

Article

A Novel Approach to Mitigate Blade-to-Blade Interactions in Vertical-Axis Wind Turbines Suitable for Urban Areas

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Abstract

With the growth of urban zones and the increasing need for energy, the use of renewable energy solutions in the built environment becomes a must. Due to their small size and the ability to capture wind from any direction, vertical-axis wind turbines are an alternative to conventional wind energy generators. However, the use of these turbines in the built environment faces difficulties due to performance inefficiencies, particularly because of the intricate aerodynamic characteristics of the blades. This work investigates a method for increasing the efficiency of VAWTs by addressing blade-to-blade interactions using Computational Fluid Dynamics simulations. The research aims to improve turbine design for urban locations, which motivates the application context of the study. The present numerical model employs a uniform inflow to isolate blade–blade interaction mechanisms under controlled conditions. The paper presents a design that minimizes aerodynamic losses, decreases turbulence-induced drag, and increases overall energy capture efficiency by modeling different blade configurations and their interactions. The performance of four asymmetric configurations of blade chord and radius was numerically studied and compared to a symmetric configuration.

Keywords: renewable energy; vertical-axis wind turbine; urban integration; computational fluid dynamics; blade-to-blade interaction; power coefficient

1. Introduction

The integration of small vertical-axis wind turbines (VAWTs) into urban environments has gained increasing attention as cities seek decentralized, low-impact renewable energy solutions [1,2]. Unlike traditional horizontal-axis wind turbines (HAWTs), which require large physical space and relatively steady wind conditions, VAWTs are compact and capable of capturing wind from any direction [3,4].

These characteristics make them particularly suitable for rooftops, facades, and other constrained urban sites, where turbulent and multidirectional flows are common [5,6]. As cities strive to reduce carbon footprints and promote energy independence, VAWTs offer a promising pathway toward small-scale, locally generated renewable energy [7].

Figure 1 illustrates the comparison between HAWTs and VAWTs, highlighting the suitability of VAWTs for compact urban applications [8–10].

Despite these advantages, urban VAWTs face several aerodynamic and structural challenges. Their compact design often results in limited efficiency and pronounced un-steady loads, amplified by turbulence, wind shear, and gusts typical of urban wind fields [12,13]. Noise emissions, aesthetic integration, and material durability further complicate their deployment [14,15]. Advanced solutions—including optimized blade shapes, lightweight composite



Academic Editors: Ali Cemal Benim,
Dimitris Drikakis, Sergey A.
Karabasov and Jeffrey S. Marshall

Received: 15 December 2025

Revised: 16 February 2026

Accepted: 18 February 2026

Published: 2 March 2026

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materials, flexible blades, real-time control systems, hybridization with solar energy, and noise reduction strategies—have been developed to address these challenges [16–25]. Computational tools such as computational fluid dynamics (CFD) and finite element analysis (FEA) are now routinely employed to evaluate turbine performance, optimize geometry, and ensure mechanical integrity under realistic operating conditions [26–37].

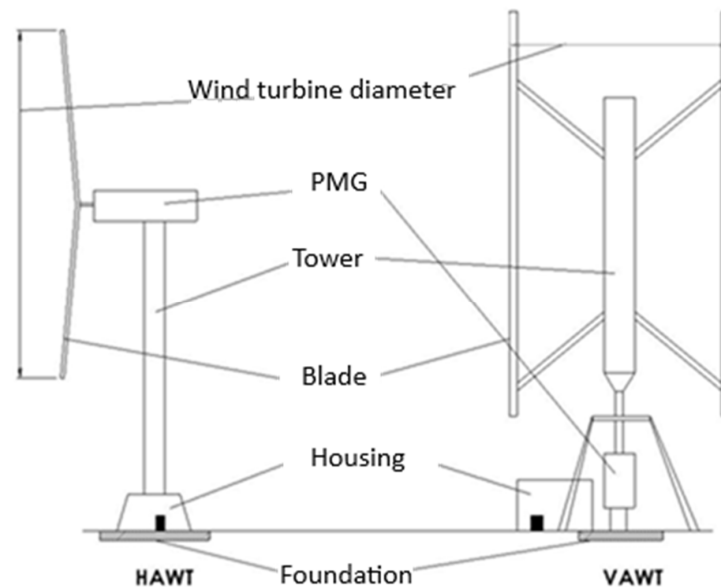


Figure 1. Comparison between Horizontal-Axis Wind Turbine (HAWT) and Vertical-Axis Wind Turbine (VAWT) (Adapted from Chaudhry, H. et al. [11]).

Figure 2 shows a CAD model of a VAWT designed for urban integration [38] and Figure 3 presents three examples of VAWT used in urban environments [39], while Figures 4–6 demonstrate how CFD simulations [40] and wind tunnel or field testing are used to assess performance, torque, and aerodynamic loading [41–45].

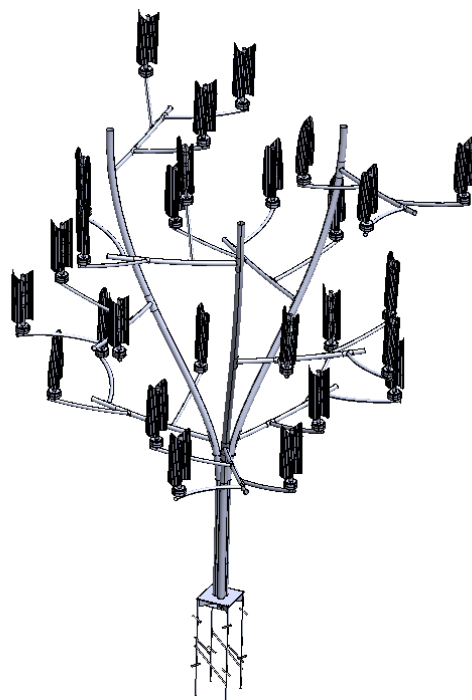


Figure 2. VAWT designed for urban integration—CAD model. Adapted from [38]. Available online: https://www.rolix.ro/proiecte_cercetare/copacel.htm (accessed on 17 December 2025).

The aesthetic integration of urban VAWTs with their surroundings is crucial. Turbines that function as architectural elements or art installations are a common topic of contemporary designs. This lessens resistance from locals and municipal planners who might be worried about the turbines' aesthetic impact.



Figure 3. Aesthetic Integration of VAWTs in Urban Architecture [39]. Available online: https://comoti.ro/wp-content/uploads/2023/11/Actualizare_paginaWeb_POC9_CrtSubs-3.pdf (accessed on 17 December 2025).

The continual feedback loop between design improvement and simulation ultimately opens the door for creative developments in compact VAWT technology [46]. It is anticipated that future simulations would integrate machine learning algorithms that can fore-cast ideal settings based on performance results and historical data as computing power progressively increases [47]. More effective and financially feasible compact vertical-axis wind turbines that may be used for a variety of purposes, from remote energy sources to urban environments, are anticipated as a result of the collaboration between sophisticated computational methods and engineering design [48].

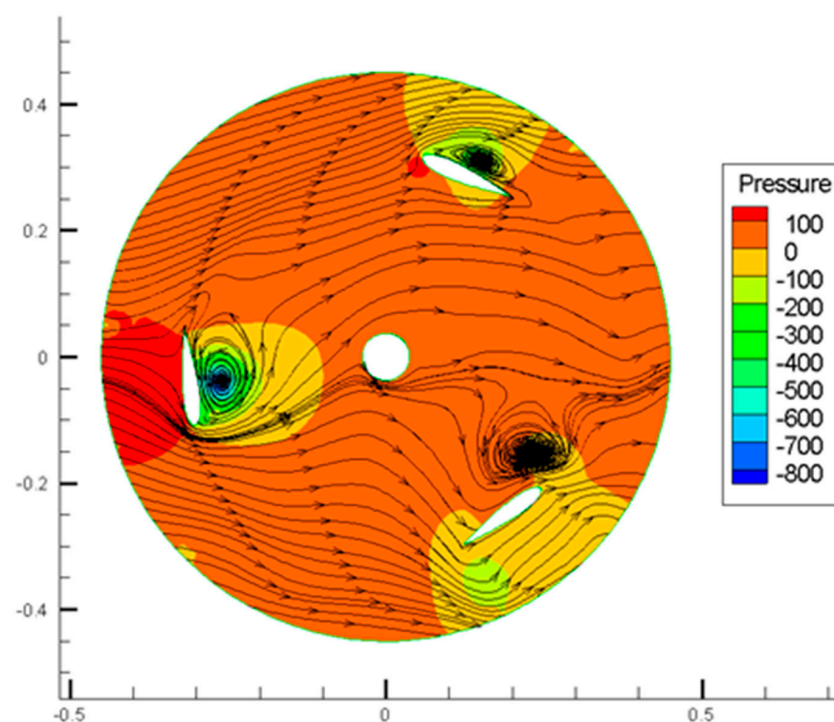


Figure 4. CFD Simulation of VAWT Performance (Pressure field) (Adapted from Mălăel et al. [49]).

The performance of small VAWTs must be verified by physical testing after a computational model has been created [50,51]. Field testing and wind tunnel testing are the two main experimental testing techniques. Wind tunnel testing is carried out in controlled settings where exact control over wind direction and speed is possible [52]. These experiments make it possible to assess the power production, efficiency, and noise levels of VAWTs as well as their aerodynamic characteristics. Prior to full-scale deployment, wind tunnel testing is a crucial stage in perfecting turbine designs.

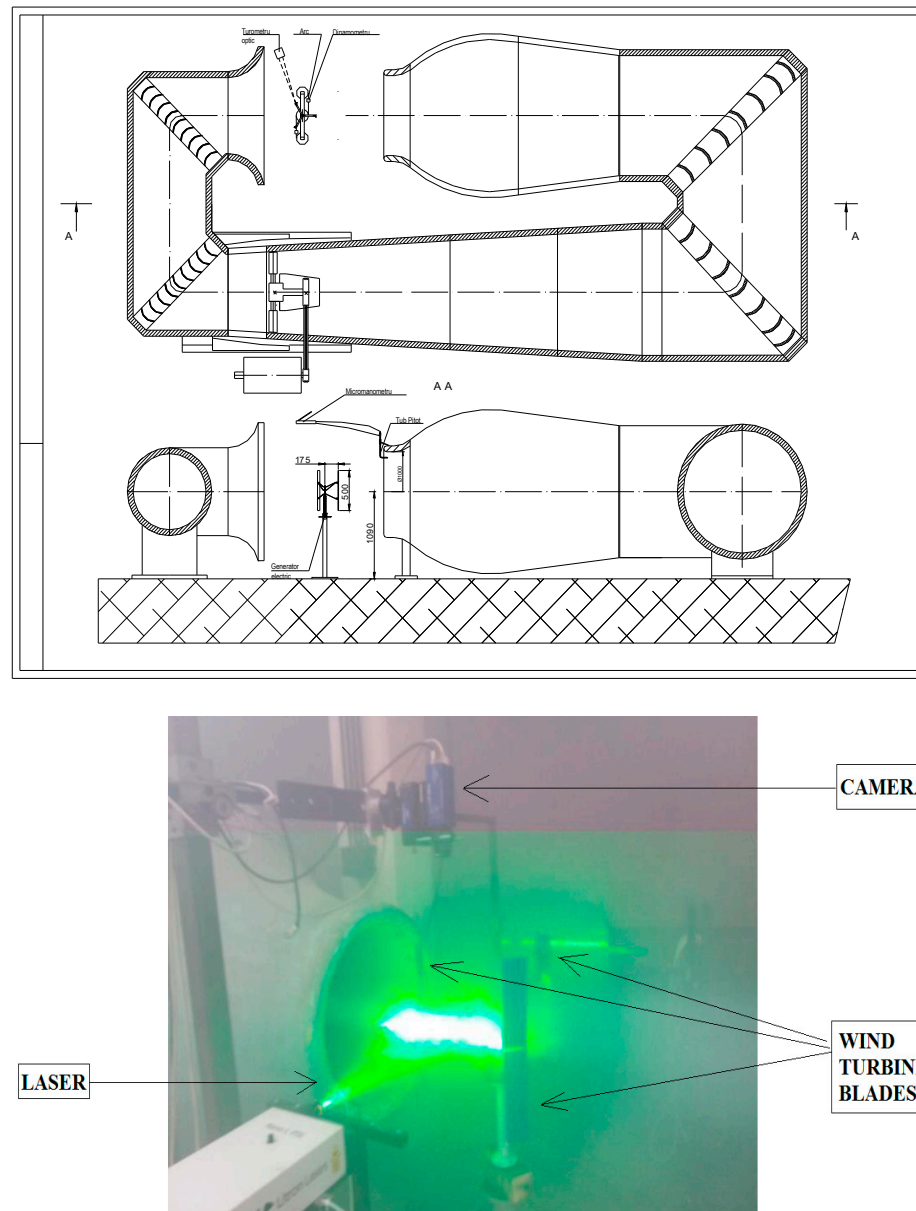


Figure 5. Wind Tunnel Testing Setup for VAWTs.

In contrast, field testing entails setting up small VAWTs in real-world urban settings, as on building facades or roofs [53]. These experiments are crucial for evaluating how well the turbine performs in actual wind conditions, which are sometimes far more erratic than those replicated in wind tunnels. Field testing data is used to improve turbine designs and make sure they can survive the difficulties and strains of urban wind conditions.



Figure 6. Field Testing of VAWT in Urban Environment [54]. Available at https://comoti.ro/wp-content/uploads/2023/11/Actualizare_paginaWeb_POC9_CrtSubs-1.pdf (accessed on 17 December 2025).

A central aerodynamic limitation of straight-bladed H-type VAWTs is blade-to-blade interaction, whereby the wake shed by an upstream blade affects the inflow of downstream blades. This phenomenon reduces power extraction, increases torque ripple, enhances unsteady loads, and can contribute to noise and fatigue damage. Blade-to-blade interaction is particularly significant in compact rotors with closely spaced blades and in urban settings where incoming flows are already distorted by surrounding structures [55]. While previous studies have explored strategies such as airfoil refinement, blade pitch control, variable solidity, and asymmetric or staggered blade configurations, most research has focused on global performance metrics or single-blade modifications. These approaches typically assume geometric symmetry, overlooking the fundamentally unsteady, azimuthally varying nature of VAWT aerodynamics. Consequently, wake–blade interaction remains a persistent performance limitation, even in otherwise optimized designs.

The research does not explicitly model urban atmospheric boundary layer effects, such as building-induced flow distortion, increased turbulence intensity, or wind-direction variability. Instead, a uniform inflow is intentionally adopted to isolate and analyses the fundamental aerodynamic mechanisms associated with blade-to-blade interaction within compact H-type VAWTs. The configurations investigated are representative of turbines intended for urban-scale deployment, but the results should be interpreted as comparative aerodynamic trends rather than site-specific urban performance predictions

The present study addresses this gap by deliberately introducing asymmetric variations in blade chord and radial position across individual blades of a single H-type VAWT, while maintaining the same blade count and overall rotor scale. Instead of conventional performance optimization, the objective is to de-phase wake–blade interactions azimuthally, reducing constructive wake overlap and smoothing the aerodynamic loading cycle. By controlling geometric asymmetry, this approach seeks to directly mitigate blade-to-blade interference and provide new insights into the aerodynamic management of VAWT wakes.

A systematic numerical investigation is carried out using two-dimensional unsteady Reynolds-averaged Navier–Stokes (URANS) simulations coupled with the $k-\omega$ SST turbulence model. Starting from a baseline three-bladed rotor, four modified configurations are examined by applying ± 5 –20% variations in blade chord and corresponding radial positions in an asymmetric manner. The study evaluates changes in torque evolution, wake structure, and overall power performance at representative operating conditions relevant to small urban VAWTs.

The present investigation is not formulated as an automated optimization problem. Although two-dimensional CFD allows relatively fast computation, the objective of the

study is to isolate and understand the physical mechanisms by which controlled blade-to-blade geometric asymmetry influences wake interaction and torque evolution.

Automated optimization frameworks typically focus on maximizing global objective functions, such as the power coefficient, and may obscure the underlying aerodynamic mechanisms driving performance changes. In contrast, the parametric approach adopted here enables direct interpretation of how individual chord–radius redistributions affect blade loading and wake interaction. The results are therefore intended to inform future optimization or design automation studies rather than replace them.

2. Numerical Setup

2.1. CAD Model

The innovative vertical-axis wind turbine model for urban integration is the main topic of this study. The new model is created from the baseline rotor, which has a straight H shape and three unstaggered blades; Figure 7 shows the turbine layout and coordinate system of one of the new configurations. This configuration is designed to maximize efficiency while minimizing the blade-to-blade impact and visual impact in urban environments.

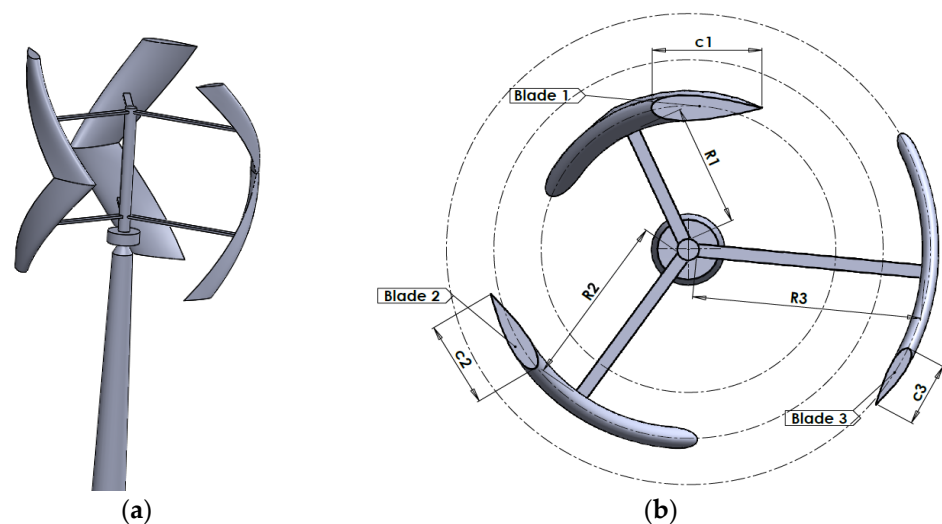


Figure 7. (a) 3D CAD VAWT experimental model; (b) top view [56].

According to the concept, the new turbine is made up of a supporting pole on the upper side that has an electric generator attached to the rotor shaft. On the upper side of the pole are supporting arms with blades fixed at the extremities. These arms have different lengths of radii $R1 < R2 < R3$, and they have aerodynamically profiled blades with chord profiles $c1 > c2 > c3$ that vary in length. This means that the arm with the longest chord is the shortest supporting arm, and the arm with the shortest chord is the one with the longest supporting arm. This configuration allows for optimized aerodynamic efficiency, as the varying lengths and profiles of the blades can better harness wind energy at different speeds. Consequently, the design maximizes the rotor's output by ensuring that each blade operates effectively within its specific radius. The innovative design of the rotor, characterized by its diverse blade lengths and profiles, demonstrates a remarkable approach to enhancing aerodynamic efficiency. By strategically supporting the longest chord blades with the shortest arms, this design not only optimizes the harnessing of wind energy across varying speeds but also ensures that each blade operates effectively within a specified radius. This thoughtful integration of engineering principles ultimately maximizes the rotor's output, reflecting a commitment to both performance and sustainability in energy production. Such advancements pave the way for more efficient renewable energy solutions

that can adapt to the ever-changing dynamics of wind resources. Table 1 lists the primary geometrical features of the baseline turbine under consideration.

Table 1. Baseline VAWT parameters.

Parameter	Value	Units
Power (design target)	2000	W
Wind Velocity	12	m/s
Rotor diameter	1.95	m
Blade height	2.93	m
Chord	0.228	m

In this work, four novel geometries that were generated from the baseline were selected for numerical investigation. Beginning with the baseline, the new configuration was established by applying a certain percentage to the values from Table 1. For instance, case 1, where the 5% ratio was applied, saw the blade 1 chord (c_1) increase by 5% and the radius (R_1) decrease from the baseline, the blade 2 chord (c_2) and the radius (R_2) remain unchanged from the baseline, and the final blade 3 chord (c_3) decrease by 5% and the radius (R_3) increase in relation to the baseline configuration. The values for all of the new configuration settings are shown in Table 2.

Table 2. New configuration parameters.

	c [m]			R [m]		
	Blade 1	Blade 2	Blade 3	Blade 1	Blade 2	Blade 3
Case 1–5%	0.239	0.228	0.217	0.928	0.977	1.026
Case 2–10%	0.251	0.228	0.205	0.879	0.977	1.075
Case 3–15%	0.262	0.228	0.194	0.830	0.977	1.123
Case 4–20%	0.274	0.228	0.182	0.782	0.977	1.172

The geometric modifications listed in Table 2 were not intended as a conventional performance optimisation exercise. Instead, the primary objective was to investigate the effect of a controlled asymmetric redistribution of blade chord and radial position on blade-to-blade aerodynamic interaction within a single rotor.

By increasing the chord and reducing the radius of one blade while applying the opposite trend to another blade, the study aims to de-phase wake–blade interaction azimuthally and to reduce constructive overlap between blade wakes. The intermediate blade maintains the baseline geometry and serves as a reference within the same rotor.

The selected variation range of ± 5 –20% was chosen to remain within a moderate and manufacturable design envelope, avoiding drastic changes in rotor solidity, swept area, or structural feasibility, while still allowing meaningful modification of interaction dynamics.

To quantify the geometric impact of the asymmetric redistribution, the global rotor solidity was evaluated for each configuration using:

$$\sigma = \frac{\sum_{i=1}^3 c_i}{2\pi R_{nom}} \quad (1)$$

where c_i represents the individual blade chord lengths and R_{nom} is the nominal baseline rotor radius used in the tip-speed ratio definition. The calculated solidity variation across all configurations remains equal to the baseline value (0% deviation), while the maximum swept area variation, corresponding to the 20% redistribution case, remains below 20%. These results confirm that the global blade area remains constant and that performance differences are not driven by increased blade solidity. Instead, the observed aerodynamic

behaviour is primarily associated with the azimuthal redistribution and de-phasing of wake-blade interactions induced by the asymmetric blade arrangement.

The baseline geometry considered in this study corresponds to a straight-bladed H-type vertical-axis wind turbine developed for research purposes within the author's research group. The rotor is not derived from a commercial turbine currently in operation, but represents a reference configuration designed to be representative of small urban VAWTs in the 1–2 kW power class.

The baseline rotor was defined for a nominal electrical power output of 2 kW at a reference wind speed of 12 m/s, which is commonly adopted as a design point for compact urban wind energy systems. The geometric parameters listed in Table 1 were selected to ensure realistic blade Reynolds numbers and rotor solidity values consistent with those reported in the literature for small straight-bladed VAWTs.

The CAD geometry was created by the authors specifically for numerical investigation and is not sourced from an open-access database. Similar baseline configurations and numerical setups have been employed in previous peer-reviewed studies by the author, ensuring methodological continuity and consistency across investigations.

2.2. Computational Model

Using the ANSYS CFD v24 software suite, flow investigations were conducted as the first step in evaluating the efficiency of these novel combinations. A rotor domain, which includes the three blades and the shaft, and a stator domain, which surrounds the rotor's domain, make up the two subdomains of the 2D computational domain for the numerical analysis. Through a specified interface, the subdomains are linked together. This setup allows for a detailed analysis of fluid dynamics by enabling interaction between the rotating blades and the surrounding stationary components. Such a framework is crucial for accurately assessing how these novel combinations perform under operational conditions. The 2D computational domain analysis stands as a pivotal element in understanding the intricate dynamics of systems composed of three blades, a shaft, and a stator domain. This interconnected framework not only facilitates detailed fluid dynamics analysis but also provides essential insights into the performance of innovative configurations under various operational conditions. By meticulously examining these components and their interactions via a specified interface, we can accurately assess the efficiency and efficacy of novel combinations. Ultimately, this approach empowers advancements in design and optimization, fostering the development of more effective engineering solutions moving forward.

A 2D computational domain for a CFD simulation of a VAWT comprises a cross-sectional slice of the physical region where the turbine functions, defined by an inlet and an outlet. The inlet boundary condition depicts the entering wind, which was created using a velocity inlet condition with a wind speed of 12 m/s and an X direction. At the outlet, a pressure outlet condition was used, with the pressure adjusted to a reference value, enabling the flow to escape the domain freely. The turbine blades are handled with a no-slip wall condition, which ensures that fluid velocity is zero at the blade surface, and the rotational motion is represented using a rotating reference frame. In the far-field zones, symmetry requirements were used to simulate an idealized, infinite domain and avoid boundary effects from distorting the results. Figure 8 depicts a $20D \times 40D$ computational domain focused on wind turbines, based on previous experience [57,58].

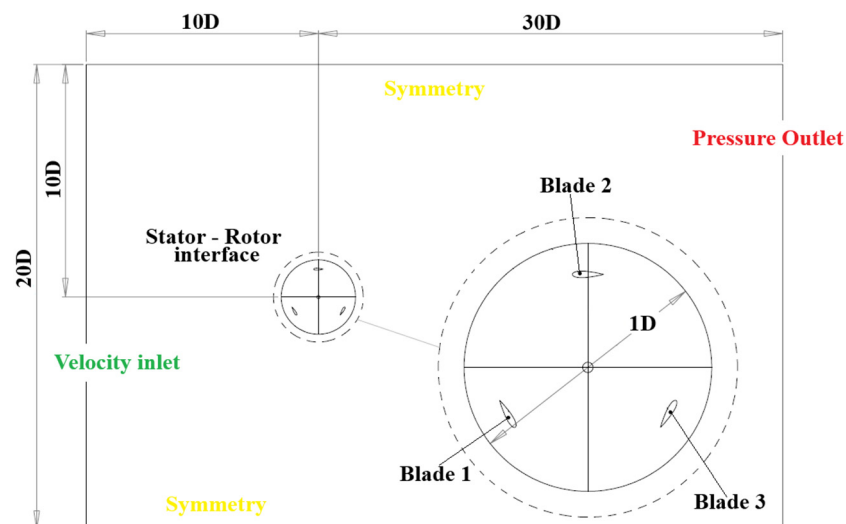


Figure 8. 2D—Computational domain.

In order to generate the 2D mesh in ICEM CFD v24, the blocking approach (Figure 9) entails building a structured grid that faithfully captures the geometry of the turbine and the flow domain around it (1). First, the computational domain is defined using an appropriate blocking structure (2), usually by splitting the flow region into a sequence of hexahedral blocks. The rotor dynamics of the turbine, including its rotation and interaction with the wind flow, are captured by the mesh (3) thanks to the careful manipulation of these blocks to fit the VAWT's geometry. Especially in areas close to the turbine blades (4), where great precision is required, the blocking approach helps regulate refinement zones while maintaining mesh quality. The mesh is created after the block structure is defined, guaranteeing that it can manage the intricate aerodynamic behaviour of the VAWT on a 2D plane while preserving the computational model's resilience and efficiency. The meticulous process of mesh creation for Vertical-Axis Wind Turbine (VAWT) geometry highlights the importance of strategic manipulation and blocking techniques. By adapting blocks to align perfectly with the complex contours of VAWT designs, refinement zones are instituted near turbine blades, ensuring enhanced aerodynamic behaviour without compromising mesh quality. This systematic approach not only facilitates a high standard of mesh integrity but also underscores the resilience and efficiency of the computational models used in simulations. The resultant mesh, born from a well-defined block structure, serves as a critical foundation for advancing VAWT performance studies, paving the way for more effective wind energy solutions.

The Ansys Fluent v24 commercial CFD tool was used to solve the two-dimensional Unsteady Reynolds-Averaged Navier–Stokes (URANS) equations, as well as the momentum and continuity equations, for velocity and pressure field simulations. The control volume approach is used in conjunction with the Semi-Implicit Method for Pressure-Linked Equations (SIMPLE) velocity–pressure coupling algorithm, as well as second-order upwind discretization. The $k-\omega$ SST turbulence model [59], often used for incompressible flows, was utilized to determine turbulence kinetic energy and specific rate of dissipation inside the model. The model's capability was further enhanced by implementing a grid refinement technique, which improved accuracy in regions with high gradients. This combination of methodologies allows for a robust analysis of complex flow behaviour in various engineering applications. Previous studies [60,61] used the $k-\omega$ SST transport model for VAWT designs.

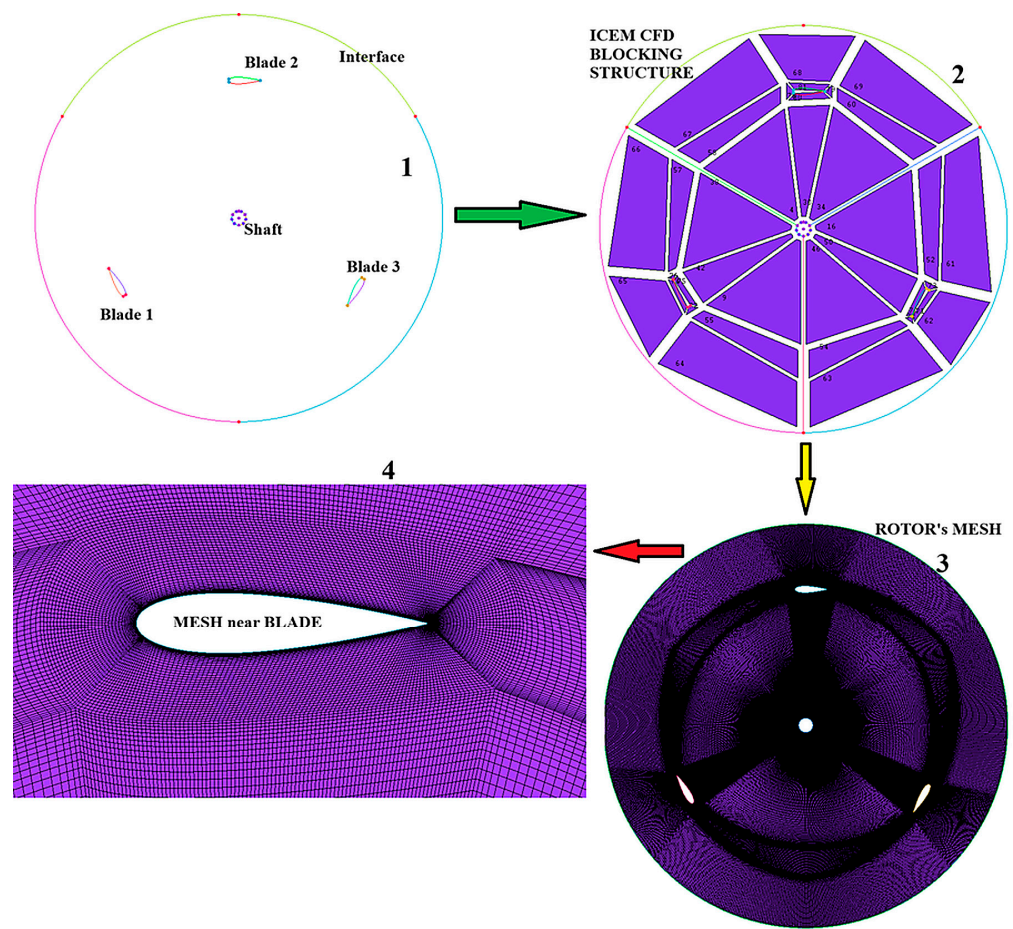


Figure 9. 2D—VAWT rotor's mesh procedure.

The numerical methodology adopted in this study is based on two-dimensional unsteady Reynolds-averaged Navier–Stokes (URANS) simulations coupled with the k - ω SST turbulence model. This approach is widely used in the literature for the comparative analysis of vertical-axis wind turbine (VAWT) configurations due to its favorable balance between computational cost and physical fidelity, particularly when investigating parametric trends and relative performance differences.

In the context of this work, the use of a 2D URANS framework is justified by the study's primary objective, which is to compare relative changes in blade-to-blade interaction mechanisms induced by controlled geometric asymmetry. Since all configurations are analysed using the same numerical assumptions, turbulence model, and operating conditions, the comparative trends observed between the baseline and modified rotors remain meaningful.

The baseline configuration, numerical setup, and turbulence modelling approach are consistent with previously validated methodologies reported in the literature for straight-bladed H-type VAWTs operating at similar Reynolds numbers and tip-speed ratios. The grid-dependency analysis further supports the numerical robustness of the adopted setup. Future work will focus on extending the present analysis to three-dimensional simulations and on experimental validation through wind tunnel testing. Such efforts will allow a more comprehensive assessment of three-dimensional flow effects, structural loading, and acoustic behaviour, and will enable quantitative validation of the interference mitigation strategy proposed in this study.

The turbine performance is analyzed in terms of the tip-speed ratio (TSR), defined as $TSR = \omega R / U_\infty$, where ω is the angular velocity of the rotor, R is the nominal rotor

radius, and U_∞ is the inlet wind velocity. The rotor motion was modelled using a sliding mesh approach, allowing full unsteady interaction between the rotating rotor domain and the stationary outer domain. Simulations were performed at $TSR = 2.0$ and $TSR = 3.0$, which are representative operating conditions for small straight-bladed H-type VAWTs and commonly reported in the literature.

The unsteady simulations were performed using a fixed angular increment per time step, corresponding to a rotor rotation of $\Delta\theta$ (1 degree) per time step. Each case was simulated for multiple rotor revolutions until periodic behaviour of the torque signal was achieved. Convergence was assessed based on the stabilization of cycle-to-cycle torque evolution and residual reduction below standard solver thresholds. Performance quantities reported in this study correspond to phase-averaged values obtained over several fully converged rotor revolutions. Each case was simulated for 10 rotor revolutions, and statistical data were collected only after periodic behavior was achieved. Periodicity was verified when the cycle-to-cycle variation in the mean torque coefficient fell below 1%.

The inlet turbulence intensity was set to $I = 5\%$, with a turbulence length scale of $L = 0.07D$, consistent with typical engineering CFD practice.

In order to quantitatively evaluate the unsteady loading behaviour, a torque ripple metric was introduced. The torque fluctuation over one rotor revolution was assessed using the standard deviation of the total torque coefficient:

$$\sigma_{C_t} = \sqrt{\frac{1}{T} \int_0^T (C_t - \bar{C}_t)^2 dt} \quad (2)$$

where C_t represents the instantaneous total torque coefficient and $\bar{C}_t$ is its mean value over one revolution. This metric enables an objective comparison of cyclic loading levels between the baseline and asymmetric configurations.

2.3. Grid Dependency

Because the flow around the blades is so complicated and unstable, grid dependence has a particularly large influence on VAWT simulations. A VAWT's rotating blades interact with the turbulent airflow to produce intricate aerodynamic phenomena that change in position and time. Incorrect estimates of the turbine's aerodynamic forces, power production, and efficiency might result from a coarse grid's inability to resolve important aspects of the flow. On the other hand, a too-fine grid would provide more in-depth information, but it would also demand more memory and processing power. Therefore, in grid-dependent CFD simulations for VAWTs, finding a balance between computing efficiency and accuracy is crucial, and careful grid resolution consideration is necessary to produce accurate and useful results.

The goal of a grid-dependent computational fluid dynamics (CFD) simulation of a vertical-axis wind turbine (VAWT) is to examine the effects of varying grid resolutions on the simulation's accuracy and convergence. More intricate flow features, including turbulence, vortex shedding, and wake effects, may be captured by the simulation as the grid resolution rises. These features are crucial for precisely simulating the turbine's operation. More computer resources are needed for finer grids, though, and this can result in more expensive and time-consuming simulations.

Adequate mesh was analyzed during the procedure to identify the grid's effect on the numerical evaluation of the VAWT performance. In this method, three grids were generated with different expansion ratios (Table 3), resulting in a coarse mesh with 130 k cells, a medium mesh with over 190 k cells, and a fine mesh with over 300 k cells. A coarser mesh size with a 1.3 expansion ratio overestimates the torque, but a refined mesh size with a 1.1 expansion ratio computes a similar solution to the medium one, a 1.2 expansion

ratio, but at a higher computational cost (Figure 10). This indicates that while finer meshes can provide more accurate results, they also demand significantly more computational resources. Thus, selecting the appropriate mesh expansion ratio is crucial in balancing accuracy and efficiency in computational fluid dynamics simulations. For all the remaining CFD simulations, the mesh with a 1.2 expansion ratio was used. The selected grid resolution was therefore adopted for all subsequent simulations to ensure a consistent balance between numerical accuracy and computational cost across all configurations.

Table 3. Key grid characteristics used in the grid sensitivity analysis.

	Cells	Faces	Nodes
Ratio 1.1	300,631	605,252	302,845
Ratio 1.2	194,399	392,758	196,583
Ratio 1.3	132,241	268,382	134,365

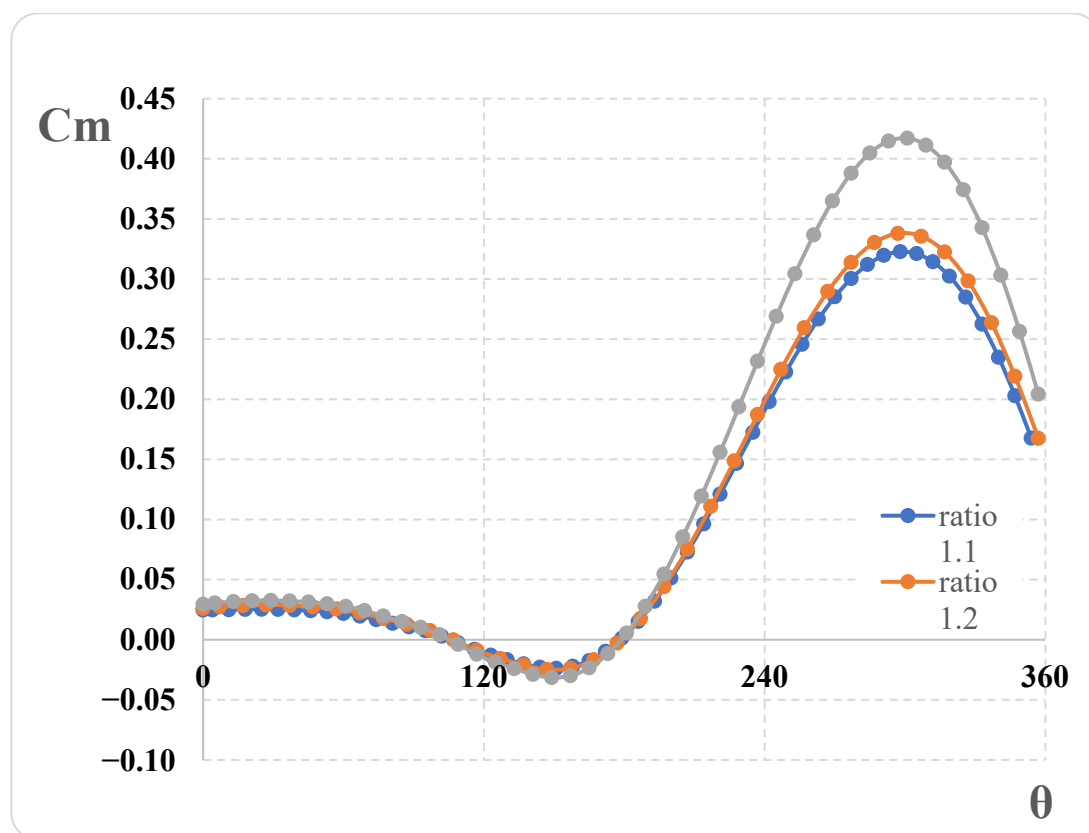


Figure 10. Grid size's impact on the baseline case's accuracy at TSR = 2.0.

3. Results and Discussions

In this study, a series of modifications were applied to the geometry of a Vertical-Axis Wind Turbine (VAWT) to investigate how changes in blade chord and radius impact the turbine's performance. The primary goal was to reduce blade-to-blade interactions, which are known to affect the aerodynamics and efficiency of VAWTs. The simulations, conducted using Ansys Fluent CFD, included five different configurations: the baseline turbine and four modified geometries with varying chord and radius adjustments. Each modification represented an increase or decrease in the blade parameters by 5%, 10%, 15%, and 20%.

The results revealed that the changes in blade geometry had a significant impact on the aerodynamic performance of the VAWT. As expected, modifying the chord length and radius altered the turbine's power output and efficiency. The baseline turbine pro-

vided a standard of comparison, with its design yielding 2000 W of power. However, its performance was limited by the significant blade-to-blade interactions that reduced the overall aerodynamic efficiency. The baseline configuration showed a steady but suboptimal performance compared to some of the modified geometries.

When the chord length was increased by a given percentage and the radius was reduced proportionally, the performance showed a noticeable improvement in certain configurations. The increase in chord length likely enhanced the lift generated by each blade, while the slight reduction in radius may have reduced the effects of blade interaction with the wake of the preceding blade. This suggests that the balance between chord length and radius is critical in minimizing drag and maximizing lift for optimal power generation.

The evolution of the torque coefficient at TSR = 3 for all four modified geometries in comparison with the baseline is shown in Figure 11 for each blade.

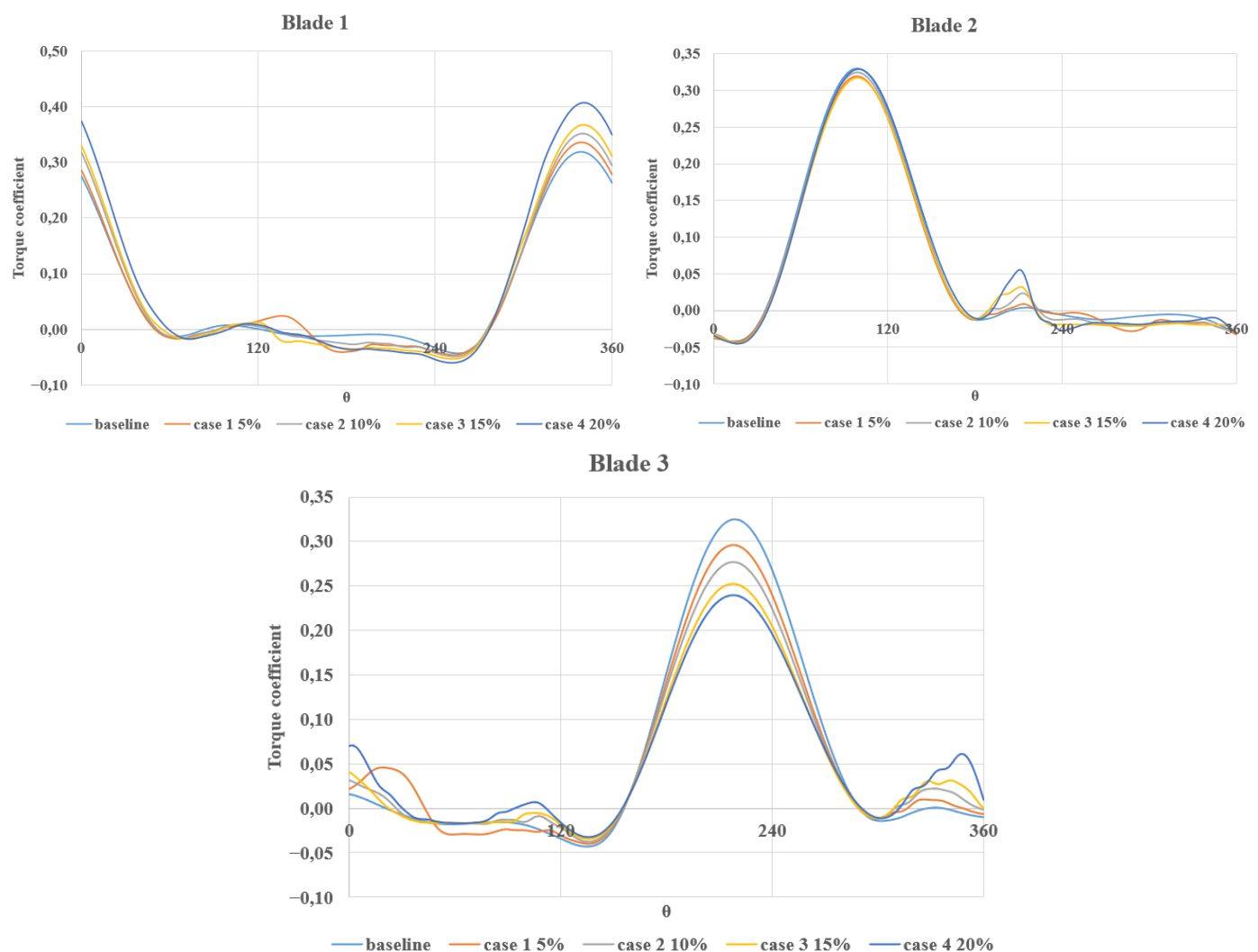


Figure 11. Torque coefficient variation.

Table 4 summarizes the mean power coefficient, mean torque coefficient, and an average torque metric for each blade over one rotor revolution.

The optimal configuration appeared to be the one with a 10% increase/decrease in chord and in radius, which resulted in the highest power output and efficiency when compared to the baseline.

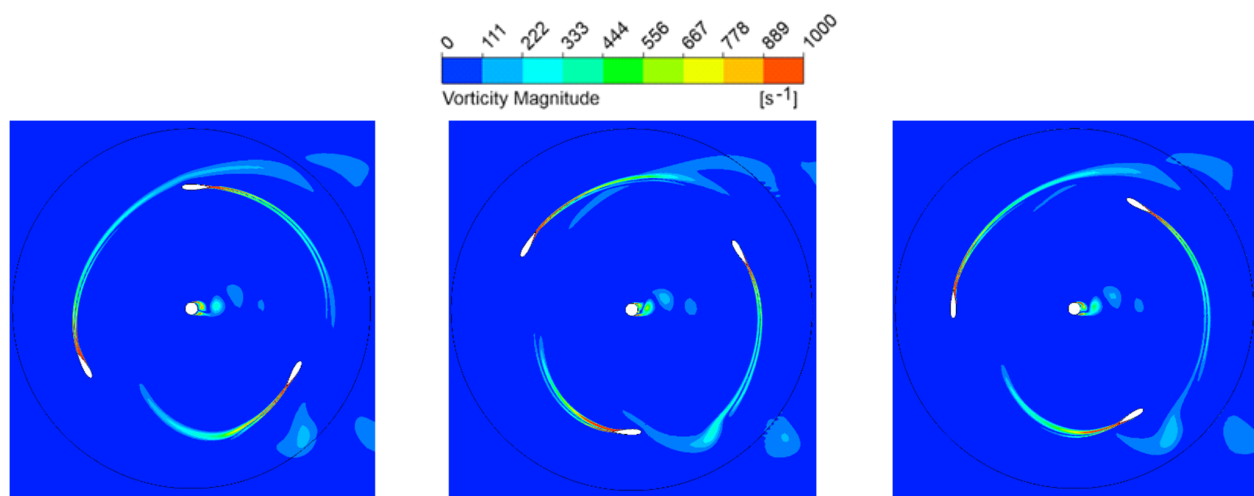
Table 4. Mean performance metrics for baseline and asymmetric configurations at TSR = 3.0.

	Mean C_p	Mean C_t	C_t			σC_t
			Blade 1	Blade 2	Blade 3	
Baseline	0.54279394	0.18093131	0.06037114	0.061137	0.059424	0.0968
Case 1–5%	0.52655599	0.17551866	0.06341521	0.058174	0.053929	0.0960
Case 2–10%	0.57287145	0.19095715	0.07534165	0.061348	0.054267	0.1024
Case 3–15%	0.5220415	0.17401383	0.06062661	0.056795	0.056592	0.1085
Case 4–20%	0.51254172	0.17084724	0.06432574	0.055941	0.05058	0.1235

As expected, the modified geometries with increased chord and reduced radius consistently demonstrated improved power output compared to the baseline. These configurations showed a trend toward maximizing the aerodynamic efficiency of the VAWT. The results indicated that the optimal blade geometry for power generation lies in fine-tuning both chord and radius to achieve a balance between reducing drag and increasing lift. However, it was evident that extreme modifications—such as large increases in chord or radius—resulted in diminishing returns or even a decrease in performance. The asymmetric redistribution of blade chord and radius inevitably modifies local blade Reynolds numbers, local blade tip speeds, and the azimuthal distribution of aerodynamic loading. However, the overall rotor scale and swept area are preserved within a narrow range, and global solidity variations remain moderate across configurations. The observed performance improvements are therefore attributed primarily to the redistribution and de-phasing of wake–blade interactions, rather than to a simple increase in blade area or rotor solidity.

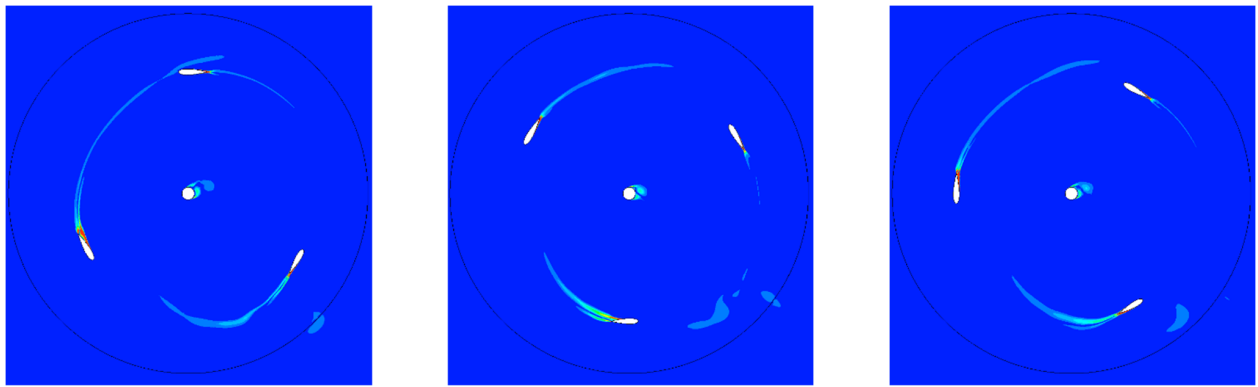
Interestingly, the 15% and 20% increases/decrease in chord and radius reductions, did not result in significant performance gains. This suggests that beyond a certain threshold, further modification to blade geometry may not contribute positively to power output, possibly due to the onset of adverse flow characteristics such as flow separation or increased drag.

The primary motivation for these geometry modifications was to mitigate blade-to-blade interactions, which can significantly influence turbine performance. The CFD simulations provided insights into the flow dynamics around the blades, highlighting how altering the geometry could reduce flow interference between adjacent blades. The increased chord length in certain configurations resulted in improved lift characteristics, which helped mitigate the negative effects of turbulence in the wake of each blade. Additionally, reducing the radius in selected configurations appears to have alleviated some of the drag-inducing interactions between blades (Figure 12).

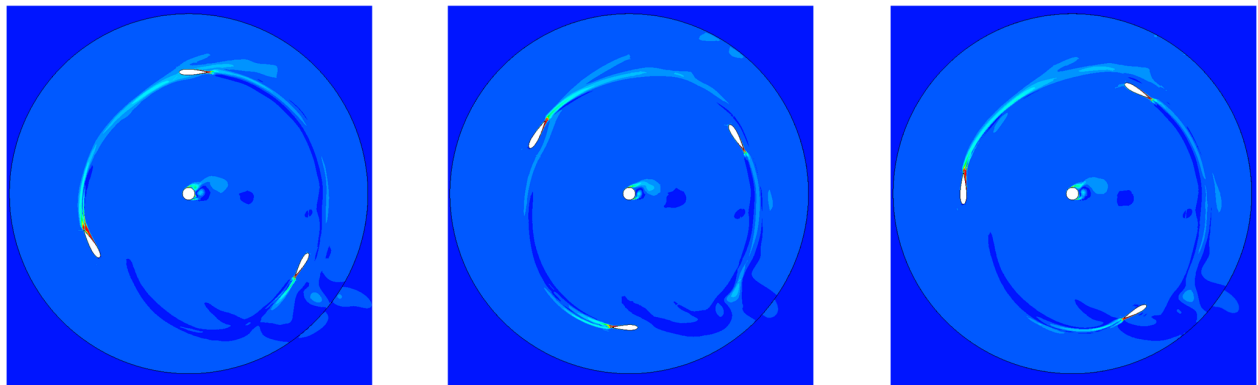


Baseline: left 0 degree; middle 60 degrees; right 90 degrees.

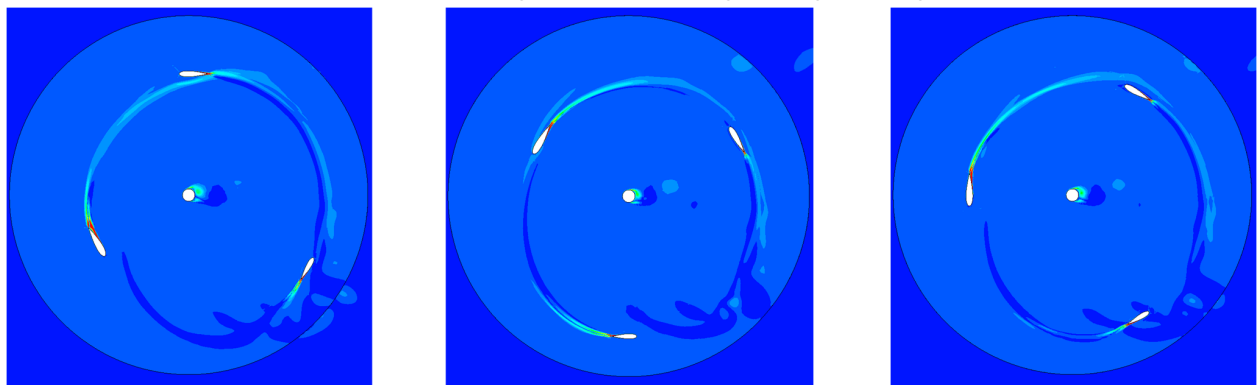
Figure 12. Cont.



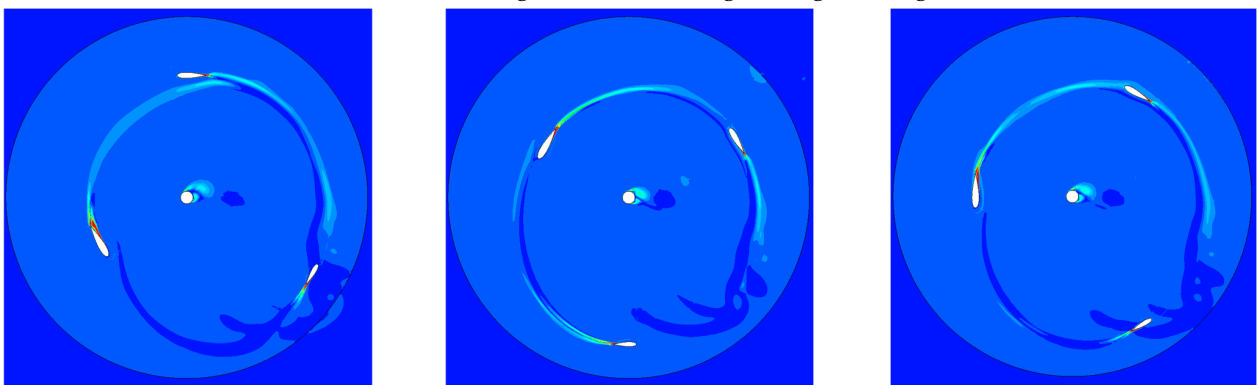
Case 1–5%: left 0 degree; middle 60 degrees; right 90 degrees.



Case 2–10%: left 0 degree; middle 60 degrees; right 90 degrees.



Case 3–15%: left 0 degree; middle 60 degrees; right 90 degrees.



Case 4–20%: left 0 degree; middle 60 degrees; right 90 degrees.

Figure 12. Vorticity magnitude.

The flow patterns in the modified models showed more uniformity and less turbulent wake formation than the baseline configuration. This was particularly evident in the 10% increase/reduction in chord and radius, where vortex shedding was reduced, and the blades experienced more stable aerodynamic forces. These findings suggest that careful tuning of blade geometry can enhance the performance by reducing the detrimental effects of wake turbulence and blade interference.

Beyond the qualitative flow-field observations, the proposed asymmetric blade chord–radius redistribution leads to measurable improvements in the aerodynamic performance of the turbine. Among the investigated configurations, the 10% modification case consistently exhibits the most favorable behaviour, showing an increase in the mean torque and a smoother torque evolution over a full rotation when compared to the baseline rotor.

Quantitatively, the 10% asymmetric configuration exhibits the highest mean power coefficient among the investigated cases at TSR = 3.0. The torque ripple metric reported in Table 4 provides additional insight into the cyclic loading behaviour. The 5% configuration presents the lowest standard deviation of the total torque coefficient, indicating the smoothest loading evolution. However, the 10% configuration provides the most favorable compromise between increased energy capture and acceptable torque fluctuation amplitude. This suggests that moderate asymmetric redistribution enhances aerodynamic effectiveness without introducing excessive unsteady loading.

From an engineering perspective, the reduction in torque ripple is particularly relevant for small VAWTs operating in urban environments. Smoother torque evolution implies lower cyclic loading on the rotor shaft, bearings, and generator, which can translate into reduced fatigue damage and extended component lifetime. This effect is especially important for compact installations, where maintenance access is limited and long-term reliability is a key design requirement.

The observed weakening and spatial redistribution of coherent vortical structures in the wake of the modified configurations further suggest potential benefits in terms of acoustic performance. Strong, coherent vortex shedding is commonly associated with tonal noise generation, whereas more diffuse wake structures tend to produce lower and less perceptible broadband noise. Although aeroacoustics simulations are beyond the scope of the present study, the reduced vorticity intensity and smoother interaction patterns observed in the optimal asymmetric configuration indicate a favorable trend for urban noise mitigation.

Reduced torque oscillations lead to more stable rotational speed and electrical output, which can improve generator efficiency and reduce losses in power conditioning systems. This is particularly advantageous for small-scale urban energy systems, where fluctuations in power quality can significantly impact overall system performance.

Unsteady simulations were run for multiple rotor revolutions until periodic behaviour was achieved. The reported torque and power metrics correspond to phase-averaged values obtained after cycle-to-cycle convergence, ensuring that transient start-up effects do not influence the comparative analysis. This confirms that the observed performance improvements are robust and repeatable under the imposed operating conditions.

Overall, the findings demonstrate that controlled asymmetric blade geometry can act as an effective mechanism for managing blade-to-blade interaction in straight-bladed VAWTs. Rather than pursuing purely global optimisation, the present approach targets the underlying unsteady aerodynamic mechanisms, offering a practical pathway toward improved efficiency, reduced unsteady loading, and enhanced suitability of VAWTs for urban deployment.

The present study is formulated as a comparative analysis of interaction-mitigation mechanisms at operating points TSR 0.5 up to 3.5 but the aerodynamic performance metrics

presented in this section correspond to a tip-speed ratio of $TSR = 3$, which is representative for small straight-bladed H-type VAWTs operating under nominal conditions.

4. Conclusions

This study numerically investigated a novel approach for mitigating blade-to-blade aerodynamic interaction in a straight-bladed vertical-axis wind turbine intended for urban applications. Instead of pursuing conventional symmetric optimisation, a deliberate asymmetric redistribution of blade chord and radial position across individual blades was proposed as a mechanism to de-phase wake–blade interactions and redistribute aerodynamic loading azimuthally.

A systematic parametric analysis was conducted using two-dimensional unsteady Reynolds-averaged Navier–Stokes simulations with the $k-\omega$ SST turbulence model. Starting from a baseline three-bladed rotor, four modified configurations were examined by applying ± 5 –20% variations in blade chord and corresponding radial position while preserving the overall rotor scale. The results demonstrate that moderate asymmetric modifications can effectively reduce blade-to-blade interference without introducing adverse aerodynamic effects.

Among the investigated cases, the configuration featuring a 10% chord–radius redistribution exhibited the most favorable performance. This configuration showed an increase in the mean power coefficient and a noticeable reduction in torque fluctuations relative to the baseline rotor, indicating smoother aerodynamic loading over the rotational cycle. Flow-field analysis revealed a weakening and spatial redistribution of coherent vortical structures, confirming that the performance gains are linked to reduced constructive wake overlap rather than to simple geometric scaling effects.

From an engineering standpoint, the observed reduction in torque ripple has direct implications for fatigue loading, mechanical reliability, and generator performance, which are critical considerations for compact VAWTs operating in urban environments. The attenuation of coherent wake structures also suggests potential benefits in terms of noise emission, although dedicated aeroacoustics analyses are required to quantify this effect.

The present study is subject to limitations associated with two-dimensional modelling and the analysis of a single operating condition. Consequently, the reported results should be interpreted as comparative trends rather than absolute performance predictions. Future work will focus on extending the analysis to three-dimensional simulations, exploring a wider range of operating conditions representative of urban wind environments, and validating the proposed interference mitigation strategy through wind tunnel experiments.

Due to the two-dimensional URANS framework and the use of uniform inflow conditions, the present results should be interpreted as comparative aerodynamic trends rather than absolute performance predictions.

Overall, the findings demonstrate that controlled blade-to-blade geometric asymmetry represents a viable and physically motivated pathway for managing unsteady aerodynamic interactions in vertical-axis wind turbines. This approach complements existing optimisation strategies and offers new design perspectives for enhancing the efficiency and durability of small VAWTs intended for urban renewable energy applications.

Funding: This research was funded by Executive Unit for Financing Higher Education, Research, Development and Innovation (UEFISCDI), grant number 89PED/05/05/2025.

Data Availability Statement: The original contributions presented in this study are included in the article material. Further inquiries can be directed to the corresponding author(s).

Conflicts of Interest: The author declares no conflicts of interest.

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