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REVIEW

Design and Analysis of Offshore Wind Turbines: Problem Formulation and Optimization Techniques

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Abstract

Researchers often explore metaheuristic algorithms for their studies. These algorithms possess unique features for solving optimization problems and are usually developed on the basis of real-world natural phenomena or animal and insect behavior. Numerous fields have benefited from metaheuristic algorithms for solving real-world optimization problems. As a renewable energy source, offshore wind energy is a rapidly developing subject of research, attracting considerable interest worldwide. However, designing offshore wind turbine systems can be challenging because of the large space of design parameters and different environmental conditions, and the optimization of offshore wind turbines can be extremely expensive. Nevertheless, advanced optimization methods can help to overcome these challenges. This study explores the use of metaheuristic algorithms in optimizing the design of wind turbines, including wind farm layout and wind turbine blades. Given that offshore wind energy relies more heavily on subsidies than fossil fuel-based energy sources, lowering the costs for future projects, particularly by developing new technologies and optimizing existing methods, is crucial.

Keywords Optimization; Metaheuristic algorithm; Wind Turbine; Design; Wind Turbine Blade

1 Introduction

The importance of climate change and environmental issues is growing as global energy use rises, and thus, the employing of renewable and clean energy sources, such as coastal wind energy, is imperative. Many studies have investigated this field, and coastal wind energy has attracted considerable interest worldwide. Offshore wind turbines are highly considered due to the concentration of populations near coastal areas in most countries. Considerable progress in offshore wind turbine design has been accomplished through the adoption and transfer of offshore wind sources. Offshore wind energy is expected to play an essential role in future energy systems as it does not cause any damaging losses or air pollution. According to a global wind report (Lee and Zhao, 2021), the global wind power volume in 2021 will reach 733 GW. The report considers countries with wind power plants' capacity of over 10 GW, such as the United States, Germany, India, Spain, and the United Kingdom. Offshore wind power technology has made substantial progress, according to current research results. In Europe, wind turbine manufacturers and wind power plant installations have achieved 90% and 75% volumes, respectively. In shallow waters, offshore wind turbines are stabilized by jacket or single-column structures, which is a common foundation, but the use of these structures is limited by geological conditions and water depth. In deep waters, fixing the piers to match a wind turbine design is difficult because of the low natural frequencies, which are closer to the frequencies of overcoming waves. For water depths greater than 50 m, a floating foundation is recommended. Floating Wind Turbines (FWTs) are cost-effective options for such depth because of their low overall cost. These systems are installed far from the shore and are thus not restricted by noise and other regulations. Additionally, FWTs can be used in waters with a depth of up to 700 m because they do not require tall towers and are made of unique construction materials (Hansen, 2006). Henderson et al. (2009) and Wang et al. (2010) discussed technical challenges associated with different types of FWTs. The

Article Highlights

- Offshore wind energy is a rapidly developing subject of research.
- Designing offshore wind turbine systems can be challenging.
- Metaheuristic algorithms help in optimizing the design of wind turbines, including wind farm layout and wind turbine blades.
- Optimization methods can help to overcome these challenges.

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concept of a Floating Offshore Wind Turbine (FOWT) was introduced by Heronemus (1972). Several other FOWT ideas were investigated in the 1990s, including barge or semisubmersible and spar platforms. A spar wind turbine is a vertical cylinder that has a rotor nacelle assembly on top of a tall tower, like an oil and gas platform. A floating foundation ensures that an FWT stands upright in the sea and during towing, offering a high bending arm and high inertial resistance against twisting movements. The efficiency of a wind-float semisubmersible FOWT hull and OC4 was compared under similar control conditions and environmental factors with a simulation program that paired a turbine-floater-mooring system and utilized a 5 MW wind turbine and catenary mooring system (Kim et al., 2017b). Additionally, a semisubmersible floating base with multiple wind turbines was proposed and analyzed using a dynamic analysis tool (Kim et al., 2017a; Jang et al., 2019; Bae and Kim, 2014). Kampitsis et al. (2022) conducted a unified simulation of offshore wind turbines with vibration control systems using Finite Element Analysis-Computational Fluid Dynamics (FEA-CFD). They showed that the extended K-Damper can be used to reduce the vibration of a monopile offshore wind turbine under the combined action of wind and sea wave excitation.

In the offshore oil and gas industry, TLPs are commonly used because they have lower torsion than fixed land wind turbines (Oguz et al., 2018). Barge-type platforms use shallow and wide barges as floating bases but are prone to wave and rotational movements. Although reducing the weight of steel coms in these platforms can greatly lower construction costs, large waves cause movements that can affect the platforms' stability. To minimize the lifter's movement and maintain the stability of a roller, the infrastructure of a floating foundation should be greater than or at least equal to the height of the center above sea level. Tables 1 and 2 present the advantages and disadvantages of fixed and floating foundations, respectively. Growing interest in offshore wind energy has prompted research on optimization methods and overall offshore wind turbine design based on time-domain, static, and frequency-domain analyses. Figure 1 shows the number of publications on optimizing offshore wind turbines. Some optimization algorithms used in optimizing offshore wind turbine design are discussed in this article.

Table 1 Analogy of infrastructures for fixed offshore wind turbines

Type of infrastructure	Benefits	Drawbacks
Jacket	• Can be installed by utilizing suction caissons or piles in average-to-compression sands or firm clays. • An economical option by utilizing a straightforward making procedure. • Can be moved by a barge.	• It may damage native marine ecosystems by allowing the entry of invasive species and changing local water types. • It has high installation and construction costs. • It can kill or injure some marine organisms by using pile drivers.
Monopile	• Does not require seabed preparation. • Suitable for deep and shallow installations of different sizes. • Economical for installations up to 40 m.	• Investigation risks and costs of installation, construction, and transport increscent of large monopiles. • Kill or injure marine organisms sensitive to pressure waves or installation noise. • Monopile foundations are negatively affected by wave, wind, and seismic loading.
Tripod	• Does not require special preparation before installation. • Practical when installed at 45 m depth or deeper. • Durability for the wind turbine.	• May require scrub/friction around the tripod and where bottom flows are significant. • High tripod maintenance and manufacture costs.

Table 2 Different infrastructures for offshore wind turbines

Type of infrastructure	Benefits	Drawbacks
TLP	• Useful in the standard period • Good and related torque and deflection motion • Appropriate for sites deeper than 50 m	• Relatively huge cost of manufacturing • Installation challenges, such as costly anchors and positive tension required in ropes
Barge	• Having reasonable floating and durability • Sizable water plane area • Suitable associated torque and yaw motion • Easy installation by utilizing simple mooring lines • Suitable for sites deeper than 50 m	• Large range of movement • Relatively huge make toll • Challenges in natural frequency
Semisubmersible	• Good durability resulting from small motion • Easy installation • Suitable for sites deeper than 50 m	• Large range of motion • Relatively huge make toll • Challenges in natural frequency
Spar-buoy	• Low cost • Easily installed with mooring categorization • Suitable for sites deeper than 150 m	• Large range of motion • Notably associated torque and deflection motion

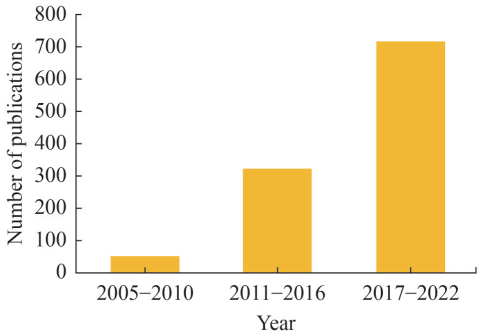


Figure 1 Number of publications about offshore wind turbine optimization

2 Design and optimization of offshore wind turbines

This section explains the design process of offshore wind turbines, covering various fields, such as frequency domain, static, and time domain. Offshore wind turbine structures are classified into three levels: macro, meso, and micro. The macro level deals with geometric dimensions similar to those of buildings or universal duty in structural treatment (Figure 2). The meso level has a specific function in a structural system, and the microlevel has a small geometric size and specialized structural task. The design process involves various steps, such as location selection, wind turbine dimension selection, subsurface consideration, geohazard evaluation, base and support structure selection, extension of design load conditions, and geotechnical and constructive analysis. Figure 3 illustrates the typical process for designing offshore wind turbines.

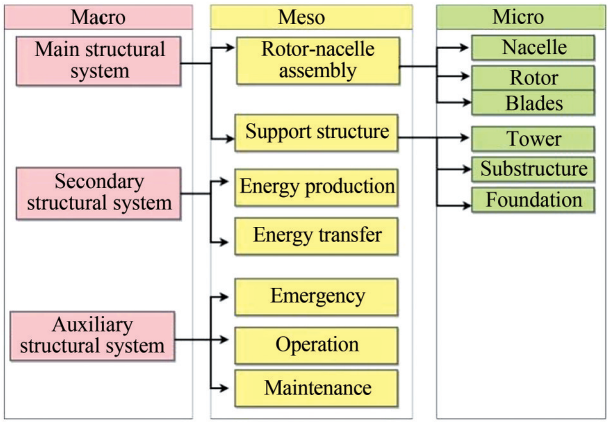


Figure 2 Structural decomposition of an offshore wind turbine. Reproduced with permission from (Bontempi et al., 2008)

2.1 Design method based on static analysis

Optimizing wind turbines is a crucial task that requires accurate finite element models, and static techniques are often used to minimize the weight and maximize the stiffness of offshore structures. These tasks are accomplished by altering a structure's geometry, particularly its thickness and diameter, and preventing system buckling. Uys et al. (2007) optimized a 1 MW turbine by adjusting the number of ring stiffeners and wall thickness variables and prevented buckling; these techniques were used for onshore wind turbines. Chantharasenawong et al. (2011) investigated a 1.0 MW turbine and were able to reduce tower weight by over 20% by increasing the diameter and decreasing the thickness of the section; these methods decreased the bulk factor for buckling failure within a permissible range. In a similar study, Gencturk et al. (2012) designed a 100 kW wind turbine and revealed that centralizing the parameters of a grid tower's transfer line decreased the turbine's weight by approximately 20%. Long and Moe (2012) used static analysis and buckling checks to determine the optimal lower base spacing for a 5 MW offshore wind turbine. Damiani et al. (2013) utilized optimization techniques to investigate a measurement tool for defining the main dimensions and topology of a jacket. van der Giessen (2021) investigated the optimization of the mooring system for FWTs in deep water through static analysis. He examined whether the mooring line specifications of a semi-taut mooring system with drag-embedded anchors for a 12 MW wind turbine supported via a semi-submersible can be optimized in deep water; they performed static analysis on the ultimate limit state scenario.

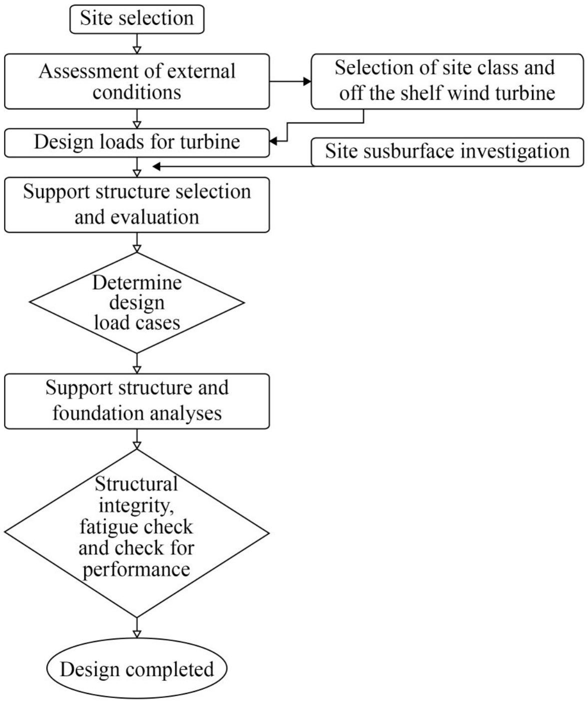


Figure 3 Design of a typical offshore wind turbine (Malhortra, 2011)

2.2 Review of domain analysis as a design method

Time domain techniques are recommended for thorough design assessment based on structural code and design standards. Yoshida (2006) investigated the optimization of the dimensions of a 2 MW onshore steel turbine by using a time domain and Genetic Algorithm (GA). Gutierrez et al. (2017) described the use of the FAST method in optimizing offshore wind turbine design. Ashuri (2012) examined forecasting offshore wind turbine design using optimization methods. Haghi et al. (2014) optimized the support structure of a 3.6 MW offshore wind turbine's monopile, reducing its weight by 12% relative to that of an initial design. Zwick et al. (2012) designed a jacket support structure by using time-domain simulation analysis. Chew et al. (2014, 2015, 2016) used iterative algorithms to compare three- and four-legged structures, and their results showed that the former is superior to the latter as an economic model. Schafhirt et al. (2014) used GA and time-domain analysis and optimized the OC4 jacket support structure; they demonstrated that the GA was slower than the time-domain analysis. Schafhirt et al. (2016) optimized an offshore wind turbine design on the basis of fatigue criteria with a gradient approach, but they did not consider the results of changes in single pipe dimensions. Oest et al. (2017) used a gradient method to optimize the total mass of offshore wind turbines with OC4 casings. Metaheuristic optimization techniques, such as GA, were reviewed by AlHamaydeh et al. (2015, 2017).

Bárcena Pasamontes et al. (2014) used a GA to minimize the weight of the offshore wind turbine and investigate the behavior of OC4 jackets. Chen et al. (2016) obtained an optimal hybrid offshore wind turbine infrastructure by using a Particle Swarm Algorithm (PSO) and time-domain analysis considering fatigue criteria. Cheng and Wang (2008) proposed a technique that utilizes time-domain analysis to identify damage to offshore platform structures.

2.3 Design method based on domain frequency analysis

One of the methods for structural investigation based on time is frequency-domain analysis, which has a low computational cost. Gentils et al. (2017) performed GA and finite element analysis to optimize the weight of a 5 MW offshore wind turbine; they found that stress, vibration, buckling, deformation, and fatigue restricted optimization. Arany et al. (2016) proposed a promising technique for designing monopile foundations on the basis of frequency-domain analysis; it can be used in designing single columns according to essential data, such as site, turbine, and terrain specifications.Thiry et al. (2011) developed a method for the optimization of single-pile steel structures with GA. Van Der Tempel (2006) and Ziegler et al. (2015) expressed a technique to calculate the exhaustion age of offshore wind turbines by utilizing frequency-domain analysis and the method of Dirlik (1985). Long and Moe (2012)investigated the fatigue loads of jacket substructures. Brommundt et al. (2012) utilized a spectral technique to optimize the self-control system of a floating structure.

Michailides and Angelides (2012) and Hall et al. (2013) described the multi-objective method for optimizing floating structures with GA. Dou et al. (2020) proposed a technique for optimizing the design of FWT support structures through frequency-domain analysis and by using analytical gradients; they utilized a four-degree-of-freedom frequency-domain model to understand the dynamic reaction of an FWT under wave and wind loads; their approach that optimized an integrated design including the geometrical features of a floater and mooring system and the coverage of long realizations of many load cases. Oh et al. (2013) performed hydrodynamic load analysis in the frequency domain and assessed the dimensions of a single pile foundation.

3 Issues in the hydrodynamics and aerodynamics of offshore wind turbines

The issue of yield and security in offshore wind turbines is a vital topic that has attracted the attention of researchers in various fields, including hydrodynamics, aerodynamics, structural dynamics, and elasticity. This section focuses on investigating the problems related to hydrodynamics and aerodynamics in the optimization of offshore wind turbines.

Micallef and Rezaeiha (2021) identified the current gaps in knowledge and challenges in the aerodynamics of FOWT rotors by leveraging previous research on fixed rotor aerodynamics. They presented the relationship between FOWT aerodynamics and other related fields in Figure 4. Gao et al. (2022) investigated essential hydrodynamic issues related to wind turbines, such as resource evaluation, wave loads on fixed turbines, rotors for single units and arrays, and floating turbines. For instance, they examined the hydrodynamic behavior of a generic bottom-fixed offshore wind turbine with a large monopile. They found that the installation, maintenance, and decommissioning steps involved specific vessels and components for the tower, which can lead to significant nonlinear hydrodynamics interplay. The density of turbines has increased, which in turn amplifies the aerodynamic interplays between the turbines. The interplays are a result of the farm layout, which is affected by macro/micro siting optimization.

He et al. (2022) introduced the modern optimization method that merges fluid mechanics techniques and mathematical models to investigate the optimal array layout of large offshore wind farms; they suggested a united interposition model explaining the aerodynamic interaction between any two adjacent turbines to determine the maximum power generation. Then, they investigated the variable connection of the layout of wind turbines and the power generation of the system and three various scenarios with equaled and staggered layouts subject to variant wind situations. Their results showed that the maximum power yield of a large-measure offshore wind farm is nearly related to dominant wind orientations. In addition, they concluded that the maximum power production of a wind farm was obtained when the largest number of wind turbines was used; however, the maximum power production of the system was not obtained, and thus, the power production yield of each wind turbine in the system decreased. In Figure 5, the process of calculating the optimal layout of their research is shown.

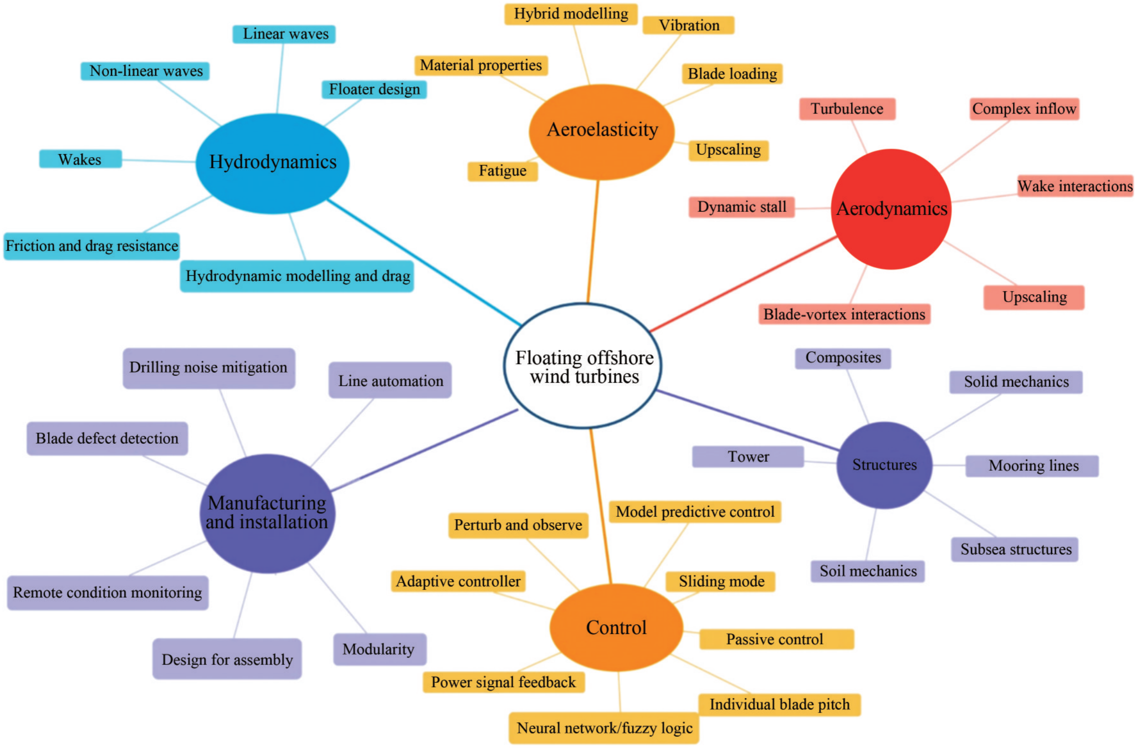


Figure 4 Studies on the circumambient FOWT aerodynamics. Reproduced with permission from (Micallef and Rezaeiha, 2021, Elsevier) © (2021)

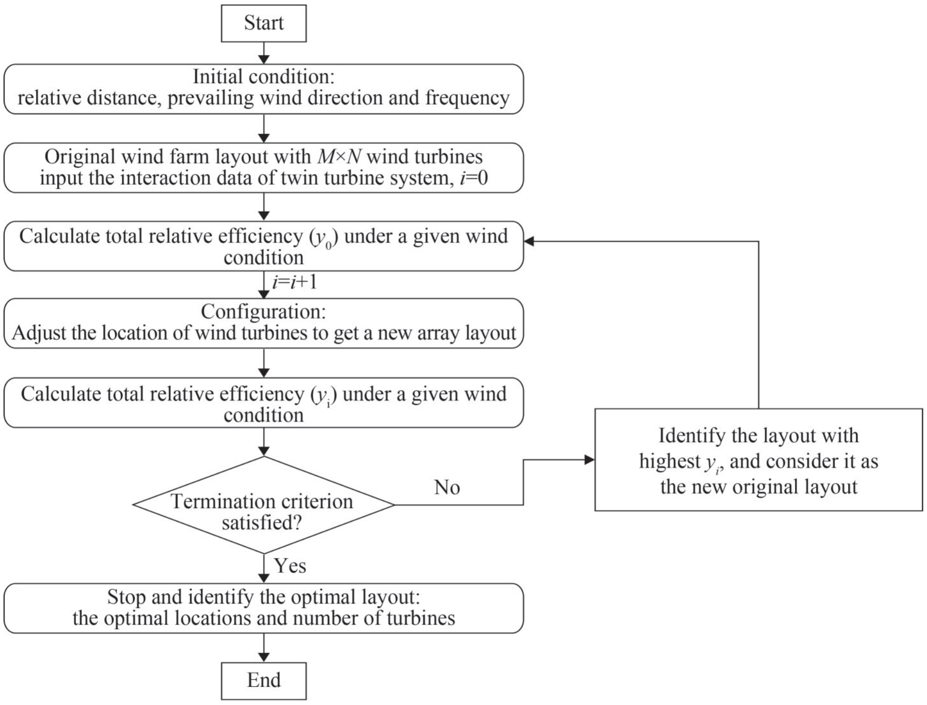


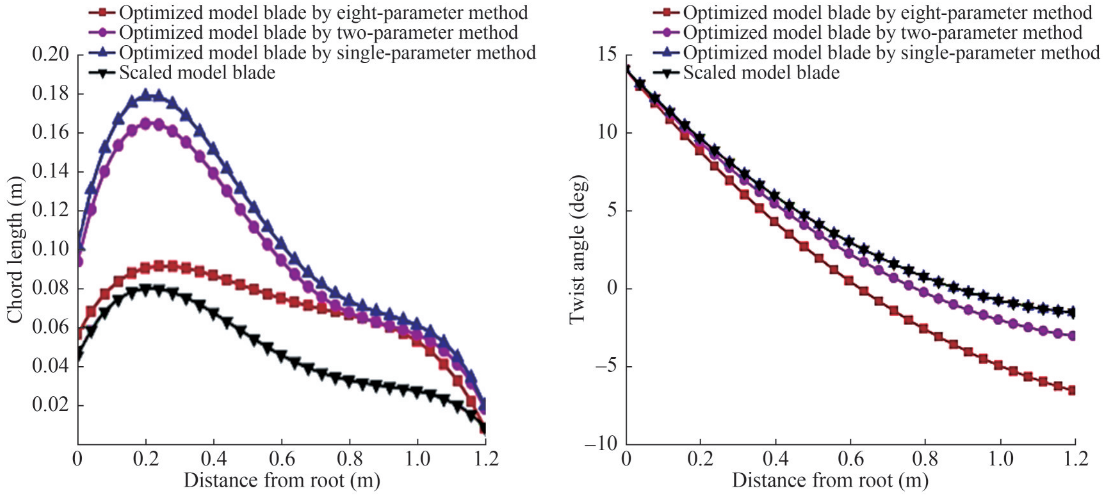
Figure 5 Calculation flowchart of the optimal layout of the wind farms. Reproduced with permission from (He et al., 2022, Elsevier) © (2022)

Chen et al. (2020) proposed four parametric models to describe the geometry of model blades that were combined individually into the optimization model; they utilized high-order redesign techniques for wind turbine blade optimization based on aerodynamic likeness to offset the effects of scale efficacy on the result of model tests for FOWTs; this approach considered aerodynamic similarity in generating an optimized lightweight blade; they concluded that the deflection between the empirical and numerical model blades subject under specific conditions was extremely small (only 3.16%). The model blade with aerodynamic similarity can amend the rotor thrust by 106.33% compared with the Froude-scaled model blade. According to Figures 6 and 7, the chord length of the model blades with aerodynamic similarity increased compared with the scaled model blade, and the major regions are concentrated near the tip of the blade compared with the scaled model blade.

Table 3 lists the main articles about the optimization of FOWT aerodynamics, providing a consolidated survey of research endeavors in the past years.

4 Investigation of optimization algorithms in coastal wind turbine design studies

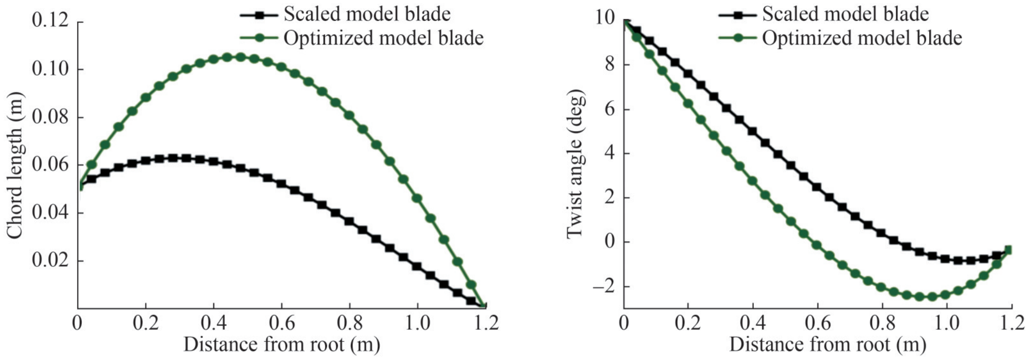
Research on offshore wind turbines is expected to grow because of the development of new optimization algorithms. Artificial intelligence is used in the computing performance–based development of novel algorithms that can incorporate an optimization problem into an optimal solution, greatly improving offshore wind turbine designs. However, various numerical simulation techniques have some shortcomings, especially in terms of dynamic effects on turbines, mooring systems, and hull-containing nonlinear factors subject to wave–hull interactions. Thus, efficient optimization technologies that can reduce computational costs are crucial. One such technology is the accelerated boundary element method, which effectively simulates offshore wind turbines under different field conditions and in environments and reduces computational costs (Willis et al., 2007; Li et al., 2019). Another important topic is the huge computational costs due to the slow convergence of opti-



(a) Distribution of chord length

(b) Distribution of twist angle

Figure 6 Comparison between the optimized and scaled model blades using polynomial curve fitting. Reproduced with permission from (Chen et al., 2020, Elsevier) © (2020)



(a) Distribution of chord length

(b) Distribution of twist angle

Figure 7 Comparison between the optimized and scaled model blades using Bessel curve fitting. Reproduced with permission from (Chen et al., 2020, Elsevier) © (2020)

Table 3 Current articles about the optimization of FOWT aerodynamics

Author (s)	Methodology	Aim/Objective/Focus of study
Shen et al. (2016)	CRAFT	Coupled dynamic motion analysis of an FWT
Liu et al. (2017)	CFD	Extension and validation of a coupled analysis tool
Shen et al. (2018)	FVM	Study of loads and wake unsteadiness
Wen et al. (2018)	Finite volume method (FVM)	Power yield with changing tip velocity ratio and reduced frequency
Rezaeiha and Micallef (2020)	CFD-AD	Study of the impact of a surging rotor on the power performance of a downstream rotor on the basis of their wake interactions
Balty et al. (2020)	Varying Permeability Model (VPM)	Wake flow study with 6DOF motion characterization
Wise and Bachynski (2020)	FAST, CFD	Effects of wake interactions between two FOWTs; the effects of wake meandering investigated under different environmental conditions
Özkan and Genç (2023)	Novel artificial bee colony algorithm based on blade element momentum (ABC-BEM) theory	Aerodynamic design and optimization of a small-scale wind turbine blade
Asadbeigi et al. (2023)	Response surface model (RSM) and Kriging model	A 3D Study of the Darrieus Wind Turbine with Auxiliary Blades
Rizk-Allah and Hassanien (2023)	Equilibrium optimizer (EO) and pattern search (PS) technique	Wind farm layout optimization using different wind speed scenarios

mization algorithms. To address this issue, an improved GA (Vairavamoorthy and Ali, 2005) can be utilized for the optimization of wind turbine designs. This algorithm has a fast convergence speed and accurate and is thus an ideal solution for optimizing wind turbines. Another way to extend design optimization methods, accelerate optimization, and increase accuracy is to replace a complex numerical model and use an approximate model. By training an example through machine learnin, Choe et al. (2021) with an artificial neural network or support vector machine, an approximate model can be obtained. The collection of data used for training is critical for this approximation rather than the use of direct scalar tools. However, access to the data set still limits the use of this technique. The size of the data set is often limited, and the state of the data cannot be ascertained. Therefore, this issue can be addressed without receiving new data through data augmentation, which can increase the diversity and facilitate data measurement. This specification can be helpful to the optimization of offshore wind turbine designs, especially for people lacking experience in this field. Research on deep-water applications should be focused on optimizing the design of mooring systems, and a critical factor is the simultaneous optimization of the restrain line system design and infrastructure according to the kind of moors in the restrain line system, geometry, and the specifications of materials.

Shourangiz-Haghighi et al. (2020) reviewed advances in wind turbine efficiency optimization utilizing CFDs; they reviewed the objective functions to distinguish the efficiency of wind turbines, CFD techniques utilized in the simulation of wind turbines, and optimization algorithms for wind turbine yields. Kale and Varma (2014) conducted an aerodynamic design and optimization of a small horizontal axis wind turbine blade according to the NACA 4412 airfoil specification, and the chord and twist angles were determined from the initially designed blade; optimization was performed to improve power and reduce startup time, and the results showed a 24% reduction in the optimized blade chord and 44% reduction in thickness; the power factor of the optimized vane increased up to 30% relative to that of the normal blade. Karthikeyan et al. (2015) investigated the aerodynamic optimization of the shapes of the blades of a small horizontal-axis wind turbine. Therefore, they optimized the profile of the blades and the geometry of the airfoils and achieved a high-power factor in Re of less than 5×10^5 in the wind turbine; they concluded that changes in the trailing edge and thickness considerable affected noise performance, and the conditions under which the airfoil started working were characterized. Some unique metaheuristic algorithms for offshore wind turbine design have been discussed. In general, optimization algorithms are divided into three categories (Figure 8). Figure 9 shows how some algorithms can address problems in offshore wind turbines.

In the optimization of offshore wind turbines, the selection of a suitable objective function is crucial. Evaluating the easy objective functions is extremely fast but may be imprecise or result in undesirable outcomes; in addition, involved objective functions can be extremely time-consuming. For the optimization of objectives, suitable candidates are as follows:

- Maximization of energy production
- Maximization of profit
- Minimization of the cost of energy

Reducing capital cost is an important duty for designing wind turbines because the utilization and maintenance costs often represent only a small fraction of the capital cost. To reach an aerodynamically effective rotor in wind turbines,

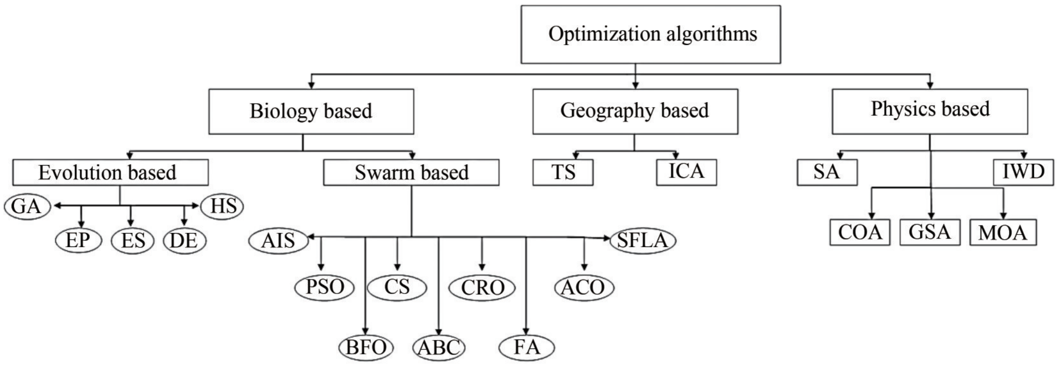


Figure 8 Classification of optimization algorithms

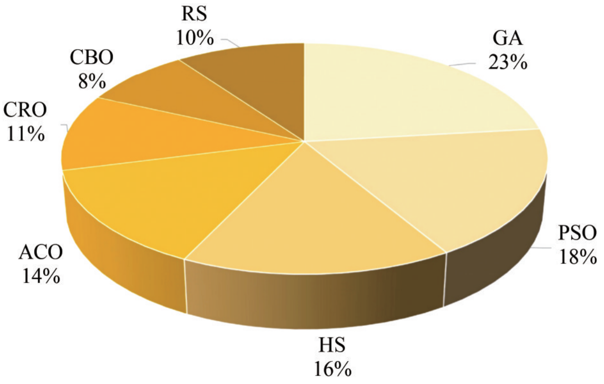


Figure 9 Percentage of using some algorithms in offshore wind turbine optimization according to the number of publications

they should be well designed with a low unit energy production cost. Designing the rotor has an essential role in the total design process of a wind turbine. To optimize the rotor of wind turbines, the objective function is determined as:

$$\text{Minimize } Z = \frac{C_{\text{rotor}}}{\text{AEP}} \tag{1}$$

where the cost of energy of a wind turbine rotor is Z; the total cost for producing, transporting, and erecting a wind turbine rotor is C_{rotor}, and annual energy production is AEP. Thus, the whole cost of a rotor, C_{rotor}, is a self-relative amount determined as follows:

$$C_{\text{rotor}} = b_{\text{rotor}} + (1 - b_{\text{rotor}})W_{\text{rotor}} \tag{2}$$

To calculate AEP, one should combine the possible wind density and power curve. The function of possible density is determined as:

$$f - (V_i < V < V_{i+1})\exp\left(-\left(\frac{V_i}{A}\right)^k\right) - \exp\left(-\left(\frac{V_{i+1}}{A}\right)^k\right) \tag{3}$$

The scale parameter, shape coefficient, and wind speed are denoted as A[-], K[-], and V (m/s), respectively. According to Rayleigh distribution, the shape coefficient K is 2. For example, if a wind turbine operates for 8 760 h per year, its AEP can be assessed as follows:

$$\text{AEP} = \sum_{i=1}^{N-1} \frac{1}{2}\left(P(V_{i+1}) + P(V_i)\right) \cdot \exp\left(-\left(\frac{V_i}{A}\right)^k\right) - \exp\left(-\left(\frac{V_{i+1}}{A}\right)^k\right) \tag{4}$$

where $P(V_i)$ is the power at the wind velocity of V_i. The power P can be calculated as follows:

$$P = \frac{1}{2}\dot{m}V_0^2 = \frac{1}{2}\rho A_0 V_0^3 \tag{5}$$

The mass flow rate, wind velocity, air density, and wind space are denoted as $\dot{m}, V_0$, ρ, and A_0, respectively. The geometry of the blade should be displayed for the reliable optimization of a wind turbine blade, and many design variables are needed. For the control of the rotor form, airfoil specifications, rotational velocity, and pitch angle, the design variables are selected. The constraints of the design variables are as follows:

$$X_{i,\min} \leqslant X_i \leqslant X_{i,\max},\ i = 1, 2, 3 \tag{6}$$

where $X_{i,\min}$ is the lower limit, and $X_{i,\max}$ is the upper limit for the chord, twist angle, and relative thickness of the blade, respectively (Eke and Onyewudiala, 2010).

4.1 Genetic algorithm

GAs are used to optimize the designs of offshore wind turbines, particularly for electrical connections and location selection. Häusler and Owman (2002) utilized a GA to optimize the electrical connection design of offshore wind farms. Zhao et al. (2004, 2006, 2009) used a GA to explore a similar issue for wind farm shape optimization. Chen et al. (2008) investigated the application of a GA in electrical system optimization for offshore wind farms. The reliability of collection systems has been the focus of some studies

(Yang et al., 2009). For a large offshore wind farm, Huang et al. (2009) optimized an electrical connection design by utilizing a GA. Lee et al. (2010) utilized a GA to maximize the energy density that meets the maximum distance from the shoreline and the criteria of maximum water depth of offshore wind turbines.

Gonzalez-Longatt et al. (2011) optimized the electrical grid design of large offshore wind farms by using an improved GA. Hall et al. (2013) optimized FOWT infrastructure by using the frequency-domain model efficiency of the FOWT to movements in six degrees of freedom and used a GA for local optimization. In 2013, Polat and Tuncer (2013) optimized the aerodynamic shapes of the blades of a 1 MW Nordtank horizontal axis wind turbine to maximize power generation with a GA; they based their studies on the movement range of a blade element and considered a certain speed for the wind and the speed and diameter of the rotor, using a specific number of blades for the rotor; the optimal distribution of the chord and twist angle of the airfoils that consisted the blades was due to the optimal geometry of the turbine blades, and the annual power production increased by 10%. To optimize the design of OC4-type support jacket structures, Bárcena Pasamontes et al. (2014) utilized a GA; each project for the load in the time domain with a complete wind turbine model was analyzed .

Pillai et al. (2016) used a GA to optimize an offshore wind farm and determine positions where turbines may be placed. Gentils et al. (2017) performed coupled parametric finite element analysis and used GA to optimize the elements of support structures, such as grouts, monopiles, transmission parts, and towers. Based on MATLAB programming, a method using GA for the optimal design of horizontal axis wind turbine blade structure was proposed by Bagherpoor and Xuemin (2017). Karimi et al. (2017) optimized FWTs with three fixed classes of spars and FWT infrastructure with a GA. Ahmadpour (2021) investigated wind efficiency with a minor horizontal axis by using the NSGII algorithm. The design of cylindrical floating hulls for the floating substructures of offshore wind turbines was optimized by Benifla and Adam (2022). Kirchner-Bossi and Porté -Agel (2024) conducted a study on the optimization of the power density (PD) in wind farms and analyzed its sensitivity to the available area size. They introduced a novel GA that optimizes PD and turbine layout. The algorithm is self-adaptive to the PD and the diversity of solutions. Table 4 lists some studies on the use of GA in wind turbine optimization between 2005 and 2021.

Table 4 Some studies on the use of genetic algorithms in wind turbine optimization

Author (s)	Subject
Grady et al. (2005)	Placement of wind turbines using genetic algorithm
Jureczko et al. (2005)	Optimization of wind turbine blades
Zhao et al. (2009)	Utilizing GA for optimization of the electrical system of offshore wind farms
Wan et al. (2009)	Optimal micrositing of wind turbines by GA based on improved wind and turbine models
Bilbao and Alba (2009)	SA for Optimization of Wind Farm Annual Profit
Emami and Noghreh (2010)	A new approach to optimization in the placement of wind turbines within wind farms by GA
González et al. (2010)	Using EA for optimization of wind farm turbines layout
Wang et al. (2011)	Improved non-dominated sorting genetic algorithm (NSGA)-II in multi-objective optimization studies of wind turbine blades
Ribeiro et al. (2012)	An airfoil optimization technique for wind turbines
Chen et al. (2013)	Using GA with different hub height wind turbines for the optimization of wind farm layout
Gao et al. (2015)	Optimization of wind turbine layout in Hong Kong, China, by using GA
Gentils et al. (2017)	Integrated structural optimization of offshore wind turbine support structures based on FEM and GA
Chan et al. (2018)	Blade shape optimization of the Savonius wind turbine using a genetic algorithm
Abdelsalam and El-Shorbagy (2018)	Optimization of wind turbines sitting in a wind farm using GA-based local search
Ju and Liu (2019)	Wind farm layout optimization using self-informed GA with information-guided exploitation
Civelek (2020)	Optimization of fuzzy logic (Takagi-Sugeno) blade pitch angle controller in wind turbines by GA
Pourrajabian et al. (2021)	Design and optimization of horizontal axis wind turbine (HAWT) blades by genetic algorithms
Liu et al. (2021)	Layout optimization of an offshore wind farm under actual seabed terrain encountering an engineering cost model by using GA
Benifla and Adam (2022)	Development of a genetic algorithm code for the design of cylindrical buoyancy bodies for floating offshore wind turbine substructures
Kirchner-Bossi and Porté-Agel (2024)	Using a novel self-adaptive genetic algorithm to optimize wind farm power density based on the area size

4.2 Sequential quadratic programming (SQP)

Optimizing the design of offshore wind turbines requires several nonlinear variables and equations. The objective function of nonlinear programming problems has conditions or nonlinear functions. Compared with linear programming problems, linear programming problems are much more complicated. The SQP algorithm, which is the most efficient technique for solving constrained nonlinear optimization problems, optimizes the designs of wind turbine blades. Kenway and Martins (2008) applied SQP to optimize blade shapes. The combined algorithm of GA and gradient-based method has been used in the optimization of thick wind turbine airfoils, 3D aerodynamic shapes, complex design in CFD (Foster and Dulikravich, 1997), and airfoil foil design (Vicini and Quagliarella, 1999). Bizzarrini et al. (2011) used a hybrid algorithm based on gradient algorithms, such as SQP and the GA, to optimize wind turbine airfoils. The SQP convergence method for wind turbine performance optimization was investigated by Ning and Petch (2016). Schröder et al. (2016) investigated damage localization in wind turbine support structures by updating the finite element model and using SQP.

4.3 Particle swarm algorithm

Liao et al. (2009) optimized wind turbine blades with an improved PSO algorithm; according to the results obtained between optimal and non-optimal blades, they concluded that this method is suitable for offshore wind turbine systems. To decrease wind turbine costs, they also investigated the minimum blade mass by utilizing an improved PSO algorithm with the FAST program (Liao et al., 2012). Wan et al. (2010) introduced PSO to solve the wind turbine location problem and ensure that this algorithm has a set of particles in the solution area, each of which shows the order of the turbine; during the progress of the group, each particle randomly moved in optimal coordinates. In another study, to reclaim the performance of PSO, they described a Gaussian particle swarm with a local differential search technique (Wan et al., 2012).

Chowdhury et al. (2013) concluded that using turbines with optimized hub height, the PSO algorithm can increase the normalized output power. Si et al. (2013) optimized offshore wind turbine blades by PSO. The pitch angle distribution along the blade span and chord length were optimized in specific wind conditions to recover the aerodynamic performance. The location of wind turbines in a large-scale wind farm by utilizing PSO was optimized by Hou et al. (2015). Chehouri et al. (2015) focused on maximizing energy production in a certain period (of the order of one year) and the spectrum of wind speed (not just a specific speed) and provided an overview of optimization techniques and strategies; they compared different algorithms and compared multi-objective optimization results (PSO and GA) and the results of the CFD solution. In this research, energy cost was minimized, electricity production was maximized, blade mass was reduced, and a suitable model for optimizing wind turbine performance was presented. To design the jacket infrastructure of a 5 MW turbine, Häafele and Rolfes (2016) proposed a general PSO-based method with some modifications; the method decreased the operational costs of offshore wind turbines.

Hou et al. (2017) proposed an integrated optimization method that simultaneously optimized the locations of FWTs and offshore substations and cable coupling configuration; they utilized a mixed integer particle swarm optimization algorithm to minimize the levelized production cost of the wind farm, and the results showed that the proposed approach can decrease the levelized production cost by 5.00%; they determined that the approach was better than the usual technique, which only achieved a 1.45% levelized production cost decreation but increased energy efficiency by 3.95%. By utilizing PSO and FAST programs, a time domain calculation model and hybrid optimization design method for wind turbine blades were developed by Ma et al. (2019). Shin et al. (2020) investigated the solution to the turbine arrangement problem in offshore wind farms by using a metamodel and EA/PSO. A foundation's effectiveness affects the energy performance of wind farms as the sizes of the wind farms increase. The behavior of wind turbines affects costs and contributes to losses due to reduced energy production. Song et al. (2023) developed a particle swarm optimization–based method capable of globally optimizing a farm layout. This method considered yaw angles for various wind speeds and directions in large-scale nonconvex joint optimization.

4.4 Other algorithms

Similar to PSO and GA, ant colony optimization and coral reef optimization use bio-inspired optimization methods (Salcedo-Sanz et al., 2014). Pouladi et al. (2013) selected an optimal location for a wind turbine farm by utilizing an improved ant colony algorithm; the performance of the proposed method contributed to the optimal localization of turbine farms. By using a developed RS algorithm, Feng and Shen (2017) examined the design optimization of offshore wind farms with different kinds of wind turbines.

Kaveh and Sabeti (2018) used the Colliding Body Algorithm (CBO) to investigate the supporting frame of offshore wind turbines. By utilizing the optimization method, the weight of the construction was decreased by about 50%. By utilizing the quantum particle swarm optimization algorithm, Furlanetto et al. (2020) minimized the weight of tubular steel towers of wind turbines. They used continuous design variables. Using three algorithms (NSGA-II, PESA-II, and NSGA-III), Mellal and Pecht (2020) proposed the identification and optimization of acceptable solutions with multi-objective wind turbine design; they aimed to minimize energy expenditure and maximize nominal power according to the limitations of the structure design, considering the radius of the rotor and the height of the hub. Settoul et al. (2021) used a salp swarm algorithm and addressed problems in the optimal placement of wind turbines on the basis of decreasing active power loss in the power broadcasting network of Constantine City.

Structural design for wind turbines can be categorized into two fields: robust optimization design and probabilistic design. Robust optimization design refers to the optimization of wind turbine structures under certain constraints in the structure's performance. By contrast, probabilistic design deals with structural design issues related to variables and parameters that may cause possible problems. While robust optimization methods are commonly used in offshore wind turbine design, there are few studies on probabilistic design for offshore wind turbine support structures. Yang et al. (2015) proposed a practical method for design optimization based on reliability for offshore wind turbine substructures subject to dynamic response. Jin et al. (2018) utilized an artificial fish swarming algorithm to optimize the mass damper parameters of FWTs. They investigated the performance of the mass damper location on loads of key components of FWT, vibration control, and the displacements of FWT. Stieng and Muskulus (2020) described a general method that integrates the use of analytical gradients as reliability-based design optimization methods. This article separated the nondeterministic response of the offshore wind turbine into two parts: probabilistic and deterministic. Furthermore, this method separates the reliability analysis from the design optimization function as a computational method to decrease the high computational cost of this factorization. Hajinezhad Dehkharghani et al. (2021) combined a nonprobabilistic method with artificial neural networks to detect damage to an FWT.

In 2015, Wang et al. (2015) proposed a method for post-optimality sensitivity analysis in multi-objective robust optimization problems. They introduced two robustness indexes, named IRS and IRL. The design parameters were divided into two types: DVs and DEPs. DVs are controllable parameters, in contrast to DEPs. The IRS determines the robustness of multi-objective optimization problems against small differences in DVs and DEPs. The IRL determines the robustness of multi-objective optimization problems against large differences in DEPs. He et al. (2022) proposed a progressive optimization technique that utilizes mathematical models and fluid mechanics approaches to analyze the optimal arrangement of offshore wind farms; they suggested using an integrated interference model to maximize power generation and considered the aerodynamic interaction between any two near turbines; they then studied the effect of the layout of wind turbines and the power generation of the system. Furthermore, they conducted a sensitivity analysis to evaluate the impact of multiple dominant wind directions on the power yield of wind farms.

Lumbreras et al. (2015) introduced a new approach that combines ordinal optimization and mixed-integer programming to efficiently solve large-scale problems with a statistical optimality guarantee; they applied this algorithm to a case study of the Barrow offshore wind farm in the East Irish Sea.

Pérez-Rúa et al. (2022) introduced an optimization framework for the global optimization of the cable layout topology for offshore wind farms; the framework was designed to compare closed-loop and radial layouts for the collection system of OWFs. They have used a two-stage stochastic optimization program based on a mixed-integer linear programming model; for the radial layout, they used a hop-indexed full binary model. The objective function allows the simultaneous optimization of three factors: (i) initial investment (network topology and cable sizing), (ii) total electrical power loss costs, and (iii) operation costs resulting from energy curtailment due to cable failures; the results indicate that (i) the profitability of each topology type depends heavily on the project size and wind turbine rating. Closed-loop systems may offer a competitive solution for large-scale projects subjected to considerable energy curtailment. (ii) The stochastic model presents difficulties when dealing with large-scale instances, requiring increased computing time and memory resources. (iii) Strategies must be implemented to simplify the mathematical models used in stochastic optimization for modern offshore wind farms, either analytically or numerically.

Göçmen et al. (2019) used the PossPOW algorithm, which uses only 1 Hz turbine data as inputs and provides an estimate of possible power outputs; it was trained and validated in Thanet and Horns Rev-I offshore wind farms under nominal operations, where the turbines followed the optimum power curve; the findings indicated that the exceptional performance of the algorithm; in the Horns Rev-I wind farm, the more than 70% of the strict power system requirements were met for a 24 h data set on which the algorithm was evaluated. Geng et al. (2021) proposed a graph neural network for offshore wind speed prediction and named it the spatiotemporal correlation graph neural network.

5 Conclusions

The objective of optimization algorithms based on natural and biological processes is to efficiently solve problems and find appropriate solutions. This paper elaborates on the various metaheuristic algorithms used in optimizing the designs of offshore wind turbines. The use of metaheuristic algorithms for structural optimization is a rapidly growing field and has considerably improved the designs of offshore wind turbines. The results suggest that metaheuristic algorithms are effective in optimizing the design and development process of offshore wind turbines.

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References

Abdelsalam AM, El-Shorbagy M (2018) Optimization of wind turbines siting in a wind farm using genetic algorithm based local search. Renewable Energy 123: 748-755. https://doi.org/10.1016/j.renene.2018.02.083

Ahmadpour F (2021) Multi objective optimization of performance of small size horizontal axis wind turbine based on NSGA-II. Journal of Mechanical Engineering 50(4(93)): 171-180

AlHamaydeh M, Barakat S, Nasif O (2017) Optimization of Support Structures for Offshore Wind Turbines Using Genetic Algorithm with Domain-Trimming. Mathematical Problems in Engineering 5978375. https://doi.org/10.1155/2017/5978375

AlHamaydeh MH, Barakat SA, Nassif OM (2015) Optimization of quatropod jacket support structures for offshore wind turbines subject to seismic loads using genetic algorithms. Proceedings of the 5th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering, COMPDYN 2015. 3505-3513, http://doi.org/10.7712/120115.3634.1443

Arany L, Bhattacharya S, Macdonald JHG, Hogan SJ (2016) Closed form solution of Eigen frequency of monopile supported offshore wind turbines in deeper waters incorporating stiffness of substructure and SSI. Soil Dynamics and Earthquake Engineering 83: 18-32. https://doi.org/10.1016/j.soildyn.2015.12.011

Asadbeigi M, Ghafoorian F, Mehrpooya M, Chegini S, Jarrahian A (2023) A 3D study of the darrieus wind turbine with auxiliary blades and economic analysis based on an optimal design from a parametric investigation. Sustainability 15(5): 4684. https://www.mdpi.com/2071-1050/15/5/4684

Ashuri T (2012) Beyond classical upscaling: integrated aeroservoelastic design and optimization of large offshore wind turbines. Delft: Delft University of Technology

Bae YH, Kim MH (2014) Coupled dynamic analysis of multiple wind turbines on a large single floater. Ocean Engineering 92: 175-187. https://doi.org/10.1016/j.oceaneng.2014.10.001

Bagherpoor T, Xuemin L (2017) Structural optimization design of 2MW composite wind turbine blade. Energy Procedia 105: 1226-1233. https://doi.org/10.1016/j.egypro.2017.03.420

Balty P, Caprace D-G, Waucquez J, Coquelet M, Chatelain P (2020) Multiphysics simulations of the dynamic and wakes of a floating Vertical Axis Wind Turbine. Journal of Physics: Conference Series. IOP Publishing, 1618:062053. http://org.doi/10.1088/1742-6596/1618/6/062053

Bárcena Pasamontes L, Gómez Torres F, Zwick D, Schafhirt S, Muskulus M (2014) Support structure optimization for offshore wind turbines with a genetic algorithm. International Conference on Offshore Mechanics and Arctic Engineering. American Society of Mechanical Engineers, V09BT09A033. https://doi.org/10.1115/OMAE2014-24252

Benifla V, Adam F (2022) Development of a genetic algorithm code for the design of cylindrical buoyancy bodies for floating offshore wind turbine substructures. Energies 15(3): 1181. https://www.mdpi.com/1996-1073/15/3/1181

Bilbao M, Alba E (2009) Simulated annealing for optimization of wind farm annual profit. 2009 2nd International symposium on logistics and industrial informatics. Piscataway:IEEE, 1-5

Bizzarrini N, Grasso F, Coiro DP (2011) Genetic algorithms in wind turbine airfoil design. EWEA, EWEC2011, Bruxelles, Belgium. ECN-M-11-035

Bontempi F, Li H, Petrini F, Gkoumas K (2008) Basis of design of offshore wind turbines by system decomposition. Proceedings of the 4th International Conference on Advances in Structural Engineering and Mechanics, Jeju, Korea. 26-28

Brommundt M, Krause L, Merz K, Muskulus M (2012) Mooring system optimization for floating wind turbines using frequency domain analysis. Energy Procedia 24: 289-296. https://doi.org/10.1016/j.egypro.2012.06.111

Chan CM, Bai HL, He DQ (2018) Blade shape optimization of the Savonius wind turbine using a genetic algorithm. Applied Energy 213: 148-157. https://doi.org/10.1016/j.apenergy.2018. 01.029

Chantharasenawong C, Jongpradist P, Laoharatchapruek S (2011) Preliminary design of 1.5-MW modular wind turbine tower. The 2nd TSME International Conference on Mechanical Engineering, Krabi, Thailad.Citeseer.AEC17

Chehouri A, Younes R, Ilinca A, Perron J (2015) Review of performance optimization techniques applied to wind turbines. Applied energy 142: 361-388. https://doi. org/10.1016/j. apenergy.2014.12.043

Chen WC, Nguyen MH, Chiu WH, Chen TN, Tai PH (2016) Optimization of the plastic injection molding process using the Taguchi method, RSM, and hybrid GA-PSO. The International Journal of Advanced Manufacturing Technology 83(9): 1873-1886. https://doi.org/10.1007/s00170-015-7683-0

Chen Y, Li H, Jin K, Song Q (2013) Wind farm layout optimization using genetic algorithm with different hub height wind turbines. Energy Conversion and Management 70: 56-65. https://doi.org/10.1016/j.enconman.2013.02.007

Chen Z, He Y, Zhao Y, Meng L, He C, Yang H, Han Z, Liu Y (2020) High-order redesign method for wind turbine blade optimization in model test considering aerodynamic similarity. Ocean Engineering 202: 107156. https://doi.org/10.1016/j.oceaneng.2020. 107156

Chen Z, Zhao M, Blaabjerg F (2008) Application of genetic algorithm in electrical system optimization for offshore wind farms. Proceedings of the 3rd International Conference on Electric Utility Deregulation and Restructuring and Power Technologies. Piscataway: IEEE

Cheng YS, Wang Z (2008) Detecting damage to offshore platform structures using the time-domain data. Journal of Marine Science and Application 7(1): 7-14. https://doi. org/10.1007/s11804-008-7046-z

Chew KH, Tai K, Ng EYK, Muskulus M (2015) Optimization of offshore wind turbine support structures using an analytical gradient-based method. Energy Procedia 80: 100-107. https://doi.org/10.1016/j.egypro.2015.11.412

Chew KH, Tai K, Ng EYK, Muskulus M (2016) Analytical gradient-based optimization of offshore wind turbine substructures under fatigue and extreme loads. Marine Structures 47: 23-41. https://doi.org/10.1016/j.marstruc.2016.03.002

Chew KH, Ng E, Tai K, Muskulus M (2014) Offshore wind turbine jacket substructure: A comparison study between four-legged and three-legged designs. J. Ocean Wind Energy 1(2): 74-81

Choe DE, Kim HC, Kim MH (2021) Sequence-based modeling of deep learning with LSTM and GRU networks for structural damage detection of floating offshore wind turbine blades. Renewable Energy 174: 218-235. https://doi.org/10.1016/j.renene.2021.04.025

Chowdhury S, Zhang J, Messac A, Castillo L (2013) Optimizing the arrangement and the selection of turbines for wind farms subject to varying wind conditions. Renewable Energy 52: 273-282. https://doi.org/10.1016/j.renene.2012.10.017

Civelek Z (2020) Optimization of fuzzy logic (Takagi-Sugeno) blade pitch angle controller in wind turbines by genetic algorithm. Engineering Science and Technology, an International Journal 23(1): 1-9. https://doi.org/10.1016/j.jestch.2019.04.010

Damiani RR, Song H, Robertson AN, Song H (2013) Assessing the importance of nonlinearities in the development of a substructure model for the wind turbine CAE tool FAST. International Conference on Offshore Mechanics and Arctic Engineering. American Society of Mechanical Engineers, V008T009A093

Dirlik T (1985) Application of computers in fatigue analysis. Coventry: University of Warwick

Dou S, Pegalajar-Jurado A, Wang S, Bredmose H, Stolpe M (2020) Optimization of floating wind turbine support structures using frequency-domain analysis and analytical gradients. Journal of Physics: Conference Series. 1618(4): 042028, https://doi.org/10.1088/1742-6596/1618/4/042028

Eke G, Onyewudiala J (2010) Optimization of wind turbine blades using genetic algorithm. Global Journal of Researches in Engineering 10(7): 22-26

Emami A, Noghreh P (2010) New approach on optimization in placement of wind turbines within wind farm by genetic algorithms. Renewable Energy 35(7): 1559-1564. https://doi.org/10.1016/j.renene.2009.11.026

Feng J, Shen WZ (2017) Design optimization of offshore wind farms with multiple types of wind turbines. Applied Energy 205: 1283-1297

Foster NF, Dulikravich GS (1997) Three-dimensional aerodynamic shape optimization using genetic and gradient search algorithms. Journal of Spacecraft and Rockets 34(1): 36-42

Furlanetto A, Gomes HM, de Almeida FS (2020) Design optimization of tapered steel wind turbine towers by QPSO algorithm. International Journal of Steel Structures 20(5): 1552-1563. https://doi.org/10.1007/s13296-020-00389-3

Gao X, Yang H, Lin L, Koo P (2015) Wind turbine layout optimization using multi-population genetic algorithm and a case study in Hong Kong offshore. Journal of Wind Engineering and Industrial Aerodynamics 139: 89-99. https://doi.org/10.1016/j.jweia. 2015.01.018

Gao ZT, Feng XY, Zhang ZT, Liu ZL,Gao XX, Zhang LJ, Li S, Li Y (2022) A brief discussion on offshore wind turbine hydrodynamics problem. Journal of Hydrodynamics 34(1): 15-30. https://doi.org/10.1007/s42241-022-0002-y

Gencturk B, Attar A, Tort C (2012) Optimal Design of Lattice Wind Turbine Towers. Proceedings of the 15th World Conference on Earthquake Engineering, Lisbon, Portugal. https://doi.org/10.13140/2.1.1976.9924

Geng X, Xu L, He X, Yu J (2021) Graph optimization neural network with spatio-temporal correlation learning for multi-node offshore wind speed forecasting. Renewable Energy 180: 1014-1025. https://doi.org/10.1016/j.renene.2021.08.066

Gentils T, Wang L, Kolios A (2017) Integrated structural optimisation of offshore wind turbine support structures based on finite element analysis and genetic algorithm. Applied Energy 199: 187-204. https://doi.org/10.1016/j.apenergy.2017.05.009

Göçmen T, Giebel G, Poulsen NK, Sørensen PE (2019) Possible power of down-regulated offshore wind power plants: The PossPOW algorithm. Wind Energy 22(2): 205-218. https://doi.org/10.1002/we.2279

Gonzalez-Longatt FM, Wall P, Regulski P, Terzija V (2011) Optimal electric network design for a large offshore wind farm based on a modified genetic algorithm approach. IEEE Systems Journal 6(1): 164-172. https://doi.org/10.1109/JSYST.2011.2163027

González JS, Rodriguez AGG, Mora JC, Santos JR, Payan MB (2010) Optimization of wind farm turbines layout using an evolutive algorithm. Renewable Energy 35(8): 1671-1681. https://doi.org/10.1016/j.renene.2010.01.010

Grady S, Hussaini MY, Abdullah MM (2005) Placement of wind turbines using genetic algorithms. Renewable Energy 30(2): 259-270. https://doi.org/10.1016/j.renene.2004.05.007

Gutierrez W, Ruiz-Columbie A, Tutkun M, Castillo L (2017) Impacts of the low-level jet's negative wind shear on the wind turbine. Wind Energy Science 2(2): 533-545. https://doi.org/10.5194/wes-2-533-2017

Häafele J, Rolfes R (2016) Approaching the ideal design of jacket substructures for offshore wind turbines with a Particle Swarm Optimization algorithm. ISOPE International Ocean and Polar Engineering Conference. ISOPE, ISOPE-I-16-143

Haghi R, Ashuri T, van der Valk PL, Molenaar DP (2014) Integrated multidisciplinary constrained optimization of offshore support structures. Journal of Physics: Conference Series. IOP Publishing, 55:012046. https://doi.org/10.1088/1742-6596/555/1/012046

Hajinezhad Dehkharghani P, Ettefagh MM, Hassannejad R (2021) Mooring damage identification of floating wind turbine using a non-probabilistic approach under different environmental conditions. Journal of Marine Science and Application 20: 156-169. https://doi.org/10.1007/s11804-020-00187-7

Hall M, Buckham B, Crawford C (2013) Evolving offshore wind: A genetic algorithm-based support structure optimization framework for floating wind turbines. 2013 MTS/IEEE OCEANS-Bergen. Piscataway:IEEE, 1-10

Hansen B (2006) Floating wind turbines expand renewable energy possibilities. Civil Engineering Magazine Archive 76(2): 30-30. https://doi.org/10.1061/ciegag.0000893

Häusler M, Owman F (2002) AC or DC for connecting offshore wind farms to the transmission grid?

He F, Wagner M, Zhang L, Shao C, Xu W, Chen W, Yan Y, Li Y (2022) A novel integrated approach for offshore wind power optimization. Ocean Engineering 266: 112827. https://doi.org/10.1016/j.oceaneng.2022.112827

Henderson AR, Witcher D, Morgan CA (2009) Floating support structures enabling new markets for offshore wind energy. Proceedings of the European Wind Energy Conference (EWEC), Marseille, France

Heronemus WE (1972) The United States energy crisis: some proposed gentle solutions. Joint Meeting of the Local Section of The American Society of Mechanical Engineers and The Institute of Electrical and Electronics Engineers, West Springfield, Mass

Hou P, Hu W, Soltani M, Chen C, Chen Z (2017) Combined optimization for offshore wind turbine micro siting. Applied Energy 189: 271-282. https://doi.org/10.1016/j.apenergy.2016.11.083

Hou P, Hu W, Soltani M, Chen Z (2015) Optimized placement of wind turbines in large-scale offshore wind farm using particle swarm optimization algorithm. IEEE Transactions on Sustainable Energy 6(4): 1272-1282. https://doi.org/10.1109/TSTE.2015.2429912

Huang L, Fu Y, Guo X (2009) Optimization of electrical connection scheme for large offshore wind farm with genetic algorithm. 2009 International Conference on Sustainable Power Generation and Supply. Piscataway: IEEE, 1-4

Jang HK, Park S, Kim MH, Kin KH, Hong K (2019) Effects of heave plates on the global performance of a multi-unit floating offshore wind turbine. Renewable Energy 134: 526-537. https://doi.org/10.1016/j.renene.2018.11.033

Jin X, Xie S, He J, Lin Y, Wang Y, Wang N (2018) Optimization of tuned mass damper parameters for floating wind turbines by using the artificial fish swarm algorithm. Ocean Engineering 167: 130-141. https://doi.org/10.1016/j.oceaneng.2018.08.031

Ju X, Liu F (2019) Wind farm layout optimization using self-informed genetic algorithm with information guided exploitation. Applied Energy 248: 429-445. https://doi.org/10.1016/j.apenergy.2019.04.084

Jureczko M, Pawlak M, Mężyk A (2005) Optimisation of wind turbine blades. Journal of Materials Processing Technology 167(2-3): 463-471. https://doi.org/10.1016/j.jmatprotec.2005.06.055

Kale SA, Varma RN (2014) Aerodynamic design of a horizontal axis micro wind turbine blade using NACA 4412 profile. International Journal of Renewable Energy Research 4(1): 69-72. https://doi.org/10.20508/ijrer.06222

Kampitsis A, Kapasakalis K, Via-Estrem L (2022) An integrated FEA-CFD simulation of offshore wind turbines with vibration control systems. Engineering Structures 254: 113859. https://doi.org/10.1016/j.engstruct.2022.113859

Karimi M, Hall M, Buckham B, Crawford C (2017) A multi-objective design optimization approach for floating offshore wind turbine support structures. Journal of Ocean Engineering and Marine Energy 3(1): 69-87. https://doi.org/10.1007/s40722-016-0072-4

Karthikeyan N, Murugavel KK, Kumar SA, Rajakumar S (2015) Review of aerodynamic developments on small horizontal axis wind turbine blade. Renewable and Sustainable Energy Reviews 42: 801-822. https://doi.org/10.1016/j.rser.2014.10.086

Kaveh A, Sabeti S (2018) Structural optimization of jacket supporting structures for offshore wind turbines using colliding bodies optimization algorithm. The Structural Design of Tall and Special Buildings 27(13): e1494. https://doi.org/10.1002/tal.1494

Kenway G, Martins JRRA (2008) Aerostructural shape optimization of wind turbine blades considering site-specific winds. 12th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference. AIAA 2008-6025. https://doi.org/10.2514/6.2008-6025

Kim HC, Kim KH, Kim MH, Hong K (2017a) Global performance of a KRISO semisubmersible multiunit floating offshore wind turbine: Numerical simulation vs. model test. International Journal of Offshore and Polar Engineering 27(1): 70-81. https://doi.org/10.17736/ijope.2017.fvr02

Kim HC, Kim MH, Lee JY, Kim S, Zhang Z (2017b) Global performance analysis of 5MW WindFloat and OC4 Semi-Submersible Floating Offshore Wind Turbines (FOWT) by numerical simulations. ISOPE International Ocean and Polar Engineering Conference. ISOPE, ISOPE-I-17-578

Kirchner-Bossi N, Porté -Agel F (2024) Wind farm power density optimization according to the area size using a novel self-adaptive genetic algorithm. Renewable Energy 220: 119524. https://doi.org/10.1016/j.renene.2023.119524

Lee J, Zhao F (2021) GWEC global wind report 2021. Global wind energy council 15: 16

Lee K-H, Jun S-O, Pak K-H, Lee D-H, Lee K-W, Park J-P (2010) Numerical optimization of site selection for offshore wind turbine installation using genetic algorithm. Current Applied Physics 10(2): S302-S306. https://doi.org/10.1016/j.cap.2009.11.031

Li C, Campbell BK, Liu Y, Yue DKP (2019) A fast multi-layer boundary element method for direct numerical simulation of sound propagation in shallow water environments. Journal of Computational Physics 392: 694-712. https://doi.org/10.1016/j.jcp.2019.04.068

Liao C, Xi G, Xu J (2009) An improved PSO algorithm for solution of constraint optimization problem and its application. Journal of Engineering Thermophysics Rus 24: 256-260

Liao CC, Zhao XL, Xu JZ (2012) Blade layers optimization of wind turbines using FAST and improved PSO Algorithm. Renewable Energy 42: 227-233. https://doi.org/10.1016/j.renene. 2011.08.011

Liu Y, Xiao Q, Incecik A, Peyrard C, Wan D (2017) Establishing a fully coupled CFD analysis tool for floating offshore wind turbines. Renewable Energy 112: 280-301. https://doi.org/10.1016/j.renene.2017.04.052

Liu Z, Fan S, Wang Y, Peng J (2021) Genetic-algorithm-based layout optimization of an offshore wind farm under real seabed terrain encountering an engineering cost model. Energy Conversion and Management 245: 114610. https://doi.org/10.1016/j.enconman.2021.114610

Long H, Moe G (2012) Preliminary design of bottom-fixed lattice offshore wind turbine towers in the fatigue limit state by the frequency domain method. Journal of Offshore Mechanics and Arctic Engineering 134(3): 031902. https://doi.org/10.1115/1.4005200

Lumbreras S, Ramos A, Sánchez-Martin P (2015) Offshore wind farm electrical design using a hybrid of ordinal optimization and mixed-integer programming. Wind Energy 18(12): 2241-2258. https://doi.org/10.1002/we.1807

Ma Y, Zhang A, Yang L, Hu C, Bai Y (2019) Investigation on optimization design of offshore wind turbine blades based on particle swarm optimization. Energies 12(10): 1972. https://doi.org/10.3390/en12101972

Malhotra S (2011) Selection, Design and Construction of Offshore Wind Turbine Foundations. Wind Turbines. Edited by Ibrahim Ai-Bahadly. Rijeka: InTech 231-264. https://doi.org/10.5772/15461

Mellal MA, Pecht M (2020) A multi-objective design optimization framework for wind turbines under altitude consideration. Energy Conversion and Management 222: 113212.https://doi.org/10.1016/j.enconman.2020.113212

Micallef D, Rezaeiha A (2021) Floating offshore wind turbine aerodynamics: Trends and future challenges. Renewable and Sustainable Energy Reviews 152: 111696. https://doi.org/10.1016/j.rser.2021.111696

Michailides C, Angelides DC (2012) Modeling of energy extraction and behavior of a Flexible Floating Breakwater. Applied Ocean Research 35: 77-94. https://doi.org/10.1016/j.apor.2011.11.004

Ning A, Petch D (2016) Integrated design of downwind land-based wind turbines using analytic gradients. Wind Energy 19(12): 2137-2152. https://doi.org/10.1002/we.1972

Oest J, Sørensen R, T. Overgaard LC, Lund E (2017) Structural optimization with fatigue and ultimate limit constraints of jacket structures for large offshore wind turbines. Structural and Multidisciplinary Optimization 55(3): 779-793

Oguz E, Clelland D, Day AH, Incecik A, López JA, Sánchez G, Almeria GG (2018) Experimental and numerical analysis of a TLP floating offshore wind turbine. Ocean Engineering 147: 591-605. https://doi.org/10.1016/j.oceaneng.2017.10.052

Oh KY, Kim JY, Lee JS (2013) Preliminary evaluation of monopile foundation dimensions for an offshore wind turbine by analyzing hydrodynamic load in the frequency domain. Renewable Energy 54: 211-218. https://doi.org/10.1016/j.renene.2012.08.007

Özkan R, Genç MS (2023) Aerodynamic design and optimization of a small-scale wind turbine blade using a novel artificial bee colony algorithm based on blade element momentum (ABC-BEM) theory. Energy Conversion and Management 283: 116937. https://doi.org/10.1016/j.enconman.2023.116937

Pérez-Rúa JA, Lumbreras S, Ramos A, Cutululis NA (2022) Reliability-based topology optimization for offshore wind farm collection system. Wind Energy 25(1): 52-70. https://doi.org/10.1002/we.2660

Pillai AC, Chick J, Johanning L, Khorasanchi M, Pelissier S (2016) Optimisation of offshore wind farms using a genetic algorithm. International Journal of Offshore and Polar Engineering 26(3): 225-234. https://doi.org/10.17736/ijope.2016.mmr16

Polat O, Tuncer IH (2013) Aerodynamic shape optimization of wind turbine blades using a parallel genetic algorithm. Procedia Engineering 61: 28-31. https://doi.org/10.1016/j.proeng.2013.07.088

Pouladi F, Gilani AM, Nikpour B, Salehinejad H (2013) Optimum localization of wind turbine sites using opposition based ant colony optimization. 2013 Sixth International Conference on Developments in eSystems Engineering. Piscataway: IEEE, 21-26. https://doi.org/10.1109/DeSE.2013.13

Pourrajabian A, Dehghan M, Rahgozar S (2021) Genetic algorithms for the design and optimization of horizontal axis wind turbine (HAWT) blades: A continuous approach or a binary one? Sustainable Energy Technologies and Assessments 44: 101022. https://doi.org/10.1016/j.seta.2021.101022

Rezaeiha A, Micallef D (2020) CFD simulation of two tandem floating offshore wind turbines in surge motion. Journal of Physics: Conference Series. IOP Publishing, 1618:052066. https://doi.org/doi:10.1088/1742-6596/1618/5/052066

Ribeiro AFP, Awruch AM, Gomes HM (2012) An airfoil optimization technique for wind turbines. Applied Mathematical Modelling 36(10): 4898-4907. https://doi.org/10.1016/j.apm.2011.12.026

Rizk-Allah RM, Hassanien AE (2023) A hybrid equilibrium algorithm and pattern search technique for wind farm layout optimization problem. ISA Transactions 132: 402-418. https://doi.org/10.1016/j.isatra.2022.06.014

Salcedo-Sanz S, Gallo-Marazuela D, Pastor-Sánchez A, Carro-Calvo L, Portilla-Figueras A, Prieto L (2014) Offshore wind farm design with the Coral Reefs Optimization algorithm. Renewable Energy 63: 109-115. https://doi.org/10.1016/j.renene.2013.09.004

Schafhirt S, Page A, Eiksund GR, Muskulus M (2016) Influence of soil parameters on the fatigue lifetime of offshore wind turbines with monopile support structure. Energy Procedia 94: 347-356. https://doi.org/10.1016/j.egypro.2016.09.194

Schafhirt S, Zwick D, Muskulus M (2014) Reanalysis of jacket support structure for computer-aided optimization of offshore wind turbines with a genetic algorithm. ISOPE International Ocean and Polar Engineering Conference. ISOPE, ISOPE-I-14-174

Schröder K, Gebhardt C, Rolfes R (2016) Damage localization at wind turbine support structures using sequential quadratic programming for model updating. 8th European Workshop On Structural Health Monitoring, Bilbao. Spain. e-Journal of Nondestructive Testing Vol.21(8). https://www.ndt.net/?id=19944

Settoul S, Zellagui M, Chenni R (2021) A new optimization algorithm for optimal wind turbine location problem in Constantine city electric distribution network based active power loss reduction. Journal of Optimization in Industrial Engineering 14(2): 13-22. https://doi.org/10.22094/joie.2020.1892184.1725

Shen M, Hu Z, Liu G (2016) Dynamic response and viscous effect analysis of a TLP-type floating wind turbine using a coupled aero-hydro-mooring dynamic code. Renewable Energy 99: 800-812. https://doi.org/10.1016/j.renene.2016.07.058

Shen X, Hu P, Chen J, Zhu X, Du Z (2018) The unsteady aerodynamics of floating wind turbine under platform pitch motion. Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy 232(8): 1019-1036. https://doi.org/10.1177/0957650918766606

Shin J, Baek S, Rhee Y (2020) Wind farm layout optimization using a metamodel and ea/pso algorithm in korea offshore. Energies 14(1): 146. https://doi.org/10.3390/en14010146

Shourangiz-Haghighi A, Haghnegahdar MA, Wang L, Mussetta M, Kolios A, Lander M (2020) State of the art in the optimisation of wind turbine performance using CFD. Archives of Computational Methods in Engineering 27(2): 413-431. https://doi.org/10.1007/s11831-019-09316-0

Si JZ, Sun G, Meng DH (2013) An optimization method for offshore wind turbine blades based on PSO. Acta Aerodyn. Sin. 31: 498-502

Song J, Kim T, You D (2023) Particle swarm optimization of a wind farm layout with active control of turbine yaws. Renewable Energy 206: 738-747. https://doi.org/10.1016/j.renene.2023.02.058

Stieng LES, Muskulus M (2020) Reliability-based design optimization of offshore wind turbine support structures using analytical sensitivities and factorized uncertainty modeling. Wind Energy Science 5(1): 171-198. https://doi.org/10.5194/wes-5-171-2020

Thiry A, Rigo P, Buldgen L, Raboni G,Bair F (2011) Optimization of monopile offshore wind structures. Advances in Marine Structures, 633-642. https://doi.org/10.1201/b10771-77

Uys P, Farkas J, Jarmai K, van Tonder F (2007) Optimisation of a steel tower for a wind turbine structure. Engineering Structures 29(7): 1337-1342. https://doi.org/10.1016/j.engstruct.2006.08.011

Vairavamoorthy K, Ali M (2005) Pipe index vector: A method to improve genetic-algorithm-based pipe optimization. Journal of Hydraulic Engineering 131(12): 1117-1125. https://doi.org/10.1061/(ASCE)0733-9429(2005)131:12(1117)

Van der Giessen M (2021) Feasibility of mooring system optimization for floating wind turbines in deep water based on static analysis. Norwegian: Norwegian University of Science and Technology (NTNU)

Van Der Tempel J, Vugts JH, van Kuik GAM (2006) Design of support structures for offshore wind turbines.Delft:Duwind

Vicini A, Quagliarella D (1999) Airfoil and wing design through hybrid optimization strategies. AIAA Journal 37(5): 634-641. https://doi.org/10.2514/2.764

Wan C, Wang J, Yang G, Gu H, Zhang X (2012) Wind farm micro-siting by Gaussian particle swarm optimization with local search strategy. Renewable Energy 48: 276-286. https://doi.org/10.1016/J.RENENE.2012.04.052

Wan C, Wang J, Yang G, Li X, Zhang X (2009) Optimal micro-siting of wind turbines by genetic algorithms based on improved wind and turbine models. Proceedings of the 48h IEEE Conference on Decision and Control (CDC) Held Jointly with 2009 28th Chinese Control Conference. Piscataway: IEEE, 5092-5096

Wan C, Wang J, Yang G, Zhang X (2010) Optimal micro-siting of wind farms by particle swarm optimization. International Conference in Swarm Intelligence. Berlin: Springer, 6145: 198-205. https://doi.org/10.1007/978-3-642-13495-1_25

Wang CM, Utsunomiya T, Wee SC, Choo YS (2010) Research on floating wind turbines: a literature survey. The IES Journal Part A: Civil & Structural Engineering 3(4): 267-277. https://doi.org/10.1080/19373260.2010.517395

Wang L, Wang T-g, Luo Y (2011) Improved non-dominated sorting genetic algorithm (NSGA)-II in multi-objective optimization studies of wind turbine blades. Applied Mathematics and Mechanics 32(6): 739-748. https://doi.org/10.1007/s10483-011-1453-x

Wang W, Caro S, Bennis F, Soto R (2015) Multi-objective robust optimization using a postoptimality sensitivity analysis technique: application to a wind turbine design. Journal of Mechanical Design 137(1): 011403. https://doi.org/10.1115/1.4028755

Wen B, Dong X, Tian X, Peng Z, Zhang W, Wei K (2018) The power performance of an offshore floating wind turbine in platform pitching motion. Energy 154: 508-521

Willis DJ, Peraire J, White JK (2007) A combined pFFT-multipole tree code, unsteady panel method with vortex particle wakes. International Journal for Numerical Methods in Fluids 53(8): 1399-1422

Wise AS, Bachynski EE (2020) Wake meandering effects on floating wind turbines. Wind Energy 23(5): 1266-1285. https://doi.org/10.1002/we.2485

Yang H, Zhu Y, Lu Q, Zhang J (2015) Dynamic reliability based design optimization of the tripod sub-structure of offshore wind turbines. Renewable Energy 78: 16-25. https://doi.org/10.1016/j.renene.2014.12.061

Yang J, O'Reilly J, Fletcher JE (2009) Redundancy analysis of offshore wind farm collection and transmission systems. 2009 International Conference on Sustainable Power Generation and Supply. Piscataway:IEEE, 1-7.https://doi.org/10.1109/SUPERGEN.2009.5348163

Yoshida S (2006) Wind turbine tower optimization method using a genetic algorithm. Wind Engineering 30(6): 453-469. https://doi.org/10.1260/030952406779994150

Zhao M, Chen Z, Blaabjerg F (2004) Optimization of electrical system for large DC offshore wind farm by genetic algorithm. Nordic Workshop on Power and Industrial Electronics. Norway, Trondheim, 1-8

Zhao M, Chen Z, Blaabjerg F (2009) Optimisation of electrical system for offshore wind farms via genetic algorithm. IET Renewable Power Generation 3(2): 205-216. https://doi.org/10.1049/iet-rpg:20070112

Zhao M, Chen Z, Hjerrild J (2006) Analysis of the behaviour of genetic algorithm applied in optimization of electrical system design for offshore wind farms. IECON 2006-32nd Annual Conference on IEEE Industrial Electronics. Piscataway:IEEE, 2335-2340. https://doi.org/10.1109/IECON.2006.347333

Ziegler L, Voormeeren S, Schafhirt S, Muskulus M (2015) Sensitivity of wave fatigue loads on offshore wind turbines under varying site conditions. Energy Procedia 80: 193-200. https://doi.org/10.1016/j.egypro.2015.11.422

Zwick D, Muskulus M, Moe G (2012) Iterative optimization approach for the design of full-height lattice towers for offshore wind turbines. Energy Procedia 24: 297-304. https://doi.org/10.1016/j.egypro.2012.06.112