Design of mooring systems for offshore structures through an optimization approach

Gabriel R. Domingos[1], Eduardo N. Lages[1], Adeildo S. Ramos Jr.[1], Alan P. de Abreu[2], Anderson T. Oshiro[3], Mauro C. de Oliveira[3]

[1]*Laboratory of Scientific Computing and Visualization, Center of Technology, Federal University of Alagoas*
Av. Lourival Melo Mota, 57072-970, Alagoas, Brazil
gabriel.domingos@lccv.ufal.br, enl@lccv.ufal.br, adramos@lccv.ufal.br
[2]*Direction of Engineering, Technology and Innovation, PETROBRAS*
EdiSen, Av. Henrique Valadares, 20231-030, Rio de Janeiro, Brazil
alan_patrik@petrobras.com.br
[3]*Center of Research Leopoldo Américo Miguez de Mello, PETROBRAS*
Av. Horácio Macedo, 21941-915, Rio de Janeiro, Brazil
mauro@petrobras.com.br, anderson.oshiro@petrobras.com.br

Abstract. The design of mooring systems for offshore structures is crucial for ensuring the safe and efficient operation of floating production systems (FPS) within the oil and gas industry. This activity is renowned for its demanding resource requirements, in terms of technical challenges, design criteria, computational cost and extensive hours of work from highly skilled professionals. In this context, structural optimization emerges as a potential solution to mitigate the use of some of these resources, introducing a design approach reliant on optimization algorithms capable of translating technical criteria into mathematical functions and proposing valid and optimized solutions. However, this optimization approach presents its own set of challenges, notably the need of evaluating thousands of structural models, which directly depend on time-consuming numerical simulations. This work aims to treat the optimization challenges by proposing strategies to expedite the computation of numerical models and to support the designing professional in determining optimized designs suitable for direct industrial application.

Keywords: Structural Optimization, Offshore Structures, Mooring Systems, Dynamic Models

1 Introduction

Offshore O&G exploration is a very important activity for the Brazilian energy sector, and the design of FPS is a necessary part of the process. Many are the challenges involved in the complex task of designing a FPS: design criteria, safety concerns, good practices, project's lifespan, maintenance and extensive hours of work from high-skilled professionals, to cite a few.

In this scenario, assessing the problem through an optimization approach brings many advantages. Translating all criteria into mathematical functions and letting an optimization algorithm seek for suitable designs has the potential of saving time and effort from high-skilled professionals, enabling a breakthrough in the traditional method of design.

In this work, an optimization model was developed to solve a problem brought from the industry, resumed in finding a conceptual design in the early stages of the mooring system design spiral. The lines have their anchor position, number of line segments, lengths and materials of the segments defined initially, with only the lengths of the top anchor segments subject to change.

Unlike Cruces Girón et al. [1] and Monteiro et al. [2], this work's goal is not to perform an integrated mooring-riser system design. Our goal is also different from Domingos et al. [3], who used optimization to reposition the FPS due to constraints of operationability, although some ideas from their methodology of Equivalent Static Analyses (ESA) were applied in this work.

Domingos et al. [3] proposed and explored a methodology to expedite the optimization process using ESA which has shown to be very effective in their example, but not as favorable when applied in this work. That is the reason why the methodology had to be adapted to this model, detailed in Section 3.

The main difference between this work's model and the model explored in the work of Domingos et al. [3] is that the previous was a shallow-water FPS, while the current is installed in ultra-deep water. The dynamic behavior of waves seem to have an amplified impact in this current model, and this may be the cause of the bad adherence of the original ESA methodology.

However, since this problem originated from an industrial demand, it was imperative to find a solution. So the more traditional approach using Dynamic Analyses (DA) was used here, importing ideas from the original methodology by Domingos et al. [3], and with the objective of finding a suitable conceptual design through an optimization approach. Note that all confidential data have been omitted.

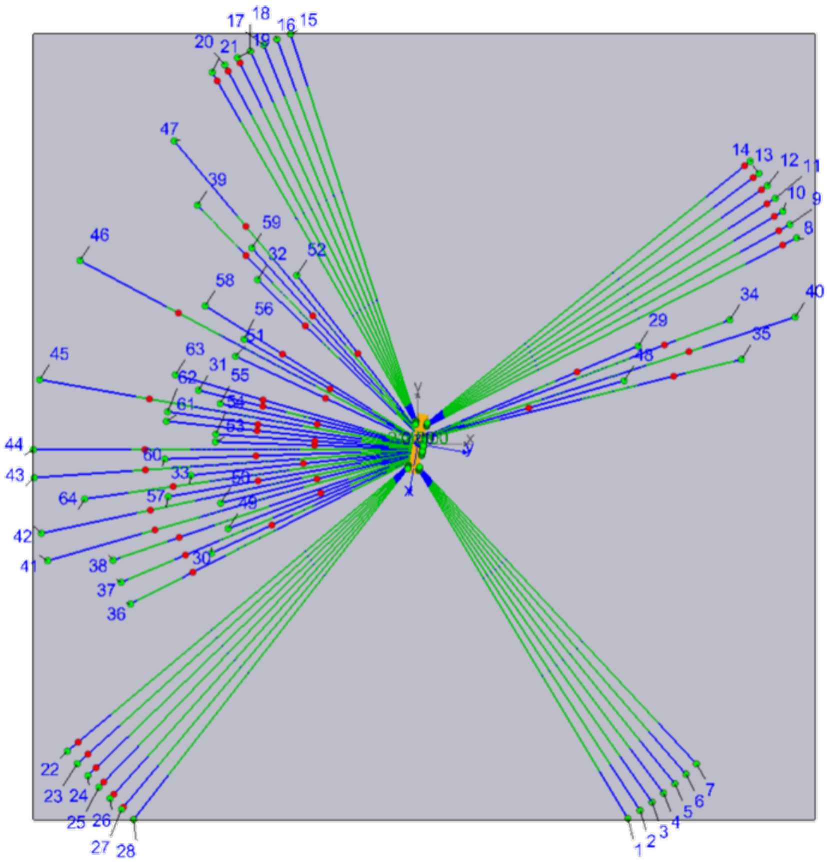


Figure 1. The model studied in this work: a FPSO with 28 mooring lines installed in ultra-deep water

The studied model is presented in Fig. 1, composed of a FPSO with 28 mooring lines (1-28) disposed in 4 clusters, with 36 risers (29-64). Each line of the model is composed of 7 segments of chain and polyester cables. Only top chain lengths are subject to be changed in the optimization.

2 Optimization model

The mathematical formulation of the optimization model consists of an objective function – which expresses a design criterion that should be improved – and a set of constraints – functions which translate real design criteria into mathematical inequalities that have to be satisfied. These functions are mathematically defined in the space of the design variables, which are essentially the parameters of the model that should be tuned in order to find the optimal solution.

A solution is considered optimal only when the objective function reaches a local or global minimum while also satisfying the set of constraints. The mathematical formulation of this problem is presented subsequently, with its variables described in next paragraph.

$$
\begin{aligned}
\min_{\boldsymbol{L}} Distance(\boldsymbol{L}) = \left|\boldsymbol{pos}^{\text{design}} - \boldsymbol{pos}^{\text{effective}}\right| \\
\text{subject to (101 and 099)}\ & \frac{\boldsymbol{\Delta}}{\text{SAFOP}} - 1 \leq 0 \\
& 1 - \frac{yaw}{\{\text{yawMin}\}} \leq 0 \\
& \frac{yaw}{\{\text{yawMax}\}} - 1 \leq 0 \\
& \frac{T^i_{\text{top chain}}}{60\% MBS_{\text{top chain}}} - \{\alpha\} \leq 0 \\
& \frac{T^i_{\text{top poly}}}{60\% MBS_{\text{top poly}}} - \{\alpha\} \leq 0 \\
& \frac{T^i_{\text{mudline}}}{\{\text{maxTensionMudline}\}} - \{\alpha\} \leq 0 \\
& \frac{T^i_{\text{pretension}}}{\{\text{maxPretension}\}} - 1 \leq 0 \\
& \frac{distTop^i}{\{\text{maxDistTop}\}} - 1 \leq 0 \\
& \frac{distBottom^i}{\{\text{maxDistBottom}\}} - 1 \leq 0 \\
& 0.5 \leq \frac{L^i}{L^i_0} \leq 1.5 \\
\text{with } & i = 1, 2, ..., n.
\end{aligned}
\tag{1}
$$

The vector $\boldsymbol{L}$ represents the set of top chain lengths. The length of $\boldsymbol{L}$ is equal to n, which is the number of design variables of the model. The constraints are subjected to models 101 and 099, which represent the variation of polyester lengths, described in Section 2.2. The first constraint represents the points of displacement, which must be contained inside the SAFOP region. All constraints with variables in curly braces represent parameters that will be calibrated by the professional according to the problem. α is a tolerance parameter, used to create a margin between the real constraint limit and the limit for the optimization. In this work, this parameter was set to 0.95, which creates a 5% margin between the optimization limit and the original limit. If no margin at all is desired, the parameter should be set to 1.0. More details on the formulation in next sections.

2.1 Design variables

The design variables of the problem are the lengths of the top anchor segments for each mooring line. In this model, 28 design variables. Since the optimization criteria involve many different dimensions – such as length, angle, tension and so on – the optimization model is defined dimensionless. This strategy has shown to improve the convergence of the optimization algorithms.

Because of that, all initial values set to 1.0. The bound constraints are set to 0.5 and 1.5, for each variable, representing a maximum absolute variation of 50% from the initial values.

2.2 Set of constraints

The set of constraints arose directly from the industry needs and are designed to meet different design criteria: the displacements of the vessel must be contained in the Safe Operational Zone for Risers (SAFOP); heading variation of the ship must not exceed a calibrated value; tensions along the line must not exceed the standards criteria and safety factors; pretensions must not exceed mooring winch's capacity; mudline tensions must be compatible with geotechnical parameters for the region; distance from polyester cables to top and bottom of water line must obey calibrated values; all criteria above must be met considering an absolute variation of 1% in all polyester lengths (fixing pretension when varying the polyester lengths).

2.3 Objective function

The objective function has the goal of minimizing the distance between the design position and the effective equilibrium position of the vessel. Due to equilibrium of forces, the vessel tend to roam around from the design position, since it is not fixed anywhere. Thus, the distance between design and effective positions must not be higher than a calibrated parameter. Although the computation of the effective equilibrium position can be determined statically, the constraints of the model require computation by dynamic analyses.

2.4 Optimization algorithm

The optimization algorithm chosen for this work was COBYLA (Powell [4]; Powell [5]), the same used by Domingos et al. [3] methodology. COBYLA (Constrained Optimization BY Linear Approximations) is a zeroth-order algorithm that supports both nonlinear inequality and equality constraints, based on the construction of linear approximations of the functions of the model via simplexes associated with a trust region procedure.

In the first $n + 1$ steps of optimization COBYLA does not seek for an optimal result. These steps are taken to build the necessary simplex structure, stressing each one of the design variables separately and evaluating the objective function and constraints, so then COBYLA can determine a direction of search. From the $(n + 2)$th and on, the optimization flows towards a search direction determined by the simplex structure seeking the optimal results.

All optimization code was written using Julia (Bezanson et al. [6]) programming language along with NLopt optimization library (Johnson [7]).

3 Dynamic model

As mentioned in Section 1, the methodology proposed by Domingos et al. [3] did not yield significant results when applied to this model. However, some of the features proposed there were applied to this DA optimization approach.

First, in the DA, the Environmental Conditions (ECs) are applied to the vessel and lines in a quasi-static analysis, without considering the dynamics of the lines (only the dynamics of the vessel are considered). The ECs are a combination of loads caused by waves, swells, winds and currents, derived from metocean studies from the model's exploration basin. The simulation is performed using a propietary software called DYNASIM (Nishimoto et al. [8]; Fucatu et al. [9]), which is a software for dynamic and static analyses of mooring and production lines.

Since we are not using the original ESA methodology proposed by Domingos et al. [3], there is no need to determine a k penalization factor for augmenting displacements, nor considering convex hulls when analyzing the displacement constraint for SAFOP criterion verification.

Nonetheless, the idea of selection of critical load cases was used in this work was based on that proposed by Domingos et al. [3]: in order to ensure safety, the model has to be subjected to a large number of different combination of loads. However, only a part of these combinations will actually lead to worst-case scenarios (for which the set of constraints has to be satisfied). Thus, selecting only the ECs that represent the worst-case scenarios is a task that, when done correctly, may save up lots of computational resources, abbreviating the optimization procedure. It is important to comment that all results generated by our optimization approach have to be validated at the end of the optimization using the original set containing all ECs.

To select the set d of critical ECs, Domingos et al. [3] proposes that the first $n + 1$ iterations of optimization, one should evaluate the model with the complete original set of ECs. At the $(n + 2)$th iteration, when the first step towards a point of minimum will be taken, one should select the critical load cases and perform the rest of the optimization with only those load cases. This procedure is automatic and does not require manual assessment in any way.

For selecting those critical load cases, the $n + 1$ previous steps have to be analyzed separately, and for each step i, a set c_i containing the critical load cases for that step should be obtained. A load case is considered critical when its point of displacement is part of the convex hull built around the points of displacements generated by all load cases.

Finally, the set d of critical load cases used for the rest of the optimization will be the union of all c_i sets generated in the $n + 1$ previous steps. This final step differs from that proposed by Domingos et al. [3], since there a histogram of frequencies had to be built and the length of the set d could be controlled by the user heuristically. In this work the length of the set d is not controlled by the user.

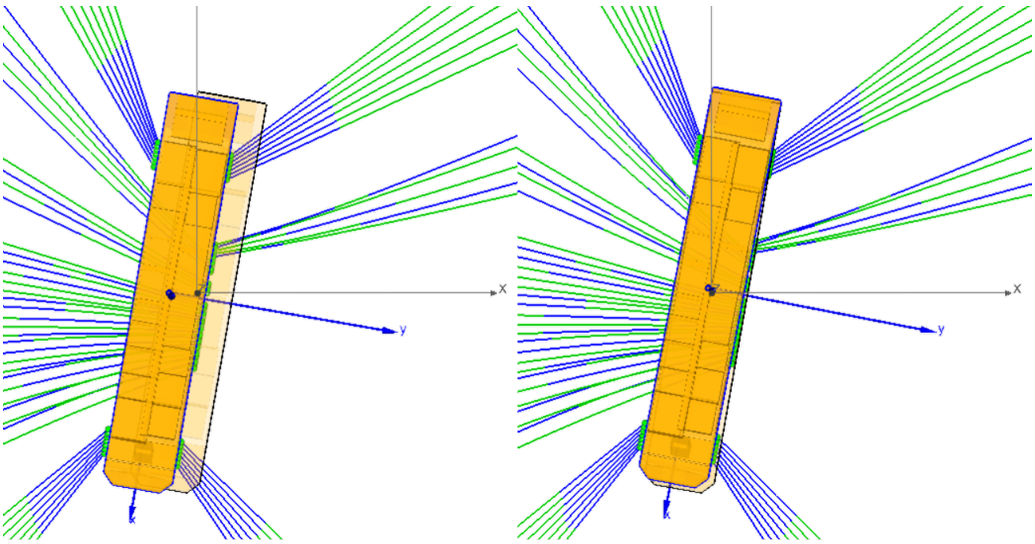
This adaptation has shown to be more effective, since heuristically the user could determine a maximum length for the set d thinking about performance, but restricting the set of critical load cases to an insufficient number of elements, causing the model to be invalid when subjected to all original ECs at the end of the optimization.

For reference, using the methodology of this work, the original model initially contained 4,516 ECs, and only 140 were used to perform the optimization. This is a reduction of almost 97% on the number of ECs of the model required for the optimization. All results still need to be validated using the full set of ECs.

4 Results

The whole optimization process took around 45.3 hours (wall-clock time) in 135 iterations. The first 29 iterations required for the selection of critical ECs took approximately 27.6 hours, while the rest of the 106 iterations using only the critical ECs took around 17.7 hours. Only for reference, the specs of the workstation used on the simulation are: Windows 11 64-bit operating system, AMD Ryzen Threadripper PRO 5995WX CPU and 256 GB of installed RAM.

The initial results shown in Fig. 2(a) belong to the initial model (also seen in Fig. 1). As it can be seen by the comparison of Figs. 2(a) and (b), the distance between the effective equilibrium position and the design position is much smaller in the optimized configuration. In fact, this distance has been reduced in almost 78%. In both initial and optimized models, their whole set of constraints were satisfied.



(a) (b)

Figure 2. Effective equilibrium position (shaded) versus design position (transparent) for the (a) initial model and for the (b) optimized model

Results of maximum offset displacements for the models are shown in Fig. 3. Red points represent the displacement under the action of the 140 critical ECs, while the envelope was generated considering the action of the original 4,156 ECs, to show how adherent the set d is in resuming critical ECs. The blue circle represents the SAFOP limits.

Results of maximum top tensions for the models are shown in Fig. 4. It can be seen that tensions are more evenly distributed in the initial model rather than the optimized. It is important to note that an even distribution of tensions was not a constraint proposed for this optimization problem, but it can be considered, as shown by Domingos et al. [3].

It is important to highlight that even though the initial model already satisfied the entire set of constraints, the objective parameter was suboptimal. Recalibrating the lengths of all lines would demand extensive hours of work from a high-skilled professional, and in this case these hours have been used with other activities while the optimization model was running. This is one of the most important goals of this optimization approach.

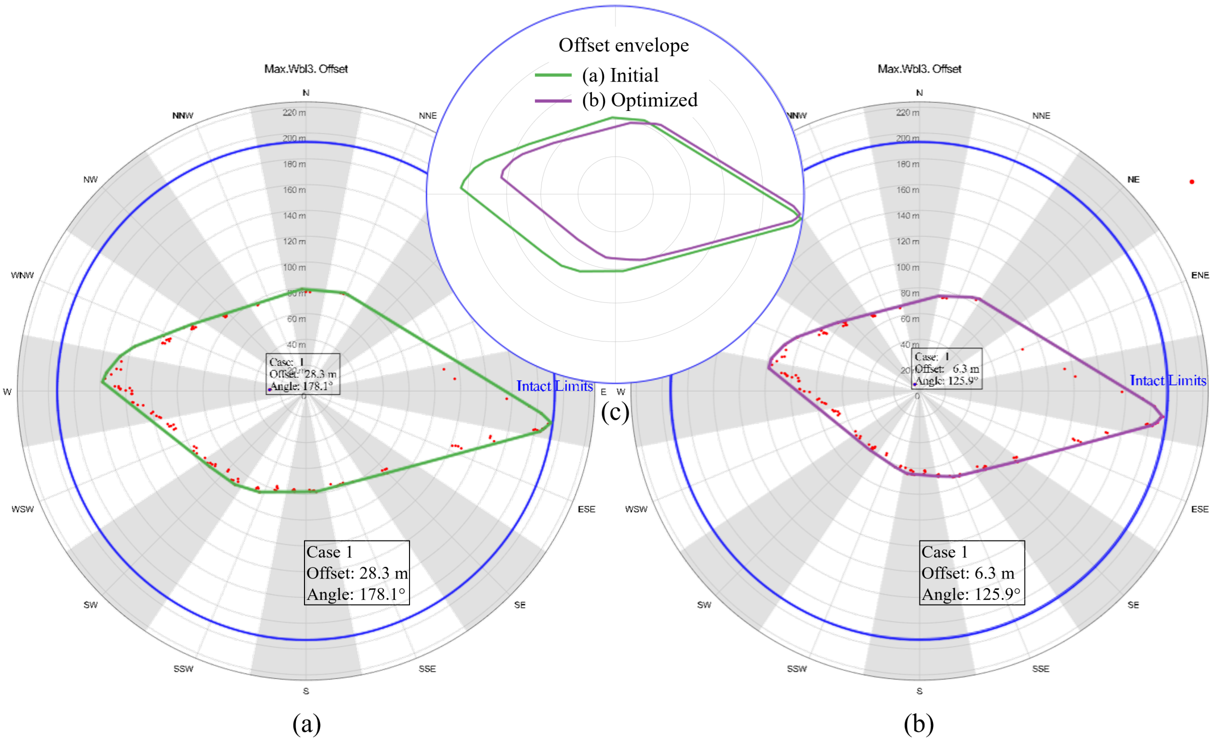


Figure 3. Maximum offset displacements along with the offset envelope for the (a) initial model and for the (b) optimized model, with both envelopes stacked in (c) for comparison

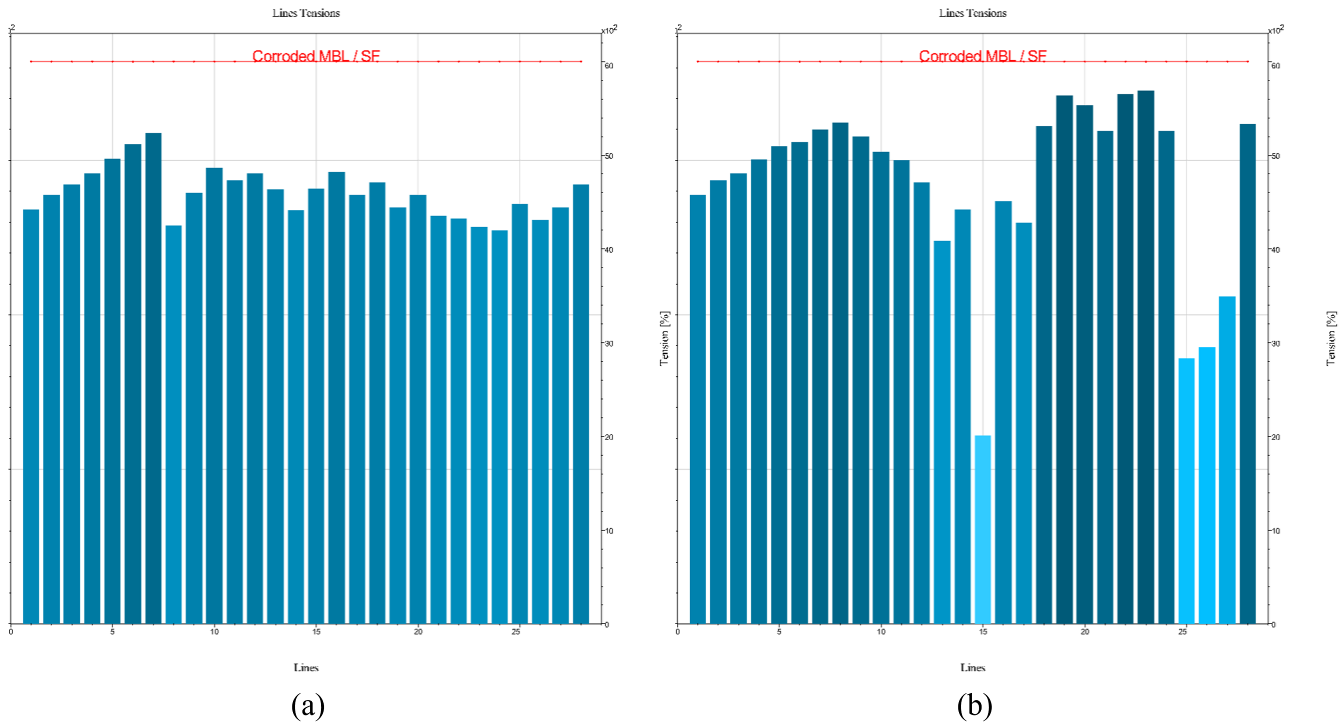


Figure 4. Maximum mooring lines top tensions generated by the original 4,516 ECs for the (a) initial model and for the (b) optimized model

5 Conclusions

This study presented an optimized approach for designing mooring systems for offshore structures using a real-case scenario. The results showed that the objective function, defined as the distance between the effective equilibrium and design positions, was minimized by nearly 78%, representing a significant improvement.

Despite yielding excellent results in some aspects, other aspects, such as the concentration of maximum top tensions in certain mooring lines, did not perform as well. This behavior underscores the need for future work to incorporate additional constraints and design criteria to enhance the quality of the results, leading to a more robust optimized solution.

Finally, the results reinforce the potential of optimization approaches to revolutionize traditional design paradigms in offshore engineering. With further refinement, these methods could lead to more efficient and robust mooring system designs that can be determined automatically by an optimization algorithm, allowing professionals to focus on validating results rather than manual trial-and-error design.

Acknowledgements. The authors acknowledge PETROBRAS and CNPq for the financial support.

Authorship statement. The authors hereby confirm that they are the sole liable persons responsible for the authorship of this work, and that all material that has been herein included as part of the present paper is either the property (and authorship) of the authors, or has the permission of the owners to be included here.

References

[1] A. R. Cruces Girón, F. N. Corrêa, A. O. Vázquez Hernández, and B. P. Jacob. An integrated methodology for the design of mooring systems and risers. *Marine Structures*, vol. 39, pp. 395–423, 2014.

[2] B. F. Monteiro, J. S. Baioco, C. H. Albrecht, B. S. L. P. Lima, and B. P. Jacob. Optimization of mooring systems in the context of an integrated design methodology. *Marine Structures*, vol. 75, pp. 102874, 2021.

[3] G. R. Domingos, E. N. Lages, A. S. Ramos Jr., A. T. Oshiro, and M. C. Oliveira. Nonlinear dynamic structural optimization of offshore structures using equivalent static models. In *Proceedings of the XLIV Ibero-Latin-American Congress on Computational Methods in Engineering*, 2023.

[4] M. J. D. Powell. *A Direct Search Optimization Method that Models the Objective and Constraint Functions by Linear Interpolation*, pp. 51–67. Springer Netherlands, Dordrecht, 1994.

[5] M. J. D. Powell. Direct search algorithms for optimization calculations. *Acta Numerica*, vol. 7, pp. 287—-336, 1998.

[6] J. Bezanson, A. Edelman, S. Karpinski, and V. B. Shah. Julia: A fresh approach to numerical computing. *SIAM Review*, vol. 59, n. 1, pp. 65–98, 2017.

[7] S. G. Johnson. The NLopt nonlinear-optimization package. `https://github.com/stevengj/nlopt`, 2007.

[8] K. Nishimoto, C. H. Fucatu, and I. Q. Masetti. Dynasim – a time domain simulator of anchored FPSO. *Journal of Offshore Mechanics and Artic Engineering-Transactions of the ASME*, vol. 124, n. 4, pp. 203–211, 2002.

[9] C. H. Fucatu, E. A. Tannuri, E. N. Lages, E. S. S. Silveira, F. M. G. Ferreira, K. Nishimoto, and M. C. Oliveira. Dynasim. Registration number: BR512014001550-5, 2016.