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Preference-based service life design of floating wind structures

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ABSTRACT: Floating wind farms are a promising solution for offshore wind energy production in deep waters. However, the design optimisation process of these farms is difficult due to their complex and multidisciplinary nature. Furthermore, current optimisation methods: 1) ignore and/or provide no insight into the dynamic interplay between the preference-dominated management domain and the object-performance-dominated engineering domain; 2) are limited to evaluating potentially sub-optimal design alternatives; 3) contain fundamental aggregation modelling errors; 4) do not return a single optimal design point. This paper presents an optimisation framework that overcomes these shortcomings and enables truly integrative multi-objective design optimisation. It includes a surrogate model that interacts with the wind turbine simulation tool OpenFAST to enable preliminary design of the structure's mooring system. Applied to a demonstration project and validated against real projects in a maritime contractor environment, the workflow shows improvements in tender performance and added value over single-sided cost optimisations.

1 INTRODUCTION

A promising solution for wind energy production in deep waters is the development of Off-shore Floating Wind Farms (OFWF), as areas with deeper water tend to have higher wind energy densities, but do not allow the economic installation of bottom-founded structures (Spring 2020). The complexity introduced by e.g. high quality requirements, the novelty of the technology and the number of (external) stakeholders (see also Van Gunsteren (2011)), together with the multidisciplinary nature of these developments, create an environment in which modelling and optimising of the (iterative) design process is of great added value, but also challenging and complicated.

In addition, classical design optimisation methods have inherent problems because they are single-sided and ignore and/or provide no insight into the dynamic interplay between the preference-dominated management domain and the object-performance-dominated engineering domain (Van Heukelum et al. 2022). Furthermore, design optimisation is often limited to a posteriori evaluation of (manually) generated design alternatives, with no guarantee that the optimal design alternative is considered because the number of feasible design alternatives is too large to evaluate them all.

Moreover, to enable proper multi-objective design optimisation (MODO), all objectives must be translated into a common domain, for which the affordability domain is commonly chosen in the offshore industry. However, according to classical utility theory, decisions are made based on value or preference and not based on money, as money is not a (fixed) property of objects (Barzilai

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2010). Moreover, classical MODO methods contain fundamental (aggregation) modelling errors because mathematical operations are applied without being defined (Barzilai 2006, 2022).

Finally, ignoring preferences is also a major shortcoming of the commonly used Pareto front (Lee et al. 2011, Kim et al. 2022). Searching for the most fit for common purpose design solution involves finding the most preferred solution, not a set of equally preferred solutions from which decision-makers still have to choose through negotiation.

To overcome all the aforementioned problems, this paper presents an optimisation method for the service-life design of OFWFs that integrates preference function modelling and engineering performance, allowing the unification of the managerial domain (subject desirability) with the engineering domain (object feasibility). To this end, an optimisation framework is created within the so-called Preferendus, a software tool that is part of the Odesys design methodology and uses the IMAP optimisation method (Van Heukelum et al. 2022). This paper demonstrates this framework through a demonstration project and gives insight into the applicability of the framework, which has been validated at the Dutch marine contractor Boskalis.

1.1 *Data availability statement*

The optimisation framework, including the input file of the demonstration projects with all the modelling information, can be found on the GitHub repository of the Preferendus: https://github.com/TUDelft-Odesys/Preferendus.

2 THE OFWF SERVICE-LIFE DESIGN DEMONSTRATOR

The optimisation framework is modelled based on the Odesys mathematical statement introduced by Van Heukelum et al. (2022), see Figure 1. Two stakeholders are considered: 1) an energy service provider (the client) and 2) the marine contractor Boskalis. They are interested in the design of the mooring system and the installation schedule, which creates an optimisation problem where feasibility plays an important role in finding the optimal solution based on the desires of the stakeholders.

Four objectives are considered: project duration, installation costs, fleet utilisation and CO_2 emissions. For the client, a shorter project duration means that the OFWF will start generating revenues sooner. In addition, reducing CO_2 emissions benefits the client's carbon footprint and the social acceptance of the project. For the contractor, the focus will be on reducing costs to make it more competitive. Secondly, its fleet management department will be interested in the opportunity to improve fleet utilisation through the project.

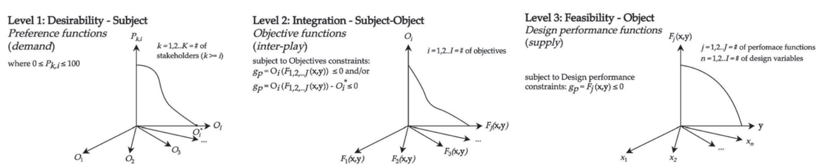

Figure 1. Conceptual threefold framework, where desirability-subject (preference functions, level 1) and the feasibility-object (design performance functions, level 3) are integrated subject-object (objective functions, level 2). Source: Van Heukelum et al. 2022.

3 LEVEL 3 – DESIGN PERFORMANCE FUNCTIONS

This section introduces the relevant design performance functions and design variables in two parts: installation scheduling and mooring system design. This mooring design is restricted to Drag Embedded Anchors (DEA), Suction Piles (SP) and Anchor Piles (AP).

3.1 *Installation schedule*

The installation schedule depends on two components: the number of available vessels (and their characteristics), and the time it takes these vessels to perform a task. The available vessels are listed in Table 1. Whether a vessel can perform a task (x_i = 1) or not (x_i = 1) is expressed by boolean design variables (x_1 to x_{21}) for all tasks except hook-up. For the hook-up, only one vessel is used (see subsection 3.1.1), and the integer design variable x_{22} expresses which vessel. All vessels have different properties (e.g. deck space for anchors) that affect their performance, which can be found in the input file of the framework (see subsection 1.1).

In addition, each task is decomposed into building blocks that describe the time required to complete a sub-activity. During optimisation, the workable months are determined based on environmental data (see subsection 3.2.1) and the overall schedule is constructed from these building blocks, which can be found in the input file of the framework.

To correctly model the installation schedule, three design performance constraints are added to ensure that: 1) the number of installation vessels is ≥ 0, since the definition of the design variables x_1 to x_{21} allows a total number of installation vessels equal to zero; 2) an equal number of vessels are present when both anchors and mooring lines (ML) are installed simultaneously; 3) a vessel does not perform overlapping tasks.

Table 1. Available vessels and the associated design variables.

Vessel	SP install	AP install	DEA install	Taut ML install	Catenary ML install	Stev-tensioning*	Hook-up
Winchester	x_1	x_5					
Atlas	x_2		x_7	x_{10}	x_{15}	x_{18}	$x_{22} = 0$
Edinburgh	x_3			x_{11}			$x_{22} = 1$
Symphony			x_8	x_{12}	x_{16}	x_{19}	$x_{22} = 2$
Legacy			x_9	x_{13}	x_{17}	x_{20}	$x_{22} = 3$
Scout	x_4	x_6		x_{14}		x_{21}	

* method to achieve higher proof-loads by vertical lifting instead of horizontal pulling (Vryhof 2017).

3.1.1 *Assumptions*

Some assumptions are made in the modelling: 1) if the design force on the DEA is greater than the bollard pull of the installation vessel, stev-tensioning will be required. If this is carried out using the Scout (a heavy lift vessel), an additional anchor handling tug will be required for the same period at a day rate of €50,000; 2) the hook-up is limited by the delivery time of new Floating Wind Turbines (FWTs), which is assumed to be one FWT every six days. As this rate is lower than the hook-up period, the number of hook-up vessels is set to one. In addition, the hook-up requires one large and one medium tug for towing and station keeping, which have a fixed day rate of €54,000 and €24,000 respectively; 3) for an AP, the ML is always installed at the same time as the anchor, as is the case for a DEA. For an SP, the ML can be installed simultaneously or separately. Stev-tensioning is always done separately.

3.2 *Mooring system design*

Most of the design variables for an OFWF mooring system are uncontrollable and result from factors like soil and environmental conditions and local marine policy. Of the controllable design variables, the following are considered in the optimisation:

- Anchor type, x_{23}: DEA, SP, or AP.
- Mooring type, x_{24}: Taut or catenary. Catenary moorings consist only of chain (d=0.333m; M=685 kg/m^3; EA=3.27E9N), taut moorings have a lower and an upper chain with polyester rope (d=0.211m; M=23 kg/m^3; EA=3.89E9N (BEXCO n.d.)) in between.
- Shared anchors, x_{25}: an AP or SP can connect two or three MLs, reducing the total number of anchors to be installed.
- Anchor diameter/width, x_{26}: the diameter (for AP or SP) or width (for DEA) of the anchors.
- Anchor length, x_{27}: the length of the anchor.
- Anchor radius, x_{28}: the radius of the anchors with respect to the FWT.
- Unstretched length, x_{29}: the unstretched length of the ML.

To check that the mooring design is sufficient, a design performance constraint is added to the model, stating that the so-called utilisation factor u should be less than 1:

$$u = \frac{design\ force\ on\ the\ anchor}{design\ resistance\ of\ the\ anchor} = \frac{F_d}{R_d} = \frac{\gamma_f F_a}{\gamma_M R_a} < 1 \quad (1)$$

Where γ_f is a safety factor for the anchor load; γ_M is a safety factor for the anchor resistance; F_a is the anchor load; R_a is the anchor resistance. For determining this force F_a, the open-source wind turbine simulation tool OpenFAST (NREL n.d.[a]) is used, together with the IEA 15MW reference turbine (Gaertner et al. 2020) and its semi-submersible platform (Allen et al. 2020).

3.2.1 *Environmental conditions*

TurbSim (NREL n.d.[b]) is used to simulate the wind field for the OpenFAST simulations. This software generates fully stochastic wind fields that allow the effect of turbulence on the dynamics of an FWT to be considered. The reference wind speed for the simulation is determined by statistical analysis of hourly data obtained via Hersbach et al. (2018).

The (irregular) wave field is generated by HydroDyn (Jonkman et al. 2014),where the wave spectrum is determined using the JONSWAP spectral equation (Katopodes 2018). This is a function of both the significant wave height H_S and the peak wave period ω_m, which can be determined by statistical analysis of the hourly data obtained via Hersbach et al. (2018). Sea currents are also simulated in the HydroDyn module, using the power law (Jonkman et al. 2014). This is a function of the velocity of the sea current at the still water level U_0 and the water depth d. U_0 is obtained either from local databases (e.g. EMODnet (n.d.)) or from scientific papers.

Two Design Load Cases (DLC) are considered in the optimisation: DLC1.6 and the Survival Load Case (SLC) (DNV 2021c). During DLC1.6, the turbine operates at the rated wind speed in waves with a 1/50-year H_S. During the SLC, both the 1/100-year wind speed and the 1/100-year H_S occur and the turbine is idling. The environmental conditions are simulated co-aligned (i.e. with the same heading) for a heading of 0°, 30°, and 60° relative to the FWT, where 60° is the heading parallel to a mooring line. A yaw-misalignment of ±8° is also included in the simulations.

3.2.2 *Integration of OpenFAST in the optimisation*

Due to the long runtime of OpenFAST simulations, the integration into the optimisation framework is currently done via a surrogate model. This integration consists of five steps divided into two phases: the offline phase (steps 1 to 3), which is performed separately and prior to optimisation, and the online phase, which is an integral part of the framework.

Step 1 – offline phase: determine mooring configurations

The reference mooring design (Allen et al. 2020) is scaled to different water depths (120-150 metres) and taut configurations, based on a comparison between the behaviour of the new design and the reference design under different (static) loads (via Hall et al. (2021)). For this scaling, the design variables have been limited to the anchor radius (x_{28}) and the unstretched length of the mooring line (x_{29}), which consequently become indirect design variables.

Step 2 – offline phase: run OpenFAST

OpenFAST is being run with six 700-second simulations per design scenario, each being a combination of two design load cases (DLC1.6 & SLC), three propagation directions (0°, 30°, 60°), two mooring types (taut & catenary) and three yaw misalignments (-8°, 0°, 8°), resulting in 216 runs per water depth. The result of a simulation is a binary file containing, among other things, the time series of forces on all three anchors of the FWT.

Step 3 – offline phase: analyse the OpenFAST results

The results of the OpenFAST simulations are processed in a script, which for each design scenario: 1) eliminates the initialisation phase of the catenary mooring systems; 2) generates 60-minute time series for three FWTs by (quasi-randomly) combining the six 700-second runs; 3) calculates the net force on the shared anchors using the time series of three FWTs; 4) finds the forces F_a for one, two and three connected MLs per design scenario. All these forces are then multiplied by a safety factor (DLC1.6: $\gamma_f = 1.35$; SLC: $\gamma_f = 1.1$ (DNV 2021c)) to give the design forces F'_d. At the same time, a script is run to determine the angles of the taut MLs with respect to the mudline.

Step 4 – online phase: determine governing forces

The final design forces F_d are determined for both catenary and taut moorings, and for both shared and non-shared anchors, by taking the maximum of the design forces F'_d from the relevant design scenarios. Note: for shared anchors, F_d is the highest of either two or three connected MLs.

Step 5 – online phase: determine anchor dimensions

For all three types of anchors, the point where the chain attaches to the anchor (i.e. the padeye) is below the mudline. Because of friction with the soil, the chain will form a (so-called) inverse catenary shape below the mudline. Neubecker & Randolph (1995) describe a system of equations to determine the tension T_d and angle θ_a of the ML at the padeye, based on the design force F_d and angle θ_m at the mudline and the ML and soil characteristics. In addition, the position of the padeye is required, which for APs and SPs is set to 1/2 the anchor length below the mudline for clay and 2/3 the anchor length for sand. For DEAs, the optimum angle θ_a is determined by the manufacturer and set as a constant in the calculation for T_d. Here $\theta_{a;DEA} = 41^\circ$ for clay and $\theta_{a;DEA} = 31^\circ$ for sand (Vryhof 2018). The anchor resistance R_d and the utilisation factor u can then be calculated, applying the safety factors γ_M according to the DNV-OS-C101 design code (DNV 2021a):

– Drag embedded anchors: the design is limited to Vryhoff's Stevin MK3, Stevpris MK5 and Stevpris MK6 anchors. ABS (2013) describes design formulae that can be used to obtain the required mass $M_{required}$ of a DEA for a given force T_d. In addition, based on the information provided by Vryhof (2018), it is possible to determine the DEA that best matches the values for the anchor length (x_{27}) and width (x_{26}). Knowing the mass of this DEA (M_{DEA}), it is possible to calculate the utilisation factor:

$$u = \frac{F_d}{R_d} = \frac{M_{required}}{0.77 \cdot M_{DEA}} \leq 1 \tag{2}$$

– Suction anchors: for SPs, first the maximum suction-assisted penetration length must be determined (Houlsby & Byrne 2005a,b), in order to calculate the horizontal (H_{ult}) and vertical (V_{ult}) capacity of the anchor (Equation 42 to 49 of Arany & Bhattacharya (2018)). Finally, T_d must be decomposed into a horizontal (H_d) and vertical (V_d) component in order to calculate the utilisation factor (Randolph & Gourvenec 2017):

$$u = \frac{F_d}{R_d} = \frac{M_{required}}{0.77 \cdot M_{DEA}} \leq 1 \tag{3}$$

– Anchor piles: for APs, the horizontal and vertical failure mechanisms are considered separately. For the horizontal failure mechanism, the 'short' pile failure mechanism can be used as described by Randolph & Gourvenec (2017), since 1) the padeye is at a significant depth below the mudline and 2) the lengths of the APs are limited compared to e.g. deepwater moorings of oil & gas platforms. Plastic hinging is therefore unlikely and only soil failure needs to be considered. The vertical failure mechanism of an AP is mainly determined by the weight of the anchor and the soil-pile friction. Therefore, the same design formulae can be used as for an SP. The utilisation factor can be calculated as:

$$u = \frac{F_d}{R_d} = \frac{M_{required}}{0.77 \cdot M_{DEA}} \leq 1 \tag{4}$$

In addition to Equation 1, the mooring system has two other design performance constraints. The first is that a DEA cannot be used for taut and shared anchor systems as it is not designed for vertical and multidirectional loads. The second restricts the L/D and D/t ratios of the APs and SPs. See ABS (2013) for reference values.

3.2.3 *Assumptions*

In the current development phase of the optimisation framework, only a preliminary design is considered, as the improvement in optimisation results that a more detailed design will entail does not currently outweigh the additional complexity of developing the necessary design calculations. For this preliminary design, some assumptions are made: 1) all MLs can be stretched indefinitely, and the minimum breaking load (MBL) is not currently considered; 2) the effect of cyclic loading on the anchors and associated fatigue is neglected, only the ultimate limit state is considered; 3) the soil is assumed to be uniform.

The current approach to determine the force F_d for shared anchors is likely to result in the over-dimensioning of anchors with three MLs, as the net force for two MLs is often greater than the net force for three MLs. Therefore the design force F_d of anchors with three MLs will be too high. This should be addressed in further development, although the current approach overcomes problems with the reliability of shared anchors in the event of ML failure (DNV 2021b).

4 LEVEL 2 – OBJECTIVE FUNCTIONS

The optimisation framework considers four objectives that form the link between the design performance (level 3) and the preference functions (level 1):

1. Project duration (PD): the project duration is determined by a proprietary Discrete Event Simulation (DES) combining the design variables with the task durations.
2. Installation cost (IC): installation costs are primarily based on the day rates of the vessels multiplied by the time they work on the project. In addition, a daily surcharge is added for anchor installation vessels, depending on the type of anchor (x_{23}).
3. Fleet utilisation (FU): fleet utilisation is represented by normalising the number of days a vessel is booked over the next 12 months (i.e. the vessel with the lowest number of days booked has a score of 0 and the vessel with the highest number of days has a score of 1).
4. CO_2 emission (CE): the CO_2 emission of a project depends on the fuel consumption of the vessels, related to the activity of the vessel (e.g. idling, sailing, towing), multiplied by a conversion rate (per tonne MGO, 3.206 tonne CO_2 is emitted).

5 LEVEL 1 - PREFERENCE FUNCTIONS

To quantify stakeholder desirability, preference functions are constructed that describe the relationship between an individual stakeholder's preference P and a particular objective O. In addition to these functions, the weights associated with the different preference functions have to be determined, both in close cooperation with the different stakeholders. Furthermore, they can change during the design process when stakeholders better understand the impact of their preference functions and associated weights on the process (Arkesteijn 2019). Both the demonstration project and the validation described in this paper, use preference functions and weights determined based on input from floating wind project experts within Boskalis.

6 DEMONSTRATION PROJECT

To demonstrate the application of the framework, a demonstration project has been set up where 45 FWTs are installed (see the data availability statement for the input file containing further project specifics). Three optimisations have been compared: Single-Objective Design Optimisation (SODO) of the installation costs, and MODO with the IMAP and min-max method (Van Heukelum et al. 2022). The final ranking and outcomes for the objectives are shown in Table 2. All designs favour (shared) SPs, MODO min-max with a taut mooring and others with a catenary mooring. The MODO IMAP achieves the best design configuration by balancing the four objectives to best reflect stakeholder preferences. Three other observations are made:

1) Due to the conflict between installation cost and fleet utilisation objectives, employing less expensive vessels will reduce the fleet utilisation factor. Rather than choosing one over the other, the min-max method finds a compromise that does not benefit the overall design configuration, revealing a significant drawback of this method.
2) The lowest cost is achieved by installing anchors and MLs separately, reducing the time one vessel has to wait for another to complete an installation task. However, this significantly

increases the duration of the project, as the hook-up will start a year later. It could be argued that this design configuration would never be considered because the project duration is unrealistically long. The fact that the actual design configuration would be similar to the configuration obtained by MODO IMAP confirms that this model is a welcome addition to design optimisation in the offshore industry.

3) The demonstration project shows the added value of integrated design optimisation. Traditionally, the anchor design is determined by the client and the contractor has to build their schedule around it (waterfall design process). However, this can lead to inefficient use of vessels and delayed project delivery. Here, the design is an integral part of the optimisation, allowing for an overall better design, even if this would deviate from a purely engineering perspective. This is particularly interesting for shared anchors, which are unfavourable from an engineering viewpoint but favourable from a schedule and cost perspective.

Table 2. Table with the results of the objectives and their ranking.

Optimisation	PD [days] *weight = 0.25*	IC [€1E6] *weight = 0.50*	FU [-] *weight = 0.20*	CE [kt] *weight = 0.05*	Final Ranking
MODO IMAP	619 (P = *96.5*)	56.81 (P = *98.5*)	0.83 (P = *74.4*)	21.9 (P = *94.6*)	1. (P = *100*)
SODO Costs	985 (P = *41.5*)	54.71 (P = *99.2*)	0.83 (P = *74.4*)	21.6 (P = *94.8*)	2. (P = *41*)
MODO min-max	619 (P = *96.5*)	61.13 (P = *96.8*)	0.98 (P = *97.6*)	19.7 (P = *96.1*)	3. (P = *0*)

7 VALIDATION OF THE OPTIMISATION FRAMEWORK

The optimisation framework has been validated during a meeting with offshore floating wind experts within Boskalis and demonstrated that it can be of great value to a tender team. A tender team always has a bias and especially when the design process consists of evaluating design alternatives, this bias can lead to eliminating alternatives based on intuition, when in fact they are competitive. The optimisation framework removes this bias from the design process, which is in line with what Kahneman (2011) suggests when he distinguishes between thinking fast (decision-making based on intuition) and thinking slow (decision-making using e.g. mathematical decision support tools). Moreover, the framework delivers initial results within an hour (if the surrogate model contains sufficient data), compared to one or more days in the current situation. This is a significant improvement and offers opportunities beyond the development of OFWF.

8 STEPS FOR FURTHER DEVELOPMENT

Based on the assumptions made, the following steps have been identified for further development. To improve the integration of the surrogate model, two steps for further development are identified: 1) consideration of the MBL of the MLs; 2) inclusion of fatigue loading in the design of the anchors. The first will address a shortcoming of the current model and resolves a problem with the script that calculates the taut mooring designs, which currently results in excessive tensions in the polyester rope. The second will add an important element to the design of the anchors, as dynamic loads have a significant effect on the anchor resistance R_a. It would also be interesting to extend the surrogate model to include platforms other than the current semi-submersible platform.

In addition, the following development steps are identified based on the validation in the tender team: 1) take the delivery of the first FWT as $t = 0$ for the schedule; 2) improve the DES with a focus on the calculation of the number of anchors and MLs on board vessels and the start of ML installation if it is done separately from the anchor installation; 3) improve the calculation of installation costs by including procurement and fuel costs; 4) improve the calculation of CO_2 emissions by including emissions from anchor fabrication and onshore activities.

9 CONCLUSIONS

This paper presents an optimisation framework that enables the unification of the engineering domain (object feasibility) with the management domain (subject desirability) and a truly integrative MODO method that can accommodate conflicting objectives of multiple stakeholders whilst simultaneously considering different engineering object variables and design constraints. The applicability of the optimisation framework is shown for a demonstration project, demonstrating its added value over a compromise solution and single-sided cost optimisation, and the efficiency of integrative design. Finally, validation of the framework shows it brings significant improvement in tender performance, both in terms of removing bias from design and improving process speed. Steps for further development include improving the surrogate model and DES and extending the installation cost and CO_2 emission calculations.

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