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Abstract

Wind energy has already been broadly explored onshore and, in the last years, it has begun to move offshore. However, moving offshore leads to more costs with the construction, installation, maintenance and decommissioning of the wind turbines. Therefore, this paper presents a methodology to optimize the structure of a monopile offshore wind turbine (OWT) in preliminary stages of design, aiming at minimizing the welding time, structural weight and, as a result, the construction costs. The constraints regard the tower top rotation and displacement, structural integrity under ultimate loads and resonance check.

1. Introduction

Once the offshore wind is significantly steadier and stronger than onshore and there is much more space at sea than in land for the installation of wind turbines, offshore wind energy plays and will continue to play an important role in the global effort towards the independence from fossil fuels, replacing than by renewable sources of energy. Consequently, due to the higher costs of moving offshore, it is important to have a sound methodology that can be utilized to obtain optimized support structures for wind energy generators.

Wind structures' optimization is not a new field of study. Since the conception of the first onshore wind turbines, there has been a concern about how to make these structures lighter and, consequently, cheaper, without compromising their operational performance and/or structural integrity. Therefore, studies develop by Negm et al. (2000), Yoshida (2006) and Uys et al. (2007) aimed at proposing an optimization methodology for onshore wind turbine towers, considering aspects such as structural constraints and the cost of construction.

Many years later, when the wind industry started moving offshore, once there was already a significant background on the optimization of wind turbine towers, researches decided to focus their attention on the optimization of the foundations, which can be of different types, such as gravity-based, tripod, tripile, jackets or monopile. Torcinaro et al. (2010) and Petrini et al. (2010) contemplate, respectively, the optimization of a tripod foundation and the comparison of three types of foundations (monopile, tripod and jacket), with regards to their natural frequencies, influence on the hydrodynamic loads and structural strength. Both studies assumed that the structures other than the foundation would remain unchanged during the design process.

Therefore, nowadays the foundations and towers are designed separately, which leads to a suboptimal overall design. However, studies have shown that an integrated design of these two components of the wind turbine support structure can be much more advantageous. For example, Haghi et al. (2012) compare the structure of an existing offshore monopile wind turbine, which had its foundation and tower designed separately, with its optimized version, which resulted in a significant reduction of structural weight. Furthermore, Ashuri et al. (2014) include not only the supporting structure but also the blades in the optimization process, resulting in a much more optimal wind turbine and Zwick et al. (2012) design a full-height lattice tower for offshore wind turbines, going on the opposite direction of the commonly used support structure, composed of foundation and tower.

Have said that, it was noticed that these studies have shown no consideration about any aspect of the construction of these structures. Therefore, the present study provides a methodology for the optimization of the support structure of a monopile offshore wind turbine, in which the foundation and tower are analysed simultaneously and an important construction parameter is optimized, the welding time.

Thiry et al. (2011), Kaveha et al. (2019) and Haghi et al. (2012) present a similar method in their studies. At the end of this paper, these will be compared to the one exposed here.

2. Simplifications

Before introducing the methodology, the simplifications assumed for this study must be outlined.

- The structure is assumed to be clamped in the seabed, in other words, there is no structure extending below the mudline. No soil-structure interaction is considered in the structural analysis, either for the ultimate strength or modal frequency assessment;
- The transition piece is not considered. The substructure is modelled from the mudline to the tower base. Therefore, a more detailed analysis is necessary once the preliminary optimal structure is obtained through the present methodology;
- All non-structural components of the wind turbine, such as work platform, intermediate platform and boat landing are disregarded;
- The loads resultant from the attached cables responsible for transferring the generated energy is not considered.

3. Methodology

The process begins with the introduction of the design variables modified by the optimization algorithm. With this information in hands, the structural dynamic response is assessed and the welding time is calculated based on the plates' thickness and structure geometry. Once this is done, the next step is the assessment of the environmental loads acting on the structure, which are a function of the incident current, wave, wind and structure geometry. Next, the structure buckling strength is verified and the finite element structural model is loaded with the pressure resulting from the aerodynamic, hydrodynamic and hydrostatic loads and the forces and moments experienced by the tower top due to the presence of the energy generator. When the structural analysis is completed, the Von Mises (VM) stress, tower top rotation and displacement are computed. Finally, the structure mode shape frequencies, VM stress, rotation and displacement on the nacelle are verified against the optimization constraints and the structural mass and welding time are compared to the designs already analysed until the optimum values are found.

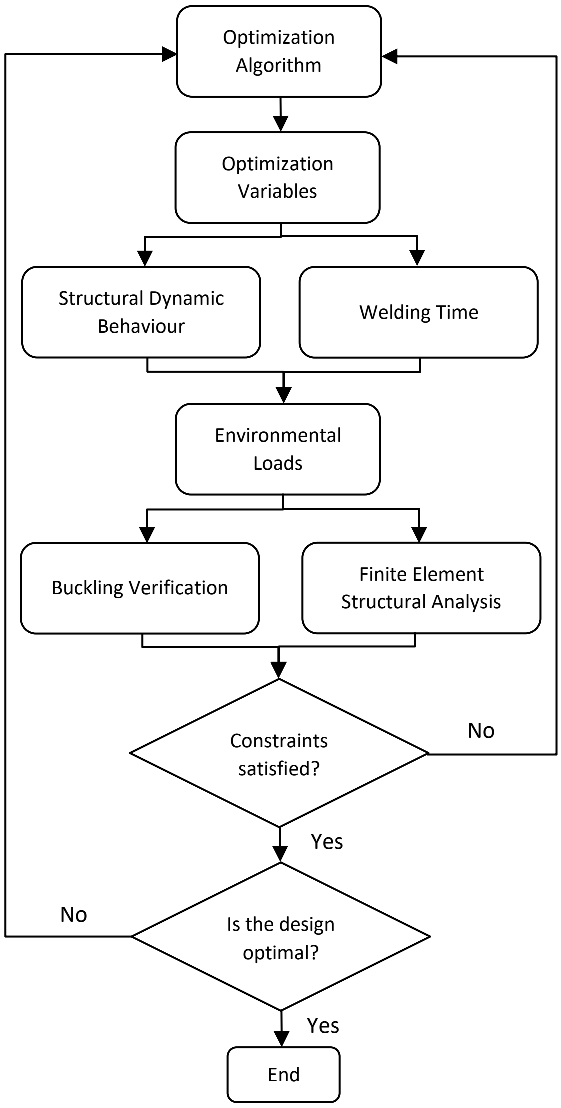

Figure 1 – Optimization Workflow

4. Optimization Algorithm

This study employs an optimization algorithm that applies the function approximation concept because it reduces the number of design iterations necessary to complete the optimization when compared to the isolated zero-order method.

The function approximation method works on the idea of the utilization of a function, that is similar to the real one used to generate the designs, which can be evaluated much faster. This new function is used with the zero-order optimization method, leading us to a first good estimate of the optimal solution, which is verified within the real function, allowing the verification if it is the best design so far and the improvement of the approximate function with the new data acquired.

The zero-order method is based on the generation of random variables and the evaluation of the designs until the goal is achieved. It receives this denomination because it does not require the evaluation of a gradient function, it focuses only on the calculation of the resultant design obtained from the optimization variables. A famous group of optimization algorithms known for utilizing this method is genetic algorithms. These work on the idea of natural selection of the most suitable individual and genetics. Firstly, several possible solutions are created to generate an initial population. Then, these individuals are given an index that indicates how suitable they are for the optimization goal. The ones with the higher index have more chances to combine themselves with other individuals, resulting in a more suitable one, whereas the undesirable designs tend to not be able to pass on their “genes”. Additionally, during this process, some mutations occur, performing fully jump in other design space regions and therefore helping the optimizer to escape from a possible local minimum.

The secret to achieving an efficient optimization algorithm that makes use of the function approximation method is a reliable mechanism responsible for generating and improving the approximate function. Therefore, this study applies the Fast Genetic Algorithm, from the Xtreme software, which combines a genetic algorithm with the approximate function approach, that is managed by an artificial neural network.

5. Optimization Variables

To manipulate the structure, some dimensions are chosen to be varied during the optimization process.

The tower height is assumed fixed and there are no longitudinal or transverse stiffeners along with the support structure. Therefore, the variables are the structure section radius and plate thickness.

Some of the aspects to be considered when deciding on the range of these variables are the construction method and the infrastructure available for the wind turbine installation.

In addition, the butt weld joints vary during the optimization, in order to reduce the welding time.

6. Dynamic Behaviour Assessment

An integral aspect of a wind turbine design is its dynamic behaviour. That is because the occurrence of resonance can lead to the overall failure of the support structure, due to an exceedance of its ultimate strength, or to a significant reduction of its fatigue life.

Therefore, the structure vibration frequency at first and second natural modes are computed by the NREL (National Renewable Energy Laboratory) code Modes v2.22. In this software, the structure is represented by a simplified model composed by its distributed mass, tower top mass, fore-aft and side-to-side stiffness.

7. Welding Time

As the time spent on welding is responsible for a significant share of the overall construction duration, its optimization results in a significant reduction of the time required to build the wind turbine support structure.

Firstly, the standard plate size is assumed, so the total weld length over the construction can be assessed. The main aspects to be considered when deciding the plates’ dimensions are the infrastructure available for their transportation from the steel factory to the shipyard and the machinery used to handle the plates along the construction process.

Following this, once welding is a complex procedure that depends on some variables such as the welding process, pulse frequency, travel speed and the welder skills, a submerged arc welding (SAW) process is assumed, once it results in high quality and uniform welds. Also, a fixed deposition rate of filling material is assumed.

For the assessment of the amount of filling material required, the American Welding Society (2006) is used as a reference for the definition of the weld joints. It is assumed that the welding will take place on only one side of the plates. Thus, for each one of the butt joints in Table 1, the weld transversal area is calculated and then multiplied by the groove length and material density, so the joint requiring less material can be utilized. Figures 2 to 5 bellow illustrate the groove types.

Table 1 – Butt weld joints

Weld type	Joint Designation
Single-V-groove weld	B-L2c-S
Single-V-groove weld	B-L2a-S
Single-V-groove weld	B-U2-S
Single-bevel-groove weld	B-U4b
Single-bevel-groove weld	B-U4a

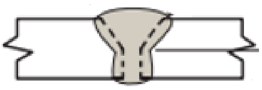

Figure 2 – Single-V-groove weld | B-L2c-S

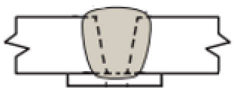

Figure 3 – Single-V-groove weld | B-L2a-S and B-U2-S

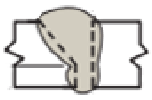

Figure 4 – Single-bevel-groove weld | B-U4b

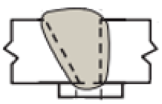

Figure 5 – Single-bevel-groove weld | B-U4a

Once the total amount of filler material is calculated, it is divided by the material deposition rate, so the welding time can be obtained. After that, an operating factor is applied.

$$W_t = \frac{W_l \, W_a \, \rho_s}{D_{fm} \, O_f} \quad (1)$$

where W_t is the welding time, W_l is the groove length, W_a is the weld transversal area, ρ_s is the filler material density, D_{fm} is the deposition rate of filler material and O_f is the operating factor.

8. Loads

The loads applied to the structural model have two distinct origins, the wind turbine components weight and the natural environment.

8.1. Components Weight

Since the wind generator is not manipulated during this optimization process, its weight is maintained as a constant. Contrarily, the structural weight varies at each iteration and, therefore, is updated constantly, so the structural integrity assessment is accurate.

8.2. Environmental Loads

The environmental loads acting on a wind turbine structure can have many sources, such as earthquakes, snow, ice and significant variations of temperature. However, the ones considered in this study can be divided into hydrostatic, hydrodynamic and aerodynamic. The first is obtained according to the following formula:

$$P = \rho_w \, g \, h \quad (2)$$

where P is the hydrostatic pressure, ρ_w is the water density, g is the acceleration of gravity and h is the water depth.

The other loads are computed by the NREL software FAST (Fatigue, Aerodynamics, Structure and Turbulence). FAST is a wind turbine multi-physics engineering tool responsible for making the connection between its six modules.

Table 2 – FAST Modules

Module	Discipline
HydroDyn	Hydrodynamic Conditions & Loads
InflowWind	Aerodynamic Conditions
SubDyn	Substructure Dynamics
AeroDyn	Aerodynamic Loads
ElastoDyn	Tower and RNA Dynamics
ServoDyn	Control System & Actuators

The output is a time series of the simulation with all the information requested in the input files, such as energy production, wave elevation, wind speed and distributed loads.

To calculate the aerodynamic loads, the wind files are generated by the NREL applications IECWind and TurbSim. The first generates a uniform wind file, whereas the second simulates a turbulent wind time series numerically through a statistical model. Then, InflowWind processes the wind files so they can be input to Aerodyn.

Once the AeroDyn input data is prepared, the distributed aerodynamic drag force along the tower and blades is computed and then transferred to ElastoDyn, which calculates the tower motions (position, speed and acceleration) due to the applied loads and then transfers that information back to AeroDyn so it can recalculate the aerodynamic forces.

Similarly, HydroDyn and SubDyn work simultaneously computing the hydrodynamic loads and the substructure motions, respectively, and exchanging information between each other.

The hydrodynamic distributed forces can be separated into three distinct types: inertia force (($\overrightarrow{F_I}$), viscous drag force ($\overrightarrow{F_D}$) and added mass force ($\overrightarrow{F}_{AM\_M}$).

$$\overrightarrow{F} = \overrightarrow{F_I} + \overrightarrow{F_D} + \overrightarrow{F}_{AM\_M} \tag{3}$$

The inertia and viscous drag forces are calculated through Morrison's equation. The first is proportional to the fluid acceleration and is composed by two terms, the Froud-Kriloff term, which computes the hydrodynamic loads due to the gradient of the undisturbed field of pressure, and the scattering force term, which is associated to the fluid disturbance due to the presence of the structure.

$$\overrightarrow{F_I} = \begin{Bmatrix} (C_P + C_A)\rho_w \pi R^2 \left(\vec{a}_f - \left(\vec{a}_f \bullet \hat{k}\right)\hat{k}\right) \\ 0 \\ 0 \\ 0 \end{Bmatrix} \tag{4}$$

where C_P is the transverse dynamic pressure coefficient, C_A is the added-mass coefficient, R is the pile section radius, $\vec{a}_f$ is the linear acceleration of the fluid and $\hat{k}$ is the unit vector along the local z-axis (vertical axis).

The viscous drag force is proportional do the squared relative velocity between the fluid and the pile.

$$\overrightarrow{F_D} = \begin{Bmatrix} C_D \rho_w R \left\| \vec{v}_{rel} - \left(\vec{v}_{rel} \bullet \hat{k}\right)\hat{k} \right\|_2 \left(\vec{v}_{rel} - \left(\vec{v}_{rel} \bullet \hat{k}\right)\hat{k}\right) \\ 0 \\ 0 \\ 0 \end{Bmatrix} \tag{5}$$

where C_D is the transverse viscous drag coefficient and $\vec{v}_{rel}$ is the relative velocity ($\vec{v}_{rel} = \vec{v}_f - \vec{v}_s$, where $\vec{v}_f$ is the linear velocity of the fluid and $\vec{v}_s$ is the translational structure velocity).

The added mass force is proportional do the acceleration of the structure and is an additional inertia force resultant from the fluid that is displaced when the structure moves.

$$AM_M = \rho_w \pi R^2 \begin{bmatrix} \left[C_A\left(I - \hat{k}\hat{k}^T\right)\right] & [0] \\ [0] & [0] \end{bmatrix} \tag{6}$$

$$\overrightarrow{F}_{AM\_M} = -AM_M \begin{Bmatrix} \vec{a}_s \\ \vec{\alpha}_s \end{Bmatrix} \tag{7}$$

where AM_M is the added mass due to Morison's equation, $\vec{a}_s$ is the linear acceleration of the structure and $\vec{\alpha}_s$ is the rotational structural acceleration.

After the distributed loads along the tower and substructure are calculated, they are integrated along with the supporting structure and then divided by its area, so the pressures resultant from the environmental loads can be obtained.

9. Design Load Case (DLC)

According to DNV GL (2016), offshore wind turbines must be designed to go through a range of design situations expected to take place during its lifetime (around 25 years). These situations are related to transport, installation, maintenance, repair, start-up, power production, power production plus the occurrence of fault, normal shutdown, emergency stop and idling conditions. However, once this study disregards fatigue life, only the most critical design situation for ultimate strength is considered. The DLC utilized during the optimization is the 6.1, which stands for a parked (standing still or idling) design situation under the 50-year return period environmental conditions (wind, wave and current). In addition, the later guideline recommends the application of a 1.35 safety factor on the loads obtained under the mentioned weather conditions.

10. Finite Elements Structural Model

The structure is represented by a finite element model with a shell type of element. The structure is modelled from the tower top to the mudline, where it is clamped. The portion of the substructure underground is not considered in this analysis. Furthermore, the tower top is dynamically coupled to a reference point where the tower top forces and moments, resultant from the energy generator presence, are applied. Once the aerodynamic and hydrodynamic loads are calculated by FAST as line loads in the x and y axis (axis perpendicular to the structure), these are transformed into pressure and applied as surface traction, which is force per unit of area acting on a specific direction. The hydrostatic pressure is applied as a pressure normal to the surface. The structural analysis used in this optimization is static, where the most critical timestep, regarding the structural integrity, among the time series obtained from FAST, was determined based on the maximum substructure base moment reaction.

11. Optimization Constraints

To guide the optimization, constraints are established regarding the vibration at first (F1) and second (F2) natural frequency, Von Mises stress, buckling, support structure geometry, top rotation and displacement.

11.1. Dynamic Behaviour

The rotor induces excitation loads in two frequencies, which must be away from F1 and F2 to prevent the occurrence of resonance. The first is the rotation frequency (1P) and the second is the blade passing frequency (3P). The whole structure experiences an excitation with a frequency equal to 1P due to a disbalance between the blades, which might be a result of fabrication defects or different levels of erosion, and equal to 3P as a consequence of the wind shadowing of the blades on the tower every time a blade passed in front of it.
There are three definitions for the overall structure stiffness, depending on the relative position of F1, 1P and 3P.

- Soft-Soft: F1 is smaller than 1P. The structure is usually too flexible, allowing significant deflection.
- Soft-Stiff: F1 is located between 1P and 3P. This approach is the most used in modern wind turbines.
- Stiff-Stiff: F1 is higher than 3P. The structure is very stiff, which requires a robust and, consequently, heavy and expensive structure.

As mentioned above, most wind turbines are designed as soft-stiff. Therefore, as recommended by DNV (2002), F1 is set between 1.10*1P and 0.9*3P. For wind turbines that will be installed in a soil that tends to become less stiff over the years, F1 Is located closer to 3P, as the wind turbine support structure natural frequency is expected to reduce over its lifetime. On the other hand, if the soil is going to become stiffer, F1 is placed near 1P.
Since no soil-structure interaction is considered in this study, the only concern is that 1P is located within the mentioned interval.
Figure 6 shows the frequency spectrum of the dynamic loads.

11.2. Structural Integrity

To assure the wind turbine structural integrity, the Von Mises stress is limited to the yielding stress of the steel used and the buckling is verified according to DNV GL (2019). Two buckling modes are checked,

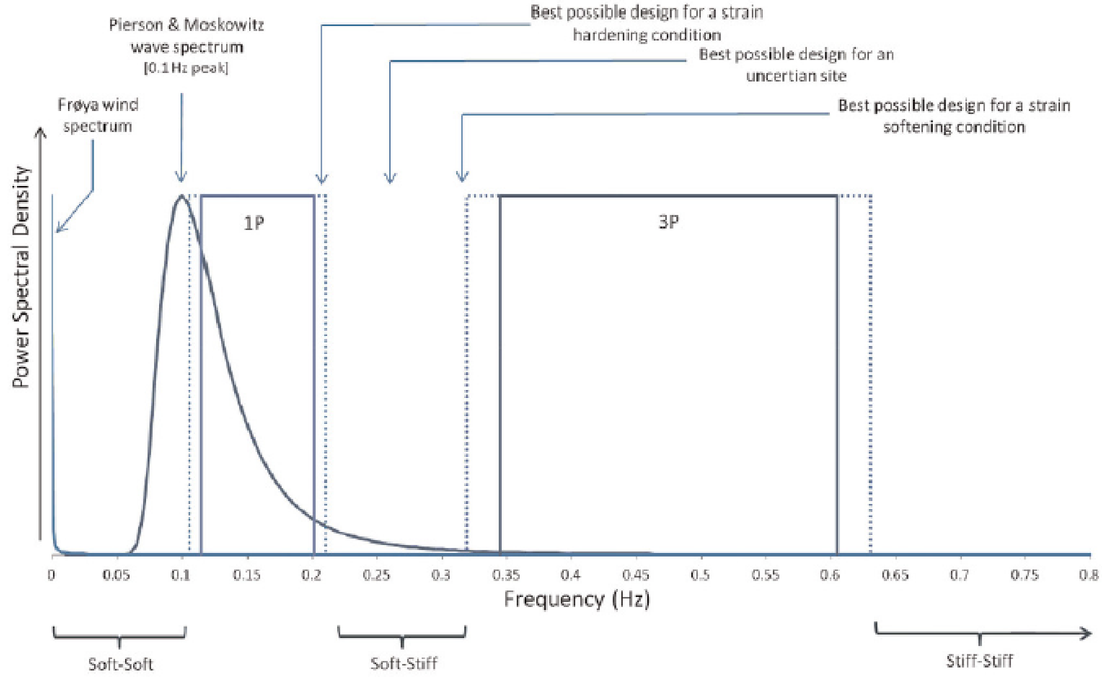

Figure 6 – Frequency spectrum of the dynamic loads exhibiting the three design options (Leite et al., 2015)

the shell and the column buckling. The first refers to the local buckling of plates whereas second regards the buckling of the overall structure.

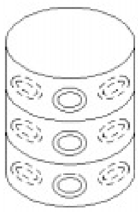

Figure 7 – Shell Buckling

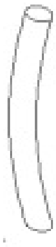

Figure 8 – Column Buckling

11.3. Geometry

The support structure geometry Is manipulated within some limitations. Firstly, the tower top radius is fixed, so the nacelle can fit. Furthermore, the tower radius is set to reduce or remain unchanged and its thickness to increase or decrease as one moves from the tower base towards its top. The monopile is a cylindrical structure with a constant thickness.

11.4. Tower Deformation

The tower deformation under environmental loads can lead to the damage of the wind turbine if, for instance, the blades collide with the tower. Therefore, following Nicholson (2011), to avoid excessive motion and the interference between the blades and the tower its top rotation is set to be less than 5 degrees and its displacement a maximum of 1% of the tower length.

12. Methodologies Comparison

As mentioned at the beginning of this study, three similar methodologies will be compared to the one presented here with regards to the disciplines considered (aerodynamics, hydrodynamics, soil mechanics and structure) and optimization parameters (goals, variables, constraints and algorithm).

Regarding aerodynamics, all studies are remarkably similar, except for Kaveha et al. (2019), where a simpler strategy is utilized to assess the wind loads (Table 3).

Looking at the modelling of the hydrodynamic loads, the most complete is Kaveha et al. (2019). Although it assumes regular waves, currents and wheeler stretching are included, what makes the analysis much more realistic. Besides, only Haghi et al. (2012) considers the interaction between the soil and the foundation (Table 4).

Except for Kaveha et al. (2019), the supporting structures are modelled as cylindrical or conical and unstiffened. With regards to the structural analysis, all studies are based partially on rules or standards, mostly to verify the buckling strength, and on a beam finite element method. The exception is Thiry et al. (2011), which utilizes beam theory, and this study, where finite plate elements are applied, resulting in a more accurate structural analysis (Table 5).

All studies focus at least on the minimization of the structural mass. Thiry et al. (2011) add cost optimization and the present study includes the reduction of the welding time. The most commonly used optimization variables are the plate thickness and structure radius, whereas this study also includes the butt welding joints (Table 6).

The modal frequencies and ultimate strength limit are a design constraint for all studies. In the one presented here, although fatigue is not considered, operating constraints such as the tower top rotation and displacement are addressed. Additionally, constraints related to the geometry variation along the structure are found in Thiry et al. (2011), where the plate thickness and radius are set to reduce from the tower base to top, and in this study, where, differently from Thiry et al. (2011), the plate thickness is allowed to increase or decrease (Table 7 and Table 8).

When it comes to the optimization algorithm, Haghi et al. (2012) use two of them, the Interior Point and Sequential Quadratic Programming algorithms. The first is responsible for transforming the unfeasible designs into a feasible, whereas the second searches for the optimal one among these designs. This approach is used to reduce the optimization time. Similarly, the algorithm employed in this study aims at the increase in the optimization speed, using the fast genetic algorithm. Thiry et al. (2011) make use of a genetic algorithm, which works in a similar way when compared to the one presented in this study, except for the function approximation method. Lastly, Kaveha et al. (2019) utilize three meta-heuristic algorithms: Colliding Bodies Optimization (CBO), Enhanced Colliding Bodies

Optimization (ECBO), and Vibrating Particle System (VPS). These first two are based on the laws governing collision of bodies, while the third on the assumption that the possible optimal solutions are vibrating particles seeking for their equilibrium position. The three of them were conceived to speed up the optimization (Table 9).

Table 3 – Aerodynamics

Paper	Aerodynamics				
	Turbulent Wind	Steady Wind	Wind Generator Reactions		Tower Drag
			Blade Element Momentum Theory	Blade Element Theory	
Haghi et al. (2012)	X		X		X
Thiry et al. (2011)	X		X		X
Kaveha et al. (2019)		X		X	X
This Study	X		X		X

Table 4 – Hydrodynamics and Soil Mechanics

Paper	Hydrodynamics				Soil Mechanics
	Regular Waves	Irregular Waves	Wheeler Stretching	Current	
Haghi et al. (2012)		X	X		X
Thiry et al. (2011)	X				
Kaveha et al. (2019)	X		X	X	
This Study		X		X	

Table 5 – Structure

Paper	Structure						
	Structural Analysis				Geometry		
	Finite Element Method		Rule or Standard Check	Beam Theory	Framing System	Conical Shape	Cylindrical Shape
	Beam elements	Shell Elements			Unstiffened		
Haghi et al. (2012)	X		X		X	X	X
Thiry et al. (2011)			X	X	X	X	X
Kaveha et al. (2019)	X		X		X		X
This Study		X	X		X	X	X

Table 6 – Optimization Goal and Variables

Paper	Optimization Goal			Variables		
	Minimize Mass	Minimize Cost	Minimize Welding Time	Plate Thickness	Radius	Butt Weld Joint
Haghi et al. (2012)	X			X		
Thiry et al. (2011)	X	X		X	X	
Kaveha et al. (2019)	X			X	X	
This Study	X		X	X	X	X

Table 7 – Optimization Constraints

Paper	Optimization Constraints					
	Modal Frequencies	Ultimate Strength	Fatigue	Tower Top Displacement	Tower Top Rotation	Tower Top Radius
Haghi et al. (2012)	X	X	X			N/I
Thiry et al. (2011)	X	X	X			N/I
Kaveha et al. (2019)	X	X		X		N/I
This Study	X	X		X	X	X

*N/I: Not Informed

Table 8 – Optimization Constraints (continuation)

Paper	Optimization Constraints		
	Geometry Variation Towards the Tower Top		
	Radius Decrease	Thickness Decrease	Thickness Increase
Haghi et al. (2012)	N/I	N/I	N/I
Thiry et al. (2011)	X	X	
Kaveha et al. (2019)	N/I	N/I	N/I
This Study	X	X	X

*N/I: Not Informed

Table 9 – Optimization Algorithm

Paper	Optimization Algorithm
Haghi et al. (2012)	Interior Point and Sequential Quadratic Programming (SQP)
Thiry et al. (2011)	Genetic Algorithm
Kaveha et al. (2019)	Meta-Heuristic Based Algorithms
This Study	Genetic Algorithm and meta-model

13. Conclusion

OWTs are already a source of affordable energy. Nevertheless, reducing the costs of electricity generation must be a permanent concern of designers.

This work presented a methodology for the optimization of offshore wind turbines mounted on a monopile foundation. It considered the optimization goals and variables, provided calculation tools and discussed the design constraints.

When compared to the methodologies proposed by Haghi et al. (2012), Thiry et al. (2011) and Kaveha et al. (2019) the one presented here has some advantages and drawbacks. Even though the optimization constraints related to the maximum von mises stress, buckling strength and vibration modes and the assumptions adopted for the environmental loads' calculation already allow an analysis very close to what is expected in real life, some improvements such as the inclusion of the soil-structure interaction, wheeler stretching, so the hydrodynamic loads above the mean sea level are computed, and fatigue analysis must be included to make the optimization more realistic and site-specific, once data such as soil stiffness, wave and wind cyclic loads would be input on the optimization. However, important considerations were included in the optimization method proposed here. Firstly, the constraints related to the deformation of the structure under ultimate loads assures that there will be no collision between the blades and the tower. Furthermore, although the reduction of plate thickness, as a result of mass minimization, leads to a positive impact on the reduction of the welding time, considering different butt joints leads to an even lower figure. The simultaneous mass optimization and analysis of which joint is the most appropriate for the reduction of the welding time is much more advantageous than the optimization of welding joints after the structure is already optimized. Lastly, the structural analysis using the finite element method with shell elements leads to a much more accurate result than what can be achieved with the calculation methods proposed by the other methodologies exposed in this study.

In the future, the current research could be further improved by a more detailed definition of the welding parameters to be manipulated during the optimization.

14. Acknowledgement

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