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**TÍTULO DO TRABALHO:**

Advancements in Computational Tools for Integrated Mooring Systems Design: a review

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## Abstract

Mooring systems undertake a fundamental role in restraining displacement, preserving structural integrity, and ensuring the safety of Floating Production Units (FPUs) and their subsystems (e.g., risers). However, the design of these systems is marked by a notable degree of complexity, owing to the interaction between various project characteristics, environmental factors, and operational requirements of the floating unit. Consequently, a comprehensive analysis of multiple design configurations is needed to ascertain their feasibility. Such thorough analysis results in a lengthy and meticulous process to determine its suitability and effectiveness in meeting the specific criteria of a mooring system, where less of 0.1% of solutions satisfy all design's requirements. In this context, computational tools and techniques perform a crucial role, being widely employed in the design and verification of offshore systems. Through sophisticated simulations of nonlinear dynamic systems, finite element methods (FEM), and computational fluid dynamics (CFD) analyses, engineers can evaluate the performance and viability of different mooring system configurations. This article presents the Synapse Multidisciplinary Engineering software, that leverages Multidisciplinary Optimization (MDO) methods to simplify and automate the design process of these systems, meeting project constraints and requirements. To mitigate the impacts associated with the high computational cost of simulations, analyses, and optimizations of the systems, the Synapse software employs machine learning algorithms, surrogate models, and the use of high-performance computing (HPC) cluster infrastructures. Following the latest trends in the field, new paradigms of human-machine interfaces (HMI), such as augmented and virtual reality (AR/VR), are being explored. These immersive technologies hold the promise of revolutionizing the design and visualization of mooring systems, offering engineers new ways to explore and interact with complex design spaces. Against this backdrop, this review highlights these trends in computational tools for the integrated design of mooring systems, emphasizing the importance of the continuous evolution and development of these technologies.

**Keywords:** Mooring System; Multidisciplinary Optimization; Integrated Design; Computational Tools.

## Introduction

Mooring systems are responsible for maintaining the positional stability, structural integrity, and overall safety of Floating Production Units (FPUs) and their associated subsystems. As reported by Rui et al. (2024), these systems are essential in the offshore industry, providing the necessary anchorage that ensures operational efficiency and effectiveness in challenging marine environments. The design of mooring systems is inherently complex due to the interplay of various project-specific factors, environmental conditions, and the dynamic behavior of the floating units. As a result, to ascertain optimal configurations, engineers must conduct analyses of multiple designs (Barrera et al., 2020).

In this context, computational tools and techniques have become indispensable (Masciola, Jonkman, & Robertson, 2014). These tools enable engineers to perform sophisticated simulations of nonlinear dynamic systems, employ finite element methods (FEM), and utilize computational fluid dynamics (CFD) analyses to assess the viability and efficiency of mooring systems.

Recent advancements in computational tools have significantly enhanced the design and verification processes of offshore systems. The integration of Multidisciplinary Optimization (MDO) methods, as exemplified by the Synapse (2023) Multidisciplinary Engineering software, has streamlined and automated the design process. Synapse provides a collaborative and user-friendly environment, enabling the optimization of single and multi-objective engineering projects, and allows integration with various Design of Experiments (DoE) and analysis tools. The software also leverages machine learning algorithms, surrogate models, and high-performance computing (HPC) cluster infrastructures to address the challenges posed by the high computational costs associated with simulations and optimizations.

Furthermore, the exploration of new paradigms in human-machine interfaces (HMI), such as augmented and/or virtual reality (AR/VR), is revolutionizing the design and visualization of mooring systems. These immersive technologies offer engineers innovative ways to interact with complex design spaces, enhancing their ability to explore and refine mooring system configurations (van den Oever, Fjeld, & Sætrevik, 2023).

This review aims to provide an overview of the latest advancements in computational tools for the integrated design of mooring systems. It emphasizes the significance of technological evolution and development in this field, demonstrating how these advancements are shaping the future of mooring system design. Through a detailed examination of current trends and emerging technologies, the features of the Synapse software are showcased, advantages and challenges in the integrated design and validation workflow are presented, and the continuous development and improvement of the software are highlighted.

## Integrated Design

The integrated design of mooring systems involves the cohesive application of various computational tools and methodologies to ensure the robustness, efficiency, and safety of these systems. This section delves into the key components that constitute an integrated design approach (*e.g.*, analysis tools, optimization techniques, and high-performance computing) and the integration of these features into the Synapse software.

### Analysis Tools

***Nonlinear dynamic systems simulations*** are widely used in the integrated design of mooring systems. These simulations account for the complex interactions and dynamic behaviors of the mooring components and the floating production units (FPUs) under varying environmental conditions. Chen, Zhang, and Ma (1999), Kim, Ran, and Zheng (2001), and Yang et al. (2012) evaluated the dynamic response to waves and currents of a coupled spar hull/mooring system in the time domain, providing insights in operational lifecycle, displacement and fatigue. However, understanding the full range of system behaviors requires more than just time-domain analysis.

In turn, frequency-domain methods analyze the system’s response to a range of frequencies, which is particularly useful for understanding the resonance behavior and dynamic stability of the system. Cunff et al. (2008) explores the motion of an FPSO platform and its risers under a frequency-domain simulation and compares it with the results obtained from a time-domain analysis. Low and Langley (2008) introduces a hybrid time/frequency-domain approach for efficient coupled analysis of vessel/mooring/riser dynamics and Jin, Bakti, and Kim (2020) focuses on multi-floater-mooring coupled time-domain hydro-elastic analysis in waves. These complementary methods provide a more comprehensive understanding of the system’s dynamic behavior, especially in the context of response amplitude operators (RAOs).

***Finite Element Methods*** are extensively used in the structural analysis of mooring systems. FEM enables the detailed assessment of stress distribution, deformation, and potential failure points within the mooring components. By discretizing the mooring lines, anchors, and connecting hardware into finite elements, engineers can model the physical behavior of these components under various load conditions. Tsukrov et al. (2005) presents a model to address non-linearity on the elastic behavior of mooring lines, and Kim et al. (2013) compares non-linear methods with linear spring approaches for predicting the most probable failure points. Lee et al. (2018) and Desiré, Rodríguez-Luis, and Guanche (2023) simulate the interaction and forces of mooring lines in complex seabed topography, showcasing the versatility of FEM in different scenarios.

***Computational Fluid Dynamics*** analysis is fundamental in understanding the fluid-structure interactions that influence mooring system performance. CFD simulations provide insights into the hydrodynamic forces exerted by waves, currents, and wind on the FPUs and mooring lines. These simulations help in evaluating the drag, lift, and inertial forces that affect the stability and positioning of the moored structure. Jiang, el Moctar, and Schellin (2019) and Huang and Chen (2020) investigate overall damping effects of mooring systems under wave and current load configurations. Jiang and Paredes (2021) perform a comparative study of available CFD models for coupled mooring systems. Chen and Hall (2022) examine the motion and displacement of floating bodies using the OpenFOAM library. These studies highlight the critical role of CFD in enhancing the design and performance of mooring systems, creating a holistic view when combined with FEM and dynamic simulations.

Synapse offers the integration with multiple analysis tools and software applications, such as: Python, MATLAB, Ansys Mechanical for FEM, Dynasim (Nishimoto, Fucatu, & Masetti, 2002) for time-domain simulations, and an integration with OpenFOAM is being developed for CFD problems. The software also allows for the automatic parametrization and execution of simulations through Design of Experiment methods on grids or clusters of computation, as demonstrated in the following sections.

**Optimization**

Multidisciplinary Optimization is a comprehensive approach that integrates various engineering disciplines to perform an automatic search for optimal designs given projects requirements and constraints. According to Sobieski, Morris, and van Tooren (2017), MDO methods can consider multiple objectives and constraints simultaneously, in mooring systems optimization the interest is usually in minimizing displacement and cost while maximizing safety and performance. Optimization is fundamentally an iterative process (Figure 1), beginning with an initial guess of the optimal values and generating a sequence of increasingly refined estimates until a solution is attained. The methodology employed to advance from one iteration to the next distinguishes various algorithms. Most techniques use the values of the objective function, the constraints, and possibly their derivatives. While some algorithms accumulate data from preceding iterations, others rely exclusively on local information from the current point (Nocedal & Wright, 2006).

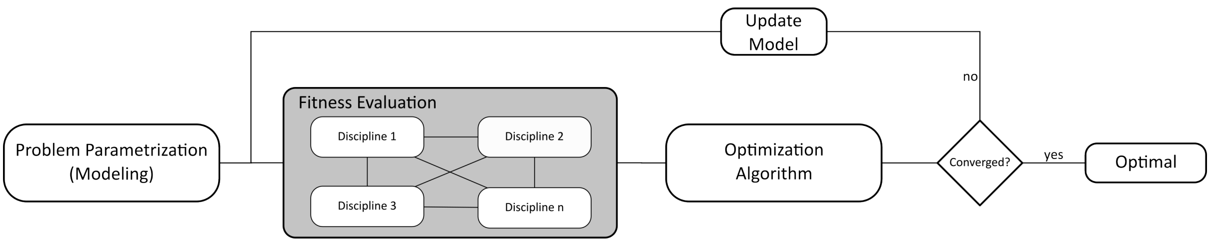


**Figure 1** Multidisciplinary Optimization process flowchart (Source: Authors).

In recent years, several notable works have illustrated the application of optimization techniques in the design of mooring systems. Liang et al. (2019) proposed a model for optimizing semisubmersible mooring systems using the Non-dominated Sorting Genetic Algorithm II (NSGA-II). Monteiro et al.

(2021) integrated finite element analyses with PSO to unify riser design with mooring system optimization. Ferri et al. (2022) proposed the use of a Multi-Objective Genetic Algorithm (MOGA) and frequency-domain simulations for Floating Offshore Wind Turbines (FOWT) optimization. Ja'e et al. (2022) integrated CFD and FEM analyses. Lim, Choi, and Lee (2023) introduced an Exotic Bayesian Optimization method specifically tailored for mooring system optimization. Table 1 summarizes the most cited works in the latest years featuring the tools, methods used and the type of FPU/mooring system they were applied to.

**Table 1.** Works using optimization techniques for integrated mooring systems design.

| Reference | Analysis Tool | Optimization Method | FPU type |
|---|---|---|---|
| Pillai, Thies and Johanning (2019) | time-domain | MOGA | VLFS |
| Liang et al. (2019) | time-domain | NSGA-II | VLFS |
| Xu et al. (2020) | time-domain | NSGA-II | VLFS |
| Monteiro et al. (2021) | FEM | PSO | FPSO |
| Wilson et al. (2021) | time-domain | Authors | FOWT |
| Ferri et al. (2022) | frequency-domain | MOGA | FOWT |
| Ja'e et al. (2022) | CFD/FEM | RegPSO | FPSO |
| Trubat, Herrera, and Molins (2023) | CFD/FEM | ANN | FOWT |
| Lim et al. (2023) | time-domain | Bayesian | FPSO |
| Jiang et al. (2024) | CFD/FEM | ANN | FOWT |

Moreover, the integration of machine learning algorithms and surrogate models has revolutionized the optimization process in mooring system design (de Pina et al., 2013). Machine learning techniques can predict the performance outcomes of different design configurations based on historical data, reducing the need for extensive simulations. As described by Wu et al. (2019), surrogate models, which approximate the behavior of complex systems, enable rapid evaluations of design alternatives with minimal computational effort. These tools significantly reduce the time and cost associated with the optimization process, allowing for more efficient exploration of the design space as demonstrated by Pillai, Thies and Johanning (2019), Trubat, Herrera and Molins (2023) and Jiang et al. (2024).

The Synapse Multidisciplinary Engineering software streamlines this approach by providing a collaborative and user-friendly environment for conducting MDO, facilitating efficient and effective design iterations. Synapse incorporates the implementation of various optimization algorithms, such as NSGA-II, MOGA, the Complex Method (also known as Modified Box Algorithm), Simplex and Vertex. Furthermore, the software has built-in artificial neural networks modelling tools for optimization processes acceleration. Figure 2 demonstrates Synapses' graphical user interface and exemplifies the flowchart-based interface for problem modeling, enabling even non-experienced users to perform sophisticated optimizations.

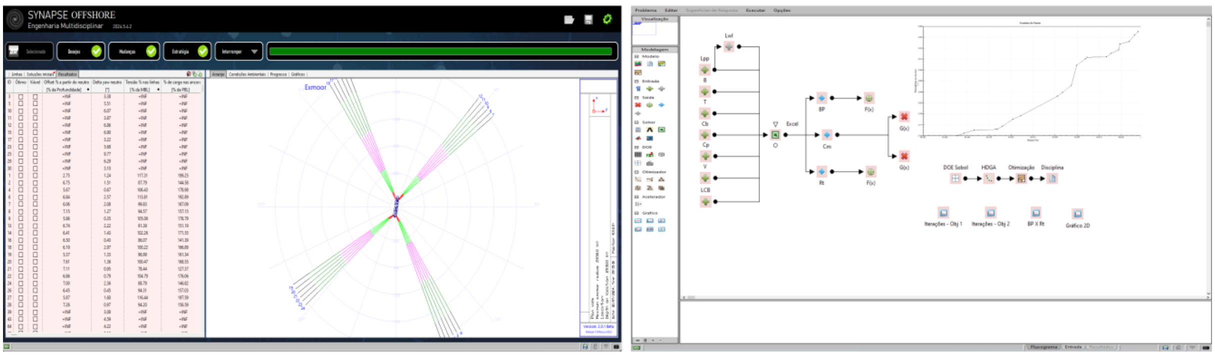


**Figure 2.** Synapse's optimization home screen and problem configuration menu (left), flowchart-based problem modeling screen (right) (Source: Authors).

**High-Performance Computing**

High-Performance Computing (HPC) clusters are critical for handling the large-scale computations required in the integrated design of mooring systems. HPC clusters provide the computational power needed to run costly simulations, optimizations, and analyses in a reasonable timeframe (Hager & Wellein, 2010). By distributing the computational load across multiple compute nodes (as shown in Figure 3), HPC clusters enable parallel processing of complex tasks, thereby accelerating the design cycle. Moreover, as stated by Sterling, Anderson, and Brodowicz (2017) HPC clusters allow for scalable resource allocation, ensuring that computational resources can be adjusted based on the complexity and size of the simulations. This flexibility enhances the efficiency of the design process, enabling engineers to conduct more comprehensive analyses and optimizations without being constrained by computational limitations (Bertsekas & Tsitsiklis, 2015).

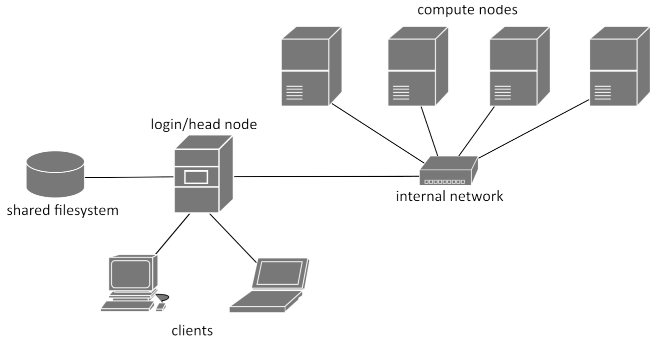


**Figure 3.** Simplified HPC cluster architecture (Source: Authors).

Indeed, as discussed in Burmester et al. (2020), HPC infrastructures became indispensable when dealing with multiple, coupled FEM–CDF and/or high-fidelity models' simulation, as even state-of-the-art workstations are insufficient for these demanding tasks. The works performed by Kyoung et al. (2019), Eskilsson and Palm (2022), and Kim et al. (2023) on fluid-structure interaction and its impacts on the dynamic behavior of mooring systems were only possible due to supercomputers. Reported by Harada and Alba (2020), there is also a surge in the development of parallel/distributed meta-heuristics for optimization procedures, aiming to exploit the resources of HPC clusters.

Synapse leverages clusters of computation by distributing and parallelizing the analyses of multiple candidate solutions through a middleware that distributes the processes in a master-worker manner (Gabardo, Jaskowiak & Tancredi, 2024), i.e., the intense computational task of evaluating the fitness of individuals is distributed while, modeling, parametrization and selection is performed in a master node (Gong et al., 2015). Figure 5 demonstrates the monitoring screen with the status of distributed processes in a cluster

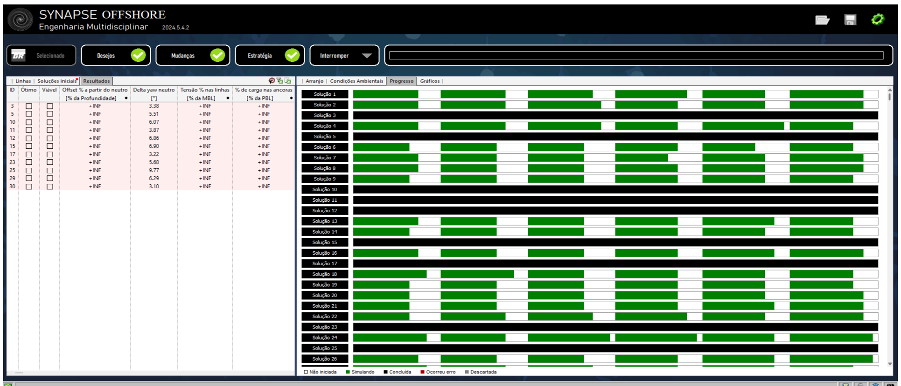


**Figure. 4.** Synapse's monitoring screen for distributed analyses, each green bar corresponds to a thread in execution (Source: Authors).

## Future Works and Conclusions

Synapse is continually evolving to advance the capabilities of integrated mooring system design optimization. The next steps include integrating additional analysis tools, such as OpenFOAM and OrcaFlex, to enhance fluid dynamics and mooring analysis, allowing for more precise and detailed evaluations. By expanding its toolset, Synapse aims to meet the growing demands of the offshore industry with a more versatile and robust platform.

A significant challenge in the design and verification of complex mooring systems is the visualization and interpretation of results within intricate design spaces (van den Oever et al., 2023). To address this bottleneck, alternatives such as mixed and augmented reality are being explored (dos Santos et al., 2012; Ismail et al., 2024; von Lukas, Vahl, & Mesing, 2014). These immersive technologies promise to revolutionize the way engineers interact with and understand complex data, offering intuitive and interactive ways to visualize design configurations and performance outcomes, leading to more informed decision-making and optimized mooring system solutions.

The design of mooring systems for floating production units is a complex, multidisciplinary task that requires advanced computational tools and techniques. This review has highlighted key components of an integrated design approach, including nonlinear dynamic systems simulations, finite element methods, computational fluid dynamics analysis, optimization techniques, and high-performance computing. Integrating these tools into the Synapse Multidisciplinary Engineering software demonstrates the potential for streamlining and automating the design process.

As the field evolves, integrating machine learning algorithms, surrogate models, high-performance computing, and new human-machine interface paradigms will further enhance computational tools, enabling more efficient and accurate design processes. The advancements highlighted in this review underscore the importance of continuous development in mooring system design. Future research should focus on integrating these advanced technologies and exploring new methodologies to enhance the design, optimization, and visualization of mooring systems.

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