Title:
Configuration and Optimization in the Early Design Phases of Offshore Buoys: A Test Case

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Introduction:
The design of offshore systems often requires the engineering of customized solutions. This approach is called Engineered-To-Order (ETO) and is typical of any industrial field where a high customization level is required. ETO companies focus the competition on how to increase and manage the variety of products to meet customers' requirements under time and cost constraints while realizing the maximization of the enterprise profit [9]. In the ETO processes, the production company develops a simplified project to rapidly evaluate the overall feasibility and possible cost of a project while responding to a request for quotation. To reduce time and cost in the phase of quotation preparation, design approaches such as modularization, configurations, and optimization can be applied. Product configuration and optimization are essential topics in several industrial applications, such as the manufacturing of ETO products [6], where there is a fierce increase in market competition.

One of the simple offshore structures is the marine buoy. Even if buoys are often pre-configured products in catalogs, the increased demand for ocean monitoring asks for customized solutions. Therefore, marine buoys can also be seen as customized offshore structures similar to ETO products. In this context, the paper aims to present an approach to optimize customized buoys for meteorological monitoring during the early design phases.

As a test case, the optimization of a moored marine buoy used for meteorological applications is proposed. A steel structure has been considered because steel buoys have a lot of advantages, such as high strength and easy manufacturing [7]. A Model-Based system has been developed to analyze the performance of the physical buoy. The design approach considers requirements, reference normative, constraints, and boundary conditions as input. The calculation analysis is based on the guideline provided by the International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA) for hydrostatic buoy design [3]. The boundary conditions considered, wind and current speed, are related to an installation in the Mediterranean Sea. The developed Model-based system has been optimized using a genetic algorithm, considering the variations of several geometrical parameters related to the components of the buoyancy body.

This paper describes the research background in engineering design and buoy applications, the proposed approach, and the test case with results and conclusions.

Marine buoys:
Marine buoys are floating objects on the sea surface, and they are used for several applications such as environmental monitoring and research, alerts, marking and diving, mooring rescue, national security, disaster warning, etc. There are numerous uses for marine buoys [8]. These objects are systems that can include various devices such as sensors, communication units, power supply units, energy storage, markers, etc. Each application requires specific configurations able to host the appropriate devices; for example, marking and diving buoys (sometimes called light buoys) are equipped with navigation signs and lighting features to guide nearby vessels showing the navigable channels while marking the presence of submerged wrecks, reefs, and shallow waters [5].

Meteorological buoys are equipped with numerous sensors for atmospheric and marine monitoring. The parameters monitored can be the atmospheric pressure, wind speed and direction, air temperature, relative humidity, solar radiation, infrared radiation, precipitation, CO_2, sea temperature and salinity, water pressure, sea waves, etc. [2]. These buoys aim to analyze the air-sea interaction processes [10], the physical properties of the water column, the bio-geo-chemical parameters, etc. These data are essential for meteorological and oceanographic studies, the comparison of in situ and remotely sensed measurements, and the development of innovative marine monitoring technologies [1].

Approach and test case:
Fig.1. describes the approach used to optimize the early model of a meteorological marine buoy. The user defines the input, such as the buoy type, layout, model of the superstructure, materials, and the list of equipment. The variable parameters used in the optimization analysis are the geometrical parameters related to every part of the buoyancy body. These parts are the cylinder body, the tail tube, and the ballast. The optimization analysis is performed using a GA approach with multi-objective functions based on the minimization of the total weight and the maximization of the reserve buoyancy volume. The main constraints are related to the maximum angle of heel and the position of the waterline.

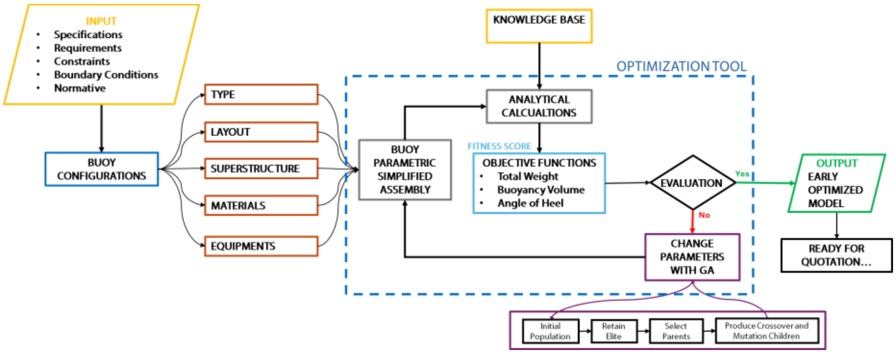

Fig. 1: Proposed approach for optimization of marine buoys.

The GA algorithm exploits the process of natural selection, in which the fittest individuals have a higher chance of surviving, procreating, and passing on their advantageous traits to the following generation. Over multiple generations, the algorithm explores the solution space and converges toward optimal or near-optimal solutions. Starting from an initial population (individuals), GA evaluates the fitness score of the objective functions, quantifying the solution's quality. Subsequently, GA selects from the current population to serve as parents for the next generation and performs crossover and mutation, creating a new population. GA repeats the evaluation, selection, crossover, mutation, and replacement until a satisfactory solution is found. The best individuals represent the optimized solutions to the problem. In the proposed test case, the individuals are the combinations of the design parameters. The best individuals are the parameter configurations that maximize the fitness score.

The approach has been implemented using the software tool ESTECO modeFRONTIER, adopting the Multi-Objective Genetic Algorithm II (MOGA-II) method as the optimization algorithm to minimize the three objective functions. A graphical workflow with parameters, model, objectives, and constraints has been defined. The calculation of the fitness score is based on the development of an analytical model, which implements the formulas reported in the IALA guideline for hydrostatic buoy design [7]. This analytical model has been implemented in Microsoft® Excel using Visual Basic Application (VBA) language. An integration with the CAD software Autodesk Inventor® has been performed by the Software Development Kit (SDK) tool to exchange data with the analytical model.

The elaborated model considers the geometrical dimensions, boundary conditions, component mass and volume, buoyant force, center of gravity, center of buoyancy, metacentric height, angle of heel, and righting moment, etc. To support the parametrical calculation, two CAD models were created. While the first model represents the simplified geometry of the buoy model, the second one represents the shape of the volume related to the buoyancy body. The buoyancy body regards the submerged parts, including the float area characterized by the waterline, excluding the superstructure. These two models are used to configure the CAD model of the buoy and to calculate parameters such as total mass, buoyancy volume, inertia, volume, etc., used to evaluate the objective functions.

Test case and results:

The case study, used to validate the proposed approach, regards the optimization of a meteorological buoy located in the Mediterranean Sea, 50 km away from the southern Italian coast in the area of the Ionian Sea. The optimized marine buoy has a final weight of 3470 kg, a body diameter of 1950 mm, and a total height of 8940 mm. This configuration provides a reserve buoyancy volume of 2.93 m^3. Fig. 2 reports the 3D CAD model of the optimized buoy with the detail of the waterline plane (placed at 983 mm from the top plate of the cylinder body).

Conclusions:

Computer-aided technology software is a powerful tool for supporting the design phases, from the concept analysis to the final solutions. The approach proposed here is focused on the design and optimization of the buoyancy body of a marine buoy. The decision variables analyzed are the main geometrical parameters of the buoyancy body, including tail tube and ballast. The application context regards the initial design phases where the main parameters of the project are defined. A similar approach can be extended to the early design of general-purpose ETO structures to reduce lead time in the quotation phase while optimizing the main parameters and considering the boundary conditions.

A design platform was implemented using ESTECO modeFRONTIER to support the optimization process driven by the MOGA-II algorithm. An analytical model was also implemented in VBA using the guidelines provided by IALA [3]. A CAD integration was also performed using Autodesk Inventor®. The results show the possibility of achieving several solutions considering the output and objectives evaluated by the analytical model. The final optimal solution was selected by studying the designs related to the Pareto front. In future development, a FEM (Finite Element Method) analysis and a parametrization of the superstructure can be introduced.

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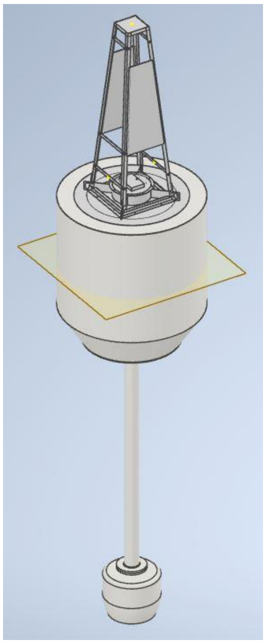

Fig. 2: the 3D CAD model of the optimized buoy with detail of the waterline plane.

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