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Enhancing Onshore Wind Tower Foundations: A Comprehensive Automated Design Approach

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Abstract: The realm of green energy is in constant flux, drawing considerable attention from stakeholders dedicated to minimizing environmental impact, reducing costs, and developing structures that align with stringent standards. This study introduces an innovative approach aimed at improving onshore wind tower foundation systems, emphasizing both engineering and financial feasibility. The approach involves a comprehensive analysis of design load cases, particularly emphasizing resistance against overturn, while ensuring compliance with Eurocode guidelines. The foundation system is conceptualized as a beam slab with voids filled by soil material. High reduction in concrete quantity is achieved by reaching 30%, while the steel reduction reaches 90%. It is worth mentioning that the total cost is reduced by up to 70%. Furthermore, as a future trend, this study aims to integrate the new foundation system with steel 3D printing technology in the manufacturing process of the wind tower's structural elements. This integration is expected to enhance the precision and customization of the superstructure-foundation system, thereby improving overall performance and efficiency. The optimized design not only significantly reduces construction costs but also streamlines installation, saving time. Simultaneously, this study enhances the structural behavior of the wind tower foundation by focusing on elements crucial to its efficiency.

Keywords: automated design process; onshore wind turbine; foundation system; construction cost

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1. Introduction and Literature Survey

The constantly increasing demand for alternative and clean energy production sets wind energy as the key element for a sustainable future. Wind energy is part of a vital push to renew the world's energy infrastructure. It has been a source of massive capital investment and one of the fastest growing new industrial sectors in the world. From 2015 to 2019 alone, wind energy generated over 652 billion dollars in investments. Ramping up installed wind capacity to above 2.0 TW of capacity, which by 2030, would create an additional annual investment of 207 billion dollars [1]. It is worth mentioning that both onshore and offshore wind turbines feature prominently in the world's energy source means, and this is evidenced also by the studies published in scientific databases, such as Scopus and Web of Science [2]. The leap of the construction of wind turbine farms fosters the exponential optimization development of the wind turbine as a system for the upper structure (wind tower), which includes the tower, the hub, and the blades, along with its foundation. In contrast with the mutual contribution of both onshore and offshore wind turbines in energy production, with the onshore wind farms accounting for 81% of new capacity in Europe 2021 with Sweden, Germany, and Turkey holding the privilege position and China for 80% of the global offshore wind capacity added in 2021 [2], most optimization studies conducted so far on wind turbine optimization have been performed focusing on wind farm layout optimization and especially for offshore wind turbines.

This study aimed to advance the design and construction of onshore wind turbine foundations, focusing on improving cost and time efficiency. The primary objectives and novel contributions of this research include the following: (i) identifying crucial parameters for foundation design; (ii) minimizing steel reinforcement requirements and installation time; (iii) reducing concrete demand, streamlining pouring processes, and saving time; (iv) determining the optimal shape for the foundation system; and (v) analyzing costs and identifying the ultimate reduction achieved through the proposed methodology. To achieve these goals, we employed an automated design algorithm based on the Exhaustive Search method, which was chosen due to the manageable number of variables: the width (B) and the length (L) of the foundation. This method ensures a thorough exploration of possible design configurations, leading to the most efficient and effective solutions.

Abdelmoteleb et al. [3] examined the preliminary sizing and the optimization of the substructures for future offshore wind turbines, and they achieved a significant reduction in steel mass and enhanced the stiffness of the tower. A review of recent advancements in offshore wind turbine technology was conducted by Asim et al. [4], highlighting key knowledge gaps in the scientific investigations on offshore wind turbine's aerodynamic and structural response and creating the base for the future improvement and development of offshore wind turbines. Notwithstanding that the foundation plays an important role in the structural system of onshore wind turbines, limited effort was invested in optimizing the foundation, whereas the wind tower has been deeply studied and optimized. Already, more studies have been conducted on how to optimize the wind tower of the wind turbine system, as well as its distinct elements, such as the hub, the blades, and the tower [5,6]. The wind turbine tower mass has been minimized under multiple design constraints, and the optimization model has been implemented in a representative 2.0 MW onshore wind turbine, resulting in a mass reduction of 2.9% [5]. The wind turbine tower was further studied, integrating also artificial intelligence, resulting in tower mass restriction, structural reliability, and wind power maximization [7], while the optimal allocation of onshore wind turbines has also been studied, resulting in electricity generation and cost reduction [8–11].

Extensive research has been conducted to identify the critical factors contributing to the structural stability of a wind turbine's foundation. This research serves as a foundational phase preceding the implementation of a targeted automated design for wind turbines. After the collapse of a wind tower due to a typhoon in Taiwan, Chou and Tu [12] studied, in 2010, the critical mechanisms that need to be secured to avoid such a case. Codes, structural elements, historical wind speeds, and construction records were examined from a risk management perspective, and Srikakulapu [13] tried to modify the current International Electromechanical Commission (I.E.C.) design standard and tried to set new directions to prevent the irreversible failure of wind turbines under extreme wind conditions such as typhoons and hurricanes.

Focusing on the effort to improve the foundation functionality and concurrently reduce the construction cost, it is proved that the conical raft design improves the resistance of the soil–structure interface and significantly decreases tilting compared to a flat circular raft. Consequently, the dimensions of the foundation are decreased, and this leads to potential cost reduction [14]. An extended study was also conducted concerning the soil–structure interface. Steel micropiles, which are mini piles of steel that are used especially for shallow foundations, have been proposed to improve the shallow foundations of wind tower systems, lead to significant reduction in the dimensions, and, as a result, reduction in the cost of the foundation [15]. Wind turbine structures are inherently dynamic since they are loaded with aerodynamic, rotational, and inertial sources. All of the above contribute to a system dominated by high overturning moments and vertical loads. The response of the foundation is dynamic, leading to the need of considering the dynamic soil response and soil–structure interaction during the design phase. Parameters like the soil stiffness and its effect on the natural frequency of the wind tower are of vital consideration in the design phase, and the natural frequency of the tower–foundation system should lie within an acceptable range [16]. In light of the growing investment in both the study and construction of the extended use of renewable energy sources, interest in the automated design process and further development of wind turbine structures seems intensified.

The global renewable energy generation capacity has increased from 1829 GW in 2014 to 3064 GW in 2021, while the power generation cost has decreased from 0.089 USD/kWh to 0.033 USD/kWh for onshore wind turbines [17]. The above data highlight the imperative need to further optimize the design of the wind turbine tower–foundation system so as to end in lower construction and assemblage costs.

Optimizing the reinforcement of the wind turbine foundation will lead to cost savings and reduced time consumption. Lago et al. [18] proposed the removal of all vertical stirrups (shear reinforcement), including those placed for shear reinforcement and those allocated in the ring of the foundation for load distribution. He also proposed shear reinforcement removal with the replacement of 50% of radial and circumferential rebars with metallic fibers dispersed in the concrete matrix. Both proposals proved to be promising and lead to cost, assemblage time, and labor reductions. It was also highlighted how essential the soil–structure interaction is, considering the cracks developed and the attainment of the soil bearing capacity close to the border of the foundation. Further attempts, focused on the wind tower of the wind turbine system and not only on the foundation, were made to achieve cost reduction. It was proved that higher hub heights for the wind turbine are not associated with higher electricity generation. There is a certain hub height that enables wind turbines to deliver lower-cost electricity and building beyond this height does not pay off the rise in capital investment and expenditures needed for a stronger foundation and taller and more stable towers. The gusts of wind at higher heights are becoming a limiting factor to taller wind turbines. This contributes to the design and construction of smaller wind turbine foundations [19]. It is of crucial importance to reduce the computational cost of the foundation of the wind turbine. Metamodels were proposed to be used as complementary steps for more accurate finite-element modeling, resulting in design optimization without compromising the accuracy [20].

Despite the trend to optimize the foundations of heavy machine tools in recent years and taking into consideration the determinant role of the foundation in wind turbine balance, more operators tend to be risk-averse and abstain from the implementation of foundation-optimized design methods. The structural design of the wind turbine foundation takes into consideration the following: moment capacity, shear capacity, crack control, anchor bolt anchorage, anchor bolt prestressed splitting, and fatigue [21]. Also, several efforts have been made for the optimization of the wind turbine placement, taking into consideration the terrain while keeping the cost low [22]. Usually, the foundation dimensions of the wind turbines are provided by their suppliers. The foundation acts as a cantilever, resulting in high thickness in the center, varying from 2.50 m to 3.00 m, and becoming thinner at the edge, close to 0.40 m. Meanwhile, broad research was carried out on onshore wind farms, siting proposed optimization methodologies that can be applied over regions worldwide so as to utilize the complementary potential of distributed wind energy, identifying also the distance between the wind turbine foundations and the wind turbine farm. Wind turbine siting optimization also includes topography characteristics such as slopes of the terrain [23,24].

Numerous studies have been conducted, focused on the consequential role of the soil–foundation and structure interaction leading in the optimum inclination of the foundation's battered piles in the case of wind turbine pile foundations [25,26]. At the same time, the main point of interest is gathered from the soil conditions. Tayeh [27] pointed out that the construction of wind turbines requires extensive geological and geotechnical investigation as the soil supports the wind turbines and their loads. It was also pointed out that gravity foundations are preferred when possible, as they are of high strength, and they can assume the desired shapes of the needed design. At the same time, since the foundation design relies on the loading design provided by the wind turbine producers, a gravity foundation may be of excessive cost under generalized loading conditions, extreme scenarios, and high safety factors.

2. The Proposed Design of the Foundation System

In this study, the automated design process for a wind tower foundation is explored, focusing on the analysis of the input data, imposed constraints, and outcomes achieved through its implementation. Key input data include both the site characteristics and the specifications of the wind turbine. Site-specific factors include soil properties such as cohesion, internal friction angle, and soil unit weight, alongside environmental factors like wind speed, wind density, and local urban density, which influence wind effects on the turbine. The wind turbine specifications cover the typeof turbine—specifically onshore turbines for this study—and the rotational orientation of the turbine's hub, with this study concentrating on turbines with a horizontal axis rotation. This rotational characteristic dictates a rectangular foundation design. Additionally, general turbine parameters are accounted for, including tower height, blade length, the diameter of the swept area, and the diameter of the wind turbine tower.

The restrictions of this study are connected, first, to the satisfaction of the check against overturn, which is considered the most crucial, and then, to the check against bending, perforation, and shear of the foundation, the fulfillment of which are achieved to reduce the overall cost of the foundation. The parameters that are taken into consideration and identified after implementing the proposed methodology are the width of the foundation B, the length of the foundation L, the width of the beams at directions x and y, $t_{beamx} t_{beamy}$, the number of beams at directions x and y, n_x and n_y, and the wind of the wind turbine base at foundations b_{wx} and b_{wy}. The method analyzed and the numerical example that the method was implemented on are presented below, certifying the cost reduction in the foundation, while the stability and strengthen requirements are fulfilled.

3. Development of Proposed Automated Design Approach

3.1. Data Required by the Proposed Design Approach and Setting the Automated Design Problem

Wind turbines are primarily categorized based on their location and the orientation of their blade rotation. Depending on whether they are installed on land or at sea, turbines are classified as onshore or offshore. Additionally, they are distinguished by the axis of blade rotation, being either vertical or horizontal axis turbines. Another key distinction arises from the rotational behavior of the blades: turbines are classified as having a fixed rotation axis or a fully rotational (360°) axis. Each of these categories can be further analyzed based on the specific parameters that define their operation and design.

The method analyzed below can be applied to onshore wind turbines featuring a horizontal, unidirectional axis of stability, with a foundation characterized as a shallow foundation (spread foundation). The algorithm incorporates data associated with factors influencing the choice of foundation type and design. These factors encompass characteristics of the wind turbine, such as the total weight, including the tower and blades, tower height, tower diameter at the base, and its reduction in relation to height, as well as the diameter of the wind turbine blades. Additionally, the soil conditions should be inserted, including the soil internal angle f, the special weight of the soil c_{soil}, the cohesion factor c, and the maximum and minimum soil allowable stresses (σ_{max} and σ_{min}). Finally, the wind velocity at the area of the wind turbine installation should be provided V_{b0} (see Table 1).

Table 1. Data required.

Wind Turbine	Soil Condition	Wind Conditions
Total height	Soil internal angle (f),	Wind velocity (V_{b0})
Tower height	Special weight of the soil (c_{soil})	
Tower diameter at the base	Cohesion factor (c)	
Tower diameter reduction	Maximum allowable soil stress (σ_{max})	
Wings diameter	Minimum allowable soil stress (σ_{min})	

The data that will be sued as given information for the automated design analysis are inserted in the analysis as global data, as follows:

$$function : function[] = givendata()$$

where *givendata* are stored in a global structure g; global data are used because these data will exist and be used from the beginning of the program until the end, and there will be continuous references to them. A name is given to the global variable, and this provides accessibility and reference to the it when this variable is used in the code.

3.2. Variables of the Proposed Design

After inserting the data needed, part of which are given by the wind turbine manufacturer and part involve the location of the foundation of the wind turbine—so that all characteristics of the soil are known—there are two variables that need to be identified through a set of values that are inserted and based on the satisfaction of the Eurocode restrictions with the parallel cost minimization, and the final accepted values of the two variables are set. The variables of the proposed design are as follows: the width of the wind turbine foundation B, and the length of the wind turbine foundation L. The code for the variable set is presented below:

$$prob = optimproblem(\text{“}Description\text{”}, \text{“}FoundationOptimization\text{”});$$

$$function : L = optimvar(\text{“}L\text{”}, n); B = optimvar(\text{“}B\text{”}, n);$$

where the automated design problem is set and named ‘Foundation automated design’, and the variables L and B are set. The syntax for the creation of automated design variables according to MATLAB R2024a is

$$function : x = optimvar(name, n);$$

and it creates an n-by-1 vector of automated design variables.

3.3. Analysis of the Forces Applied on the System Wind Turbine—Foundation and Check Analysis

To identify the design of the wind turbine foundation, the loads on the system wind turbine–foundation should be specified. The relevant loads, as depicted in Figure 1, include the wind turbine self-weight W_w. This load is specified according to the foundation type and should be included in the wind turbine characteristics provided by the manufacturer. The wind force F_w defined according to the area of wind turbine allocation, according to the regulations of Eurocode 1, and the foundation self-weight W_G, which is derived by the foundation dimensions and the stress under the foundation s_{max} and s_{min} according to the soil. The wind turbine is founded, and the passive soil stresses P_p are developed due to the tendency of the foundation to overturn due to the wind force applied on the wind tower and the soil resistance.

It is important to clarify the functioning of the interface between the tower and the foundation. The connection is established using bolted components, with a plate serving as an intermediary to ensure secure and effective load transfer. This design choice ensures structural integrity and stability under various loading conditions. The foundation utilized in our study is a shallow foundation, chosen for its cost-effectiveness and suitability for onshore wind turbine installations. Our current research primarily focused on optimizing this shallow foundation to effectively manage and distribute the forces transmitted from the wind turbine. This includes addressing axial loads, shear forces, and bending moments, ensuring that the foundation can reliably support the operational demands of the wind turbine while maintaining structural performance and safety. By refining the shallow foundation design, we aimed to enhance its capacity to resist the dynamic loads generated by the wind turbine, thereby improving the overall efficiency and longevity of the wind energy system.

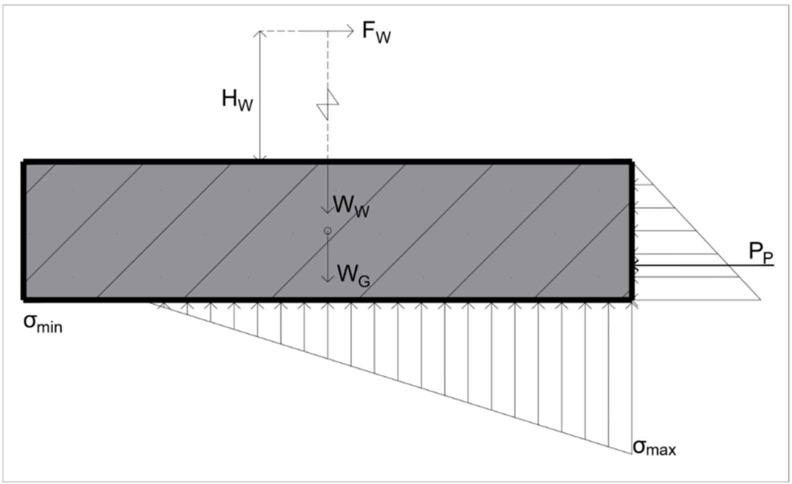

Figure 1. Forces applied on the wind turbine foundation.

The forces applied lead to specific checks that should be conducted, including the check against overturn in the x and y direction, the check against bending in the x and y direction, the check against shear, the check against perforation, and the check that verifies that the soil stress developed is within the approved soil limits. The crucial equation to be satisfied is the check against overturn. The overturn check requires more mass at the foundation without higher strength. So, a foundation with a lower quantity of concrete and supplementing with stones is proposed. As a result, the automated design procedure is focused mainly on this part. If the overturn equation is satisfied, the rest are also satisfied, while on the other hand, if all equations are reached and overturn is left, the analysis should be run again.

3.4. Design Objective—Criterion of the Proposed Design

In taking into consideration that the crucial equation to be satisfied is the check against overturn, the automated design process starts with the identification of the volume that is needed, as the overturn is prohibited. For this reason, a repetitive procedure is executed with cost minimization as a criterion, while the above-mentioned equations are satisfied as per Table 2. The criterion of the repetitive procedure is as follows:

$$C_{total} = C_{excavation} + C_{concrete} + C_{steel} + C_{backfilling} + C_{recycling} \tag{1}$$

where $C_{excavation}$ is the cost of the excavation, and the price varies depending on the soil quality; $C_{concrete}$ is the cost of the concrete procurement and pouring; C_{steel} is the cost of the procurement and installation of the steel reinforcement; $C_{backfilling}$ is the cost of the backfilling of the foundation from excavation products; and, finally, $C_{recycling}$ is the cost of the excavation material recycling.

Table 2. Checks that should be satisfied in the wind turbine–foundation system.

Type of Design Check	Importance
Overturn resistance	High
Bending resistance	Normal
Shear resistance	Normal
Perforation	Normal
Soil stress limits	Normal

The criterion is the function of the automated design problem, which, in our case, needs to be minimized. It should be highlighted at this point that only the cost of the concrete procurement and pouring are considered, omitting any framework cost. After installing the steel reinforcement of the foundation forming the steel beams, rock aggregates like those used for marine works are used to fill in the voids between the beams. The diameter of the aggregates is larger than the net distance between the steel bars of the beams, as they do not enter the beam area. In this way, the inserted rock items are forming the framework of the foundation, preparing it to receive the concrete and, at the same time, eliminate the framework cost. It is acceptable that very little concrete material will pass slightly at the adjacent layer between the steel and the rocks, as the whole foundation structure is basically serving the needs against overturn. As a result, the additional material of rocks used to contribute to the stability of the foundation is, at the same time, used to form the framework and reduce the overall cost of the foundation. It should be highlighted that taking into consideration that the wind turbine examined has a stable axis and is not rotated, the forces are calculated on two axes, one vertical and one horizontal, and the same applies for the reinforcement calculation.

4. Design Checks

For the rectangular foundation, at the x and y axis, the forces below are calculated for the foundation with width B, length L, and height H, and the relevant equations should be satisfied.

4.1. Stability Forces along Global y Axis

The foundation self-weight is defined by the following expression:

$$W_G = B \cdot L \cdot H \cdot g_c \tag{2}$$

where g_c is the specific weight for concrete. The wind turbine weight W_w is provided by the manufacturer. The passive forces from the soil are calculated as follows:

$$P_p = 0.5 \cdot s_h \cdot H \cdot B \tag{3}$$

where s_h is the horizontal stresses applied on the lateral limit of the foundation, which is in touch with the soil. It is equal to

$$s_h = K_p \cdot s_v \tag{4}$$

and s_v is the vertical stress of the foundation and soil interaction. It is equal to

$$s_v = g_{soil} \cdot H \tag{5}$$

where g_{soil} is the specific weight for the soil, and

$$K_p = tan^2(45 + 0.5 \cdot f) \tag{6}$$

where f is the internal angle of the soil. The stability moment is expressed as follows:

$$SM_{stability} = W_G \cdot (0.5 \cdot L) + W_W \cdot (0.5 \cdot L) + PP \cdot (0.67 \cdot H) \tag{7}$$

4.2. Overturn Forces at y Axis

The wind force Fw_y is calculated separately at the tower and at the wings. More specifically, the wind force at the wings is calculated according to Eurocode 1, §6.2 [28], counting the wings as a mesh where the wind is applied on. The final wind force is equal to

$$Fw_y = c_s \cdot c_d \cdot c_f \cdot q_p(z_e) \cdot A_{ref} \tag{8}$$

The wind force at the tower is calculated using Eurocode 1 (see §6.2) [28], taking into consideration the reduction in the diameter of the wind turbine tower as the height increases. It should be mentioned that on the y axis, the wind force applies only at the tower of the wind turbine as the vector of the wind force is parallel to the wings, while on the axis x, the wind force applied on the wind turbine is the sum of the wind force on the tower and the wind force on the wings as the wind force is applied vertically to the wings. As a result, the wind force on the x axis is higher than the one on the y axis.

$$FW_x = Fw_{wings,x} + FW_{tower,x} \tag{9}$$

$$FW_Y = FW_{tower,y} \tag{10}$$

This creates the expectations of the derived foundation to be rectangular with a larger dimension and to be parallel with the higher wind force. The overturn force is defined by the following expression:

$$SM_{overturny} = FW_y \cdot (0.67 \cdot H_w) \tag{11}$$

where H_w is the height of the wind turbine from the upper base of the foundation to the hub. The first expression to be satisfied is the following: $SM_{stability,y} = SM_{overturny}$, where $SM_{stability}$ represents the forces that tend to keep the foundation stable without overturning. These forces are the self-weight of the foundation, the self-weight of the wind turbine, and the passive soil stresses. On the other hand, $SM_{overturn}$ is expressed by the forces that tend to overturn the foundation. This force is the wind that applies on the wind turbine. The same process is followed for axis x, and the relevant forces are calculated, resulting in the prerequisite. The second equation to be satisfied is the following: $SM_{stability,x} = SM_{overturn,x}$.

The active applied moment on the y axis is equal to

$$M_{Ed,y} = SM_{overturn,y} \tag{12}$$

The moment applied on the foundation is equal to

$$M_{sd,y} = s_{sd} \cdot ({L_{D_T}}^2) \cdot B/8 \tag{13}$$

where

$$s_{sd} = (1.35 \cdot N_{total})/(B \cdot L) + (6 \cdot M_{total})/(B^2 \cdot L) + 1.35 \cdot g_{soil} \cdot t \tag{14}$$

where D_T is the diameter of the wind turbine tower at the point where it touches the foundation. t is the depth of the foundation. N_{total} is the sum of the total vertical forces that are applied on the foundation and are the wind turbine self-weight and foundation self-weight. $M_{total} = SM_{stability}$ is the sum of the stability forces that contribute to the prevention of the foundation overturn.

$$m_{sd} = M_{sd,y}/(B \cdot d^2 \cdot f_{cd}) \tag{15}$$

and the required reinforcement against bending is equal to

$$A_S y = w \cdot B \cdot D \cdot (f_c d/f_y d) \tag{16}$$

where

$$w = (A_s \cdot f_y d)/(B \cdot L \cdot f_c d) \tag{17}$$

The same procedure is followed for the axis x, and the relevant reinforcement AS_x is derived. For the foundations, the check against shear is also crucial. Consequently, the relevant check is included in the repetitive procedure. The acting force that causes shear on the foundation is the weight of the wind turbine.

$$V_{Ed} = V_{sd} = W_w \tag{18}$$

The strength of the foundation against shear is equal to

$$V_{Rd1} = (t_{RD} \cdot k \cdot (1.2 + 40 \cdot r_l) + 0.15 \cdot s_{cp}) \cdot B \cdot d \quad (19)$$

where t_{RD} is the concrete strength against tension in the presence of vertical compression, and k is the factor that represents the reduction in the concrete strength with the parallel increase in the static height, d, of the section. r_l is the percentage of the longitudinal reinforcement, which passes and is anchored after the section point with a potential crack. The presence of the longitudinal reinforcement constitutes the reduction in the crack opening and the effective aggregates intertwined. s_{cp} is the stress due to axial forces. With this factor, the beneficial role of the compressive forces in the increase in shear strength is taken into consideration. It should be noted that the following condition should be fulfilled: $V_{Ed} < V_{Rd1}$.

The repetitive process will stop when all the above equations are satisfied, and the cost is the minimum. After identifying the volume of the counter-weight, including the concrete and reinforcement needed for the wind turbine as per current regulations, the following step is to identify the excess of concrete. This will be derived by considering the foundation as a beam slab, taking into consideration that at the lower level of the foundation, a last layer of slab will be placed so that the forces transferred to the ground are equally spread. The forces that load the beam slab are the wind tower forces, which are transferred under the foundation as soil stresses and load the elements in sequence. The soil stresses are

$$s_{max} = N_{tot}/A + g_{soil} \cdot t + M_{final}/W \quad (20)$$

$$s_{max} = N_{tot}/A - g_{soil} \cdot t + M_{final}/W \quad (21)$$

So, the load applied on the slab beams is equal to

$$q_{sb} = \sigma_{max} \cdot b_{eff} \quad (22)$$

The effective width of each beam, denoted as b_{eff}, is considered for beams examined in both the x and y directions. The height of each beam, combined with the uniform part of the slab, equals the initial height of the foundation, H_F. In the x direction, the length of each beam matches the length of the initial single foundation, L, while in the y direction, it matches the width of the initial single foundation, B. The initial widths of the beams and the voids between them are set to random values. These values are then refined through an iterative process to determine the optimal beam and void widths. This optimization aims to minimize the shear reinforcement required for the beams and ensure that the entire foundation resists overturning. The beam and void widths also determine the number of beams in each direction. This automated process ultimately reduces the quantities of concrete and steel needed. Beams are evaluated for bending and shear in both the x and y directions. Regarding bending, the required reinforcement for each beam is calculated as follows:

$$A_s = M_{sd}/(d - h_f/2 \cdot f_{sd}) \quad (23)$$

where M_{sd} is the moment applied on the beam; d is the static height of the beam; h_f is the height of the uniform part of the beam slab and is equal to $0.25 \cdot d$, where d is the static height of the foundation; and f_{sd} is the characteristic quality of the steel. The beam is also checked against shear. The shear that the concrete compressive zones undertake is equal to

$$V_{Rd2} = 0.5 \cdot v \cdot f_{cd} \cdot b_w \cdot 0.9 \cdot d \quad (24)$$

where v is Poisson's ratio, f_{cd} is the design quality of concrete, b_w is the width of the beam in each direction, and d is the static height of the beam. The acting load of the beam, V_{sd}, should be less than V_{Rd2}. This reveals that the range of the compact zone is adequate. Then, the strength that the concrete of the beam can bear without any reinforcement is equal to

$$V_{Rd1} = (t_{RD} \cdot k \cdot (1.2 + 40 \cdot r_l)) \cdot b_w \cdot d \quad (25)$$

where b_w is the width of the beam in each direction. The shear that the shear reinforcement would undertake is equal to

$$Vw_d = V_{sd} - V_{Rd1} \quad (26)$$

The shear reinforcement percentage, r_w, that is required to sustain V_{wd} is compared with the minimum shear reinforcement, which depends on the quality of concrete and steel; $r_{w,min}$ is the lower bound, i.e., $r_w <= r_{w,min}$, and for this reason, we chose $r_w = r_{w,min}$ and set the minimum shear reinforcement. The reinforcement of the uniform part of the beam slab is equal to $A_{s,min} = 0.001 \cdot A_c$, where A_c is the area of the slab apart from the beams.

The reinforcement obtained for the slab beams against bending and shear is significantly reduced compared to the calculation for the entire foundation. This is because the minimum and maximum requirements are now calculated in sections with smaller dimensions. The voids between the beams will be filled in with stones, which may be either excavation product or brought on site through relevant soil storage. Filling with stones is mandatory as it contributes highly to the stability of the foundation and the overturn check. The criterion remains the minimization of the cost, and the design variables of the automated design process remain the width B and the length L, given by the equation below:

$$C_{total} = C_{excavation} + C_{concrete} + C_{steel} + C_{stonefilling} + C_{lightconcrete} + C_{recycling} \quad (27)$$

The distinction between the original and modified criteria lies in the nature of backfilling. In the original expression, backfilling is accomplished with soil, whereas in the modified one, stones are used, accompanied by the additional cost of lighter concrete filling. The current cost diverges from the initial one in two significant ways. Firstly, the cost of backfilling now encompasses filling voids with stones, and secondly, it incorporates the cost of light concrete—a lower-strength concrete layer placed over the stones to immobilize them. Notably, a critical modification is the recalibration of minimum and maximum reinforcement calculations, now performed on individual beams rather than the entire foundation. Each beam along the x and y axes undergoes scrutiny for both bending and shear stress.

This concluding stage results in the overall design of the structural system. The iterative process concludes upon reaching the minimum cost, considering the crucial check for overturn, which is now met by the slab beams, the overarching slab, and the filled stones. Additionally, compliance with checks for beam bending, beam shear, and slab bending between the beams is also ensured.

4.3. Flowchart of the Automated Design Process

The proposed automated design analysis is succinctly summarized in the diagram presented in Figure 2. This diagram meticulously outlines each step of our proposed methodology, providing a clear and comprehensive visual representation of the entire process. By following this diagram, readers can easily understand the sequential flow and interconnections between the various stages of our automated design approach. This detailed illustration serves as a valuable tool for grasping the intricacies and innovations of our method for enhancing onshore wind tower foundations.

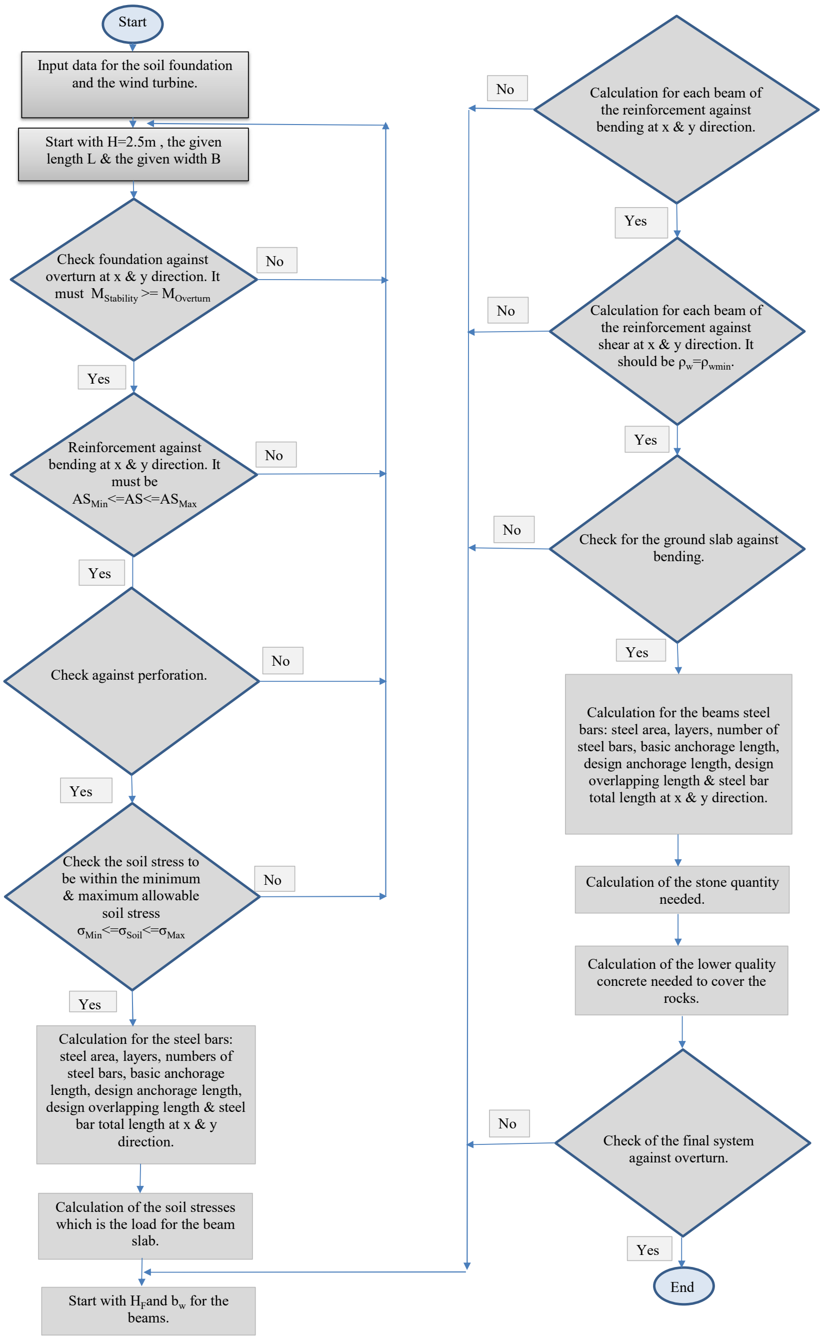

Figure 2. Flowchart of the automated design process.

5. Computational Analysis and Design Evaluation—The Case Study

To evaluate the previously outlined design methodology, a practical scenario was examined, focusing on the specifications of the wind tower for which the foundation system is to be devised. The pertinent characteristics of the wind turbine V52-850 kW from Vestas are detailed in Table 3, offering a comprehensive overview of essential parameters. Simultaneously, Table 4 delves into the characteristics of the underlying soil, providing crucial information that plays a pivotal role in shaping the foundation design. This use case serves as a concrete application of the proposed methodology, utilizing real-world data to test and validate the effectiveness of the design approach. The numerical investigation was implemented in Greece.

The wind speed impacting the wind turbine is considered to be 16 m/s. In using the equations and constraints specified in Eurocode 1 [29], the wind force is calculated as follows: $F_{wx} = 254.80$ kN and $F_{wy} = 228.84$ kN. As previously analyzed, the wind force is greater in one direction because it acts on both the tower and the blades, whereas in the perpendicular direction, it only acts on the tower.

Table 3. Wind turbine V52-850 (Vestas) characteristics.

Wind Tubrine Characteristcs	Value
Wind turbine height (Hw) (m)	86
Wings diameter (Dw) (m)	52
Wind turbine self-weight without the foundation (Ww) (kN)	1391.6

Table 4. Soil characteristics.

Soil Characteristics	Value
f (raD)	28
c_{soil} (kN/m^3)	22
c (kN/m^3)	120

The foundation dimensions are specified as follows: the foundation height (H_F) is equal to 2.5 m, the width (B) is equal to 11 m, and the length (L) is 13 m. The proposed methodology results in a rectangular foundation, with the longer dimension oriented to withstand the predominant wind force (see Figure 3). To begin constructing the foundation system, the first step involves excavating the foundation area to the specified dimensions plus an additional 10 cm in depth to allow for the pouring of lean concrete. For rocky soil, rock lateral walls created during excavation eliminate the need for a separate concrete framework. However, up to 2% more concrete may be required to fill potential recesses in the rocky soil. Conversely, with soft soil, an extra 10 cm must be excavated around the perimeter of the foundation to provide a working space for building the framework that shapes the foundation, ensuring that no concrete is lost. In both scenarios, after installing the steel components, concrete is poured, and measures are taken to protect it from adverse weather conditions. This comprehensive process ensures that the foundation is constructed with precision, taking into account soil characteristics and potential environmental variations during construction.

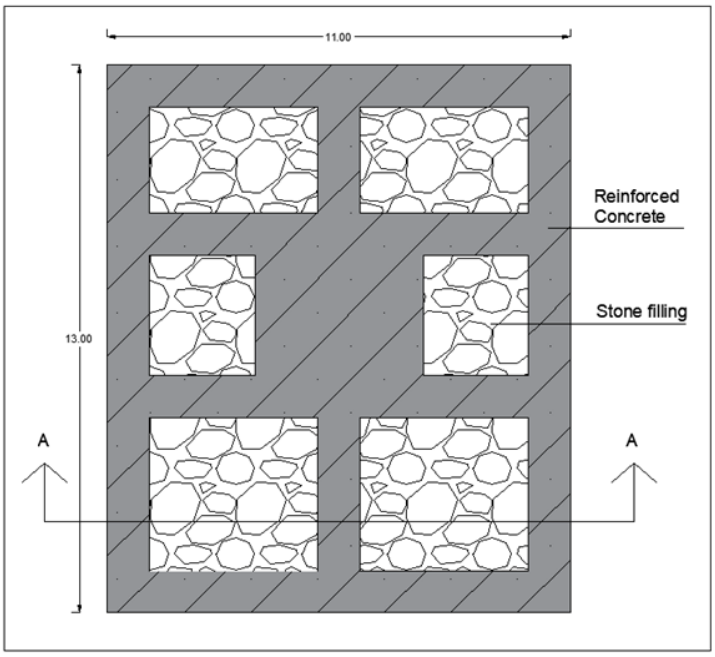

Figure 3. Lay out of the proposed foundation system.

In Figure 4, light concrete is used solely to cover the stones, ensuring that they remain securely in place. Table 5 details the quantity and cost associated with a single foundation following the specified procedure:

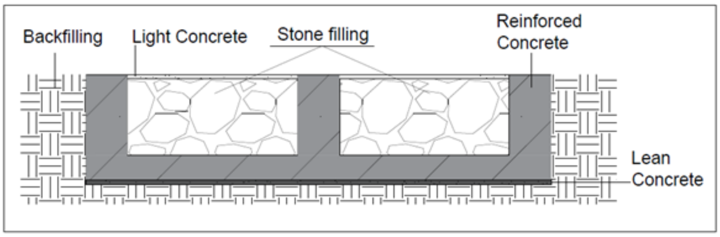

Figure 4. Section A of the proposed foundation.

Table 5. Cost calculation of single foundation.

Description	Unit Costs (MU)	Quantity	Cost: Rock (MU)	Cost: Soft Soil (MU)
Excavation/m^3 (rock)	18	357	6.435	
Excavation/m^3 (soft)	13	357		
Concrete price/m^3 (rock)	80	357	28,600	
Concrete price/m^3 (soft)	100	357		35,750
Steel price/kg (kg)	1.50	70,000	105,000	105,000
Recycling cost/m^3 (rock)	8	357	2900	
Recycling cost/m^3 (soft) (rock)	5	357		
Total Cost (soft) (rock)			143,000	147,200

After implementing the procedure analyzed above for the wind turbine automated design process, the excess concrete quantity is calculated, and it is expressed in voids for the under-discussion foundation system. The beams calculated in direction x are of a width equal to 1 m, and the void between them is 0.2 m, and in direction y, the beam width is 0.6 m, and the void between them is 0.2 m. As already mentioned, the width of the beams and the width of the voids are of crucial importance as they are selected so that the shear reinforcement needed for each beam is the minimum according to the regulation. The number of beams derived for direction x is equal to 9, and in direction y, equal to 16. As a result, we have a mesh of beams, and the stones will be placed between the beams. The full slab under the beams that comes in contact with the soil and distributes the forces at the ground was calculated to have a width equal to 0.6 m. For the additional site activities that will take place in the beam foundation, first, a different framework is needed to form the beams. The steel reinforcement is now placed in the formed beams and not in the whole area of the foundation. Secondly, backfilling activity will take place using either excavation materials, which may be rocks or soft soil, which will also need compression after backfilling, or rocky materials from deposit areas. Finally, low-quality concrete will be poured over the backfilling materials so as to avoid stone removal. The total quantity and cost are presented below Table 5.

It is clearly demonstrated that the implementation of our proposed study on real-world wind turbines within the relevant market aligns with our research findings and validates our innovative approaches. These innovations include a significant reduction in the quantity of concrete and steel used in the construction of wind turbine foundations. By optimizing material usage, we not only achieve cost savings but also streamline the construction process, thereby minimizing the overall time required for foundation installation. Moreover, our approach substantially reduces the environmental footprint of wind turbine installations. By cutting down on the materials needed, we lessen the environmental impact associated with their production and transportation. This commitment to sustainability ensures that our design not only meets industry standards but also contributes positively to environmental conservation efforts. In summary, the practical application of our study confirms the effectiveness of our strategies in reducing material consumption and construction time while enhancing the environmental sustainability of wind turbine foundations.

6. Results and Discussion

6.1. Analysis of the Numerical Investigation for the Wind Turbine Examined (V52-850 kW)

The current section is focused on analyzing the results of the examination of the proposed automated design implementation on the wind turbine foundation. The proposed foundation is a beam slab of reinforced concrete beams with voids that are filled in with excavation materials and covered with light concrete of C12/15 quality. The proposed analysis was conducted taking into account all aspects and restrictions targeting the reduction in cost, and the analysis aims to clarify how the soil quality affects the results (see Table 6).

Table 6. Cost calculation of beam foundation.

Description	Unit Costs (MU)	Quantity	Cost: Rock (MU)	Cost: Soft Soil (MU)
Excavation/m^3 (rock)	18	357	6.35	
Excavation/m^3 (soft)	13	357		4650
Concrete price/m^3 (rock/soft)	100	245	24,500	24,500
Steel price/kg (kg)	1.50	5300	7900	7900
Stone filling/m^3 (rock)	0.003	618,550	1850	
Stone filling/m^3 (soft)	0.010	618,550		
C12/15 procurement and pouring (m^3)	67	25	1650	1650
Total Cost			42,300	44,900

For this reason, the cost analysis of the single foundation, which includes steel reinforcement procurement and installation, as well as concrete procurement and pouring, was conducted for both rock and soft soils using the proposed method. In rock soil conditions, excavation costs were 27.7% higher compared to those in soft soil due to the difficulty of the excavation requiring tools like a hammer. However, in rock soil, there is no additional cost for concrete formwork since the rock walls serve as natural formwork, whereas in soft soil, formwork costs are included. Consequently, the overall concrete cost, including formwork, procurement, and installation, is 20% lower in rock soil conditions. The procurement and installation costs of steel are identical in both scenarios. Excavation materials must be recycled since they are not utilized in the construction process. The cost of rock recycling exceeds that of soil by 37.5%. Considering these factors, the total cost for a single foundation in rock soil is ultimately reduced by 3% (see Table 7).

Table 7. Single foundation on rock and soft soil—comparison (Increase: arrow up, Reduction: Arrow down, No change: dash).

Single Foundation	Soft Soil	Rock (the Coefficients Are the Percentage of the Cost for Soft Soil)	Status
Excavation Cost	a	$1.38 \cdot a$	↑
Concrete Framework, Procurement, and Installation Cost	b	$0.80 \cdot b$	↓
Steel Procurement and Installation Cost	c	c	-
Recycling of Backfilling Material Cost	d	$1.61 \cdot d$	↑

After implementing the aforementioned method analyzed in the previous paragraphs, the final cost for the foundation is reduced by 70% in the case of rock ground and by 69% in the case of soft soil. More specifically, the excavation cost for both rock ground and soft soil remains the same as in the case of the single foundation. The difference is due to additional activities that need to be executed for rock soil.

The concrete cost is reduced by 14% and 31% in the case of rock ground and soft soil, respectively, and the steel reinforcement installation is also reduced by 90% both in the case of rock ground and soft soil after comparing the single and the beam foundation. In the case of beam foundation, the cost of backfilling, which is the soil filling the voids between the beams, is added, which is 4.3% and 13.7% of the total cost in the cases of rock ground and soft soil, respectively. The cost of excavation material recycling is restricted only to the soft soil, and the procurement and pouring of low-quality concrete (indicative C12/15) is added to cover the rock backfilling, and it is 3.9% of the total cost for rock soil and 3.7% for soft soil. As far as the concrete and steel quality is concerned, the concrete quantity is reduced by 31%, while the steel quantity is reduced by 90% (see Tables 8 and 9).

It is crucial to clarify that the primary function of the rocky items within the foundation is to supply the necessary weight to counteract overturning forces. This weight ensures the stability of the structure, even if voids exist between the rocky items. The presence of these voids does not significantly impact the foundation's overall effectiveness in resisting such forces. In scenarios where the foundation is constructed on soft soil, compression techniques are employed to eliminate voids, thereby enhancing stability and load distribution. Conversely, when the foundation is situated on rocky soil, the inherent stability and load-bearing capacity of the rocky material render such compression unnecessary. The natural compactness and interlocking properties of rocky soil provide sufficient support, making additional void elimination redundant. This distinction between soft and rocky soil foundations underscores the adaptability and robustness of our design approach.

Table 8. Single and beam foundation—cost comparison for rock (Increase: arrow up, Reduction: Arrow down, No change: dash).

Related Cost	Single Foundation	Beam Foundation	Status (Increase, Reduction)
Excavation	a1	a1	-
Concrete Framework, Procurement, and Installation	b1	$0.85 \cdot b1$	↓
Steel Procurement and Installation	c1	$0.08 \cdot c1$	↓

Table 9. Single and beam foundation—cost comparison for soft soil (Increase: arrow up, Reduction: Arrow down, No change: dash).

Related Cost	Single Foundation	Beam Foundation	Status (Increase, Reduction)
Excavation	a2	a2	-
Concrete Framework, Procurement, and Installation	b2	$0.68 \cdot b2$	↓
Steel Procurement and Installation	c2	$0.08 \cdot c2$	↓

After stating the adaptability of the proposed automated study to any soil condition, the efficient usage of the steel reinforcement is presented so as to underscore the magnitude of the effective use of less steel versus the higher steel quantity.

It is important to note that despite the reduction in steel quantity from a single foundation to a beam foundation, the resistance against overturning is actually increased. This is because not all the steel in a single foundation is used for overturn resistance; a significant portion is dedicated to addressing bending, shear, and perforation resistance. In a single foundation, the minimum steel reinforcement must meet the requirements for the entire structure. Conversely, in a beam foundation, the necessary steel for bending, shear, and perforation resistance is calculated for individual beams, resulting in a reduction in the overall steel usage. This approach not only decreases the total steel required but also enhances overturn resistance by 20% for the beam foundation.

Focusing on the concrete quantity used, it should be mentioned that as with the steel reinforcement, the higher quantity of concrete is not equivalent with higher effectiveness, especially as far as the cost is concerned.

Despite the concrete quantity reduction, the overturn check is satisfied, and the resistance is increased. This improvement is due to the replacement of excess concrete with rocks, which provide additional resistance against overturning through their self-weight. Instead of incurring higher expenses for concrete to ensure overturn resistance, excavation materials are effectively utilized as counterweights, and the concrete used is restricted to the beams formed. Consequently, the overturn resistance is enhanced by 20% when transitioning from a single foundation to a beam foundation.

In summary, the key innovations of our proposed study bring several noteworthy advancements. First is the robustness of its implementation on any kind of soil, either rocky or soft. Second, the significant reduction in the quantity of concrete used in the foundation design directly translates to lower material costs and a reduced environmental footprint. Next, the near elimination of steel usage not only further decreases costs but also simplifies the construction process, making it more efficient and less labor-intensive. These material optimizations lead to a marked reduction in construction time, accelerating the overall construction procedure. This efficiency gain ensures that the foundation can be brought to full operational status much more quickly, which is crucial for meeting project timelines and reducing downtime. Overall, these advancements collectively enhance the feasibility and sustainability of wind turbine foundation construction, making it faster, more cost-effective, and environmentally friendly.

6.2. Impact Analysis of the Proposed Design Approach in Wind Farm Industry in Europe and Worldwide

Wind farm installations occur across Europe and the globe. It is crucial to investigate how the proposed foundation design might reduce construction costs and impact the overall cost of these wind farms. Wind energy projects comprise various cost components, each contributing a specific percentage to the total cost, as detailed in Table 10 [30]. Understanding the potential savings in foundation construction is essential to evaluating its effect on the overall project expenses.

Table 10. Cost contribution for wind turbine installation components [30].

Cost Center	Contribution (Percentage)
Turbine	68–84
Foundation	1–9
Grid Connection	2–10
Control Systems	1–2
Consultancy	1–3
Land	1–5
Financial Costs	1–5
Road	1–5
Total	**100**

The primary cost in wind farm construction is the wind turbine itself. The second major expense is the grid connection, which is the physical link between the wind turbine and the national grid, allowing electricity to be exported for public use. The foundation cost ranks third in terms of its share of the total construction cost, typically ranging from 1% to 9%. Other cost components represent a relatively small portion of the total cost. Considering that the wind turbine accounts for 20% to 25% of the total cost, excluding the turbine itself, maximizing the potential 9% savings on foundation costs can lead to significant overall savings. The foundation cost varies significantly by country, accounting for 32% of total turbine costs in Portugal and 24% in Germany. These variations are influenced by the size of the turbine and the country of installation. Overall, the cost per kilowatt (kW) for a wind farm installation, including all necessary components, ranges from 1000 MU/kW to 1350 MU/kW depending on the location [30]. Further studies were conducted focusing on the structural health monitoring of onshore steel wind turbines, specifically examining how the wind tower is affected by fatigue issues. These investigations aim to extend the lifespan not only of the tower itself but also of other critical wind turbine components, such as the blades and the hub. By addressing and mitigating fatigue-related challenges, these studies contribute to the overall durability and longevity of the entire wind turbine system; see the work of Simoncelli et al. [31].

To assess the impact of the proposed design approach combined with the new structural system for the footings, a sample list of wind farms currently being installed in Europe and worldwide is provided below. Tables 11 and 12 present information about the area and type of each wind farm, as well as the cost per kilowatt (kW). These data allow us to calculate the final cost of each farm and the total savings achievable from the foundation improvements.

Table 11. Cost savings achieved by implementing the proposed design approach and the novel structural system for the footings in wind farms in Europe.

Country	Number of Turbines	Total Power (kW)	Cost/Kw (MU)	Total Cost of the Wind Farm (MU)	Foundation Cost Share (7%) (MU)	Saving (69%) (MU)
Belgium	8	16,000	1250	20,000,000	1,400,000	966,000
Belgium	6	9000	1250	11,250,000	787,500	543,375
Belgium	1	2350	1250	2,937,500	205,625	141,881
Belgium	6	9000	1250	11,250,000	787,500	543,375
Germany	1	600	1300	780,000	54,600	37,674
France	8	5280	1200	6,336,000	443,520	306,029
France	6	9000	1200	10,800,000	756,000	521,640
France	5	3000	1200	3,600,000	252,000	173,880
France	13	9750	1200	11,700,000	819,000	565,110
France	5	11,500	1200	13,800,000	966,000	666,540
France	4	3000	1200	3,600,000	252,000	173,880
France	10	8000	1200	9,600,000	672,000	463,680
France	5	7500	1200	9,000,000	630,000	434,700
France	1	1500	1200	1,800,000	126,000	86,940
France	12	10,200	1200	12,240,000	856,800	591,192
France	2	4000	1200	4,800,000	336,000	231,840
France	6	9000	1200	10,800,000	756,000	521,640
France	5	12,000	1200	14,400,000	1,008,000	695,520
France	2	5000	1200	6,000,000	420,000	289,800
Total				**164,693,500**	**11,528,545**	**7,954,696**

Table 12. Cost savings achieved by implementing the proposed design approach and the novel structural system for the footings in wind farms worldwide.

Continent	Country	Number of Turbines	Total Power (kW)	Cost/kW (MU)	Total Cost of the Wind Farm (MU)	Foundation Cost Share (7%) (MU)	Saving (69%) (MU)
Oceania	Australia	20	12,000	1300	15,600,000	1,092,000	753,480
Oceania	Australia	20	12,000	1300	15,600,000	1,092,000	753,480
Europe	Belgium	8	16,000	1200	19,200,000	1,344,000	927,360
Europe	Belgium	6	9000	1200	10,800,000	756,000	521,640
Europe	Belgium	1	2350	1200	2,820,000	197,400	136,206
Europe	Belgium	6	9000	1200	10,800,000	756,000	521,640
North America	Canada	45	67,500	1350	91,125,000	6,378,750	4,401,338
North America	Canada	73	109,500	1350	147,825,000	10,347,750	7,139,948
Europe	France	8	5280	1250	6,600,000	462,000	318,780
Europe	France	6	9000	1250	11,250,000	787,500	543,375
Europe	France	5	3000	1250	3,750,000	262,500	181,125
Europe	France	5	11,500	1250	14,375,000	1,006,250	694,313
Europe	France	10	8000	1250	10,000,000	700,000	483,000
Europe	France	7	10,500	1250	13,125,000	918,750	633,938
Europe	France	5	7500	1250	9,375,000	656,250	452,813
Europe	France	12	10,200	1250	12,750,000	892,500	615,825
Europe	France	2	4000	1250	5,000,000	350,000	241,500
Europe	France	6	9000	1250	11,250,000	787,500	543,375
Europe	France	6	9000	1250	11,250,000	787,500	543,375
Europe	France	5	12,000	1250	15,000,000	1,050,000	724,500
Europe	France	2	5000	1250	6,250,000	437,500	301,875
Total				**428,145,000**	**29,970,150**	**20,679,404**	

The analysis of wind farms in Europe and worldwide indicates that significant cost savings can be achieved per wind farm if the proposed design practice and the novel structural system of the footing are adopted.

6.3. Future Trends: Integrating Steel 3D Printing Technology

As a future trend of this study, the integration of steel 3D printing technology into the manufacturing process of the wind tower's structural elements is anticipated. This integration aims to enhance the precision and customization of a superstructure–foundation system, leading to improved overall performance and efficiency.

6.3.1. Advancements in Steel 3D Printing

Steel 3D printing, also known as additive manufacturing, is a cutting-edge technology that allows for the creation of complex geometries and customized components with high precision. Unlike traditional manufacturing methods, which often involve subtractive processes, 3D printing builds structures layer by layer from a digital model. This approach not only reduces material waste but also enables the production of components that are tailored to specific engineering requirements.

6.3.2. Benefits for Wind Tower Foundations

The application of steel 3D printing in wind tower foundation systems presents several significant advantages. (i) Enhanced Precision: Three-dimensional printing technology allows for the creation of highly precise components, ensuring that the foundation system can be manufactured to exact specifications. This precision reduces the likelihood of errors during construction and improves the overall stability and performance of the wind tower. (ii) Customization: Each wind tower site has unique geological and environmental conditions. Three-dimensional printing enables the customization of foundation components to suit these specific conditions, optimizing the structural integrity and efficiency of the foundation system. (iii) Material Efficiency: In utilizing additive manufacturing techniques, the amount of steel and other materials required for construction can be minimized. This not only reduces costs but also aligns with sustainability goals by minimizing resource consumption. (iv) Speed of Construction: The ability to quickly produce customized components on-site or near the construction site can significantly reduce the time required for foundation installation. This streamlined process can lead to faster project completion and lower labor costs.

6.4. Implementation Challenges

While the integration of steel 3D printing technology offers numerous benefits, it also presents certain challenges that need to be addressed. (i) Technological Adaptation: The construction industry must adapt to new technologies and processes, which may require training and investment in new equipment and software. (ii) Quality Control: Ensuring the consistent quality of 3D-printed components is crucial. Rigorous testing and quality assurance protocols must be established to maintain the structural integrity of the printed elements. (iii) Regulatory Compliance: Compliance with existing construction standards and regulations, such as the Eurocode guidelines, must be ensured for 3D-printed components. This may involve updating current standards to accommodate new manufacturing technologies.

In addition to the challenges associated with 3D printing, the current study encountered several obstacles during the computational phase, which were successfully managed to overcome. The first major challenge was identifying the predominant phenomenon that needed to be addressed. After extensive analysis, it was determined that the primary concern was the risk of overturning. The wind exerts a horizontal force on the wind turbine, creating a moment at the top of the foundation that can lead to overturning. To mitigate this, all forces were considered to contribute to stability, including soil stresses and, most importantly, the self-weight of the foundation itself. Ensuring the foundation's stability against overturning also inherently satisfies the checks for penetration and bending, though the reverse is not necessarily true.

Once the overturning issue was resolved, the next challenge was determining the optimal shape of the wind turbine foundation. The shape is dictated by the forces it needs to withstand. Initially, a square foundation is used to assess the counterweight required to prevent overturning. Given that the wind force perpendicular to the circular area created by the wind turbine blades is greater than the force parallel to this area, a rectangular foundation proved more effective. The longer side of the foundation aligns with the greater wind force, and the shorter side with the lesser force. It is important to note that our study involves a wind turbine with a stable axis. If the axis were rotating, a polygonal or circular foundation would be necessary.

Another significant challenge was ensuring compliance with Eurocodes. All forces and phenomena in the conducted study had to be addressed according to Eurocode restrictions. The wind force applied to the wind turbine was analyzed and calculated following Eurocode 1, considering factors such as the turbine's location (urban, mountainous, or flatland), the shape and length of the blades, the circular area they cover, the height of the turbine, local wind speed, wind density, temperature, pressure, and soil quality. Additionally, checks for bending and perforation were conducted in accordance with Eurocode guidelines.

Further challenges faced were observed in identifying soil conditions at the turbine site, which are critical for calculating soil stresses that contribute to the overturning check. Soil conditions are part of the essential initial data for our study and are vital for accurate analysis. Identifying the wind turbine's characteristics was another challenge. This required coordination with wind turbine manufacturers and consulting brochures to obtain specific information, including the tower height and base diameter, blade length and diameter, and the self-weight of the turbine without the foundation. By addressing all these challenges, we were able to develop an optimized design for the wind turbine foundation, achieving significant cost and time savings while accelerating on-site construction.

6.5. Comparison with Existing Design Approaches

The need to enhance and optimize the current method of an onshore wind turbine's foundation results from the need to minimize cost and time during the design and construction phase. As already mentioned, the current tendency is to receive the wind turbine foundation designed by the wind turbine producers. In the past, some attempts were made to improve the way in which the wind turbine foundation is calculated.

One of these attempts aimed to avoid massive gravity foundations and design foundations using sophisticated 3D soil modeling and by entering material parameters, while the concrete is considered to have a nonlinear behavior [24]. Despite the intention to eliminate the cost, the aforementioned approach encountered the significant limitation of receiving the loads applied on the wind turbine from the wind turbine manufacturer, whereas the proposed study analyzed in the above paragraphs highlights the importance of calculating the wind force based on the Eurocodes and more specifically on Eurocode 1. An additional limitation is the fact that only the reinforced concrete is used as a counterweight to the structural system, while the proposed optimization method entails the removal of steel and concrete excess, which have high costs, and their replacement with soil material, which in most cases, are already available on site. Last but not least is the limitation of the focus on the soil conditions. This is a limitation because despite the fact that the soil conditions are of high importance to the structural system, they are not the basic factor that defines the stability of the wind turbine foundation. The proposed study clarifies that the basic factor is the self-weight of the wind turbine foundation that actually acts as a counterweight to the overturn tendency of the structure, and the soil pressure contribution is less important.

The analytical laboratory test conduction of testing and analyzing the behavior of wind turbine foundations, resulting in the potential removal of larger aggregates from the concrete and replacing steel with fibers, was another design approach that took place [18]. Despite the fact that the proposed methods may contribute to the improvement of the foundation materials, it should be highlighted that the previously mentioned study is followed by the limitation of the cost increase during the construction of the wind turbine due to custom-made concrete and steel production, while the proposed method presented in this paper makes effective use of the current well-approved way of concrete and steel construction without increasing the cost in this manner. An additional limitation is the lack of a full approach for the wind turbine foundation design itself, while the proposed study presents and underscores the force system applied on the wind turbine, how it affects the foundation, and how it could be optimized so as to eliminate the cost and the construction time.

Another approach was the creation of a meta-model development process that was based on establishing a database, where a generative design was proposed to be derived under given design constrains [20]. The critical limitation of this approach is that only the moment rotation behavior is considered an output, while the proposed study takes into consideration all the phenomena developed on the foundation. Furthermore, the specific approach bases its design on the database, while the foundation type, wind turbine, and soil conditions are unique and require a unique approach for their case study. Designing a wind turbine foundation based on a database and by creating models with specific restrictions may eliminate the computational time, but at the same time, it may impose the risk of leading to a result, based on statistical numbers, that leads to inaccuracy. Additionally, no actual cost control is calculated based on a database, as there should be calculation tailored for each situation. On the contrary, the proposed study faces each case of wind turbine foundations by taking into consideration the actual soil conditions, actual wind conditions, and actual wind turbine characteristics, and as a result, the design is unique, taking into account all restrictions and moreover complying with the Eurocodes. This underscores the safety and stability of the wind turbine design and, as analyzed, the significant elimination of cost and time.

Another approach is the critical review of three papers on the design approach for the wind turbine foundation [27]. Despite the fact that the importance of soil condition investigation and the nonlinear analysis of the structural system are highlighted, the critical limitation is that the papers under study base their design on the loading scenarios given by the wind turbine producers and not in certified restrictions as with the Eurocodes. Designing a wind turbine foundation by entering generic loads leads to excessive use of steel and concrete, which leads to unmanageable costs. In contrast, the proposed design approach analyzes the forces applied on the whole system of the wind turbine and foundation, follows the guidelines and specifications as determined in the relevant Eurocode, and analyzes how the forces applied on the wind turbine affect the foundation, finally resulting in the wind turbine foundation design and final reinforcement.

It should be highlighted that the current study presents a complete optimized solution of wind turbine foundations while taking into consideration all forces applies, all Eurocode restrictions, and all environmental restrictions, including the wind and soil conditions. This contrasts any attempts conducted until now and certifies the time and cost elimination of wind turbine foundations for the construction field.

7. Conclusions

This study introduces a novel approach used to design onshore wind turbine foundation systems, with the primary goal of attaining designs that are optimized in terms of cost limitations. The methodology was applied to a specific test case of a wind tower in Greece, and the resulting outcomes were thoroughly examined. The analysis incorporated factors such as soil and wind characteristics to arrive at conclusive findings. The key conclusions are outlined below:

1. A pivotal aspect that demands meticulous attention during the design process is the critical check against overturn. Regardless of the fulfillment of other design criteria, the design process cannot be deemed complete unless the overturn check is met. As a result, this check takes precedence, positioned as the primary consideration, with all subsequent checks conducted in a secondary phase. In essence, the entire design process hinges on the successful fulfillment of the overturn check, highlighting its paramount importance in the overall design procedure.

2. The most effective configuration for the wind tower foundation in order to undertake the moment applied on the foundation by the wind force applied on the wind turbine is a rectangular layout featuring beams extending in both directions. This optimal shape involves strategically filling voids within the foundation structure with soil material that contribute significantly to meeting the crucial criteria for overturn stability. In incorporating beams in both directions, the foundation gains structural robustness, while filling voids enhances overall stability. This design not only ensures an optimal foundation shape but also plays a pivotal role in satisfying the critical checks against overturn, thereby reinforcing the structural integrity of the wind turbine foundation.
3. Upon delineating the foundation as a unified structural system with designated dimensions, the surplus quantity of concrete is determined through an assessment of its resistance against shear forces. Subsequently, a significant reduction of up to 31% is applied to the final concrete quantity specifically at the beam foundation, compared to a full rectangular foundation. This meticulous process not only optimizes the overall material usage but also ensures that the concrete composition aligns seamlessly with the foundation's structural requirements. The reduction in concrete quantity at the beam foundation represents a targeted and calculated approach to streamline resources while maintaining the foundation's integrity against shear forces.
4. The steel reinforcement is calculated for the beams derived, and as a result, the minimum steel requirements are now implemented on beams and not on the whole foundation. The steel quantity is reduced by 90% at the beam foundation compared to the foundation without beams.
5. The cost for the wind tower foundation is calculated for the single foundation and for the beam foundation, taking into consideration the excavation, steel installation, concrete pouring, back filling, compressing, and light concrete cover, and it was derived that the final cost is reduced by 70% and 69% in the cases of rock ground and soft soil, respectively. As far as the construction time is concerned, it will be reduced due to the fact that less reinforcement needs to be installed and less concrete needs to be poured.

The integration of steel 3D printing technology into the manufacturing process of wind tower structures supported by the proposed foundation system represents a promising future trend in the field of green energy, as part of the project entitled "Additively Manufactured Optimized 3D Printed Steel Structures". By enhancing precision, customization, and efficiency, this technology has the potential to significantly improve the performance and sustainability of onshore wind tower foundations. As the construction industry continues to evolve, embracing innovative technologies like 3D printing will be essential for meeting the growing demand for renewable energy solutions.

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Abbreviations

The following abbreviations are used in this manuscript:

TW	Tera Watt;
MW	Mega Watt;
GW	Giga Watt;
kW	kilo Watt;
MU	Money Unit.

List of Symbols

Symbol	**Description**
f	Soil internal angle
c_{soil}	Special weight of the soil
c	Cohesion factor of the soil
σ_{max}	Maximum soil allowable stress
σ_{min}	Minimum soil allowable stress
Vb_0	Wind velocity
C_{total}	Total cost of the wind turbine foundation
$C_{excavation}$	Cost of the excavation of the wind turbine foundation
$C_{concrete}$	Cost for concrete pouring for the wind turbine foundation
C_{steel}	Cost for steel reinforcement of wind turbine foundation
$C_{backfilling}$	Cost for backfilling of wind turbine foundation
$C_{recycling}$	Cost for recycling of excavation material
W_G	Wind turbine foundation self-weight
B	Wind turbine width
L	Wind turbine length
H	Wind turbine height
g_c	Concrete special weight
P_p	Soil passive forces
s_h	Horizontal stress applied on the lateral limit of the foundation
K_p	Impel coefficient
s_v	Vertical stress applied on the lateral limit of the foundation
g_{soil}	Special weight of the soil
$SM_{stability}$	Total stability moment at the most distanced point of the foundation
W_W	Self-weight of the wind turbine
F_{Wy}	Wind force in the y axis
c_s	Size factor
c_d	Dynamic factor
c_f	Force coefficient
qp_{ze}	Peak speed pressure at reference height ze
A_{ref}	Reference surface
F_{Wx}	Wind force at x axis
$F_{Wxwings}$	Wind force at the wings in the x axis
$F_{Wxtower}$	Wind force at the tower in the x axis
F_{Wtower}	Wind force at the tower
$SM_{overturny}$	Total overturn moment at the most distanced point of the foundation in the y axis
H_W	Height of the wind turbine
$SM_{stabilityx}$	Total stability moment at the most distanced point of the foundation in the x axis
M_{Edy}	Active moment in the y axis
M_{RD}	Strength moment at the foundation
A_C	Foundation section area
f_{cd}	Concrete strength
A_{sy}	Steel reinforcement in the y direction

f_{yd}	Steel strength
z	Internal forces lever arm
AS_{min}	Minimum allowable steel reinforcement
AS_{max}	Maximum allowable steel reinforcement
V_{Ed}	Vertical designed action on the foundation that causes perforation
V_{sd}	Vertical action on the foundation that causes perforation
V_{RDc}	Strength of the foundation against perforation
k	Coefficient depending on static height d
f_{ck}	Designed concrete strength
d	Static height
a	Check distance
$V_{sd,par}$	Shear load on the foundation
V_{RD1}	Shear strength
N_{tot}	Total axial force
A	Area of the applied axial forces
t	Soil height
M_{final}	Final moment
W	Resistance moment
q_{sb}	Load applied on the slab beams
b_{eff}	Effective width of the slab beam
p_l	Reinforcement percentage
$C_{filling}$	Cost for filling the void of the beam foundation with stones
C_{light}	Concrete cost for covering the stones with light concrete

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