters in a BU approach; the energy source column specifies the target technology, if any, since energy systems vary significantly in geometry and cost. Further insights are provided in Figs. 3 and 4, which show how many reviewed publications considered each anchor type and cost item, respectively. DEAs and SAs are the most commonly considered anchors, as expected, with a noticeable presence of DPs. A large percentage of publications, however, omit cost estimation entirely.

The conception of the anchor selection strategy should integrate scientific literature and industrial experience to bridge the gap often found between preliminary studies and real-world practice. Table 2 summarizes information on the projects reported as online and operating in Europe according to WindEurope (WindEurope, 2024) and EMODNET databases (Activities, 2024), along with projects at advanced development stages for which detailed information was available. The reported date is the official commissioning year or the envisioned one. Table 2 offers a quick reference of industrial examples in terms of employed line and anchor types and explored seabed types. Only two anchor types appear in Table 2, *i.e.* DEAs and SAs, regardless of floater type. Similarly, only sand seabed has been explored to date, partly due to its prevalence in the North Sea, partly because installation is relatively simple. Most projects have been deployed in the Atlantic Ocean or North Sea, at depths not exceeding 100m. The only exceptions are TetraSpar Demo (220 m), Hywind Tampen (260–300 m), and Provence Grand Large, currently the only operating floating offshore wind farm in the Mediterranean (although at 100 m). Notably, Hywind Tampen is the first reported project in Europe employing shared anchors[3].

The limited variety of solutions in commercial projects highlights the need to provide a broader range of alternatives and a flexible tool to explore new configurations that might contribute to the decrease of offshore floating wind farm costs, representing better techno-economic solutions and allowing the installation in more challenging areas.

4. Cost functions

As previously mentioned, the proposed selection strategy aims to identify the cheapest system that meets operational and safety requirements. The total cost of an offshore wind farm is typically categorized into project development (prior to the final investment decision), P&F, I&C, O&M, and decommissioning phases (Díaz and Soares, 2023). The first three phases form the CAPEX, while the remaining two are classified as OPEX and decommissioning expenditures (DECEX), respectively. A detailed definition of all cost items is relevant in a comprehensive evaluation of CAPEX, OPEX, and DECEX, but not all indices vary significantly between mooring line and anchor alternatives. Since including fixed costs in comparative analyses introduces uniform shifts, only variable costs are considered in the proposed strategy. Under this assumption, only P&F- and I&C-related CAPEX is included in this study. O&M costs are assumed uniform across mooring line and anchor types. Mooring materials have different degradation mechanisms and time frames (Pham et al., 2019) and long term changes in soil properties and stress conditions affect anchors differently (Cerfontaine et al., 2023; Kwa et al., 2023). However, defining degradation or failure rates for O&M planning strategies is complex, and to the authors' knowledge, there is no available literature that effectively distinguishes between technological solutions. In fact, both O&M and LCA studies often adopt the same values for different technologies (Garcia-Teruel et al., 2022; Elusakin et al.,

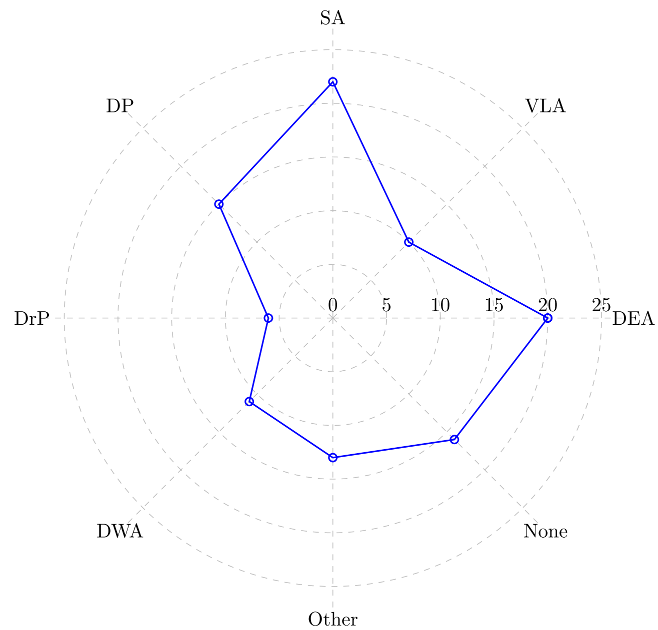

Fig. 3. Number of revised publications considering either anchor type or none of them.

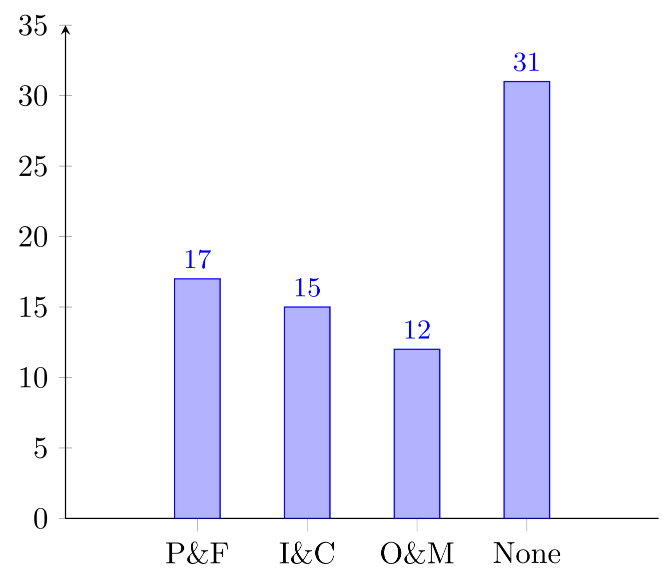

Fig. 4. Number of revised publications reporting either cost item between P&F, I&C, and O&M or none of them.

2021). A synthetic flowchart of the cost estimation is reported in Fig. 5, in which it is evident that costs of mooring lines and anchors can be separated. In this work, the I&C cost will be determined based on the anchor type as it will be clear from the following subsection.

Adapting Giglio et al.'s BU approach to FOWTs (Giglio et al., 2023), each relevant physical component is individually designed, and logistical and installation operations are detailed. P&F costs are obtained from the component's mass and cost per unit mass, while I&C costs are the result of operation time and vessel cost per unit time. Costs are scaled based on the number of turbines, mooring lines, and anchors, reflecting the size of the wind farm. The resulting cost function for the mooring and anchoring system is expressed as follows:

$$C_{Tot} = \left(\sum_{1}^{N_L} C_L + \sum_{1}^{N_A} C_A \right) \cdot f_t \cdot N_T + C_I, \tag{1}$$

[3] For a complete overview on shared moorings, the interested reader is referred to (Xu et al., 2024; Saincher et al., 2025; Paduano, 2026).

Table 1
Relevant papers for the literature review.

Author	Year	Mooring	Anchor	Costs	Time	Vessel	Tech
Allen et al. (2020)	2020	Yes	No	No	No	No	Wind
Altuzarra et al. (2022)	2022	Yes	DEA	I&C	Yes	Yes	Wind
(ABS)	2014	No	DEA, VLA, DP, SA	No	No	No	Wind
Aubeny and Murff (2005)	2005	No	SA	No	No	No	No
Bañuelos-García et al. (2021)	2021	No	DrP, DWA	No	No	No	Current
Boo et al. (2024)	2024	Yes	DP	No	No	No	Wind
Campanile et al. (2018)	2018	Yes	No	P&F, O&M	No	Yes	Wind
Castro-Santos (2013)	2013	Yes	DEA, VLA, DP, SA, DWA	P&F, I&C, O&M	Yes	Yes	Wind
Castro-Santos et al. (2018)	2018	Yes	Yes	I&C	Yes	Yes	Wind
ORE Catapult and ARUP (2024)	2024	Yes	DEA, VLA, SA, DP, DrP, DWA	No	Yes	Yes	Wind
Cerfontaine et al. (2020)	2020	No	Screw	No	No	No	Wave, Wind
Cerfontaine et al. (2021)	2021	No	DrP	No	No	No	Wave
Cerfontaine et al. (2023)	2023	No	DEA, DP, SA, DrP, DWA	No	No	No	Wind
de Mécanique des Sols et (2024)	2024	No	DEA, VLA, DP, DrP, SA, DWA	No	Yes	Yes	Wind
Corewind (2020)	2020	Yes	DEA, DP, SA, DWA	P&F	No	Yes	Wind
Devin et al. (2021)	2021	Yes	SA	P&F, O&M	Yes	Yes	Wind
Diaz et al. (2016)	2016	No	SA, DEA, VLA	No	No	No	Wind
Díaz and Soares (2023)	2023	Yes	DP, DEA, SA	P&F, I&C	No	No	Wind
Elusakin et al. (2021)	2021	Yes	Yes	O&M	No	No	Wind
Filgueira-Vizoso et al. (2022)	2022	Yes	Yes	P&F, I&C, O&M	No	Yes	Wind
Fletcher et al. (2025)	2025	Yes	SA	P&F, I&C	No	No	Wind
Garcia-Teruel et al. (2022)	2022	Yes	SA, DEA	O&M	Yes	Yes	Wind
Ghigo et al. (2022)	2022	Yes	DEA, DP, SA, DWA, Screw	P&F	No	No	Wind
Giglio et al. (2023)	2023	Yes	DEA, VLA, SA, DP, DWA	P&F, I&C, O&M	Yes	Yes	Wave
Hallowell et al. (2018)	2018	Yes	SA	No	No	No	Wind
Huang and Yang (2021)	2021	Yes	No	P&F	No	No	Wind
Ioannou et al. (2018)	2018	No	No	P&F, I&C, O&M	No	Yes	Wind
Ivanov et al. (2025)	2025	Yes	No	P&F, I&C	Yes	Yes	Wind
Jiang (2021)	2021	No	No	I&C	No	Yes	Wind
Koh et al. (2016)	2016	Yes	No	No	No	No	Wind
Kwa et al. (2023)	2023	No	Plate	No	No	No	Wave
Lee et al. (2024)	2024	Yes	No	No	No	No	Wind, Wave
Lee and Ong (2025)	2025	Yes	DEA, SA	No	No	No	Wind, Wave
Ma et al. (2019)	2019	No	DWA, DP, DEA, SA, VLA, Dynamically installed, SEPLA	No	No	No	No
Ma et al. (2024)	2024	No	DP, SA, DEA, dynamically installed	No	No	No	Wind
Maienza et al. (2020)	2020	Yes	Plate	P&F, I&C, O&M	No	Yes	Wind
McMorland et al. (2022)	2022	No	No	O&M	Yes	Yes	Wind
Montes et al. (2025)	2025	Yes	DEA, SA, VLA	P&F, I&C, O&M	No	No	Wind
Myhr et al. (2014)	2014	Yes	VLA, DEA, SA	P&F, I&C, O&M	Yes	Yes	Wind
Pham et al. (2019)	2019	Yes	No	No	No	No	Wind
Qiao et al. (2024)	2024	Yes	VLA	No	No	No	Wind
Raaj et al. (2023)	2023	Yes	Dynamically installed	No	No	No	No
Ramachandran et al. (2021)	2021	No	No	I&C	No	Yes	Wind
Rijken (2013)	2013	No	No	No	No	Yes	O&G
Rui et al. (2024)	2024	Yes	SA, DEA, DP	No	No	No	Wind, O&G
Uzunoglu and Guedes Soares (2019)	2019	Yes	No	No	No	No	Wind
Uzunoglu et al. (2025)	2025	Yes	DWA	No	No	No	Wind
VanZwieten Jr et al. (2014)	2014	No	DWA, DEA, DP, plate	No	No	No	Current
Verde and Nobre Lages (2023)	2023	Yes	Yes	No	No	No	Wind
Vijay et al. (2018)	2018	Yes	No	No	No	No	Wind
Vijayvergiya et al. (1977)	1977	No	DP, DrP	No	No	No	O&G
West et al. (2021)	2021	Yes	No	P&F	No	No	Wind
Xu et al. (2021)	2021	Yes	DEA, SA	P&F, I&C	Yes	Yes	Wind
Ye et al. (2024)	2024	Yes	No	No	No	No	Wind
Zhang et al. (2024)	2024	No	Dynamically installed	No	No	No	No

Table 2
Overview of mooring and anchoring characteristics in online, under-construction, and permitted European floating offshore wind projects of interest.

Project	Nation	Date	Anchor	Mooring line	Seabed type	Floater	Ref.
TetraSpar Demo	NOR	2021	DEA	Synthetic rope	-	Pendulum	Borg et al. (2020)
DemoSATH	ESP	2023	DEA	Synthetic rope	-	Single-point mooring	RWE (2026)
WindFloat Atlantic	PRT	2020	DEA	HMPE rope	Sand	Semisubmersible	WindFloat Atlantic (2024)
Kincardine	GBR	2021	DEA	Polyester rope	Sand	Semisubmersible	Principle Power (2025)
Hywind Scotland	GBR	2017	SA	Chain	Sand	Spar	Masdar and Statoil (2017)
Hywind Tampen	NOR	2023	SA	Steel wire	-	Spar	SEMAR (2022)
SeaTwirlS1	SWE	2015	-	-	-	Spar/single-point mooring	Seatwirl (2017)
Hywind Demonstrator	NOR	2009	-	-	-	Spar	Equinor (2008)
Floatgen	FRA	2018	DEA	Semi-taut nylon	Sand	Barge	Ideol (2018)
Provence Grand Large	FRA	2025	SA	Steel wire	-	TLP	Large (2024)
Eolmed	FRA	2025	DEA	Synthetic rope	Sand	Barge	Eolmed (2026)
Les éoliennes flottantes du golfe du Lion	FRA	2025	DEA	Chain	Medium Clay	Semisub	Ocean Winds (2018)
Project Erebus	GBR	2027	DEA	Synthetic rope	Sand	Semisubmersible	Wind (2024)
Green Volt	GBR	2029	DEA/SA	Chain/tendon	Sand	Semisubmersible/TLP	Volt (2024)

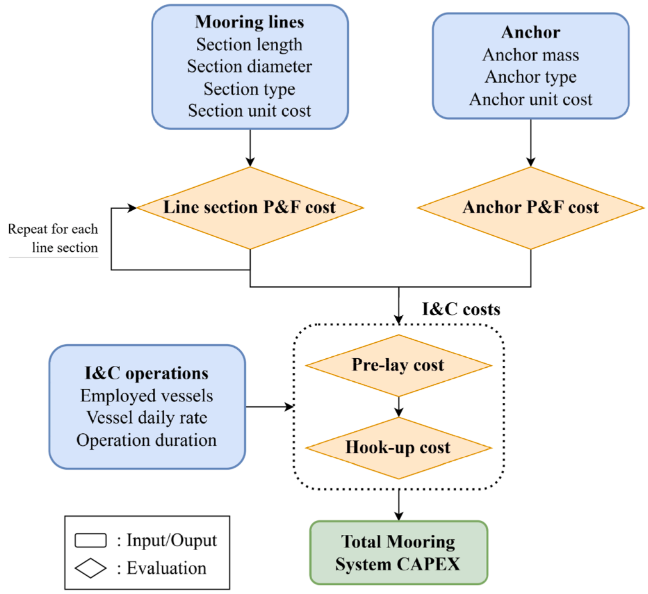

Fig. 5. Synthetic flowchart for the cost estimation strategy.

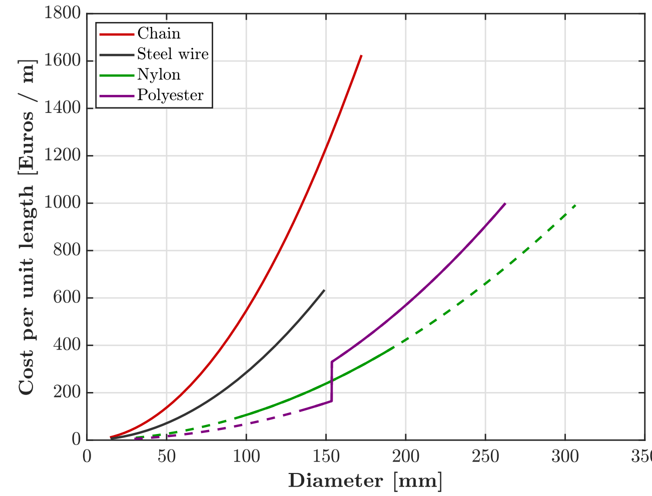

Fig. 6. Comparison of mooring line cost per unit length as a function of the line's nominal diameter (chain)/rope diameter (nylon, polyester, and steel wire) in a reference MBL window. Dashed line refers to costs extended outside the original range of validity.

where C_{Tot} is the total mooring and anchor cost for the wind farm, C_L is the P&F cost of a mooring line, N_L is the number of lines per floater, C_A is the P&F cost of an anchor, N_A is the number of anchors per floater, f_t is a factor accounting for transportation costs to the port (set to 1.02 per (Altuzarra et al., 2022), though project-specific supply chains may require reassessment), N_T is the number of turbines in the farm, and C_I is the total I&C cost. If not all turbines in the farm have the same mooring lines or anchors, Eq. (1) should be adapted. Installation costs however, should be assessed holistically for the entire wind farm, accounting for efficiencies achieved through shared transport operations, reduced round trips, and optimized fuel consumption. For clarity, it should be noted that this study does not directly match case studies involving shared mooring lines or anchors, due to the limited development stage of such solutions. Accounting for these systems would require specific modifications. The lack of consensus in the literature on design procedures and technological solutions for shared systems introduces complexity (Hallowell et al., 2018). Eq. (1) can still be adapted as a sum of individual component cost increased by factor f_t. Usually, shared anchors involve additional mooring length to reach the anchor point (Catapult, 2024), due to large inter-turbine spacing to avoid wake interference. It is reasonable to assume that at greater depths, the cost of the additional mooring length required to reach the shared anchor has a lower impact on the overall cost.

In the next subsections, cost functions for P&F costs of mooring lines and anchors are discussed, followed by a brief summary of installation strategies for different anchors and floater designs. Unit costs and installation procedures are derived or adapted from scientific literature, technical datasheets, and industrial examples. They have been updated when necessary to 2025 costs, applying the same principles as Giglio et al. (2023) and keeping the North Sea as a target area. Future applications of these cost functions should account for potential changes in material costs, vessel daily rates and fuel prices.

4.1. Purchase & fabrication cost of mooring lines

In a BU approach, mooring line P&F cost functions rely on the mooring line length, diameter and material, capturing fine variations between different designs. Conveniently, these functions can be used for individual sections of each line, *e.g.* to explicitly consider the chain sections of taut and semi-taut systems.

Mooring lines are usually characterized by their MBL, but unit costs are commonly expressed in terms of unit mass. Therefore, a procedure is reported to relate mooring design to cost estimation:

- Input values of MBL in (kN) and length L in (m) are required for each line section made of a different material.
- The line's diameter or the chain's nominal diameter d, in (mm), is obtained from the MBL. Various strategies can be used, like fitting catalogue data, empirical formulas, or theoretical ones. Examples used in Section 6 include commercial data for nylon and polyester ropes from Bridon-Bekaert (Bridon-Bekaert, 2026), and formulas for chains and steel wires from DNV E302 (DNV, 2022) and Barltrop (Barltrop, 1998), respectively.[4]
- The line's diameter or nominal diameter is used to evaluate the line's linear weight w in (kg/m). In this study, linear weight is obtained from DNV regulations for chains (DNV, 2022), from OrcaFlex averaged formulas for synthetic ropes (Orcina, 2024), and from Barltrop for steel wires (adapted to express the dry weight of the sheathed wire) (Barltrop, 1998).
- Line cost C_{line} is obtained as follows:

$$C_{Line} = c_{Line} \cdot w_{Line} \cdot L, \tag{2}$$

where c_{Line} is the cost per unit mass in $(€/kg)$.

Detailed equations and unit costs are reported in Table 3. The equations have been used to unify unit costs from the literature, before averaging them to obtain a reference value. Please notice that the cost per unit mass of polyester rope changes from $11€/kg$ to $22€/kg$ when the linear weight exceeds $15kg/m$ (Giglio et al., 2023). Fig. 6 compares line cost per unit length as a function of line diameter. The comparison is done in a diameter range equivalent to lines with an MBL between 200 and 20000 kN, extending formulas outside the original validity range when needed.

4.2. Purchase & fabrication cost of anchors

In this study, the P&F cost of anchors C_{Anchor} in (€) is assumed to be proportional to the anchor's mass W_{Anchor} in (kg), as in:

$$C_{Anchor} = c_{Anchor} \cdot W_{Anchor}, \tag{3}$$

[4] In this manuscript, grade R3 studlink chain is the reference for chain lines and spiral strand is the reference for steel wires.

Table 3
Proposed formulas and unit costs for different mooring lines materials.

	MBL (kN)	Linear density $\left(\frac{kg}{m}\right)$	Unit cost $\left(\frac{€}{kg}\right)$	Ref.
Chain	$f_g \cdot d^2 \cdot (44 - 0.08 \cdot d)$	$0.0219 \cdot d^2$	2.5	DNV (2022), Giglio et al. (2023), Xu et al. (2021), West et al. (2021), Myhr et al. (2014), Castro-Santos (2013), Montes et al. (2025)
Nylon	$0.2117 \cdot d^{2.001}$	$0.6071 \cdot 10^{-3} \cdot d^{1.994}$	18	Bridon-Bekaert (2026), Giglio et al. (2023), West et al. (2021), Myhr et al. (2014), Castro-Santos (2013)
Polyester	$0.1529 \cdot d^{2.115}$	$0.4514 \cdot 10^{-3} \cdot d^{2.068}$	11 or 22	Bridon-Bekaert (2026), Giglio et al. (2023), West et al. (2021), Myhr et al. (2014), Castro-Santos (2013)
Steel wire	$0.9 \cdot d^2$	$\frac{0.043}{g} \cdot d^2 + \rho_{water} \cdot 10^{-6} \cdot \frac{d^2 \cdot \pi}{4}$	5.5	Barltrop (1998), Giglio et al. (2023), Castro-Santos (2013)

Table 4
Proposed unit costs for different anchor types.

	Unit cost $\left(\frac{€}{kg}\right)$	Ref.
DEA	6.5	Castro-Santos (2013), Giglio et al. (2023), Maienza et al. (2020), Myhr et al. (2014), Díaz and Soares (2023), Xu et al. (2021)
VLA	5.2	Castro-Santos (2013), Giglio et al. (2023), Maienza et al. (2020), Myhr et al. (2014), Díaz and Soares (2023), Xu et al. (2021)
SA	10	Castro-Santos (2013), Giglio et al. (2023), Myhr et al. (2014), Díaz and Soares (2023), Xu et al. (2021), Devin et al. (2021)
DP	10	Castro-Santos (2013), Giglio et al. (2023)
DrP	10	Inferred
DWA	0.15	Castro-Santos (2013), Giglio et al. (2023)

where c_{Anchor} is the cost per unit mass in $(€/kg)$ and W_{Anchor} can be estimated from the line's MBL through the procedure in the supplementary material. Unit costs are reported in Table 4 and averaged over literature data when available. The only exception is the DrP cost, which could not be found in the literature: due to geometrical similarity, it has been set equal to the unit cost of DPs. Notice that, in this study, only concrete DWAs are accounted for.

4.3. Installation & commissioning costs

This study only considers the pre-lay and hook-up steps out of the detailed list from Corewind (2020). I&C cost functions require the duration of each procedure and the number and type of mobilized vessels, carefully considering that some vessels might be shared across more installation phases. For example, the vessels that tugged the FOWT assembly to the final location can be used to keep it in position during the hook-up phase. The C_I term in Eq. (1) sums pre-lay and hook-up costs, as follows:

$$C_I = F_{l,pl} \cdot \sum_{v=1}^{V} \frac{t_{pl,v} \cdot N_A}{24} \cdot c_v \cdot N_v + \\ + F_{l,hu} \cdot \sum_{v=1}^{V} \frac{t_{hu,v} \cdot N_T}{24} \cdot c_v \cdot N_v, \quad (4)$$

where t_{pl} and t_{hu} are the time in (h) needed to complete the operation, N_A is the number of anchors to be pre-laid, N_T is the number of turbines to be hooked-up, c_v is the daily rate in $(€/d)$ of vessels of type v, N_v is the number of vessels of type v mobilized for the operation, and $F_{l,pl}$ and $F_{l,hu}$ are correction factors that account for logistic operations. Detailed planning studies demonstrate that weather windows, number of trips, and vessel carrying-capacity constraints significantly influence mooring installation operations (Altuzarra et al., 2022). These correction factors can take into account the increased time needed and they can be defined for each anchor alternative.

Anchor pre-lay follows the operations briefly introduced in Section 2.2. Although not mandatory for all anchor types (Jiang, 2021), it is assumed that a portion of the mooring line is always left attached to the anchor, ready for retrieval at the start of hook-up operations.

In the literature, the same acronyms are used for installation vessels with significantly different onboard equipment. Based on consulted publications (Myhr et al., 2014; ORE Catapult and ARUP, 2024; Vryhof Anchors, 2015; Altuzarra et al., 2022; Campanile et al., 2018; Castro-Santos et al., 2018), project data from Table 2, and public information from ship owners and installers, three vessel categories were identified: anchor handling tug supply (AHTS) vessels, anchor handling vessels (AHV), and construction support vessels (CSV). Their key characteristics and a daily rate averaged from literature data are reported in Table 5. The installation time of one anchor and the corresponding vessel type can be found in Table 6. These values exclude the considerations that lead to the values of $F_{l,pl}$ and $F_{l,hu}$ in Eq. (4). DrP installation time has been set to 80h per anchor and line pair, covering all operations: drilling, inserting the pile, and cementing[5]. Some anchors can only be installed by CSVs, due to their large size or specialized equipment, while the others can be installed by both AHTS and AHV, depending on mass. If site-specific data is available, seabed preparation time and costs could be added, including: removal of superficial rocks and ground leveling for DPs, SAs, and DrPs; deposition of material to create a flat platform for DWAs; and removal of poor-quality sediments for all anchors. Currently, no reliable data on duration or cost of these operations is found in the literature, but the authors consider it important to involve industrial experts to improve future research.

Hook-up and tensioning procedures mainly depend on the floater and relate to the type and number of mooring lines. Including their cost better characterizes the economic impact of mooring line and anchor selection. Semi-submersible, spars, and pendulum floaters require an AHTS or AHV to retrieve, connect and tension mooring lines, while one or more tugs assist with hook-up, ballast and towing. This procedure has been documented for the Hywind Tampen wind farm (Subsea, 2023). TLP line hook-up and tensioning are more conveniently performed by varying floater ballast to increase draft for line connection, then generating tension through buoyancy. Examples are documented for O&G TLPs (Rijken, 2013; Wetch and Wybro, 2004) and proposed for FOWTs (Ramachandran et al., 2021). During both tow-out and hook-up, temporary buoyancy modules can stabilize the floater or reduce its draft, as documented in the Provence Grand Large project. Multiple AHTS or AHV must be used, equipped with sufficient crane capacity, ROV capability, and water pumps for ballasting. Alternative strategies include simultaneous tensioning of all lines using heavy lift vessels or the patented crawl-down method by Pelastar (LLC, 2024). ORE Catapult, Altuzarra et al. and Hasumi et al. report individual operative times for mooring hook-up and tensioning, coherently summing to 34.5h, 42h and 36h, respectively (Catapult, 2024; Altuzarra et al., 2022; Hasumi et al., 2025).

[5] The installation time of DrP has been provided, in the context of the FLOWAM HiFi project, by ENI SpA based on experience in the O&G sector.

Table 5
Daily rate and relevant characteristics of the vessel classes defined in this study.

Vessel	Daily rate (k€\d)	Crane capacity	Notes	Ref.
AHTS	30	2-10t, up to some meters	Bollard pull should be sufficient for load-proof testing of DEAs and VLAs (Vryhof Anchors, 2015; de Mécanique des Sols et, 2024). Winch capacity requirement depends on mooring line type and water depth. Deck space usage should account for additional equipment like signalling buoys.	Giglio et al. (2023), Maienza et al. (2020), Castro-Santos (2013), Ramachandran et al. (2021)
AHV	80	15t-250t	Bollard pull should be sufficient for load-proof testing of DEAs and VLAs (Vryhof Anchors, 2015; de Mécanique des Sols et, 2024). Winch capacity requirement depends on mooring line type and water depth. Deck space usage should account for additional equipment like signalling buoys.	Altuzarra et al. (2022), Campanile et al. (2018), Castro-Santos (2013), Giglio et al. (2023), Maienza et al. (2020), Myhr et al. (2014), Xu et al. (2021)
CSV	110	1000t, up to 50m	CSV cranes normally reach 500t. The limit has been extended to include some heavy lift vessels for bigger DWAs. Deck space and equipment should account for the possibility of hosting additional machinery like vibrating hammer or upending frame for DPs.	Jiang (2021), Maienza et al. (2020), Myhr et al. (2014), Xu et al. (2021), Ioannou et al. (2018)

Table 6
Installation details for different anchors.

Anchor	DEA	DWA	SA	DP	VLA	DrP
Vessel	AHTS or AHV	CSV	CSV	CSV	AHTS or AHV	CSV
Installation time	8h + 30 min per 100m water depth	8h	12h + 30 min per 100m water depth	12h + 30 min per 100m water depth	9h + 30 min per 100m water depth	80h
Notes	One vessel required with dynamic positioning and ROV capability (Vryhof Anchors, 2015; Altuzarra et al., 2022; Myhr et al., 2014; ORE Catapult and ARUP, 2024).	Crane capacity constitutes a limiting factor. Site preparation is necessary.	ROV capability required to activate the pump.	The order of operations may vary. Hammer can be retrieved and used again (ORE Catapult and ARUP, 2024).	One vessel required with ROV capability (Vryhof Anchors, 2015).	Different installation strategies are possible, including grouting, pre-drilling, and drive-drill-drive.

An average value of 38h is assumed in this study. Note that if mooring line design is fixed, hook-up costs do not affect anchor selection, as in Section 6. However, a correct definition of operative details is crucial when mooring and anchoring systems are co-designed, as well as in cost estimation and LCA studies.

5. Decision making strategy

The proposed decision making strategy for preliminary FOWT anchor selection, based on the previously defined anchor set and cost functions, is schematized in Fig. 7. In this figure, the cost estimation box contains the steps illustrated in Fig. 5.

Before anchor selection, input information must be defined. Many factors may be considered, including, but not limited to, seabed instability, cyclic displacements, positioning precision, and potential embedment loss (de Mécanique des Sols et, 2024; Diaz et al., 2016). Since the goal is not to perform a definitive anchor design but to explore alternatives in a preliminary stage, a simplified selection strategy is employed. The technical characteristics of the wind turbine or wind farm must first be specified, including the floater type and physical properties, mooring configuration and properties, number of mooring lines per turbine, and number of turbines. Then, the installation site must be characterized by water depth, seabed type and geotechnical properties, and metocean conditions. Water depth and seabed type, in particular, are essential for the proposed strategy. Given the costly nature of such data, some preliminary analysis can be carried out using online datasets (see Section 5.1).

Once input data are retrieved, the seabed type and load angle are used to reduce a predefined anchor set, as per Sections 5.1 and 5.2, to only include suitable ones. Each suitable anchor's mass and geometry relate to its ultimate holding capacity (UHC), or the horizontal and vertical projections H_d, V_d of an equivalent design load. The required UHC is generally set to 1.1 times the line MBL, to ensure the line fails before it can detach from the anchor (ISO, 2013; DNV, 2024; Vryhof Anchors, 2015). Representative design equations are reported in Table 7 [6]. More accurate methods can be used if additional geotechnical data are available, *e.g.* (API,, 2014; Randolph and Murphy, 1985; Aubeny and Murff, 2005).

Finally, P&F and I&C costs are estimated for mooring lines, anchors, and other equipment, and the cheapest option is selected as optimal. Given the preliminary nature of this strategy, additional selection criteria or KPIs beyond cost can be introduced. This optional step can further reduce available technical solutions. Possible indicators and considerations are discussed in Section 6.

5.1. Anchor limitations: seabed type

Each anchor proposed in Section 2 is suitable for a subset of seabed categories, based on its working principle and installation technique. Anchor design studies typically employ a detailed soil profile to characterize performance. At the preliminary design stage, only superficial seabed strata data are assumed available. Characterizing the full soil profile would require more costly geophysical surveys, bathymetric surveys, seabed sampling, and geotechnical testing. For example, soil information can be obtained from datasets such as EMODnet GIS maps (Kaskela et al., 2019), which use a modified Folk classification method, the simplest version of which identifies five soil classes. As anchor selection studies tend to use a different classification (VanZwieten Jr et al., 2014; Cerfontaine et al., 2023; Diaz et al., 2016; , ABS; Bañuelos-García et al., 2021), EMODnet soil classes are remapped in this study to match relevant literature, following the conversion rules in Table 8. Then, soil compatibility of each anchor type with the five seabed categories has been determined according to the available literature (Giglio et al., 2023; Cerfontaine et al., 2023; Corewind, 2020;

[6] The interested reader is referred to the supplementary material for a more detailed discussion on equations and assumptions.

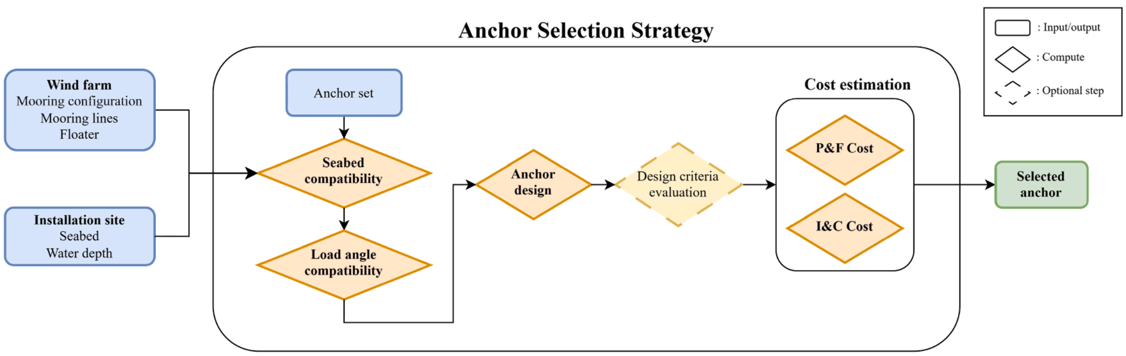

Fig. 7. Anchor design and selection decision making strategy flow chart.

Table 7
Most relevant equations from proposed methods for preliminary anchor design.

Anchor	Design equations	Notes	Ref.
DEA	$m = \left(\frac{UHC}{a_1}\right)^{\frac{1}{a_2}}$	Parameters a_1 and a_2 depend on seabed type. Penetration depth is ignored.	(ABS), Vryhof Anchors (2015)
VLA	$A = e_1 \cdot UHC + e_2$ $m = (\rho_s \cdot A \cdot F/2.5) + (4 \cdot \rho_{chain} \cdot E_0/\sin(\alpha))$	Parameters e_1 and e_2 depend on seabed type, while F and E_0 are geometric properties.	(ABS), Giglio et al. (2023)
SA, DP	$L, D, T = b_1 \cdot UHC^{b_2}$ $V = (D^2\pi/4 - (D-2t)^2\pi/4) \cdot (L-t) + D^2\pi t/4$ $m = \rho \cdot V$	Parameters b_1 and b_2 depend on seabed type and anchor type.	(ABS)
DrP	$A_g = 1.3 \cdot (2 \cdot H_d)/(0.6 \cdot f_y \cdot 0.9)$ $A_g = D^2\pi/4\pi - (D-2t)^2\pi/4$ $t = 6.35 + D/100$ $L = 4 \cdot (E_s \cdot I/n_h)^{\frac{1}{5}}$ $V = (D^2\pi/4 - (D-2t)^2\pi/4) \cdot (L-2t) + D^2\pi 2t/4$ $m = \rho \cdot V$	An iterative procedure must be followed to ensure structural and geotechnical verifications are respected. For purely vertical load, use UHC as design load.	Bañuelos-García et al. (2021)
DWA	$m_{wet} = H_d/(9.81 \cdot \tan(\phi - 5°)) + V_d/9.81$ $m_{dry} = m_{wet} \cdot (\rho + \rho_{H_2O})/\rho$	The angle of internal friction ϕ depends on the seabed type. Shear keys are ignored.	Bañuelos-García et al. (2021), Vryhof Anchors (2015)

ORE Catapult and ARUP, 2024; Vryhof Anchors, 2015; Diaz et al., 2016; , ABS; Vijayvergiya et al., 1977) and it is reported in Table 9:

- DEAs are suitable for very soft clay, medium clay, hard clay, and sand. Excluding innovative designs, penetration is not possible for harder seabed classes, but is for cohesive sediments, as installation requires dragging them on the seabed.
- DWAs are suitable for all compact soils, which is necessary to support their weight. Therefore, only very soft clay is excluded. Seabed preparation might be needed due to the typically large size and weight, including flattening the landing area.
- SAs are suitable for very soft clay and medium clay, in which they can penetrate thanks to their weight and the pressure difference generated by a pump. Hard clay and sand might work only with specialized procedures, and are therefore excluded from this study.
- DPs are usually discussed with SAs, but can also be installed in sand and weak rock, in addition to very soft and medium clay. Based on these considerations, these anchors are deemed suitable for hard clay, but not rock seabed due to a lack of coherent anchor design data. A hard seabed or the presence of boulders can inhibit installation or cause pile refusal.
- VLAs are sometimes considered suitable for harder soils, but reviewed studies only agree on their use for very soft and medium clay.
- DrPs are suitable for rock seabed, the most challenging condition in terms of anchor compatibility. To provide an alternative to DWAs, DrPs are considered for this seabed type. As they are not typically reported as viable for offshore wind, their use in this study is limited to rock seabed only.

Layered or stratified seabeds are not considered in this work, as their analysis would require depth-resolved geotechnical data that are not typically available from open-access databases such as EMODnet. Characterizing such profiles would necessitate site-specific surveys and dedicated anchor sizing procedures, which are beyond the scope of the preliminary framework presented here.

5.2. Anchor limitations: fairlead load angle

How the anchor interacts with the soil also influences compatibility with different mooring configurations and, thus, load orientations. This work follows the load angle categorization from Cerfontaine et al. (2023), extending their considerations to avoid having angles for which no anchor is considered suitable. In particular, horizontal loads have a load angle below 20°, while vertical loads are above 80°. All angles between these limits are grouped in the mixed loads category. The upper limit on horizontal loads aligns with DEAs limits detailed in ISO 19901-7 (ISO, 2013). There is a good superposition between load angle and mooring line material, as chain lines need a final segment laying horizontally on the seabed, while vertical and mixed loads correspond to taut mooring configurations or vertical tethers, and therefore to synthetic or steel ropes. Table 10 summarizes compatibilities according to the reviewed literature (Cerfontaine et al., 2023; Corewind, 2020; Vryhof Anchors, 2015; Diaz et al., 2016). Only DEAs and VLAs are limited

Table 8
Conversion table from Folk classification to seabed categories for anchor selection.

Folk classification	Folk class description	Corresponding seabed for anchor selection
Rocks and boulders	Rocks and boulders	Rock
Coarse sediment	Gravel ≥ 80% or (gravel ≥ 5% and sand ≥ 90%)	Sand
Mixed sediment	Mud 95-10%; sand < 90%; gravel ≥ 5%	Hard clay
Mud to muddy sand	Mud 100-10%; sand < 90%; gravel < 5%	Very soft clay/medium clay
Sand	Sand	Sand

Table 9
Compatibility of different anchors with different soil types.

	Very Soft Clay	Medium Clay	Hard Clay	Sand	Rock
DEA	✓	✓	✓	✓	
DWA		✓	✓	✓	✓
SA	✓	✓			
DP	✓	✓	✓	✓	
VLA	✓	✓			
DrP					✓

Table 10
Compatibility of different anchors with different load orientations.

	Horizontal Load	Mixed Load	Vertical Load
DEA	✓		
DWA	✓	✓	✓
SA	✓	✓	✓
DP	✓	✓	✓
VLA			✓
DrP	✓	✓	✓

to horizontal and vertical loads alone, respectively. DWAs are preferably used for vertical loads, but mixed and horizontal loads are accepted as well, provided enough friction with the seabed is generated. All other anchors are suitable for any angle.

6. Discussion

This section discusses the implications of the proposed anchor selection strategy from three complementary perspectives. First, a probabilistic cost sensitivity analysis is presented to assess the robustness of anchor-type ranking under uncertainty in dominant cost drivers and to address the use of literature-averaged unit costs. Second, the strategy is applied to selected literature case studies in order to evaluate consistency with published designs and to highlight the effects of systematic sizing and cost evaluation. Finally, the main limitations of the framework are discussed, together with directions for future extensions.

6.1. Probabilistic cost sensitivity analysis

A probabilistic sensitivity analysis was performed to quantify the impact of uncertainty in dominant cost drivers on total anchoring cost and on the resulting anchor-type ranking. The analysis explicitly propagates uncertainty through the cost model and evaluates the robustness of cost-optimal selections. A fictitious case study is proposed, involving a single FOWT with a fixed mooring configuration, installed at a site with medium clay seabed, a water depth of 400m, and using three anchors. The seabed type has been chosen to allow for the broadest possible set of anchor types, as only DrPs are excluded. Considering the simplifications of a single turbine, with no target installation site, we fixed logistic correction factors in Eq. (4) to 1. For a discrete set of MBL and load angle combinations, the anchor selection framework is first applied to identify the feasible anchor concepts and compute a baseline cost breakdown in manufacturing and installation components.

Uncertainty was then propagated through Monte Carlo sampling, applying multiplicative factors to the dominant cost drivers. Manufacturing costs were scaled through an anchor-price factor within ±10%, while installation costs were affected by vessel day-rate uncertainty within ±30% and installation-duration uncertainty within ±30%. For each sample, anchor manufacturing costs were scaled directly, while installation costs were recomputed by applying the duration factor to pre-laying and hook-up hours, converting hours to days using a ceiling operation, and scaling vessel and hook-up day rates accordingly.

For each anchor concept, the resulting ensemble of total costs was summarized through the 10th, 50th, and 90th percentiles. In addition, for each Monte Carlo draw, the least-cost concept among the feasible set was selected, and the corresponding selection frequency was used to estimate the selection probability.

Fig. 8 reports, for each load angle, the percentile envelopes of total cost as a function of MBL and the corresponding probability of selecting each feasible anchor type as the least-cost option. The percentile bands capture the combined effect of uncertainty in manufacturing and installation costs, while the selection probabilities provide a direct measure of ranking robustness. The comparison of cost trends shows that selection plays a key role in the economic performance of the stationkeeping system, reflecting differences in anchor efficiency (Cerfontaine et al., 2023).

At 10°, DEAs are consistently selected with probability equal to one across the investigated capacity range. This indicates that, under predominantly horizontal loading, the cost separation between DEAs and alternative feasible concepts is sufficiently large that the plausible cost variations do not alter the ranking. At 30° and 60°, SAs become the dominant least-cost concept for MBL values above 2000 kN. At lower capacities, and for 60° also at intermediate loads, the selection probability is shared between SAs and DWAs. This behavior reflects a near-tie regime at low capacities, in which the absolute cost differences between concepts are small and installation-related uncertainty, which exceeds manufacturing uncertainty, is sufficient to shift the ranking across Monte Carlo realizations. For increasing capacity, the SA selection probability rapidly converges to one, indicating a robust optimum. At 90°, VLAs are selected with unitary probability essentially over the full capacity range. This is consistent with the feasibility constraints and with the clear cost separation observed in the percentile envelopes. However, scaling and availability of large commercial VLAs may be a limiting factor. Across all load angle regimes, it is important to notice that DWAs rapidly become unfeasible as MBL increases, as their size is incompatible with crane capacities, but for low capacities they may represent the optimal choice under specific cost scenarios. SAs always outperform DPs, except in the vertical load case due to different geometric proportions in the design.

The box plots in Fig. 9 report the empirical distributions of cost shares obtained from the Monte Carlo ensemble for every load angle and MBL value. For each box, let Q_1 and Q_3 denote the 25th and 75th percentiles of the cost-share samples, and let $\mathrm{IQR} = Q_3 - Q_1$ denote the interquartile range. The box center line indicates the median share and the box limits indicate the interquartile range. The whiskers extend to the most extreme samples that remain within the interval

$$\left[Q_1 - 1.5\,\mathrm{IQR},\ Q_3 + 1.5\,\mathrm{IQR}\right], \tag{5}$$

and any sample outside this interval is plotted as an outlier. In the present context, each outlier corresponds to a specific Monte Carlo realization in which the selected least-cost solution exhibits an unusually high or unusually low anchor share compared with the bulk of the ensemble. Since the installation share is complementary, the same realization produces a correspondingly low or high installation share.

At 10°, DEA is always the selected concept. At low capacities, installation dominates the total cost, with anchor shares concentrated around approximately 0.1 to 0.2. As capacity increases, anchor mass and manufacturing cost grow more rapidly than installation costs, which increase discretely due to day-based costing. Consequently, the median anchor share rises to approximately 0.7 at 20000 kN, while the installation share decreases accordingly. The larger spread observed at low capacity is consistent with installation costs being the dominant and most uncertain component in that regime. At 30° and 60°, a stronger transition toward anchor-dominated cost is observed. Above approximately 5000 kN, the median anchor share exceeds 0.6 and reaches values close to 0.9 at the highest capacities. This behavior is consistent with SA manufacturing costs scaling strongly with required capacity. Outliers and heavy tails are associated with the ceiling-based conversion from hours to billed days, that introduces discrete cost increments that can be triggered by small changes in duration. Larger boxes at lower capacities are instead associated to regions where multiple concepts have similar expected costs, so that occasional switching of the selected least-cost concept introduces additional variability in cost composition. At 90°, where VLA is always the selected concept, the anchor share increases with capacity, but it remains more balanced than in mixed load cases. Even at the largest values of MBL, installation costs account for approximately 30% of the total. This indicates that, under vertical loads, vessel day and installation duration uncertainties play a structurally relevant role alongside manufacturing cost variability.

Taken together, the probabilistic results highlight two complementary aspects of robustness. Selection probabilities identify capacity and load-angle regions in which the cost-optimal concept is insensitive to uncertainty, as observed for DEAs under horizontal loading and VLAs under vertical loading. Cost-share distributions, in turn, reveal whether the residual uncertainty of the selected solution is dominated by manufacturing or installation drivers. This distinction is critical for decision making, as it informs whether risk mitigation efforts should focus on procurement strategies and exposure to material cost variability, or on installation planning, vessel contracting, and schedule control.

Within the investigated uncertainty ranges, the results indicate that the anchor selection routine reliably identifies the appropriate anchor concept for the given loading regime, while the associated total cost may vary. This behavior extends to other seabed types and water depths. Deviations from the selected concept are therefore more likely to arise from additional geotechnical information introduced at later project stages than from cost uncertainty alone. Finally, the analysis confirms that improper scaling of mooring lines or transmitted loads, even at a preliminary stage, can lead to substantial differences in anchor cost, and that the economic evaluation of a floating offshore wind turbine cannot neglect the combined influence of seabed conditions, mooring design, and installation planning.

6.2. Application to literature case studies

Following the probabilistic sensitivity analysis, the validity of the assumptions behind the proposed strategy was tested by applying it to anchor selection in relevant case studies from the literature. The comparison aims to highlight benefits and limitations of the method, or inaccuracies in the literature. However, the reviewed studies did not consistently report stationkeeping equipment size, costs, scheduling, or environmental conditions. For some studies (Díaz and Soares, 2023; Castro-Santos et al., 2018; Campanile et al., 2018), comparison was deemed impossible. Only five provided sufficient detail to perform new anchor design and selection (Catapult, 2024; West et al., 2021; Myhr et al., 2014; Xu et al., 2021; Altuzarra et al., 2022). It is noteworthy that all studies considered water depths between 50 m and 200 m, preventing direct comparison in very deep-water conditions. Results are compared in Table 11 by anchor type and size. Cost plays a key role in anchor selection; however, the values reported in the reviewed studies lacked sufficient detail or presented inconsistent cost breakdowns. In our decision-making framework, cost is explicitly evaluated, and the selected anchor always corresponds to the lowest total cost that satisfies the imposed compatibility and sizing assumptions. To allow a consistent comparison with literature data, a cost ratio is reported, defined as the ratio between the total P&F and I&C costs obtained with the new anchor and those corresponding to the original case-study design (when available). Both totals were evaluated using the cost model presented in this work, thereby ensuring consistency across the different references. The seabed was arbitrarily set to medium clay to allow for the broadest set of anchor types. Both nylon and polyester formulas were used for synthetic fiber lines unless more detail was available, leading to multiple possible solutions for the same case. The load angle was set to 0° for all catenary cases and approximated using water depth and anchor radius in others. Table 11 confirms the selection of DEAs for catenary cases and SAs in the others, as in Fig. 8. The comparison shows that arbitrary anchor sizing can be significantly inadequate, under- or over-estimating anchor mass. Similarly, seabed type and load angle can affect the selection. The following additional remarks can be made:

- Of the three cases reported in Catapult (2024), only the “sensitivity case” is included in Table 11, as the proposed strategy does not currently handle shared anchors. The other two cases consist of a “base case” with shared anchors and a “future case” for which insufficient information on mooring line parameters is available. DEAs are confirmed to be the best option, despite a significant size difference.
- TLP concepts from Myhr et al. (2014) had to be ignored due to a lack of information on steel cylindrical tendons. Among the four remaining cases, the load angle has been set to 45° for cases 1 and 2, corresponding to the tension leg buoy “TLB” concepts, and an equivalent total load equal to the sum of the two lines’ MBL is used, avoiding the complex modeling of two lines reaching the same anchor at different angles.
- The arbitrary selection of anchors in Xu et al. (2021) identified the cheapest anchor type, but could not capture differences due to line material. Functional equipment does not seem to affect the line size, so that it does not affect the anchor size either. While their cost is expected to be small, they could reduce the required MBL and thus cut both line and anchor costs. Further investigation is required. The load angle for cases 6 to 8 was set to 3° using anchor radius and water depth data, but repeating the evaluation for an angle of 45° was deemed necessary to try to capture the effect of buoys. This is why both DEA and SA results are reported.
- The proposed anchor selection strategy results in either increased or decreased costs relative to the reported case studies, with no clear trend. In fact, the cost ratios in Table 11 are not intended to demonstrate cost reduction, but rather to illustrate how appropriate anchor selection and sizing, performed within a consistent and transparent framework, can substantially influence the overall cost of the mooring system. The broad range of cost variations, from -43% to +66%, highlights the sensitivity of results to the underlying design assumptions and the importance of adopting a structured approach to anchor choice and scaling.

Table 11 aligns with real world examples in Table 2, confirming that DEAs and SAs are currently the cheapest options. Both DEAs and VLAs, however, require the seabed to allow full embedment and soil mobilization, which can not be inferred from superficial soil data alone. In the future, innovative anchor designs could prevail in difficult terrain conditions, extreme depths, or in case advanced shared anchoring is employed. Compared to ORE Catapult and ARUP (2024), our strategy determines the suitability of anchor types more clearly and it defines a quantitative selection criterion. Compared to Ma et al. (2024), instead, it reduces the amount of information needed, making it suitable for preliminary evaluations. Unlike traditional, experience-based design methods, the proposed strategy follows a structured and

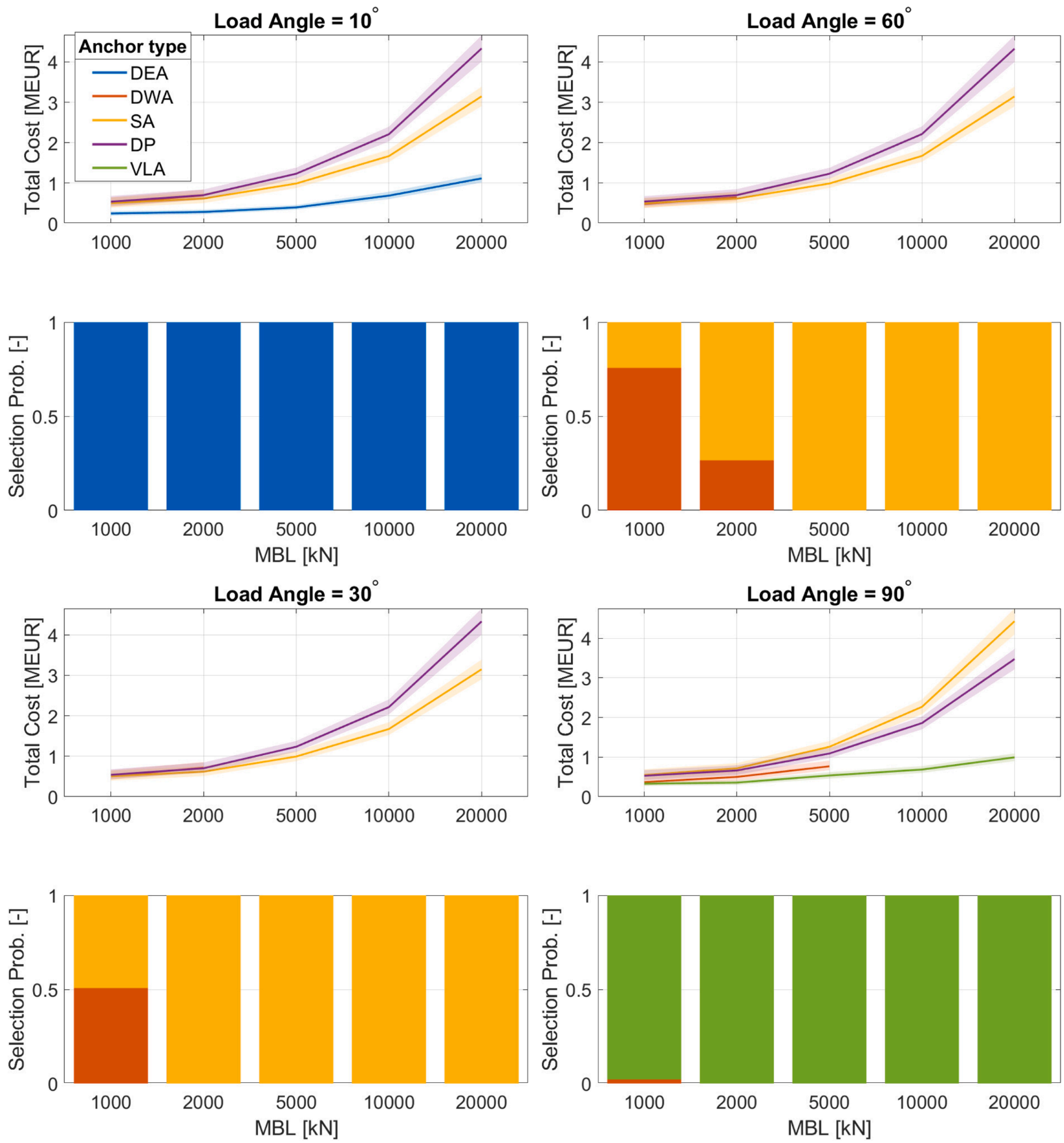

Fig. 8. Probabilistic total-cost envelopes (upper panels) and selection probabilities (lower panels) for medium clay seabed in a range of load angle and line MBL values.

transparent framework, which facilitates comparison and reproducibility of results. The mooring cost functions and corresponding design criteria are formulated to be readily implementable as subroutines within any mooring analysis framework, *e.g.*, a multi-objective optimization algorithm. Because all steps are algebraic, the method can enhance the consistency of design comparisons without increasing computational time. In this context, preliminary anchor selection can also influence the outcome of such optimization processes. The choice of anchor type at the early design stage can have a non-negligible impact on mooring configuration optimization. As observed by Niosi (2025), load-angle compatibility considerations often lead to the adoption of less inclined mooring lines favouring DEAs for their cost efficiency. Although bathymetry may constrain this effect, it demonstrates that anchor selection and mooring design are interdependent and should be assessed concurrently in preliminary evaluations. Furthermore, the strategy can support the identification of future challenges in FOWT and wind farm development related to anchor and vessel requirements. Its modular structure also enables straightforward integration of emerging anchor concepts and updates to unit costs.

6.3. Limitations and potential extensions

While the application to literature case studies demonstrates the internal consistency and practical relevance of the proposed framework, several limitations must be acknowledged, together with opportunities for further refinement. The logistics correction factor in Eq. (4) can oversimplify the interplay between weather windows, component size, and vessel constraints. A more detailed planning of operations is expected to introduce non-negligible effects on costs, *e.g.* considering mobilization/demobilization time, number of vessel trips, and the distance between port and installation site, the additional vessel rental time would likely favor mooring solutions with fewer, shorter, thinner lines and smaller anchors (Catapult, 2024). Similarly, Eq. (1) could be improved including OPEX and DECEX costs. To align with the BU

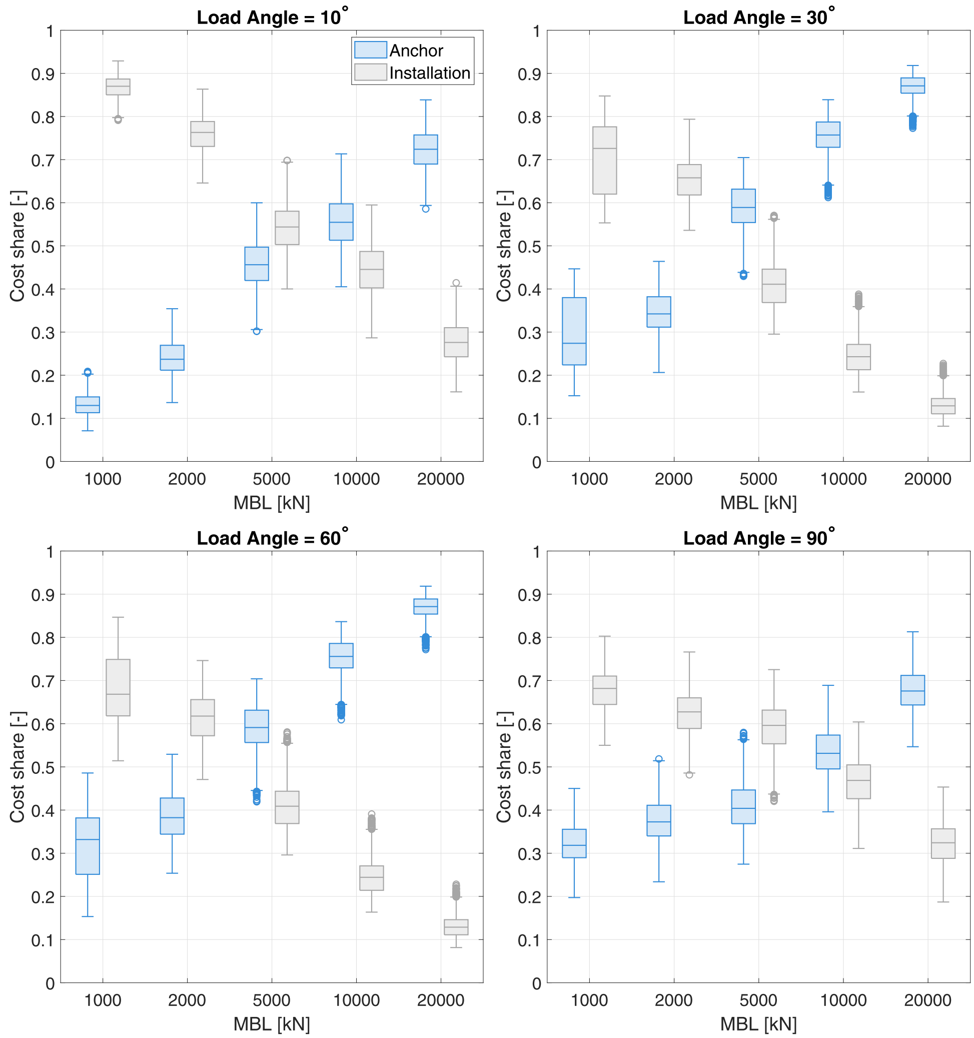

Fig. 9. Cost-share distributions for the selected least-cost concepts for medium clay seabed in a range of load angle and line MBL values.

approach, both should be separated into their constitutive elements, *e.g.*, scheduled and unscheduled maintenance operations, with respective times, vessel requirements, etc. However, uncertainty remains in the literature regarding operation frequency and how they should be performed (McMorland et al., 2022). Moreover, OPEX and DECEX require financial indicators to actualize the corresponding costs. As a first guess, a hybrid approach might be used, expressing OPEX and DECEX as percentages of the total wind farm cost or their corresponding CAPEX.

The preliminary nature of the framework also entails explicit limitations related to seabed characterization. At early design stages, superficial or regional-scale seabed data may not capture the presence of layering, boulders, hard lenses, or shallow rock, that could potentially lead to pile refusal, tip damage, or structural instability and fatigue issues (de Mécanique des Sols et, 2024). As a result, the framework may overestimate feasibility or underestimate risk for some anchor concepts. To mitigate this limitation, the proposed strategy should be complemented by conservative screening rules, *e.g.* defining trigger conditions for additional geotechnical investigations when selected anchors rely on full embedment or soil mobilization, or retaining second- and third-best anchor options where cost differences are small, to preserve design flexibility. If subsequent site investigations reveal geotechnical constraints that are incompatible with the preliminarily selected concept, anchor re-selection may be required. Otherwise, the framework provides a consistent basis for progressing to detailed design, where refined soil models and installation analyses are expected in any case.

Environmental impact is excluded due to the lack of readily available quantitative indicators. However, environmental impacts mitigation techniques, such as bubble curtains used to reduce noise from DP hammering, can add significant I&C costs or make certain solutions unfeasible. It is therefore recommended to incorporate additional selection criteria or KPI-based ranking strategies to identify second- and third-best options. These criteria can constitute the optional “design criteria evaluation” step in Fig. 7, and they may include: environmental impacts (*e.g.*, noise pollution, pollutant and debris generation); mitigation and compensation of such impacts, considering the cost, added effort during installation, and potential regulatory non-compliance if left unaddressed; anchor recoverability, *i.e.*, the feasibility and cost of retrieving the anchor at decommissioning; vessel availability, which is already limited in the North Sea (Catapult, 2024) and expected to become increasingly constrained as more turbines are deployed in new regions; operation planning, including weather window considerations; additional installation aspects such as accuracy; and seabed-related factors like slope and scour that may influence performance.

In addition to these limitations, the proposed framework currently excludes shared anchors and novel concepts. To extend its applicability, future implementations would need to define a new set of suitable anchors and formally describe their soil and load angle compatibility. For innovative designs, this requires a clear and well-documented description of the system. The main challenge would be to develop simple design methods that can work with the limited seabed information

Table 11
Preliminary anchor selection comparison from literature case studies.

Case Study	Depth	Mooring lines	Anchor	New anchor	Cost ratio
Ref 1, Case 1 (Catapult, 2024)	100m	SEMITAUT 850m, 132mm ∅ chain + 40m, 296mm ∅ nylon + 50m, 132mm ∅ chain	DEA, 25t	DEA, 37.7t	1.076
Ref 2, Case 1 (West et al., 2021)	55m	TAUT 10m, 133mm ∅ chain + 167m, 121mm ∅ synthetic + 10m, 133mm ∅ chain	//	SA, 56.2t	//
Ref 3, Case 1 (Myhr et al., 2014)	200m	TAUT 956m, 0.1416m ∅ upper fiber rope + 811m, 0.1495m ∅ lower fiber rope	VLA, 40t	SA, 48.4t (polyester) or 36.9t (nylon)	1.663 or 1.333
Ref 3, Case 2 (Myhr et al., 2014)	200m	TAUT 956m, 0.1388m ∅ upper fiber rope + 811m, 0.1754m ∅ lower fiber rope	VLA, 36t	SA, 58.9t (polyester) or 44.3t (nylon)	1.655 or 1.445
Ref 3, Case 3 (Myhr et al., 2014)	200m	CATENARY 1800m, 61mm ∅ steel wire + 150m, 76mm ∅ chain	DEA, 17t	DEA, 9.6t	0.805
Ref 3, Case 4 (Myhr et al., 2014)	200m	CATENARY 2640m, 61mm ∅ steel wire + 200m, 76mm ∅ chain	DEA, 17t	DEA, 9.6t	0.847
Ref 4, Case 1 (Xu et al., 2021)	200m	CATENARY 835.5m, 0.0766m ∅ chain	//	DEA, 9.1t	//
Ref 4, Case 2 (Xu et al., 2021)	50m	CATENARY 835.5m, 0.175m ∅ chain	DEA, 17t	DEA, 41.3t	1.104
Ref 4, Case 3 (Xu et al., 2021)	50m	CATENARY 835.5m, 0.124m ∅ chain + 28t clump	DEA, 17t	DEA, 22.8t	1.044
Ref 4, Case 4 (Xu et al., 2021)	50m	CATENARY 835.5m, 0.124m ∅ chain + 330kN buoy	DEA, 17t	DEA, 22.8t	1.044
Ref 4, Case 5 (Xu et al., 2021)	50m	CATENARY 935.5m, 0.124m ∅ chain + 28t clump + 330kNx4 buoy	DEA, 17t	DEA, 22.8t	1.040
Ref 4, Case 6 (Xu et al., 2021)	50m	TAUT 1000m, 0.203m ∅ fiber	SA, 50t	DEA, 22.7t (polyester) or 16.7t (nylon) or SA, 48.9t (polyester) or 35.7t (nylon)	0.943 or 0.574 or 0.991 or 0.865
Ref 4, Case 7 (Xu et al., 2021)	50m	TAUT 1000m, 0.203m ∅ fiber + 70kN buoy	SA, 50t	DEA, 22.7t (polyester) or 16.7t (nylon) or SA, 48.9t (polyester) or 35.7t (nylon)	0.943 or 0.574 or 0.991 or 0.865
Ref 4, Case 8 (Xu et al., 2021)	50m	TAUT 1000m, 0.203m ∅ fiber + 15t clump + 70kN buoy	SA, 50t	DEA, 22.7t (polyester) or 16.7t (nylon) or SA, 48.9t (polyester) or 35.7t (nylon)	0.943 or 0.574 or 0.991 or 0.865
Ref 5, Case 1 (Altuzarra et al., 2022)	75m	CATENARY 60m, 133mm ∅ studless chain + 414m, 133mm ∅ studless chain R3	DEA, 15t	DEA, 25.9t	1.119

typically available at the preliminary stage, and to establish realistic cost figures. For shared anchor configurations, soil compatibility is not expected to change significantly. However, the range of applicable anchors would likely be smaller, with pile-type anchors becoming more relevant (Paduano, 2026). New design methods would be needed to account for multidirectional and out-of-plane loading. These methods should be applied to each configuration with a different number of attached lines, meaning that several anchor designs would need to be evaluated within the selection process. Cost figures should also be adjusted to reflect differences in fabrication complexity and installation procedures compared with non-shared systems.

7. Conclusion

Mooring systems are inherently complex to design, particularly during the early stages of a project. Although the associated cost accounts for a significant portion of the mooring expenditure of any floating structure, state-of-the-art studies often overlook anchoring systems or fail to incorporate well-defined design criteria.

The present study described a decision making strategy for the preliminary selection of anchors for FOWTs. The proposed methodology determines suitable solutions from a predetermined set of anchors based on soil and load angle compatibility. Then, the proposed method is able to identify the best techno-economic option based on P&F and I&C costs estimated through a BU approach.

Given the importance of mooring systems and the strong interdependence among their components, a review of the current literature is presented. The aim is twofold: to highlight existing limitations and to develop a dataset of tailored, up-to-date cost functions that can be readily integrated into the proposed design strategy.

Compared to the methodologies available in the state-of-the-art, the developed strategy requires a minimum amount of site-specific input information and does not require qualitative evaluations based on the designer's experience, making it ideal for the preliminary stages of the design of an offshore wind farm. The modular structure of the strategy and the adoption of a BU cost estimation approach make the tool flexible, facilitating the expansion of the anchor selection pool or the adaptation to other offshore applications. The review of technological solutions, installation methodologies and, most importantly, costs ensures that the described version of the strategy is updated and predictions are realistic.

Future research could extend the strategy to resolve its current limitations, *e.g.* focusing on:

- A more detailed operation planning for I&C cost estimation, including weather window estimation.
- The implementation of KPIs to improve the ranking of anchor options based on qualitative criteria.
- The definition of a set of anchor alternatives for shared anchor configurations and their corresponding suitability limits. Critical aspects include load angle compatibility and installation procedures. Potentially, an adapted version of the anchor selection strategy could be employed to assess whether shared solutions can cut costs on a project. This is of particular interest as it has been showed that it might sometimes be better to rely on non-shared solutions, especially at intermediate water depths (Catapult, 2024).

CRediT authorship contribution statement

Lorenzo Dutto: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization; **Francesco Niosi:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization; **Bruno Paduano:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization; **Simone Di Carlo:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization; **Simone Ambrosini:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization; **Stefano Bontumasi:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Funding acquisition; **Giovanni Bracco:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary material

Supplementary material associated with this article can be found in the online version at 10.1016/j.oceaneng.2026.124768.

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