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

Paolo Cicconi[1], Guido Della Gatta[2], Francesco Menon[3], Sebastiano G. Paradiso[4], Michele Trovato[5] and Nadia Lo Bue[6]

[1]Università degli Studi ROMA TRE, paolo.cicconi@uniroma3.it
[2]Università degli Studi ROMA TRE, gui.dellagatta@stud.uniroma3.it
[3]Università degli Studi ROMA TRE, fra.menon@stud.uniroma3.it
[4]Università degli Studi ROMA TRE, seb.paradiso@stud.uniroma3.it
[5]Università degli Studi ROMA TRE, michele.trovato@uniroma3.it
[6]Istituto Nazionale di Geofisica e Vulcanologia, nadia.lobue@ingv.it

Corresponding author: Michele Trovato, michele.trovato@uniroma3.it

Abstract. The design of offshore systems often requires the engineering of customized solutions. This approach, called Engineered-To-Order (ETO), is typical of any industrial field where a high customization level is required. One of the simplest offshore structures is the marine buoy. Even If these systems are often pre-configured products available in catalogs, the increased demand for ocean monitoring is asking for customized solutions. In this context, the paper aims to present a design approach to optimize customized buoys for meteorological analysis far from the coast. The proposed approach supports the configuration of buoys during the early design phase. A Model-Based system has been developed to analyze the performance of the physical buoy, considering requirements, normative constraints, and boundary conditions. A Genetic-Algorithm has been used for searching the parameters configuration that optimizes the objective functions.

Keywords: Design Optimization, Model-Based System, Genetic Algorithms, Meteorological Buoys.
DOI: https://doi.org/10.14733/cadaps.2025.673-684

1 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 [23]. 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 [12], 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 [19]. 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 [7]. 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, the marine buoys, the proposed approach to optimize the geometrical parameters, the test case, the results, and the conclusions.

2 RESEARCH BACKGROUND IN THE DESIGN METHODS OF ENGINEERING SYSTEMS

The multidisciplinary approach used to define successful systems is called Systems Engineering (SE) [8]. This approach is used in mechatronic products and offshore systems and applied to the entire system or sub-systems. The main design phases of SE regard the requirements analysis, functional analysis, and synthesis to achieve the system architecture.

Model-Based System Engineering (MBSE) is an approach that facilitates the knowledge exchange between different actors to validate the design of complex systems [1]. Generally, in industrial companies, CAD tools are used by CAD specialists, but the system engineers make decisions about the solutions. The use of System Modeling Language (SysML) diagrams is a good practice to enhance the collaboration between CAD users and system engineers [5]. SysML is a graphical modeling language used to represent different concepts in a system that may include hardware, software, information, personnel, procedures, and facilities. This general-purpose graphical modeling language can support the analysis and specification of complex systems using up to nine types of diagrams [18]. SysML representation can be used to model the Requirements Diagram, System Hierarchy (using the Block Definition Diagram, BDD), Internal Structure (using the Internal Block Diagram, IBD), and Functional Analysis with parameters and activities.

The model-based approach allows complex systems to be configured. The product's system model can be configured using the dependencies between each module without using pre-defined rules [24]. The configuration and analysis of modular products include the analysis of each module. In modular architectures, each module is a functional unit that can be replaced with another. Modularity allows the variance of variants to be controlled without reducing productivity [11]. Modular products need configuration systems to address customer requirements. An MBSE approach can support the configuration process because optimal variants can be configured while taking quantities and characteristics into account [24]. Therefore, this approach can support the customization of products.

CAD tools are widely used to support product customization in different industrial fields. Moreover, these tools can also be used to develop customized tools to be involved in the design workflow. In the literature, it is well known that one of the most powerful features of CAD systems is customization. With customization is possible to create new commands and ways of human-machine interaction in design, supporting repetitive and complex tasks [20]. Therefore, CAD system is the tool used for both the definition of customized products and the implementation of customed software tools. Generally, CAD systems support designers while defining the geometry of a product and other characteristic such as physical properties, stiffness, kinematic and kinetic behavior. They can include advanced functionalities for supporting the problem-solving activities at different levels [14]. The role of these tools is essential for the product digitalization. The CAD assembly defines the structure of a product through an objected-oriented representation. The integration between CAD models and SysML diagrams can determine a Model-Based System because the SysML diagrams defines the relationships within the product structure [15].

In the context of ETO, the delivery of new configurations of products requires a technical feasibility analysis. There is a lack of commercial tools which can support the designer from the early configuration phases to the product optimization with the automatic generation of geometric models and simulations [3]. Solutions to reduce cost and time in product configuration can be obtained using a Multi-Objective Optimization (MOO) analysis to maximize the product performance while minimizing weight and cost [13]. An MOO approach can be used to support the search of feasible solutions that satisfy customer requirements and product constraints using Genetic Algorithms (GAs) [22]. Theses algorithms take inspiration from the natural selection and evolution processes. They are applied in optimization problems to identify the optimal solution within a large search space [17].

The design of complex systems also requires the development of a tailored software platform capable of integrating different tools for MBSE, configurations, optimization, etc. The scope of this contribution is the study of design methodologies to integrate design optimization inside the configuration activities of customized products. The research aims to reduce the time and cost related to the early design phases of marine buoys. The approach studies the technical feasibility of the configurations while optimizing the parameters under specific boundary conditions.

3 MARINE BUOYS

Marine buoys are floating objects on the sea surface, used for several applications such as environmental monitoring and research, alert, marking and diving, mooring rescue, national security, disaster warning, etc. The uses of marine buoys are numerous for different applications [21]. 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 [10].

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, CO2, sea temperature and salinity, water pressure, sea waves, etc. [6]. These buoys aim to analyze the air–sea interaction processes [25], 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 [2].

3.1 Model and Buoyancy

This section introduces the modeling of a meteorological marine buoy, resolving the stability at small angles of heel. The main steps for the buoyancy analysis are reported here. The calculation approach is related to the guideline provided by IALA for hydrostatic buoy design [7]. Figure 1 (a) shows an example of a 3D CAD assembly related to a marine buoy, where the main components are reported in the parts list. Figure 1 (b) describes the motion of the center of buoyancy (B) about the metacenter point (M). This scheme is used for calculating the metacentric height (GM). To provide stability, one of the constraints requires that M is always above G ($GM > 0$).

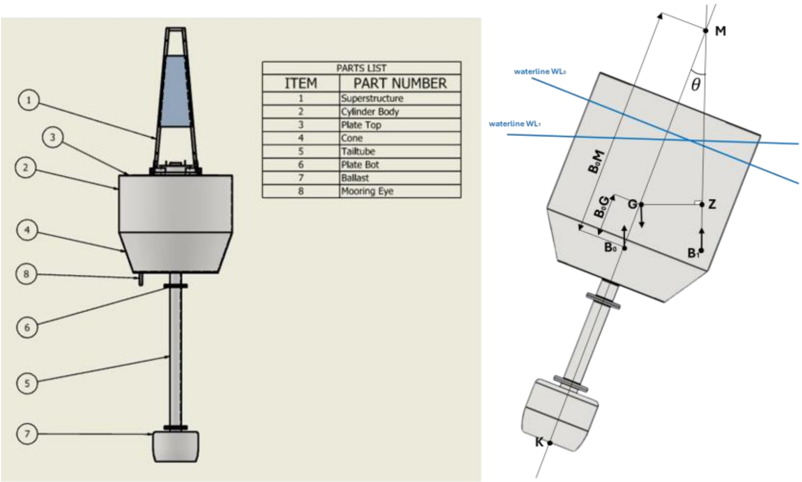

Figure 1: (a) An example of meteorological marine buoy with the main parts list; (b) Description of the motion of the center of buoyancy (B) about the metacenter point (M).

In the equilibrium condition, the weight force (W) is balanced with the buoyant force (F_B), as reported in Equation (3.1). The weight force is defined in Equation (3.2) as sum (m_{tot}) of all mass of each i^{th} component (m_i) multiplied acceleration of gravity ($g = 9{,}81\, m/s^2$). Equation (3.3) shows the definition of the Buoyant force ($\mathrm{F_b}$); where ρ is the sea water density in Kg/m^3 related to the installation site and V_b is the volume of the portion of the buoy immersed in water, evaluated in m^3.

$$W - F_b = 0 \tag{3.1}$$

$$W = \sum_{i=1}^{n} m_i \cdot g = m_{tot} \cdot g \tag{3.2}$$

$$F_b = \rho \cdot V_b \cdot g \tag{3.3}$$

In Equation (3.4), by imposing the balance between W and F_b, it is possible to obtain the immersed volume.

$$W - F_b = 0 \rightarrow (m_{tot} \cdot g) - (\rho \cdot V_b \cdot g) = 0 \rightarrow \; V_b = \frac{m_{tot}}{\rho} \tag{3.4}$$

A fundamental condition is that the immersed volume (V_b) is less than the total volume of the buoy to avoid sinking. Equation (3.5) shows the floating condition, where V is the total volume of the buoy. The difference between these two volumes is the reserve buoyancy (R) defined in Equation (3.6). The reserve buoyancy does not consider the volume of the superstructure.

$$V_b < V \tag{3.5}$$

$$R = V - V_b \tag{3.6}$$

Metacentric height (GM) and metacentric radius (BM), reported in Figure 1 (b), are two important parameters to evaluate the stability of a buoy. In free floating condition, for small angles of heel (less than 10°), the center of buoyancy (B) follows a circular path centered at the metacenter (M) with a radius equal to the metacentric radius (BM). While the initial position of the center of buoyancy is B^0, B^1 is the center of buoyancy related to the tilted configuration (Figure 1 (b)). The metacenter is the intersection point of the line B^0G and the vertical line passing through B^1. If the metacentric height (GM) is positive, the object will return to its original upright position after being tilted. The buoy will capsize if the angle of heel becomes too great or if the metacentric height is negative.

The metacentric position is evaluated by calculating KM as reported in Equation (3.7)–(3.9), where K is a chosen reference origin (see Figure 1 (b)).

$$GM = KM - KG \tag{3.7}$$

$$KM = KB_0 + B_0M \tag{3.8}$$

$$GM = (KB_0 + B_0M) - KG \tag{3.9}$$

B_0M is calculated using Equation (3.10), as the inertia of the water plane I_f (m^4) about the axis of the center of water plane per buoyancy (V_b).

$$B_0M = \frac{I_f}{V_b} \tag{3.10}$$

The external disturbing forces, which can cause instability, are related to wind and current loads. Equation (3.10) shows the wind force, where ρ_{air} is the air density, C_d is the drag coefficient ($C_d = 1{,}1$), A is the area in m^2 of the superstructure, and v_{wind} is the wind speed. The moment related to the wind force is described in Equation (3.11), where b is the moment arm which can be calculated as the distance between the center of gravity of the superstructure and the rotation point (which can be approximated with the mooring eye).

$$F_{wind} = \frac{1}{2} \cdot \rho_{air} \cdot C_d \cdot A \cdot v_{wind}^2 \tag{3.11}$$

$$M_{wind} = F_{wind} \cdot b \tag{3.12}$$

Equation (3.13) defines the calculation of the drag force related to the current load, where A_{tot} is the area of the submerged body, v_{wave} is the wave speed and C_d is the drag coefficient ($C_d = 1{,}1$). The moment related to the sea current force is described in Equation (3.14), where b_2 is the moment arm, which can be calculated as the distance between the center of buoyancy and the rotation point (which can be approximated by the position of the mooring eye).

$$F_{sea} = \frac{1}{2} \rho\, C_d\, A_{tot}\, v_{sea}^2 \tag{3.13}$$

$$M_{sea} = F_{sea} \cdot b_2 \tag{3.14}$$

M_{tot} reported in Equation (3.15) is the sum of the moments related to the defined disturbing forces.

$$M_{tot} = M_{wind} + M_{sea} \tag{3.15}$$

The moment contrasting the sum of the external moments (M_{tot}) is shown in the Equation (3.16). This moment is called the righting moment (RM). During the design phase, RM can be calculated with Equation (3.17) to evaluate the capacity of the buoy of contrasting the overturning moment and of returning in the vertical position.

$$RM = W \cdot GZ \tag{3.16}$$

$$RM = m_{tot} \cdot g \cdot (B_0M - B_0G) \cdot \sin\theta \tag{3.17}$$

Considering small angles od heel (less than 10°), the θ angle can be calculated as reported in Equation (3.18).

$$\tan\theta = \frac{M_{tot}}{W \cdot GM} \rightarrow \theta = \tan^{-1}\left(\frac{M_{tot}}{W \cdot GM} \cdot \frac{180}{\pi}\right) \quad (3.18)$$

4 APPROACH

Figure 2 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.

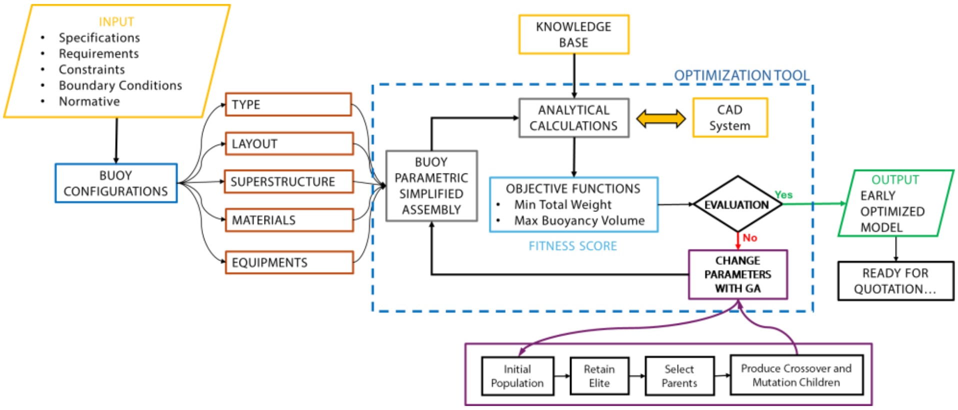

Figure 2: Proposed approach for optimization of marine buoys.

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). An example of the graphical workflow with parameters, model, objectives, and constraints is reported in Figure 3.

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.

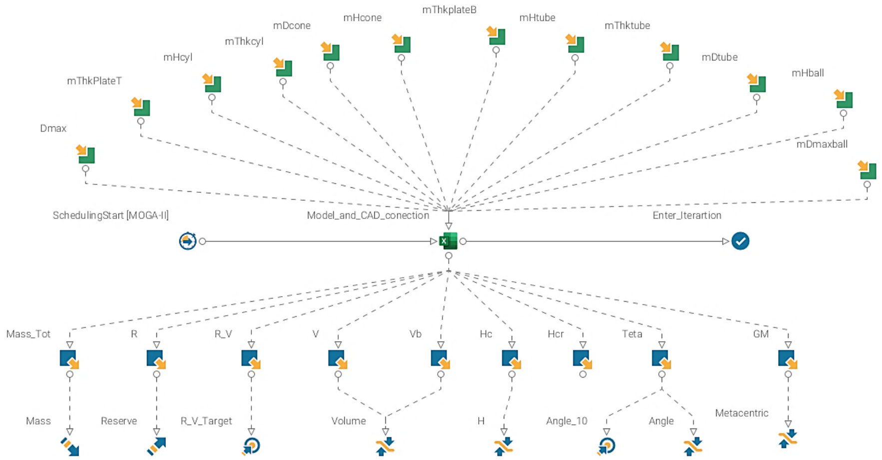

Figure 3: An example of the optimization workflow implemented in ESTECO modeFRONTIER. This workflow refers to the case study reported in Section 5.

4.1 Parameters and CAD models

The optimization approach considers only geometrical parameters. The parametrization here regards the buoyancy body without considering the superstructure. The configuration of the superstructure is constant and related to the customer's requirements. The geometric parameters used to optimize the buoyancy body concern the main dimensions, such as the diameter and thickness of each component. Some of these parameters can be defined by the user, while others are determined by user-defined functions. Figure 4 shows the parametric CAD models realized to model a generical meteorological buoy. The geometrical parameters are managed with the GA method, and a CAD tool connection rebuilds the models to calculate weight, center of mass, and center of buoyancy.

4.2 Objectives, Variables, and Constraints

To guide the GA algorithm, it is necessary to identify objective functions and constraints. This paper analyzes two objective functions. While the first one is the minimization of the total mass, the second one is the maximization of the reserve volume. These objective functions are conflicting because the maximization of the reserve volume could enlarge the body of the buoy, increasing the resulting weight. The genetic algorithm modifies the initial population (variables) by applying the concepts of evolution of mating, mutation, and crossover, searching for the optimal solution. The variables selected for this application are the geometric dimensions of the parts of the buoy related to buoyancy. Table 2 shows all the geometrical variables and their variable range.

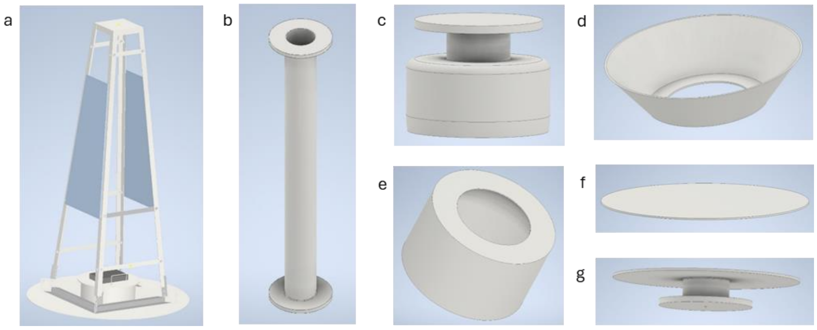

Figure 4: Example of CAD models related to parametric buoy: (a) Superstructure, (b) Tail Tube, (c) Ballast, (d) Cone, (e) Cylinder Body, (f) Plate Top, (g) Plate Bottom.

The approach also considers the study of a list of constraints to guide the search for feasible solutions, avoiding unfeasible ones. Examples of constraints are related to the buoyancy volume, i.e. $V_b < V$, $\theta < 12°$, positive metacentric height, etc. Moreover, knowledge-based conditions can be added to search for solutions with specific target values. For example, a target value can be defined for the ratio Reserve/Volume (R/V) and another one for the angle of the heel (θ).

5 TEST CASE

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 Ionian Sea. Table 1 reports the in-situ boundary conditions considered for the calculation. The wind speed of 12 m/s refers to the peak value reported in the Copernicus Marine Service data [4]. The current speed of 0,5 refers to data reported in the Atlas of surface currents of Italian seas [9]. A safety coefficient (=2) was considered for the calculation of the forces related to wind and current speed. The weight of one operator was also considered to avoid an excessive reduction of the reserve volume during the maintenance operation.

Table 2 shows the list of parameters used for the test case optimization. These parameters are used for resizing the buoyance body of the structure. For each parameter are defined the range of variation in terms of lower bound, upper bound, and step. The resizing of the superstructure is not considered in this optimization workflow. The weight of the superstructure is considered constant (see Table 1).

Wind speed	$v_{wind} = 12\ m/s$ (23,33 knots)
Current speed	$v_{wave} = 0{,}5\ m/s$ (0,97 knots)
Water density	$\rho_{water} = 1028\ kg/m^3$
Air density	$\rho_{air} = 1{,}225\ kg/m^3$
Superstructure weight	$165\ kg$
Operator weight	$100\ kg$

Table 1: Boundary conditions analyzed for the meteorological buoy located in the Ionian Sea.

Parameters	*Description*	*Lower Bound [mm]*	*Upper Bound [mm]*	*Step[mm]*
Dmax	Diameter	1500	2000	50

ThkPlateT	Plate Top Thickness	5	20	5
Hcyl	Cylinder Height	800	2000	120
Thkcyl	Cylinder Thickness	5	20	5
Dcone	Lower Cone Diameter	1000	1500	50
Hcone	Cone Height	500	1000	100
ThkPlateB	Plate Bottom Thickness	5	20	5
Dtube	Tail Tube Diameter	200	450	50
Thktube	Tail Tube Thickness	5	20	5
Htube	Tail Tube Height	2000	4500	250
Dmaxball	Ballast Diameter	600	1000	100
Hball	Ballast Height	600	800	400

Table 2: List of parameters and their range value.

5.1 Results

The workflow described in Figure 3 produced about 3000 design solutions. Most of these solutions were feasible. The final optimal solution was selected by studying the designs related to the Pareto front. This curve is achieved when the combination of parameters is such that it is not possible to make improvements to the system. In this condition, it is not possible to improve the condition of one parameter without worsening the condition of another. Among the solutions belonging to the Pareto front, it was selected the solution that minimizes the weight while providing values of ratio Reserve/Volume (R/V) and angle of heel (θ) close to the target values. The optimized marine buoy has a final weight of around 3470 kg, a body diameter of 1950 mm, and a total height of 8940 mm (see the simplified CAD model in Figure 5). This configuration provides a buoyancy volume 3,38 m^3 and a reserve of 2,93 m^3. Table 3 shows the values of the parameters for the optimized solution.

Parameter	Dmax	ThkPlateT	Hcyl	Thkcyl	Dcone	Hcone
Value [mm]	1950	5	1640	5	1300	500

Parameter	ThkPlateB	Dtube	Thktube	Htube	Dmaxball	Hball
Value [mm]	10	200	10	3250	760	700

Table 3: The values of the parameters for the optimized solution.

6 CONCLUSIONS

The approach proposed here is focused on the design optimization of the buoyancy body of a meteorological 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 phase, in which 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 [7] to calculate the buoyancy and the stability at small angles of the heel. A CAD integration was also performed using Autodesk Inventor® to calculate mass and center of gravity. The GA-based approach guides the generation of several design solutions, changing the set of parameters. A final optimal solution has been selected and reported in the case study results. In future development, a Finite Element Method (FEM) analysis and a parametrization of the superstructure will be introduced.

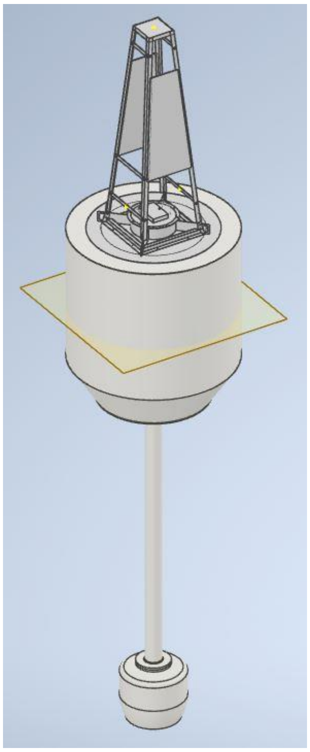

Figure 5: CAD model of the optimized buoy with detail of the waterline plane, placed at 983 mm from the top plate of the cylinder body.

ACKNOWLEDGMENTS

Project ECS 0000024 Rome Technopole, Concession Decree No. 1051 of 23 June 2022 adopted by the Italian Ministry of University and Research, CUP B83C22002820006, Rome Technopole. The authors would like to acknowledge ESTECO software company.

Paolo Cicconi, https://orcid.org/0000-0002-5154-8821
Guido Della Gatta, https://orcid.org/0009-0006-1018-6760
Francesco Menon, https://orcid.org/0009-0003-7267-7002
Sebastiano Giuseppe Paradiso, https://orcid.org/0009-0005-1333-1903
Michele Trovato, https://orcid.org/0000-0003-3068-8005
Nadia Lo Bue, https://orcid.org/0000-0002-5160-941X

REFERENCES

[1] Brahmi, R.; Belhadj, I.; Hammadi, M.; Choley, J.Y.; Aifaoui, N.: Design Requirements Validation Based on MBSE and CAD Models, Design and Modeling of Mechanical Systems – V, 2022; 35–41. http://dx.doi.org/10.1007/978-3-031-14615-2_5.

[2] Canepa, E.; Pensieri, S., Bozzano, R.; Faimali, M.; Traverso, P.; Cavaleri, L.: The ODAS Italia 1 buoy: More than forty years of activity in the Ligurian Sea, Progress in Oceanography, 135, 2015, 48–63

[3] Cicconi, P.; Raffaeli, R.; Marchionne, M.; Germani, M.: A Model-Based Simulation Approach to Support the Product Configuration and Optimization of Gas Turbine Ducts, Computer-Aided Design and Applications, 15(6), 2018, 807–18. http://dx.doi.org/10.1080/16864360.2018.1462564

[4] Copernicus Programme of the European Union, Copernicus Marine Data Store, site accessed in 6th February 2024, https://data.marine.copernicus.eu/products?facets=areas%7EMediterranean+Sea

[5] Hampson, K.: Technical Evaluation of the Systems Modeling Language (SysML), Procedia Computer Science, 44, 2015, 403–12. https://doi.org/10.1016/j.procs.2015.03.054

[6] Harden, B. E.; Renfrew, I. A.; Petersen, G.N.: Meteorological buoy observations from the centralIceland Sea,J. Geophys. Res.Atmos.,120, 2015, 3199–3208, https://doi.org.10.1002/2014JD022584.

[7] IALA, G1099 HYDROSTATIC BUOY DESIGN, https://www.iala-aism.org/product/g1099/

[8] INCOSE, INCOSE Systems Engineering Handbook: A Guide for System Life Cycle Processes and Activities, International Council of Systems Engineering, Cecilia Haskins edition, 2006.

[9] Istituto Idrografico Marina, Atlante delle correnti superficiali dei mari italiani, ISBN 97888II3068, 1982.

[10] Jeong, S.M.; Son, B. H.; Lee, C.Y.: Estimation of the Motion Performance of a Light Buoy Adopting Ecofriendly and Lightweight Materials in Waves. J. Mar. Sci. Eng. 8, 2020, 139. https://doi.org/10.3390/jmse8020139

[11] Krause, D.; Schwede, L.N.; Dambietz, F.M.; Hanna, M.: Model-Based Systems Engineering: Discovering Potentials for Methodical Modular Product Development. Design Methodology for Future Products, 2021, 265–85. http://dx.doi.org/10.1007/978-3-030-78368-6_14

[12] Kristianto, Y.; Helo, P.; Jiao, R. J.: A system-level product configurator for engineer-to-order supply chains, Computers in Industry, 72, 2015, 82-91. http://dx.doi.org/10.1016/j.compind.2015.04.004

[13] Li. B.; Chen, L.; Huang, Z.; Zhong, Y.: Product configuration optimization using a multiobjective genetic algorithm, International Journal of Advanced Manufacturing Technology, 30, 2006, 20–29. https://doi.org/10.1007/s00170-005-0035-8

[14] Meng, X.: Design Method of Product Concept Model Based on CAD Technology, Scientific Programming, 2022, 3605987. http://dx.doi.org/10.1155/2022/3605987

[15] Meussen, B.: On the use of model-based systems engineering and CAD for the design of physical products, Proceedings of the Design Society, 1, 2021, 2317–26. http://dx.doi.org/10.1017/pds.2021.493

[16] Mhenni, F.; Choley, J.Y.; Penas, O.; Plateaux, R.; Hammadi, M.: A SysML-based methodology for mechatronic systems architectural design, Advanced Engineering Informatics, 28(3), 2014, 218–31. http://dx.doi.org/10.1016/j.aei.2014.03.006

[17] Ngatchou, P.; Zarei, A.; El-Sharkawi, A.: Pareto Multi-Objective Optimization. Proceedings of the 13th International Conference on, Intelligent Systems Application to Power Systems. https://doi.org/10.1109/isap.2005.1599245

[18] OMG SysML, OMG Systems Modeling Language. http://www.omgsysml.org/, The Official OMG SysML Site

[19] Park, Y.W.; Kim, T.W.; Kwak, J.S.; Kim, I.K.; Park, J.E.; Ha, K.H.: Design of Korean Standard Modular Buoy Body Using Polyethylene Polymer Material for Ship Safety, Journal of Materials Science and Chemical Engineering, 04(01), 2016, 65–73. http://dx.doi.org/10.4236/msce.2016.41011

[20] Scheer, S.; Bogado, W.H.: A systematic approach to CAD systems customization, Proceedings of Computational Mechanics, Barcelona, Spain, 1998.

[21] Wang, C.; Song, X.; Fu, Q.; Cui, L.; Chen, P: Design and Optimization of PV Power Supply System for Marine Buoys, Journal of Marine Science and Engineering, 11, 2023, 1808. https://doi.org/10.3390/jmse11091808

[22] Wei, W.; Fan, W.; Li, Z.: Multi-objective optimization and evaluation method of modular product configuration design scheme, International Journal of Advanced Manufacturing Technology, 75, 2014, 527–1536. https://doi.org/10.1007/s00170-014-6240-6.

[23] Wei, W.; Liu, A.; Lu, SC-Y.; Wuest, T.: Product Requirement Modeling and Optimization Method Based on Product Configuration Design, Procedia CIRP, 36, 2015, 1–5. http://dx.doi.org/10.1016/j.procir.2015.01.020

[24] Wyrwich, C.; Jacobs, G.; Siebrecht, J.; Konrad, C.: Model-based product configuration of high variety product portfolios, Proceedings of the design society: design conference, 2020, 2435–2444. https://doi.org/10.1017/dsd.2020.287

[25] Zhang, S.W.; Tian, C.; Zhou, F.H.: Design and optimization of buoy mooring with single-point cable for seafloor observatories, Front. Mar. Sci., 9, 2023, 1048048. https://doi.org/10.3389/fmars.2022.1048048