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Coupled aerodynamic–structural optimization of floating wind farms with heterogeneous turbine configurations under wake interactions and turbine yaw misalignment

Weiye Ding^a, Yingjie Jang^a, Hongyue Sun^a, Congfang Ai^{b *}, Jiahui Qiu^a, Naibo Sun^a, Zhihua Xie^c

Affiliations:

^a School of Marine Engineering Equipment, Zhejiang Ocean University, Zhoushan 316022, China

^b State Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology, Dalian 116024, China

^c Hydro-environmental Research Centre, School of Engineering, Cardiff University, CF24 3AA, UK

*Correspondence: Congfang Ai, aicongfang@dlut.edu.cn

Abstract

The expansion of large-scale offshore wind energy into deep-water regions represents a crucial step toward achieving global renewable energy goals. However, this expansion is significantly complicated by wake effects, which intensify turbine wake interactions, diminish power generation efficiency, and heighten structural safety risks. To address these challenges, this study introduces a Pareto-front identification framework to identify high-value configurations for floating wind farms by integrating yaw control and heterogeneous turbine configurations. A high-fidelity numerical investigation was conducted to systematically quantify how mean turbulent wind speeds (7.6–12.7 m/s), turbine configurations, and yaw misalignment collectively influence wake characteristics, system efficiency, and structural responses. Results show that deploying heterogeneous turbines with distinct ratings and hub heights for leading turbines emerges as a key strategy to co-optimize wake management and overall power output. The investigation of yaw misalignment verifies the existence of a compensatory mechanism, characterized by a trade-off where upstream power losses are offset by corresponding downstream gains. A Pareto-front analysis was conducted over a discrete design space consisting of eight turbine layout configurations and three yaw angles.. This Pareto-front analysis identified the "large(L)-small(S)-small(S)" layout as the optimal solution, which effectively balances superior energy capture with enhanced structural resilience. Collectively, the research paradigm provides a foundational framework for designing next-generation wind farms which are both highly efficient and structurally resilient.

Keywords: Pareto-front analysis; Floating offshore wind farm; Active yaw control; Heterogeneous turbine layout

1. Introduction

Wind energy has witnessed rapid and substantial growth over recent decades. By the end of 2024, global installed wind capacity had exceeded 1.1 TW (Global Wind Energy Council, 2025). Wind turbine technology is evolving toward larger scales and in deeper offshore waters (Garcia-Teruel A et al., 2022; Jiang Y et al., 2024). This trend can exert a positive effect on marine hydrodynamics and ecosystems while supporting global dual-carbon goals (Akhtar N et al., 2024). Offshore wind farms typically deploy multiple turbines in arrays to enhance total power generation. However, such layouts introduce complex wake interference issues. Research confirms significant wake effects from the upstream to the downstream turbines. Energy extraction from incoming wind reduces flow velocity and increases turbulence intensity. Consequently, downstream turbines experience reduced efficiency and accelerated fatigue damage (Zhang J et al., 2024).

Wake-induced energy losses pose challenges to the economic viability of wind farms, with power losses reaching 40% when turbines operate entirely within wake regions (Sanderse B, 2009). Enhanced turbulence also exerts larger structural loads and fatigue impacts on downstream turbines, compromising operational safety and structural integrity (Grady SA et al., 2005; Liu Y, 2023; Vera-Tudela L et al., 2017; Zhang Z et al., 2023).

Current wake modeling approaches fall into three categories: engineering wake models (EWM), computational fluid dynamics (CFD) models, and dynamic wake meandering (DWM) models. EWM offers computational efficiency

but struggles to capture nonlinear dynamics from floating platform motions(Xu X et al., 2022). While large-eddy simulation (LES) in CFD provides high accuracy, it requires excessive computational resources, limiting its applicability to large-scale wind farm optimization(Benard P et al., 2018; Jimenez A et al., 2007). FAST.Farm balances computational efficiency and accuracy by integrating DWM with aero-hydro-servo-elastic coupling effects, serving as a mid-fidelity multiphysics tool(Larsen GC et al., 2008; Feng D et al., 2024).

Most existing offshore wind farms employ layouts with identical turbine types. However, mixing turbines with different hub heights and ratings enable more compact arrangements, reduce subsea cable costs, enhance downstream turbine performance, and improve overall cost-effectiveness(Abdulrahman M et al., 2017; Ciavarra AW et al., 2022; Feng J et al., 2017; Stanley APJ et al., 2019; Chen K et al., 2016). Thus, this configuration shows broad application potential.

The application of yaw misalignment to deflect wake trajectories laterally has been demonstrated to increase the total energy yield of wind farms(Churchfield M et al., 2015; Doekemeijer BM et al., 2021). Yin et al (2020;2020) further validated sustained power gains using data-driven yaw control. However, the prevailing focus of most studies remains on turbine thrust and local structural load responses, with less attention paid to the structural safety over long-term yaw-controlled operation.

Recent research has begun to examine the implications of yaw control on structural loads. For instance, Shaler and Jonkman(Shaler and Jonkman, 2021) explored cooperative yaw optimization using FAST.Farm, with a sensitivity analysis assessing fatigue and ultimate loads for three laterally aligned NREL 5MW turbines. Their results showed strong consistency in power output and structural loads between FAST.Farm and the high-fidelity SOWFA-OpenFAST model. He et al.(He et al., 2023) conducted an optimal yaw strategy and fatigue analysis of wind turbines under the combined effects of wake and yaw control, providing a multi-dimensional fatigue assessment for 5MW turbines in turbulent flow conditions. Other contributions include Yang et al.(Yang et al., 2024) integrated machine learning methods to optimize wind farm layout and yaw strategy, further enhancing power generation efficiency, Ekelund's work on reducing dynamic loads via continuous yaw control(Ekelund T, 2000), Jeong et al.'s identification of optimal yaw angles to minimize loads for offshore turbines(Jeong MS et al., 2015), and Aju et al.'s correlation of power fluctuations with unsteady aerodynamic loads under yaw misalignment(Aju K et al., 2023). Liu et al. (Liu et al., 2024) investigated blade-flap vibrations during yaw for small turbines, while another study analyzed the impacts of yaw errors on platform motions and structural loads for a 15MW semi-submersible turbine under fault conditions (Zhu Y et al., 2024).

Notwithstanding these efforts, significant limitations persist. The studies cited above primarily focus on individual turbine responses, largely neglecting the critical turbine-turbine interactions inherent to large-scale farms. Zhang et al.(Zhang et al., 2022) systematically analyzed the performance and cost of two floating offshore wind turbines with significant interactions, examining power generation, torque response, and six-degree-of-freedom motion characteristics for 6MW semi-submersible turbines. Moreover, research on non-rotating components such as foundations and platforms remains particularly underdeveloped. Lozon and Hall(Lozon E and Hall M, 2023) conducted a coupled loads analysis of a novel shared-mooring floating wind farm, investigating platform displacements and tower base forces for 10MW turbines. Qiao et al.(Qiao et al., 2024) balanced platform motions and structural constraints via multi-objective optimization. Souleymane Drabo(Souleymane Drabo, 2024) optimized a 10MW platform along the Pareto front, improving platform weight, pitch motions, and stresses. Wang et al.(Wang et al., 2025) performed multi-objective optimization design for a 15MW semisubmersible floating offshore wind turbine using an evolutionary algorithm, optimizing its structural performance. Annan et al.(Annan R-J et al., 2023) applied multi-objective optimization for an autonomous unmoored offshore wind energy system substructure, enhancing the stability of the platform's substructure using non-genetic algorithms. It should be noted that offshore wind turbines include not only floating systems but also fixed-bottom turbines, which remain the most widely deployed offshore wind energy technology. For both fixed-bottom and floating turbines, mitigating the dynamic response of the support structure under complex aerodynamic and hydrodynamic loading is a common research

objective. Recent advances in innovative support-structure designs have addressed this challenge; for instance, hybrid foundation systems (e.g., monopile-bucket hybrid foundations) have been shown to effectively reduce excessive rotation and lateral displacement while optimizing load sharing under coupled wave-current loading conditions (Chen et al., 2020). Furthermore, alongside aerodynamic layout optimization, passive structural vibration control techniques offer a complementary pathway for mitigating wake-induced fatigue damage. For example, multiple tuned mass dampers (MTMDs) have been demonstrated to effectively suppress the vibration of offshore wind turbine foundations and towers under combined wind-wave-current loading conditions (Chen et al., 2021). Despite progress in offshore wind turbine platform design, multi-objective optimization for wind farm layouts remains limited.

Moving beyond the traditional optimization of power generation alone, the objective of this study is to address the integrated challenges of power maximization and load mitigation for floating wind farms. An innovative framework is proposed to evaluate turbine configurations (hub height and rating together) and yaw control strategies via a Pareto-front based analysis of a discrete set of candidate designs. The core of this study lies in a coupled aerodynamic-structural evaluation that simultaneously quantifies power output, structural loads, and platform dynamic motions and mooring line tensions, thereby enabling the identification of configurations that achieve an optimal trade-off between overall energy generation and structural durability in realistic marine operating conditions. The remainder of the paper is structured as follows. Section 2 details wind farm modeling approaches and layout designs. Section 3 analyzes wind speed and yaw control impacts on wake behavior. Section 4 investigates optimized layouts under fixed wind speeds and varying yaw angles. Section 4 also conducts Pareto-front analysis to evaluate comprehensive performance in power efficiency, platform motions, and structural responses. Conclusions are summarized in Section 5.

Definition of Key Performance Terms

In this study, the following terms are defined in relation to the quantitative metrics employed in the numerical analysis:

Structural resilience refers to the structural system's ability to withstand wake-induced and yaw-induced disturbances with limited load variability and extreme load excursions. It is assessed via the coefficient of variation (CoV) and range of key loads (e.g., tower-base bending moments, yaw-bearing loads), as well as fatigue damage equivalent loads (DEL). A configuration with lower CoV, narrower load range, and lower DEL is considered more resilient.

Stability is specifically quantified as the fluctuation magnitude of a given response (load or motion) over the simulation period, measured by the coefficient of variation (CoV) of the corresponding time series. A lower CoV indicates higher stability. This metric is applied consistently to hub thrust, yaw-bearing loads, tower-base loads, and platform motions.

Dynamic performance describes the temporal characteristics of platform six-degree-of-freedom (6-DOF) motions and structural load responses under turbulent wind and wake interactions. It is quantified using time-domain statistics (mean, standard deviation, range) and fatigue damage equivalent loads (DEL).

2. Numerical Methodology

2.1 FAST.Farm Modeling Tool and Principles

2.1.1 FAST.Farm Framework

FAST.Farm is a multi-physics engineering tool that extends NREL's OpenFAST framework as shown in Fig. 1. It quantifies the effects of wake interactions on turbine performance and structural loads within wind farms. Building upon OpenFAST's aero-hydro-servo-elastic coupling capabilities for single turbine, FAST.Farm incorporates farm-

scale functionalities, including the modeling of wake deficit, advection, deflection, meandering, and merging phenomena. The tool employs the Dynamic Wake Meandering (DWM) model. Jonkman et al(2021). documented the DWM model's development and mathematical foundations. DWM captures key wake features governing farm power performance and structural load predictions, encompassing wake deficit and wake meandering. Through judicious simplification of physical laws, the DWM model reduces computational costs, while its sub-models are calibrated and validated using high-fidelity modeling solutions. FAST.Farm adheres to OpenFAST's modular programming framework, integrating sub-models that model distinct physical domains. A driver code links these components into a cohesive modular architecture, with the system comprising four primary modules and one driver. The wake dynamics module includes sub-models for wake advection, deflection, meandering, near-wake correction, and wake deficit increment. Ambient wind and wake merging are handled by the ambient wind and array effects module. Separate instances of OpenFAST and wake dynamics modules are created per turbine, which interface with a super controller. This configuration enables the simulation of complex farm operating conditions.

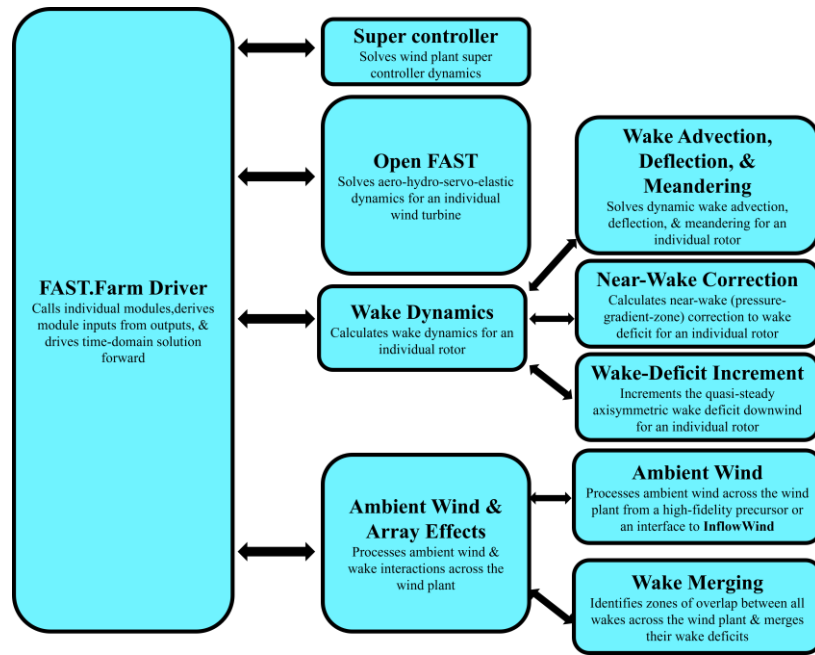


Fig. 1. FAST.Farm submodel hierarchy

2.1.2 Wake Velocity Deficit Model

The Dynamic Wake Meandering (DWM) model in FAST.Farm divides wakes into near-wake and far-wake regions. Total velocity deficit is defined as:

$$\Delta U(x, y, z) = \Delta U_{\text{near}}(x, y, z) + \Delta U_{\text{far}}(x, y, z) \quad (1)$$

Here, $\Delta U(x, y, z)$ denotes the total velocity deficit at the spatial coordinate (x, y, z) . This represents the reduction in local wind speed relative to the free-stream velocity. This decomposition accounts for vortex-dominated characteristics in the near-wake and turbulent diffusion in the far-wake. The near-wake velocity deficit follows a Gaussian distribution(Feng et al., 2023):

$$\Delta U_{\text{near}} = C_{\text{decay}} \cdot \frac{U_{\infty} \cdot C_T}{8\pi\sigma_y\sigma_z} \exp\left(-\frac{(y-y_c)^2}{2\sigma_y^2} - \frac{(z-z_h)^2}{2\sigma_z^2}\right) \quad (2)$$

This formulation derives from momentum conservation theory. It models turbine wakes as turbulent shear layers dominated by tip and hub vortices. U_{∞} is the free-stream wind speed. C_T denotes the thrust coefficient representing rotor drag. σ_y and σ_z quantify lateral and vertical wake expansion. These two expansion parameters increase with downstream distance. y_c indicates lateral wake center deflection (e.g., under yaw conditions). z_h is the hub height for geometric alignment. C_{decay} is an empirical correction factor addressing deviations between

Gaussian theory and actual wakes. The far-wake advection-turbulent diffusion equation is:

$$\frac{\partial \Delta U_{far}}{\partial x} + U_{\infty} \frac{\partial \Delta U_{far}}{\partial t} = \frac{\partial}{\partial y} \left(\nu_T \frac{\partial \Delta U_{far}}{\partial y} \right) + \frac{\partial}{\partial z} \left(\nu_T \frac{\partial \Delta U_{far}}{\partial z} \right) \quad (3)$$

The left-side term $\frac{\partial \Delta U_{far}}{\partial x}$ describes spatial evolution along the streamwise direction (x -axis). Term $U_{\infty} \frac{\partial \Delta U_{far}}{\partial t}$ captures unsteady temporal evolution. These coupled derivatives characterize convective transport in wake meandering. Right-side terms $\frac{\partial}{\partial y} \left(\nu_T \frac{\partial \Delta U_{far}}{\partial y} \right)$ and $\frac{\partial}{\partial z} \left(\nu_T \frac{\partial \Delta U_{far}}{\partial z} \right)$ model turbulent diffusion in lateral (y) and vertical (z) directions. The effective turbulent viscosity ν_T is a critical parameter, which combines the effect of background atmospheric turbulence and turbine-induced turbulence (tip/hub vortices).

2.1.3 Wake Meandering Model

Wake meandering is driven by low-frequency large-scale lateral turbulence. Its center position $y_c(x, t)$ can be described by a second-order lag-oscillation model. This modeling approach was originally proposed by Larsen et al.(2008). NREL later implemented and extended it in FAST.Farm(Jonkman and Shaler, 2021). The model formulation is:

$$\frac{d^2 y_c}{dt^2} + 2\zeta \omega_n \frac{dy_c}{dt} + \omega_n^2 y_c = K_w \cdot v'(t) \quad (4)$$

Here, ζ denotes the damping ratio. $\omega_n = 2\pi St \cdot U_{\infty}/D$ represents the natural frequency. St is the Strouhal number. K_w is the turbulence gain coefficient. $v'(t)$ indicates the lateral wind velocity fluctuation.

2.1.4 Wake Turbulence Enhancement Model

Turbulence intensity in turbine wakes comprises background turbulence(I_{amb}), wake-induced turbulence (I_{wake}), and meandering-induced turbulence($I_{meander}$) (Jonkman and Shaler, 2021):

$$I_{total} = \sqrt{I_{amb}^2 + I_{wake}^2 + I_{meander}^2} \quad (5)$$

The wake-induced turbulence term is modeled as:

$$I_{wake} = k_1 \left(\frac{\Delta U}{U_{\infty}} \right)^{k_2} \exp\left(-\frac{r}{D}\right) \quad (6)$$

Here, $\exp\left(-\frac{r}{D}\right)$ captures the radial decay of wake turbulence. k_1 and k_2 are empirical coefficients. These coefficients modulate wake turbulence intensity and decay characteristics. Meandering-induced turbulence is expressed as:

$$I_{meander} = \frac{\sigma_{y_c}}{x} \cdot f(L_{turb}) \quad (7)$$

σ_{y_c} denotes the standard deviation of lateral wake center displacement. $f(L_{turb})$ is a turbulence scale correlation function. It accounts for turbulence structure effects on wake meandering.

2.2 Turbulence Tools, Wind Conditions, and Turbine Configurations

2.2.1 TurbSim Principles and Wind Condition Visualization

Wind speed consists of two components: mean wind speed and turbulent wind speed. The turbulent component is generated using the IEC Kaimal spectrum model(Jonkman et al., 2012). Its power spectral density (PSD) is defined as:

$$S_v(f) = \frac{4I^2 L_C}{(1+6fL_C/\bar{V}_r)^{5/3}} \quad (8)$$

$S_v(f)$ denotes the PSD function. f is frequency in Hz. L_C is the integral scale parameter. Parameter I represents wind turbulence intensity. $\bar{V}_r$ is mean wind speed at reference height. Spatial coherence between points m and n is described by cross-spectrum:

$$S_{mn}(f) = r_{mn}(f)\sqrt{S_{mm}(f)S_{nn}(f)} \quad (9)$$

S_{mn} is the cross-spectrum between points m and n . S_{mm} and S_{nn} are auto-spectra at points m and n . The spatial coherence function $r_{mn}(f)$ is calculated as(IEC, 2009):

$$r_{mn}(f) = \exp(-a_0 \sqrt{(\frac{fL_{mn}}{\bar{V}_r}) + (\frac{0.12L_{mn}}{L_C})^2}) \quad (10)$$

$a_0=12$ is the coherence decay coefficient. L_{mn} denotes distance between grid points m and n . Equations (8)-(10) are implemented in TurbSim(NREL, 2005) to generate 3D wind field profiles covering the rotor area. The IEC Kaimal turbulence model (IECKAI) is employed. Medium turbulence intensity ($I=10\%$) under the Normal Turbulence Model (NTM) is selected. Wind speed modeling uses a power-law wind profile. Linear interpolation in MATLAB is then applied. The resulting hub-height wind speed variation is shown in Fig. 2. Four mean turbulent wind speeds are selected: 7.6 m/s, 9.3 m/s, 11 m/s, and 12.7 m/s. Fig. 2 illustrates the case with 7.6 m/s mean turbulent wind speed. This speed is the primary focus of the subsequent analysis.

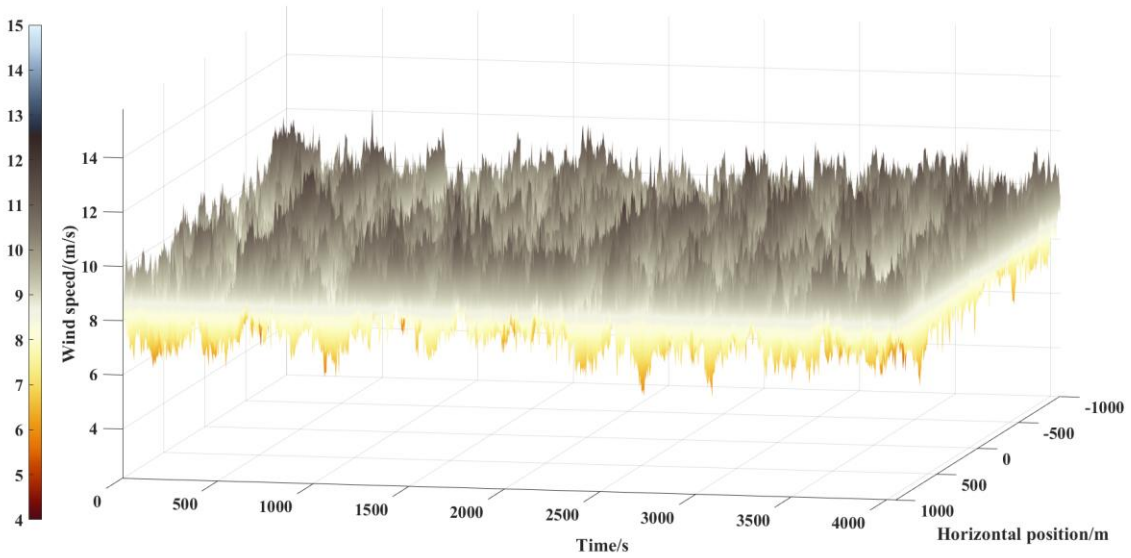


Fig. 2. Spatiotemporal wind speed distribution at hub height

2.2.2 Turbine Types and Layout Combinations

The IEA 15 MW and IEA 22 MW offshore wind turbines are selected for investigation, as they represent trends toward large-scale turbines and deep-water applications. Table 1 and Fig. 3 list the key design parameters for both turbines, including power rating, rotor dimensions, hub height, and operating wind speed ranges. This dataset supports comparative studies on wind farm layout optimization and load response analysis.

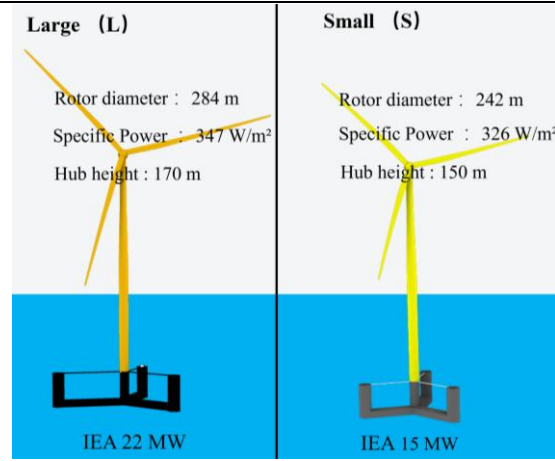


Fig. 3. Schematic diagrams of two turbine types

Table 1. Parameters of IEA 15 MW and IEA 22 MW turbines

Parameter	IEA 15 MW	IEA 22 MW
Power rating [MW]	15	22
Rotor diameter [m]	241.94	283.21
Number of blades	3	3
Cut-in wind speed [m/s]	3	3
Rated wind speed [m/s]	10.6	10.9
Cut-out wind speed [m/s]	25	25
Hub height [m]	150	170
Rotor orientation	Upwind	Upwind
Semi-Sub Platform mass [t]	14993	21165
Platform center of gravity [m]	-12.9	15.25
Mooring line diameter [m]	0.12	0.225
Mooring system	Three-line catenary	Three-line catenary

The FAST.Farm computational domain uses a nested grid strategy. It contains low-resolution global grids and high-resolution local grids. Global grids cover the entire wind farm area. Dimensions are 5000 m (length) $\times$ 1180 m (width) $\times$ 350 m (height). They capture large-scale flow structures and long-distance wake propagation. Local grids surround individual turbines. Dimensions are 500 m $\times$ 500 m $\times$ 350 m. These resolve detailed wake structures and local turbulence evolution. This nesting couples large-scale flow features with local fluid details. It optimizes computational accuracy and efficiency. Both grid types share a 350 m vertical dimension. This fully covers the operating zones of both turbines. Table 2 summarizes the operational parameters, including four turbulent wind speeds: 7.6 m/s, 9.3 m/s, 11 m/s, and 12.7 m/s. For each wind speed, a single turbulent inflow realization (seed) is used as the primary case for the main analysis presented in this study. To assess the sensitivity of the results to turbulent inflow randomness, three additional independent seeds are employed exclusively for the LSS layout (see Section 4.2), confirming that its performance is robust. In this study, only the upstream turbine T1 is subjected to yaw control (0° , 10° , 20°), while the downstream turbines T2 and T3 remain at a fixed 0° yaw. This setup replicates the typical first step in offshore wind farm yaw operations: the front-row turbine is yawed to deflect the wake, and subsequent adjustments to downstream turbines can be made based on local inflow conditions. This work focuses on the mechanisms of this first step, providing a foundation for future development of adaptive coordinated yaw control driven by downstream turbine feedback. Three yaw angles (0° , 10° , 20°) for the upstream turbine are considered, and their impacts on downstream wake characteristics are analyzed. Wave loads are calculated using the JONSWAP spectrum with significant wave height $H_s = 1.1$ m and peak period $T_p = 5.0$ s, representative of moderate sea states and aligned with the wind direction. Mooring dynamics are modeled via MoorDyn with a three-line catenary system for each platform; key mooring parameters are listed in Table 1. IEA 15 MW turbine with

lower hub height and smaller rating and IEA 22 MW turbine with higher hub height and larger rating are abbreviated as S and L, respectively. Eight three-turbine arrangements (LLL, LLS, LSL, LSS, SSL, SLS, SLL, SSS), which include combinations of heterogeneous turbine configurations including both mixed-type and single-type deployments, are aligned with the inflow direction in a series arrangement. The spatial configurations are illustrated in Fig. 4. T1, T2, and T3 denote the first, second, and third turbines, respectively. This arrangement directly reveals the progressive impact of upstream wakes on downstream turbines. Additionally, it helps reduce computational costs. The turbine spacing is set to 3D (where D is the rotor diameter of the IEA 15MW turbine). This spacing simulates strong wake impacts on overall farm performance, thereby enabling the evaluation of potential power generation improvements.

Table 2. Operating conditions in this study

Parameter	Values
Reference wind speed	7.6 m/s, 9.3 m/s, 11 m/s, 12.7 m/s
RandSeed	207344854, 107344544, 303448544
Yaw angle of T1	0°, 10°, 20°
Peak period	5 s
Wave spectrum	JONSWAP
Significant wave height, Hs	1.1 m
Arrangement	LLL, LLS, LSL, LSS, SSL, SLS, SLL, SSS

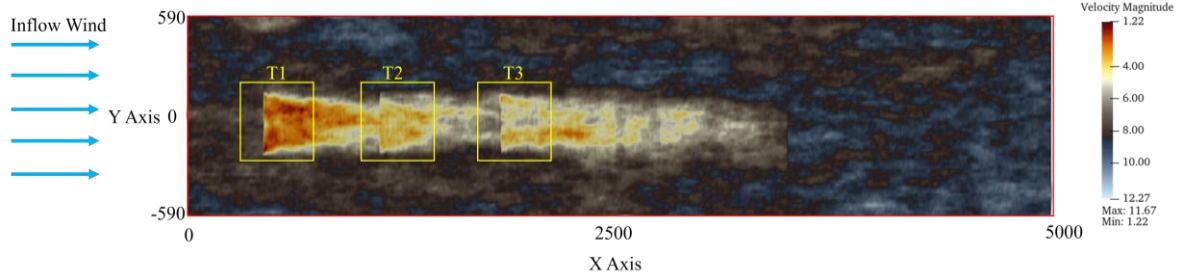


Fig. 4. Turbine layout schematic.

2.3 Model Validation

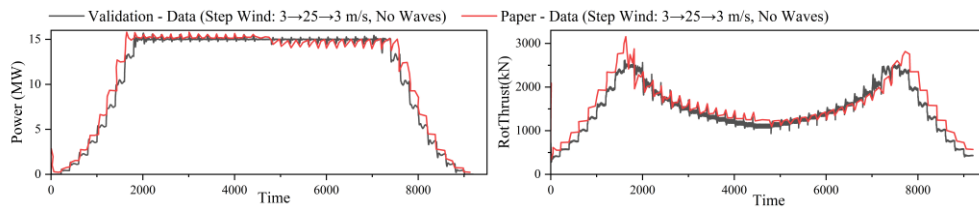


Fig. 5. Validation of the numerical model under a wind-step condition (Case 7): Comparison of power output and hub thrust between the present model and the benchmark data from Mahfouz et al.(Mahfouz et al., 2021). To validate the parameter configurations in the proposed methodology, simulations of power output and hub thrust were conducted for a 15 MW FOWT. The numerical model established by Mahfouz et al. (Mahfouz et al., 2021) for the IEA Wind 15 MW reference turbine served as the benchmark model. Under the wind-step condition without waves (Case 7 in the reference), the results presented in Fig. 5 show close agreement with the benchmark data, and as expected, both the hub thrust and power output exhibit a clear stepwise pattern, thereby demonstrating the high accuracy of the present model configuration.

3. Wake and Yaw Effects on Turbine Performance in Coordinated Layouts

3.1 Wind Speed Impacts (Wake Effects on Downstream Turbines)

In multi-turbine systems, turbine type and spatial arrangement significantly affect the propagation paths of wake disturbances and the structural responses of downstream turbines. Wake interactions exhibit strongly nonlinear coupling behavior, and such wake disturbance intensity amplifies structural load responses in downstream turbines. This section has revealed systematic variations in wake evolution paths and structural excitations across different configurations, thereby demonstrating complex fluid-structure interaction characteristics. A systematic comparison of power output, turbulence characteristics, and structural loads for layouts with single-type and heterogeneous turbine configurations is conducted to clarify how arrangement patterns influence wake interactions. This analysis can provide data support for subsequent Pareto optimization.

3.1.1 Uniform Single-Type Layout

This study examines turbines with identical hub heights, using the "LLL" arrangement as a representative case for subsequent analyses. Fig. 6 presents bar-line combination charts illustrating power generation trends under varying mean turbulent wind speeds. Power output variations of T1 are referenced against the 7.6 m/s wind speed baseline, with deviations from this output calculated accordingly. For T2 and T3, wake loss rates are determined using free-stream power (i.e., in the absence of upstream wakes) as the baseline, quantifying the extent of wake-induced power suppression.

At wind speeds ranging from 7.6 to 9.3 m/s, T2 and T3 exhibit substantially increased wake loss rates, both exceeding 70%, confirming the pronounced adverse impact of wake effects on their performance. Above 11 m/s, turbines progressively enter rated operation, leading to diminished wake intensity and reduced downstream effects. T3 consistently demonstrates higher wake losses than T2, with a peak difference of approximately 20% observed at 11 m/s. This phenomenon arises because T3 experiences compounded wakes from both T1 and T2, whereas T2 is only affected by the single wake from T1. At 11 m/s, T1 operates near rated conditions, and T2's wake-affected output approaches full power. When the mean turbulent wind speed exceeds 11 m/s, T1 begins to operate steadily, as indicated by the blue dotted line in the figure. The wake losses of T2 and T3 also decrease, though T3 consistently exhibits higher losses than T2. The box plots in the right panel of Fig. 6 analyze the power deviations of T2 and T3 relative to T1 across wind speeds. At 7.6 m/s, both turbines show similar wake-induced power deficits, while performance divergence between T2 and T3 emerges at higher wind speeds. This further verifies the governing role of wind speed in power performance.

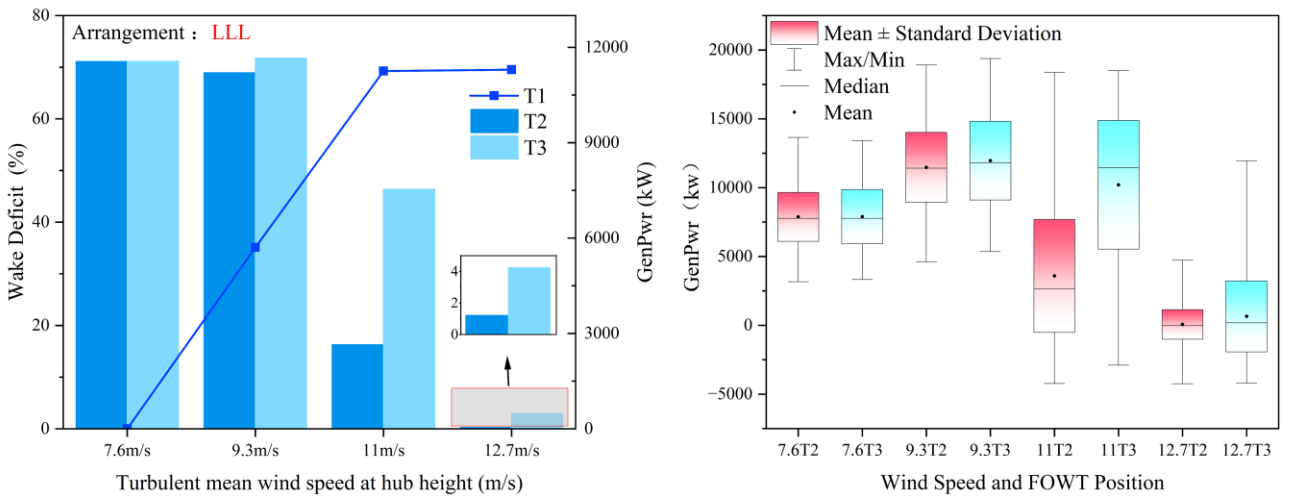


Fig. 6. Power Loss Rate at Mean Turbulent Wind Speed and Power Output Difference Between Downstream

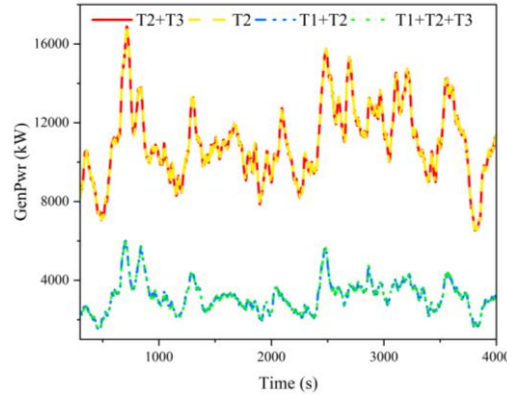


Fig. 7. Power efficiency under four layouts at 7.6 m/s mean wind speed

To isolate wake effects from turbine interactions, four control cases under a mean turbulent wind speed of 7.6 m/s are analyzed (as shown in Fig. 7): red represents T2-T3 turbines only; yellow indicates the case with a T2 turbine alone; blue denotes T1-T2 turbines, and green shows all turbines (T1-T2-T3). Results reveal nearly identical power characteristics across blue-green series cases, with similar behavior is observed in Red-yellow series cases. Notably, outputs from Red-yellow series significantly exceed those from blue-green series cases, demonstrating that upstream wakes dominate over reverse effects from downstream turbines. However, this macroscopic power analysis cannot reveal microscopic wake dynamics; thus, turbulence characteristics must be examined to resolve spatiotemporal wake evolution.

Fig. 8 illustrates turbulence intensity evolution at hub-height upstream points. Measurement points are 90 m upstream of each turbine at hub height. Turbulence intensity at T1 remains stable at approximately 0.09 across all wind speeds, confirming undisturbed inflow conditions consistent with free-stream characteristics. At T2, turbulence intensity remains 0.161 for wind speeds ranging from 7.6 to 9.3 m/s. Above 11 m/s, it decreases from 0.145 to 0.111 at 12.7 m/s, which correlates with rapid dissipation of turbulent kinetic energy in wakes at high wind conditions. At T3, intensity remains stable at 0.130 for wind speeds of 7.6-9.3 m/s. The intensity reaches its peaks at 0.19 under the mean turbulent wind speed of 11 m/s, and decreases slightly to 0.138 at 12.7 m/s. This trend aligns with T3's lower efficiency relative to T2 at 11 m/s (observed in Fig. 6), as elevated turbulence degrades T3's aerodynamics and power efficiency. At 12.7 m/s, high winds facilitate the redistribution of kinetic energy within wake regions, leading to stabilized turbulence and reduced intensity.

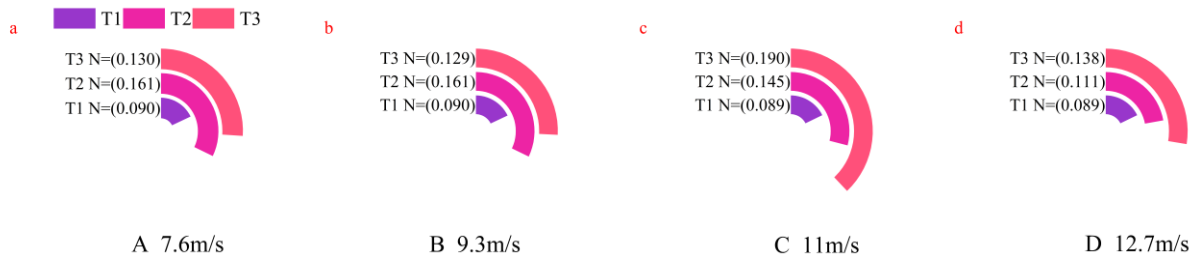


Fig. 8. Turbulence intensity for LLL layout across wind speeds

3.1.2 Heterogeneous Turbine Layouts

Fig. 9 displays power deficit distributions for six layouts under four mean turbulent wind speeds. The x -axis shows T2's power deficit, while the y -axis represents that of T3. Blue lines indicate the linear regression between T2 and T3 wake deficits, with all regression slopes being negative, revealing an inverse relationship where an increase in one turbine's deficit typically corresponds to a reduction in the other turbine's deficit. This negative correlation

weakens as wind speed increases: both turbines share a rated wind speed of 11 m/s, and higher wind speeds extend the duration of rated power operation. The marginal influence of wake effects consequently diminishes. This aligns with previous observations in uniform hub-height layouts.

At 11 m/s (Fig. 9 (c)), T3 exhibits significantly more severe wake deficits than T2, consistent with trends observed in the uniform hub-height configurations. At 12.7 m/s (Fig. 9 (d)), deficits for downstream turbines decrease across all layouts, though T3's wake losses remain higher than T2's. This also corresponds to uniform hub-height observations.

Blue and purple scatter points represent SLS and SLL arrangements, both featuring small turbines at the T1 position and large turbines at the T2 position. Upstream small turbines cause weaker wake blockage effects on downstream large turbines. This weaker wake blockage enhances power generation at large-turbine T2 positions. T2 deficits are notably lower than those in layouts with large turbines at T1.

As shown in Fig. 9, the pink and yellow scatter points correspond to the LSL and LSS layouts, respectively. Across all tested wind speeds, these two configurations exhibit superior overall performance compared to the other evaluated layouts. Quantitatively, under low inflow wind speeds of 7.6 m/s and 9.3 m/s, the wake deficits of T3 for the LSL and LSS layouts are maintained below 68% and 66%, respectively, which is significantly lower than the 69%–75% wake deficit range observed for the SSL, SLS, SLL, and LLS configurations. Under the moderate wind speed of 11 m/s, the LSL layout achieves the second lowest T3 wake deficit of 38%, followed by the LSS layout at approximately 41%, both of which substantially outperform the LLS layout with a wake loss as high as 46%. At the high wind speed of 12.7 m/s, the LSL layout attains the second lowest T3 wake deficit among all configurations (approximately 1.8%), while the LSS layout yields a wake deficit of about 4.9%. Across all four wind speed conditions, the scatter points of LSL and LSS are generally located in the low deficit region of the negative correlation fitting curve between T2 and T3 wake deficits. The overall wake deficit magnitudes of both T2 and T3 are consistently smaller, particularly under low wind speed conditions, demonstrating that these two layouts can more effectively mitigate wake interference between upstream and downstream turbines.

Notably, a closer inspection reveals that the SSL configuration (green triangle) in Fig. 9(c) and 9(d) exhibits lower wake deficits than the LSS configuration in Fig. 9(a) and 9(b). This indicates that SSL has a distinct advantage in wake-loss reduction under medium-to-high wind speed conditions (11 m/s and 12.7 m/s). Therefore, while LSL and LSS provide robust all-round performance, the SSL layout merits specific attention for its superior wake-loss mitigation at higher wind speeds, making it a competitive candidate in those scenarios.

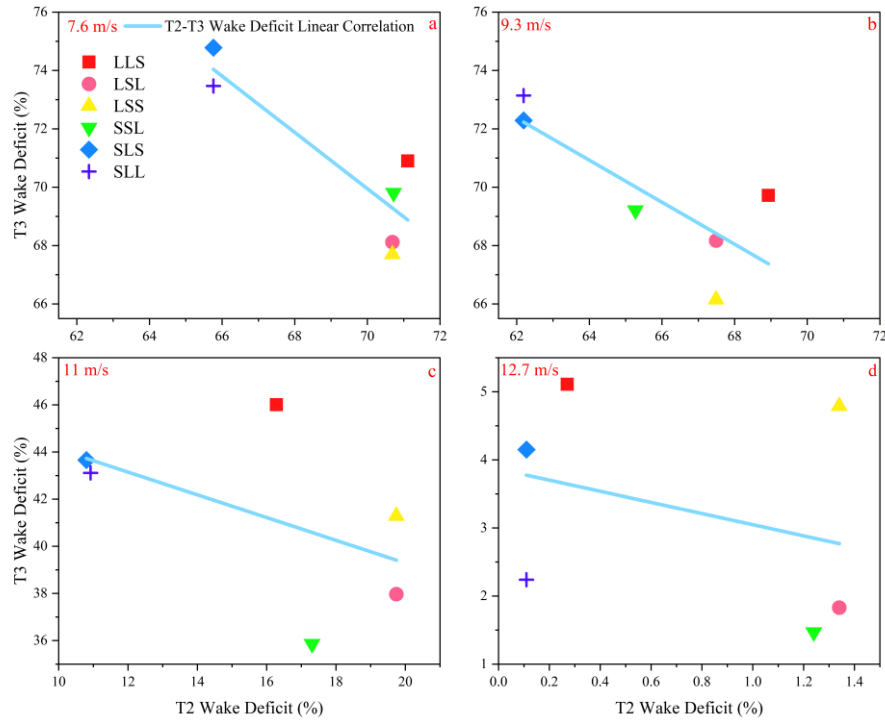


Fig. 9. Wake losses and linear fitting for six layouts

Fig. 10 presents the 6-Degree-of-Freedom (6-DOF) box plots for T2 (green) and T3 (light yellow) turbines across the six distinct layout configurations under 7.6 m/s turbulent wind conditions. At this wind speed, the turbines operate below rated power, and the coupled effects of wake interaction and layout arrangement are clearly observable. The hub-height wind speed distribution confirms the representativeness of this wind speed for typical offshore conditions; all subsequent analyses are exclusively based on this wind speed, and no further specification will be repeated.

This study focuses on the dynamic responses of T2 and T3 turbines. With no yaw misalignment and collinear wind-wave excitation, the most significant platform motions are surge, heave, and pitch. Among these, the heave motion exhibits relatively small magnitudes and is turbine-size-dependent: large turbines, due to their greater mass, demonstrate superior heave performance.

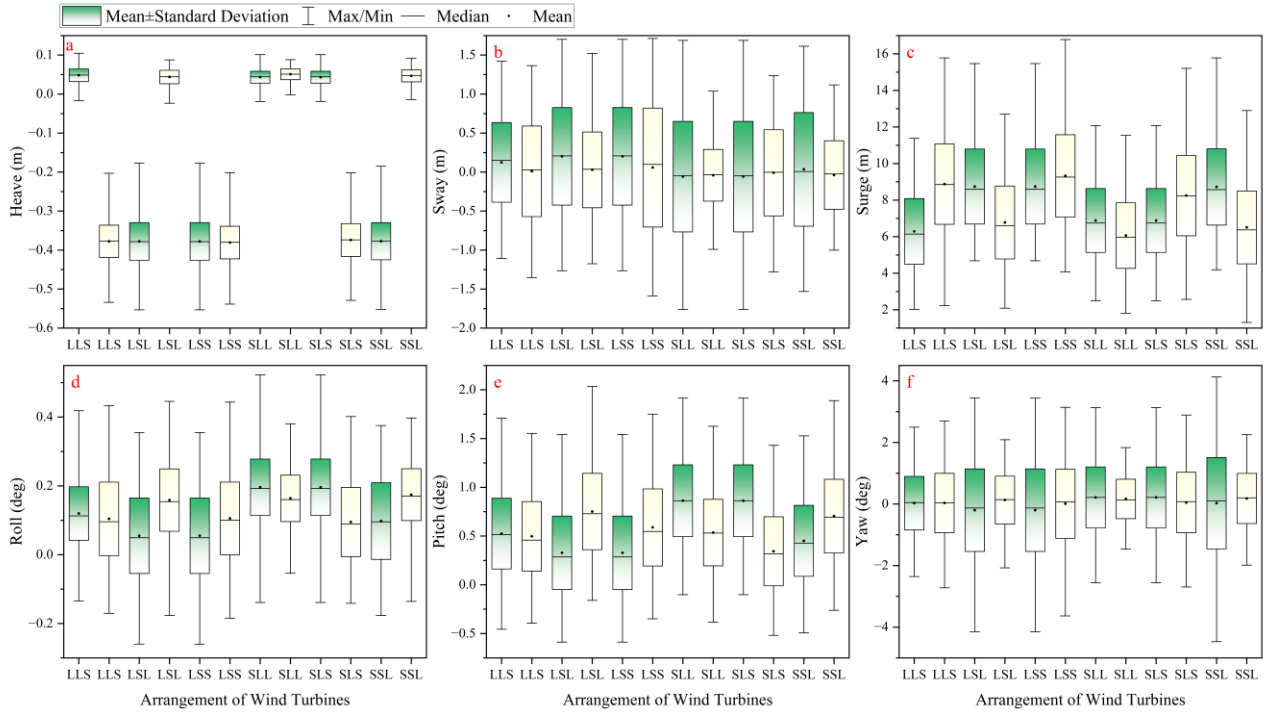


Fig. 10. 6-DOF platform motions for 2nd/3rd-row turbines at 7.6 m/s (T2: green and T3: slight yellow)

In terms of surge, large turbines outperform small turbines at identical positions. For example, the surge response of T2 in the LLS layout is superior to that of T2 in the LSS layout. When both downstream turbines (T2 and T3) are small turbines, T2 exhibits better surge stability than T3; conversely, when both are large turbines, T3 outperforms T2. The pitch stability of T2 is governed by the size of the upstream T1 turbine: when T1 is a large turbine, T2 shows improved pitch performance. Notably, in the LLS layout, the pitch responses of T2 and T3 exhibit minimal divergence, a stark contrast to the significant fluctuations observed in the SLS layout. This further confirms that a large upstream T1 turbine beneficially influences the pitch motion of downstream turbines. Fig. 11 presents hub thrust and 3D tower-base loads for T2 (red) and T3 (yellow) at 7.6 m/s. Load characteristics exhibit distinct turbine-size dependency, with significant differences observed between the load distributions of large and small turbines. Hub thrust and tower-base X -loads remain collinear without yaw changes as displayed in Figs. 11(a-b). Only vertical position differences exist between the hub and tower base (Fig. 11(d)), and the statistical distributions of their (hub and tower base) loads exhibit high consistency. Larger hubs on large turbines increase the loads transferred to tower bases, causing their hub thrust and X -loads to exceed those of small turbines. For identical turbine types, load variations across different turbine positions are minimal. Notably, T3 in the SLS layout exhibits significant anomalies. Its hub thrust and X -loads are notably lower than those of T2, which aligns with T3's maximum wake deficit observed in the top-left panel of Fig. 8. Variations in tower-base Y -load remain relatively small, limiting the overall significance of these variations.

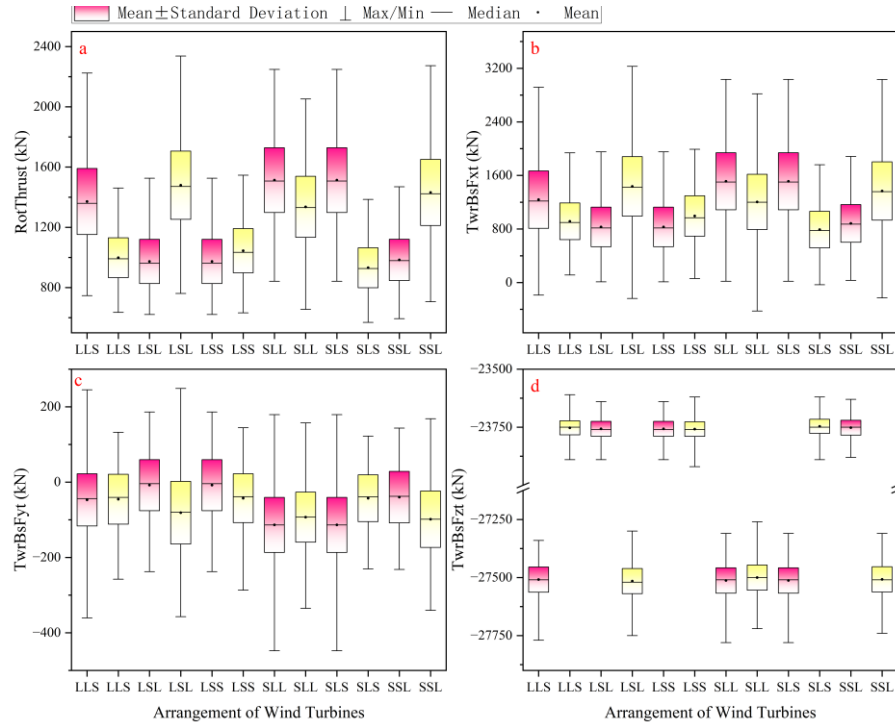


Fig. 11. Hub thrust and tower-base loads for 2nd and 3rd-row turbines at 7.6 m/s (T2: red and T3: yellow)

Fig. 12 presents the average total power output and capacity factor of six wind turbine layouts. The capacity factor (CF), defined as the ratio of the average power output to the installed rated capacity, reflects how efficiently each layout utilizes the total turbine capacity. An increased proportion of large turbines correlates positively with both total power output and CF. Installing large turbines at the T1 position significantly enhances overall power generation, as these turbines improve initial energy capture via their larger swept areas, thereby elevating wind-to-power conversion rates. As the lead turbine, T1 remains unaffected by wake effects, further boosting its power generation performance.

Among the six arrangements, the LSS layout yields the highest total power output and also the highest CF (0.303), indicating the most efficient utilization of installed capacity. The LSL and LLS configurations rank second and third, with CF values of 0.284 and 0.278, respectively. In contrast, layouts with a small turbine at the first position, such as SLL (CF = 0.243), exhibit a noticeably lower capacity factor. This confirms that placing a large turbine at the lead position significantly enhances the overall capacity utilization efficiency of the entire layout.

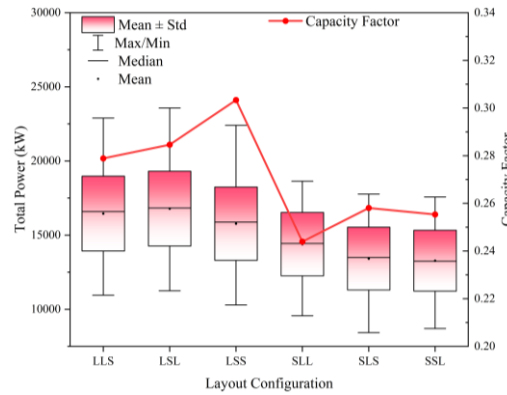


Fig. 12. Average total power output (box plots) and capacity factor (point-line plots) for six wind turbine layouts. at 7.6 m/s

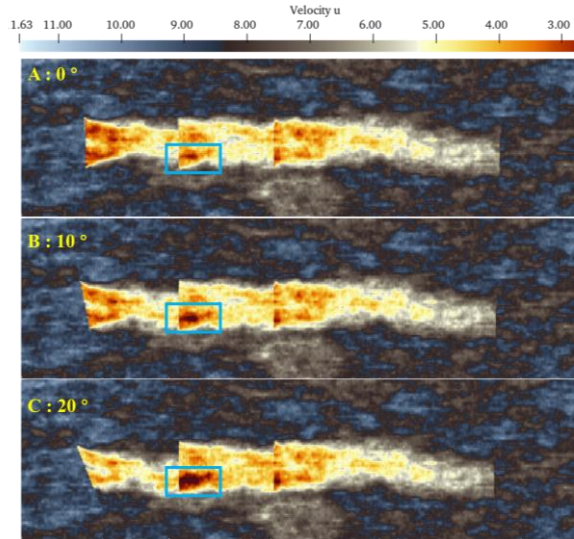
3.2 Upstream Yaw Angle Impacts on System Performance

In this study, only the yaw angle of the front-row turbine T1 is adjusted, with all downstream turbines kept at a fixed yaw position, to quantify how single upstream wake deflection affects heterogeneous downstream wind turbines. This simplification conforms to the operational logic of practical wind farm yaw control: the foremost turbine is prioritized for yaw adjustment, and further tuning of downstream units is implemented later according to measured local wake characteristics. Therefore, the present work focuses on the basic wake-interaction mechanism induced solely by upstream turbine yaw, laying a theoretical foundation for the development of downstream feedback-based coordinated yaw strategies. It should be noted that simultaneous coordinated yaw actuation of multiple turbines is excluded from the current framework, which is a major simplification limitation. Subsequent research can integrate active yaw control for downstream turbines by leveraging the conclusions drawn in this paper. Fig. 13 compares wake evolutions at identical time and height under three yaw conditions. Increasing T1's yaw angle induces pronounced deflection of the wake centerline, causing the wake to progressively deviate from T2's central position. This reduces the wake-affected area of T2. In the blue-marked region, wake velocity decreases, and the rate of wake area reduction consequently slows. As a result, T2 ultimately experiences weaker wake effects. It should be noted, however, that T2 still encounters asymmetric flow during wake deflection. This asymmetric flow induces uneven blade loading on T2. Such imbalance affects structural dynamic responses and may also compromise the effectiveness of downstream turbines' control strategies. Thus, wake deflection mechanisms under yaw changes require further analysis, and the potential implications for downstream turbine stability and structural integrity warrant further investigation.

Table 3. Maximum mooring line tension and safety factor for the leading turbine (T1) under different yaw angles.

Turbine type	Yaw angle (°)	Max. mooring tension (kN)	MBL (kN)	Safety factor	SF $\geq$ 1.67?
S	0°	4568.0	22286	4.88	Yes
S	10°	4414.7	22286	5.05	Yes
S	20°	4133.4	22286	5.39	Yes
L	0°	7855.6	22286	2.84	Yes
L L	10°	7593.4	22286	2.93	Yes
L	20°	7044.3	22286	3.16	Yes

To evaluate the safety of the mooring system, Table 3 lists the maximum mooring line tensions of the leading turbine (T1) under three yaw angles. The minimum breaking load (MBL) of 22,286 kN (from the 15 MW turbine mooring lines) is adopted as a common reference for both the small (S) and large (L) turbines, because MBL data for the 22 MW turbine are unavailable. The safety factor is defined as MBL divided by the maximum line tension; all six cases satisfy a minimum safety factor of 1.67 according to DNV standards. Consequently, the maximum tension in all cases falls below the corresponding safety threshold, thereby establishing a mooring safety



prerequisite for the subsequent analysis.

Fig. 13. Wake propagation under three yaw angles (LLL)

3.2.1 Effects on 2nd and 3rd Turbines under Uniform Single-Type Layouts

Building on the prior methodology, this chapter examines the impact of yaw control on the power performance of downstream turbines, aiming to reveal the spatial propagation of aerodynamic interference in turbine arrays. Fig. 14 displays the power loss of three turbines in the LLL layout under 7.6 m/s mean turbulent wind conditions at yaw angles of yaw angle 0°, 10° and 20°. T1's power loss increases with rising T1's yaw angle, while T2's power loss decreases significantly, exhibiting a reduction of approximately 7% for every 10° increase in yaw angle. This indicates that although yaw operation imposes a power penalty on T1, this yaw operation effectively mitigates wake shading effects on T2, thereby enhancing T2's power generation efficiency.

Fig. 14 reveals that the combined power loss of T1 and T2 approximately equals the stable power loss of T3 across all yaw angles ($T1 \text{ loss} + T2 \text{ loss} \approx T3 \text{ loss}$). Given the near-constant loss of T3, this relationship implies a direct power compensation between the upstream turbines: a loss in T1 is largely offset by a gain in T2. This suggests that aerodynamic interference in turbine arrays exhibits transferability and controllability. As an active control parameter for front-row turbines, the yaw angle not only affects each front-row turbine's own energy capture efficiency but also indirectly influences downstream turbines through wake restructuring, consequently altering the system-wide power distribution.

The heatmap in Fig. 15 further verifies this phenomenon: as the yaw angle of T1 increases, the progressively lighter color in its corresponding region indicates a decrease in power output. Meanwhile, in the T2 region, the dark blue portions at the upper and lower ends of the T2 region transition to light blue, suggesting improved power generation efficiency. The mixed blue-yellow-green area in the center shifts to darker yellow and lighter blue, also reflecting an overall increasing power output trend. This visually demonstrates the power loss trade-off relationship between T1 and T2.

It is worth noting that at a wind speed of approximately 9 m/s, all three turbine regions appear in similar shades of blue. This phenomenon is primarily attributed to the turbine start-up process: during initial operation, the turbines accelerate from zero rotational speed under high turbulence, yet they have not reached the steady-state power generation efficiency corresponding to that wind speed. Consequently, all three turbines exhibit low power output, resulting in the uniformly blue coloration. This behavior is a consequence of the turbines' operational characteristics at low wind speeds rather than wake interactions or the plotting method.

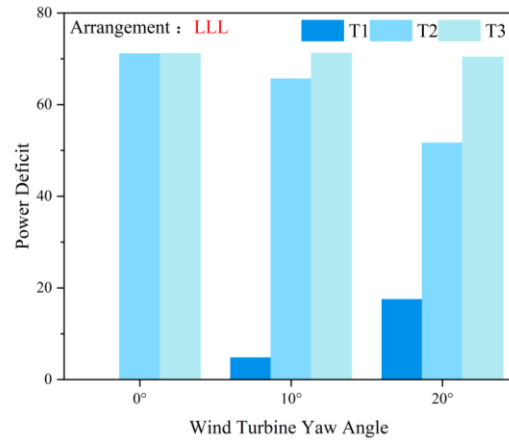


Fig. 14. Wake-induced power losses per turbine at 0°/10°/20° yaw

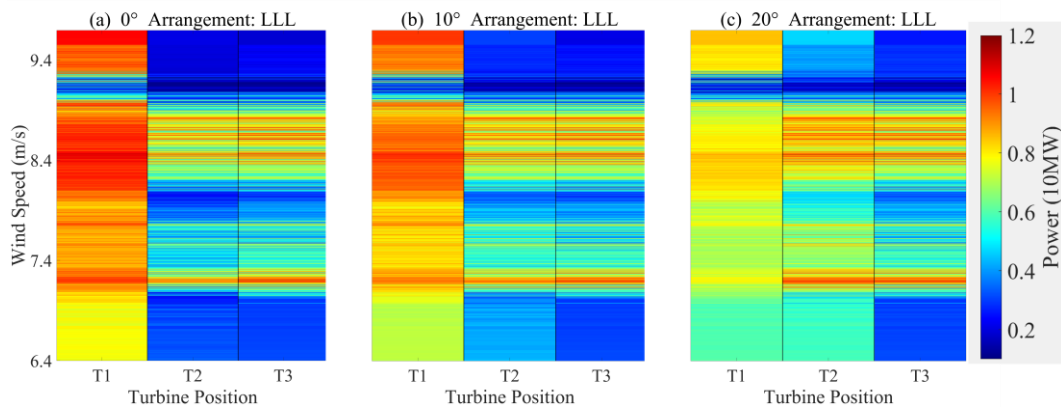


Fig. 15. Wind-speed-to-power heatmaps under yaw variations

Fig. 16 illustrates the differential 6-DOF responses of T2 and T3 turbines to changes in T1's yaw angle. As T1's wake deflects with varying yaw angles, aerodynamic loads on downstream T2 and T3 turbines are consequently redistributed. For both T2 and T3, heave, roll, and sway responses exhibit minor variations. However, T2 shows a pronounced peak in these heave, roll, and sway responses at a 20° yaw angle. Yaw responses monotonically increase with higher yaw angles, with T2's increase significantly exceeding that of T3, which directly validates the presence of asymmetric loading on T2 induced by wake deflection. Pitch and surge responses follow trends similar to yaw responses. The comprehensive analysis reveals that T2 is most sensitive to wake interference, as the amplitudes of its DOF response variations significantly exceed those of T3. These findings provide critical insights for optimizing cluster yaw control strategies for wind turbine arrays.

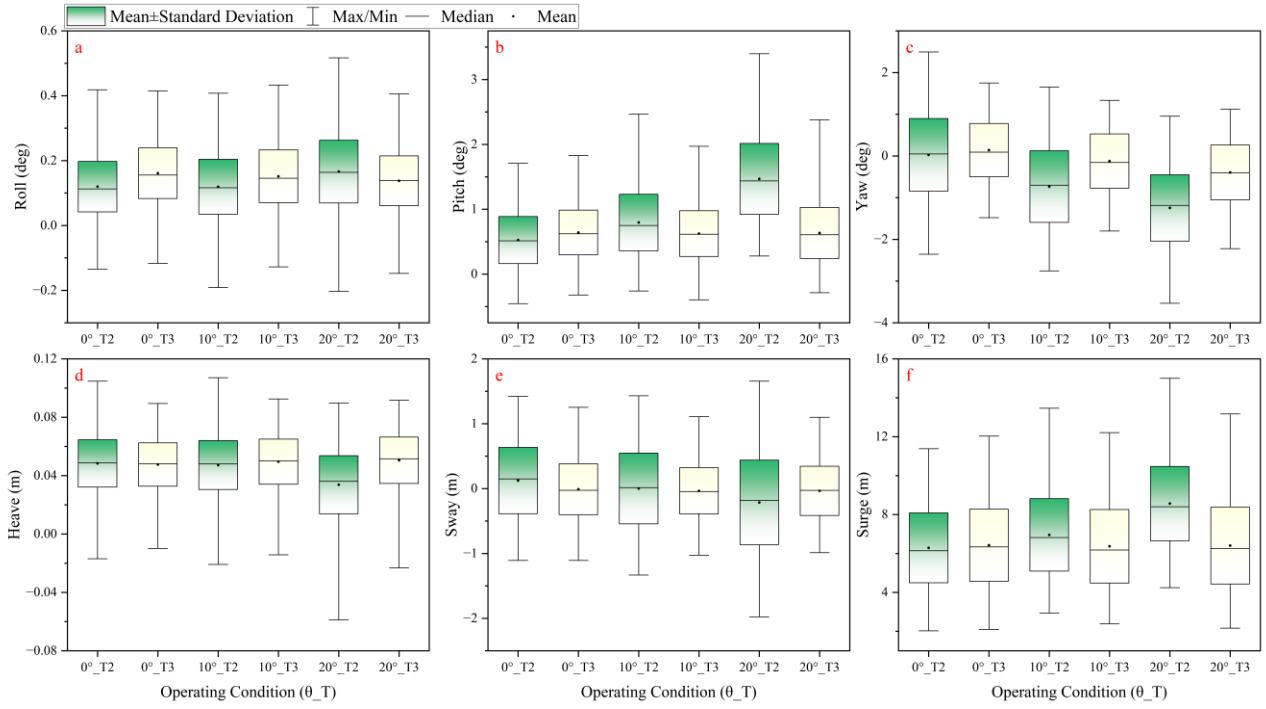


Fig. 16. 6-DOF motions of 2nd/3rd-row turbines under yaw variations (LLL)

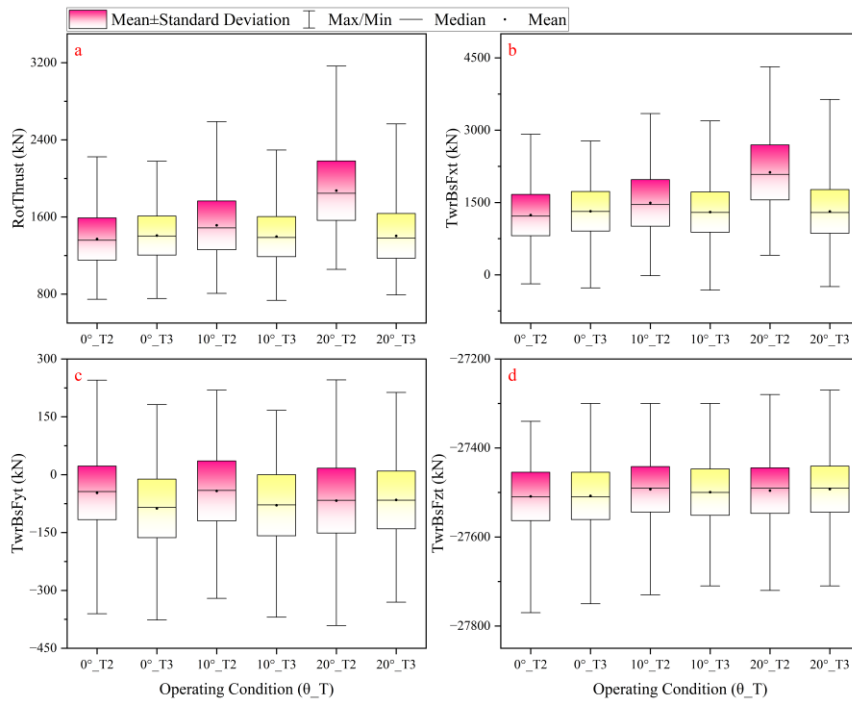


Fig. 17. Structural loads on 2nd/3rd-row turbines (LLL)

Fig. 17 demonstrates structural load patterns for turbines at identical hub heights. Altering the yaw angle of front-row turbine induces systematic variations in hub thrust and tower-base load distributions on T2 and T3. Hub thrust and tower-base X -direction loads follow trends identical to those of surge responses and align closely with power generation trends, as shown in Fig. 15. This behavior can be explained by the wind turbine dynamic transfer mechanisms: aerodynamic loads are transmitted through blade-hub interfaces to tower structures, causing tower-base X -loads and hub thrust to vary synchronously with power efficiency. Specifically, as T1's yaw angle increases, T2 exhibits monotonic increases in hub thrust and tower-base X -direction loads. Conversely, tower-base Y - and Z -

direction tower loads show milder variations. T2's tower-base Y -direction loads maintain stable oscillatory ranges, while T3 demonstrates analogous stability characteristics in its tower-base Y -direction loads.

3.2.2 Effects on 2nd and 3rd Turbines under Heterogeneous Layouts

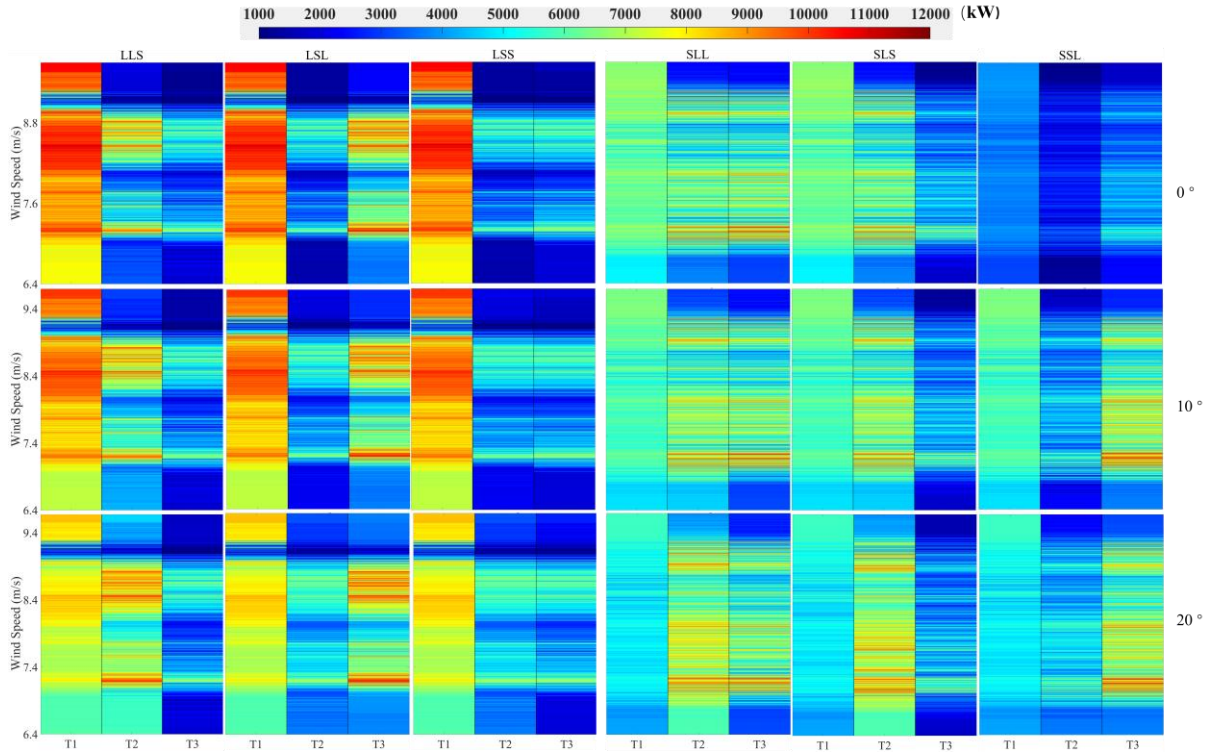


Fig. 18. Wind-speed-to-power heatmaps for six layouts at 7.6 m/s

This study systematically analyzes six heterogeneous turbine configurations under various yaw conditions using the wind-speed-to-power conversion heatmap presented in Fig. 18. The horizontal axis denotes the six hub-height configurations, while the vertical axis displays the power generation of T1–T3 turbines for each configuration. The results align with previous findings from studies using identical hub heights: the power output of T1 decreases with increasing yaw angles, as visually indicated by the color transition from red to lighter shades. Overall, configurations with large-capacity turbine positioned as T1 yield better power generation performance than those with small-capacity turbine as T1, particularly when comparing the LSS and SSL layouts. Although both layouts have the same total rated capacity, the large-capacity turbine in the third position of the SSL configuration does not fully utilize its potential to capture more wind energy. In contrast, the output of T2 increases correspondingly, reflected in the heatmap by a color shift from dark blue to light blue and then to red. This pattern demonstrates a compensation effect between T1 and T2 that partially offsets the yaw-induced losses of T1. Meanwhile, T3 exhibits minimal power variations across conditions, maintaining stable performance.

Fig. 19 presents boxplots of 6-DOF responses for T2 (green) and T3 (pale yellow) turbines across the six configurations at 10° and 20° yaw angles of T1. T2 generally exhibits more pronounced response magnitudes than T3 across most 6-DOF, indicating its greater susceptibility to upstream wake disturbances, particularly when exacerbated by the yaw of the front-row turbine (T1). Heave responses show minimal sensitivity to yaw variations of T1, and are characterized by low magnitudes, standard deviations, and response ranges. Turbine rated power dominates this influence of yaw angle variations on 6-DOF responses, with turbines with higher-rated-power enhancing stability at both T2 and T3 positions. This correlation is expected, as the higher rated power generally corresponds to larger turbine dimensions, which directly improve structural stability.

1 Surge responses demonstrate significant yaw sensitivity: T2 and T3's surge responses increase synchronously with
2 higher yaw angles, and this trend is particularly pronounced for T2. In the sway direction, T2 shows higher
3 sensitivity to T1's yaw variations but limited overall magnitudes, while T3's sway responses are statistically tightly
4 distributed with negligible fluctuations. Pitch responses resemble sway patterns: T2's pitch responses intensify at a
5 20° yaw angle of T1, while T3's show negligible changes. This confirms weaker wake interference on T3. Roll
6 responses maintain low magnitudes overall; however, only T2 exhibits slight increases by T1's yaw. Yaw responses
7 show limited fluctuations across T1's yaw conditions and remain stable. Crucially, T3 experiences reduced yaw-
8 induced wake effects with insignificant dynamic variations, whereas T2 undergoes stronger inflow disturbances,
9 exhibiting heightened dynamic instability under T1's yaw conditions. This reflects T2's greater sensitivity to both
10 turbine hub-height configurations and inflow conditions.

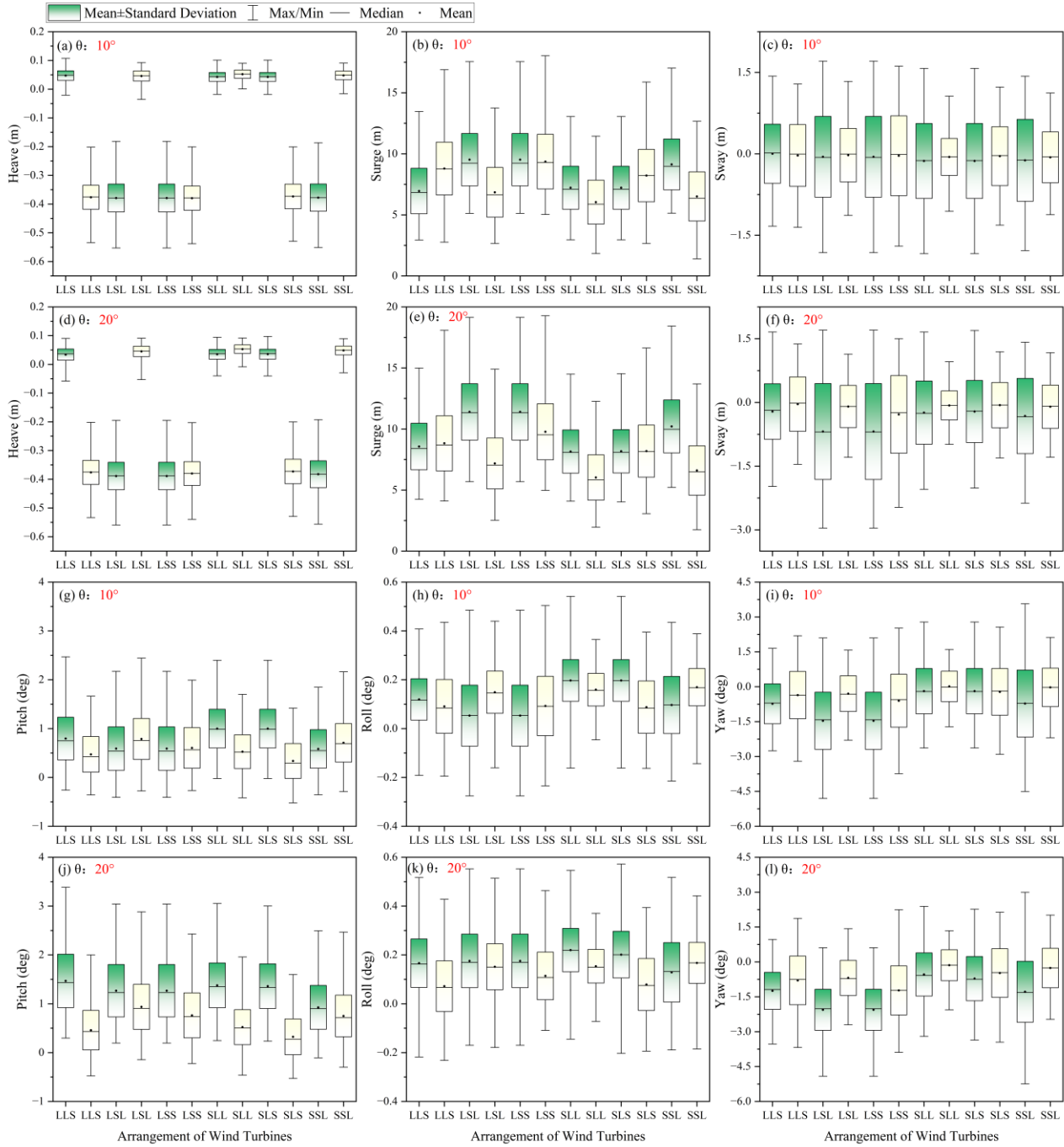


Fig. 19. 6-DOF motions at 10° and 20° yaw across six layouts (T2: green and T3: slight yellow)

1 Fig. 20 displays boxplots of 3D tower-base loads and hub thrust for T2 (pink) and T3 (yellow) turbines across the
2 six hub-height configurations at 10° and 20° yaw angles of T1. T3 exhibits minimal overall load variations in all
3 four load components, thus confirming limited wake effects at the current spacing. For T2, loads increase
4 significantly in the tower-base X and Y directions as well as in hub thrust with higher yaw angles of T1, with tower-
5 base X -loads and hub thrust showing the most pronounced increases while tower-base Z -load variations remain
6 minor. T2's load magnitudes exceed T3's in all directions, and this disparity is particularly prominent in tower-base
7 X -loads at a 20° yaw angle of T1. This indicates T2's heightened sensitivity to the front-row turbine (T1) wake and
8 yaw disturbances from T1, which aligns with the 6-DOF response patterns observed earlier.

9 Notably, in the SLL arrangement, both turbines show stable tower-base X -loads. Specifically when T1 is the small-
10 capacity turbine and T2 is the large-capacity turbine, T2 displays significant increases in tower-base Y -loads—
11 though absolute values remain below those of X -loads—which warrants attention due to its potential structural
12 safety implications. Z -direction loads exhibit low fluctuations, and their low fluctuations are governed by gravity-
13 buoyancy force equilibrium. Crucially, hub thrust and tower-base X -loads follow identical monotonic increasing
14 trends with rising yaw angles of T1.

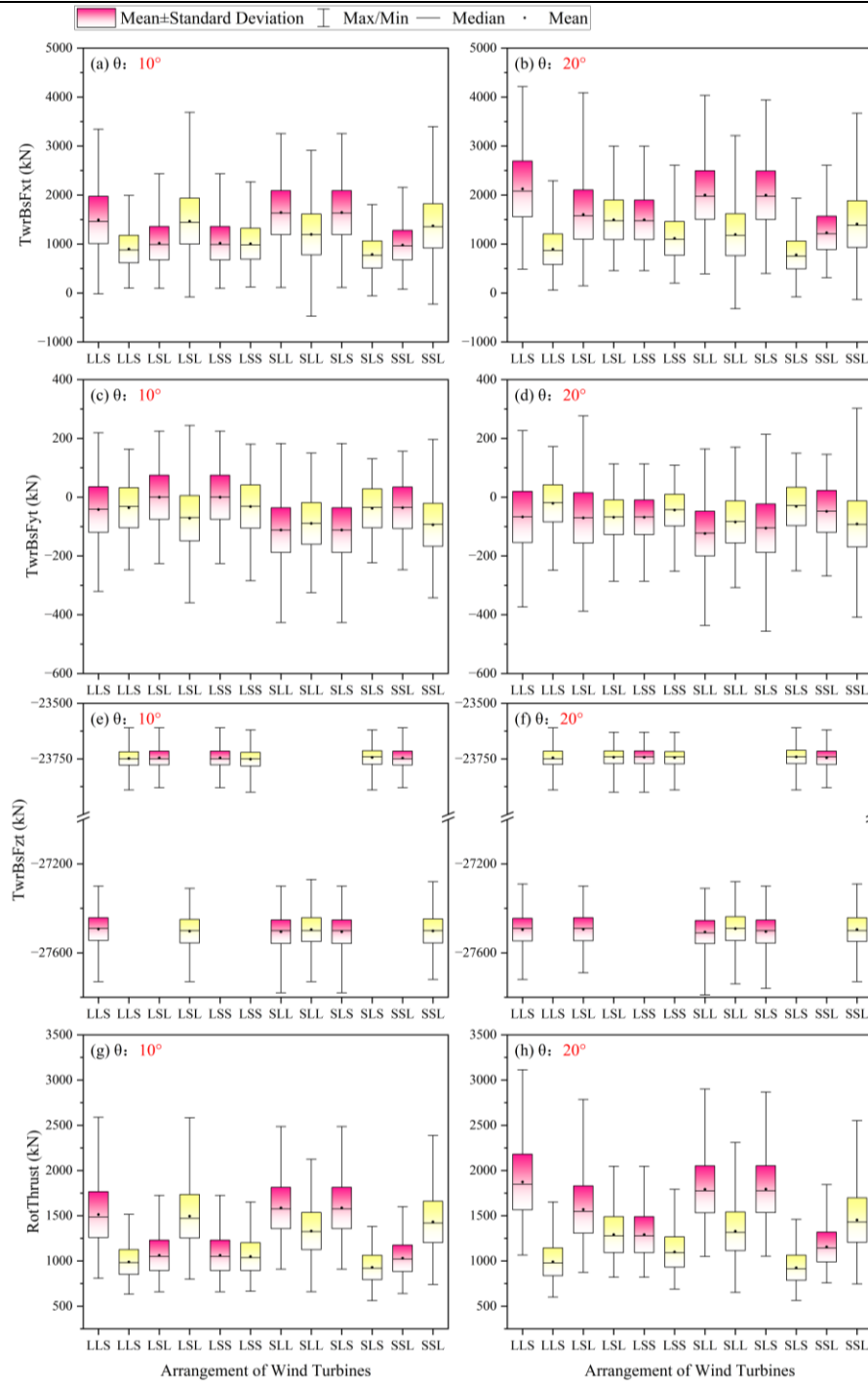


Fig. 20. Tower-base loads at 10° and 20° yaw across six layouts (T2: pink and T3: yellow)

4. Comprehensive Analysis of Optimal Turbine Layouts

This chapter focuses on a mean turbulent wind speed of 7.6 m/s, representing a typical offshore condition. Therefore, the advantageous combinations observed at other wind speeds (as discussed in Section 3) are not addressed here. Instead, this chapter aims to identify an optimal layout under this moderate sea state. This chapter investigates eight turbine layout schemes for optimizing wind farm arrangements, comprising two uniform single-type configurations and six heterogeneous turbine configurations. Systematic analyses encompass hub thrust, yaw-system loads, and tower-base dynamic responses. The coefficient of variation (defined as the ratio of standard deviation to mean) is used to quantify system stability by assessing response fluctuations of the aforementioned parameters under

operational conditions, enabling scientific comparisons of stability across schemes. Concurrently, a Pareto-front identification is employed to maximize total power output while minimizing tower-base horizontal displacement and tower-base structural loads, with Pareto front analysis identifying optimal solution sets. This research elucidates the performance advantages and applicable scenarios of each scheme under varying yaw angles, providing a quantitative foundation for scientific data-driven wind farm layout decisions.

4.1 Power-Load Trade-off Analysis at Fixed Yaw Angles (Stability, Performance Range)

Under inflow conditions with a mean turbulent wind speed of 7.6 m/s, a systematic analysis is conducted to evaluate the impacts of yaw angles (0°, 10°, and 20°) on the power performance and structural responses of large-scale turbines. Three key load metrics are examined: hub thrust, yaw-bearing loads, and tower-base loads. This analysis quantifies the stability and fluctuations of structural responses across heterogeneous turbine configurations. Dimensionless stability indices based on the coefficient of variation (CoV) are proposed as follows:

$$\text{Stability}_{\text{Rot}} = \frac{\sigma_{F_R}}{\text{Mean}_{F_R}} \quad (11)$$

$$\text{Stability}_{\text{YawBr}} = \frac{\sigma_{F_Y}}{\text{Mean}_{F_Y}} \quad (12)$$

$$\text{Stability}_{\text{TwrBs}} = \frac{\sigma_{F_T}}{\text{Mean}_{F_T}} \quad (13)$$

Here, the three stability indices represent the stability of hub thrust, yaw-bearing system, and tower-base loads, respectively. In the equations, σ denotes the standard deviation of the load time series and Mean represents the mean value. Subscripts F_R , F_Y and F_T indicate hub thrust, yaw-bearing loads, and tower-base loads, respectively. Lower stability indices signify more stable responses with reduced fluctuations, which benefit the enhancement of operational reliability. Range values are used to supplement the CoV, providing additional insights into extreme load variations. Comparative analysis across yaw angles of T1 reveals distinct patterns of structural response variation, enabling the identification of configurations with superior structural safety and operational stability. These findings provide theoretical bases and technical references for wind farm cooperative control and layout optimization.

4.1.1 Structural Responses and Optimal Matching at 0° Yaw

This section analyzes the dynamic stability of turbine systems at 0° yaw angle of T1 for T1-leading configurations. Fig. 21 displays the range values and coefficient of variation (CoV) distributions for key loads across different turbine combinations. The figure is organized into three columns, presenting data for Turbine T1 (left), T2 (middle), and T3 (right), respectively. Accordingly, the subsequent analysis follows this sequence, beginning with T1, proceeding to T2, and concluding with T3.

For T1 at 0° yaw angle, its system loads are concentrated primarily in the windward (X) direction, with lateral (Y) responses playing an auxiliary role in load distribution. A comprehensive evaluation reveals that the large-capacity T1 turbine intensifies global load fluctuations of the system (as indicated by elevated range values); however, it enhances structural stability (Fig. 21, left panel) due to superior load-bearing capacity and structural robustness. Thus, large-capacity turbines are prioritized for front-row placement in T1-leading configurations.

Given a large-capacity T1, T2 with low rated power (T1-T2 high-low configuration: high-capacity T1, low-capacity T2) improves stability of X-direction hub thrust and yaw-bearing loads (Figs. 21b, k). With the addition of a small-capacity T3 (LSS configuration), X-direction hub thrust and yaw-bearing responses achieve optimal stability (Figs. 21c, l). For Y-direction yaw-bearing responses, the T1-T2 LL configuration exhibits the best stability (Fig. 21n),

1 with the LLL configuration marginally outperforming the LLS configuration in terms of Y-direction yaw-bearing
 2 response stability.

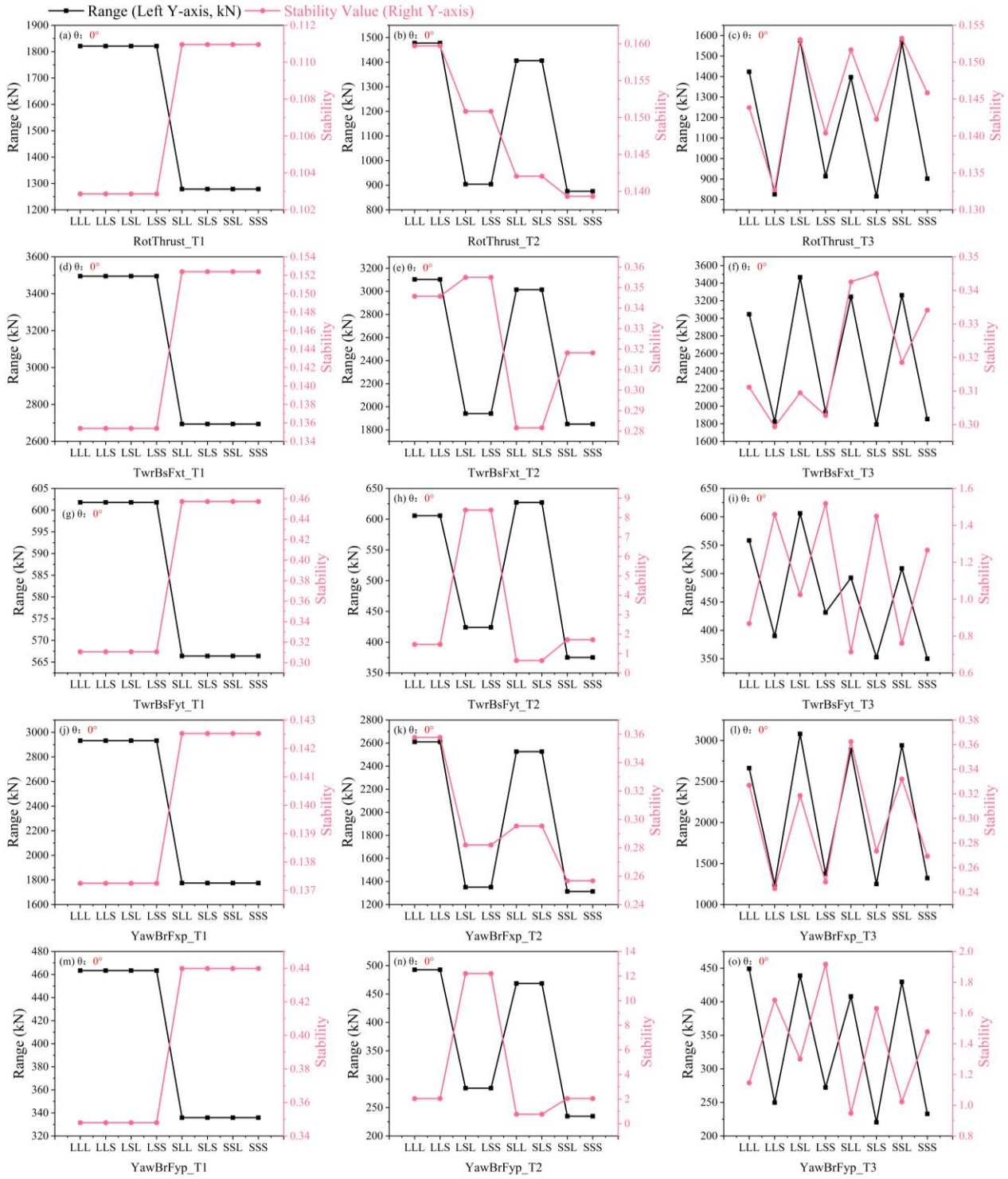


Fig. 21. Load stability metrics for eight layouts at 0° yaw, representing rotor thrust (RotThrust), tower-base shear forces (TwrBsFxt, TwrBsFyt), and yaw-bearing shear forces (YawBrFxp, YawBrFyp).

Tower-base analysis shows maximum X -direction stability with a large-capacity T2 (Fig. 21f), and this stability is further enhanced by the LLS configuration (incorporating a small-capacity T3). Y -direction stability peaks in the T1-T2-T3 LLL configuration (all three turbines: large-capacity). Synthesizing these findings, the LSS configuration optimizes hub thrust and yaw-system responses at 0° yaw angle of T1, while the LLS configuration offers advantages for tower-base X -responses. Therefore, the LSS configuration is recommended for drivetrain systems (hub and yaw components), and the LLS configuration is recommended for substructures (tower-base components).

4.1.2 Structural Responses and Optimal Matching at 10° Yaw

Following the analytical sequence from the preceding section, the evaluation proceeds from the data of Turbine T1 (left column) to T3 (right column) in Fig. 22. With the T1 yaw angle set at 10° , this figure is used to present system stability responses across turbine configurations. Comparative analysis reveals that a large-capacity (L) T1 significantly enhances stability for hub thrust (Fig. 22a), tower-base X - and Y -direction loads (Figs. 22d and g), and yaw-bearing X -direction loads (Fig. 22j). In contrast, a small-capacity (S) T1 improves stability only in the yaw-bearing Y -direction (Fig. 22m).

Optimal T2-T3 configurations are determined as follows: For hub thrust, small-capacity T2 improves stability (Fig. 22b), with the LSS configuration (large-capacity T1, small-capacity T2, small-capacity T3; incorporating small-capacity T3) delivering optimal performance (Fig. 22c). Identical trends apply to the yaw-bearing X -direction responses: small-capacity T2 enhances stability (Fig. 22k), with the LSS configuration confirmed as superior in stability (Fig. 22l). For the yaw-bearing Y -direction responses (where small-capacity T1 excels in enhancing stability), furthermore, small-capacity T2 (Fig. 22n) and small-capacity T3 (Fig. 22o) collectively maximize stability, supporting the recommendation of the SSS configuration.

Tower-base analysis shows the LLS configuration optimizes X -direction stability (supported by large-capacity T1 and T2 in Figs. 22d and e), while LLL configuration maximizes Y -direction stability (Fig. 22g-i). Thus, optimal configurations at a 10° yaw angle of T1 are: LSS for hub thrust and yaw-bearing X -responses, SSS for yaw-bearing Y -responses, LLS for tower-base X -direction, and LLL for tower-base Y -direction. Synthesizing these findings, the LSS configuration demonstrates superior drivetrain stability to other configurations with significant application potential under a 10° yaw angle of T1.

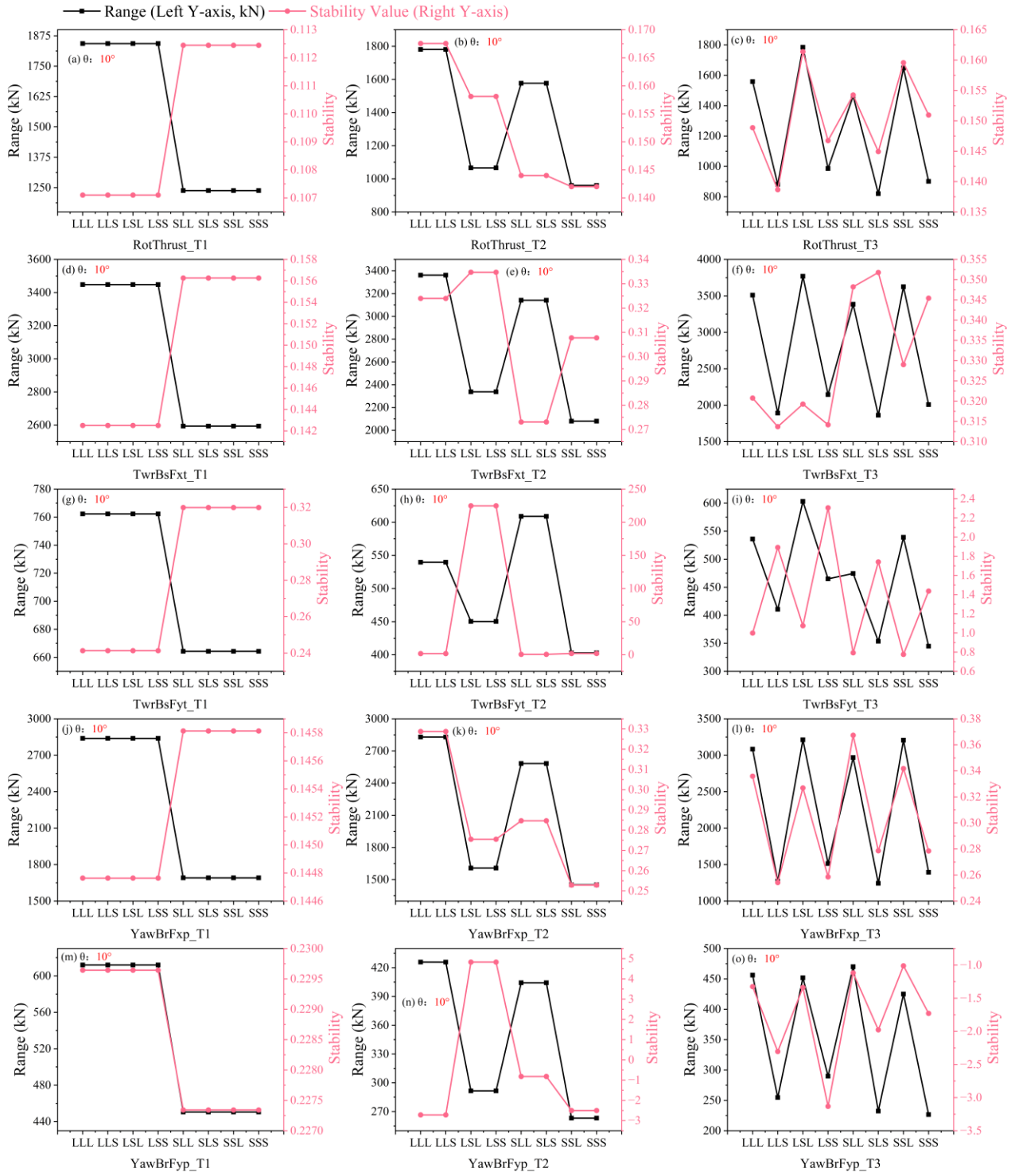


Fig. 22. Load stability metrics for eight layouts at 10° yaw, representing rotor thrust (RotThrust), tower-base shear forces (TwrBsFxt, TwrBsFyt), and yaw-bearing shear forces (YawBrFxp, YawBrFyp).

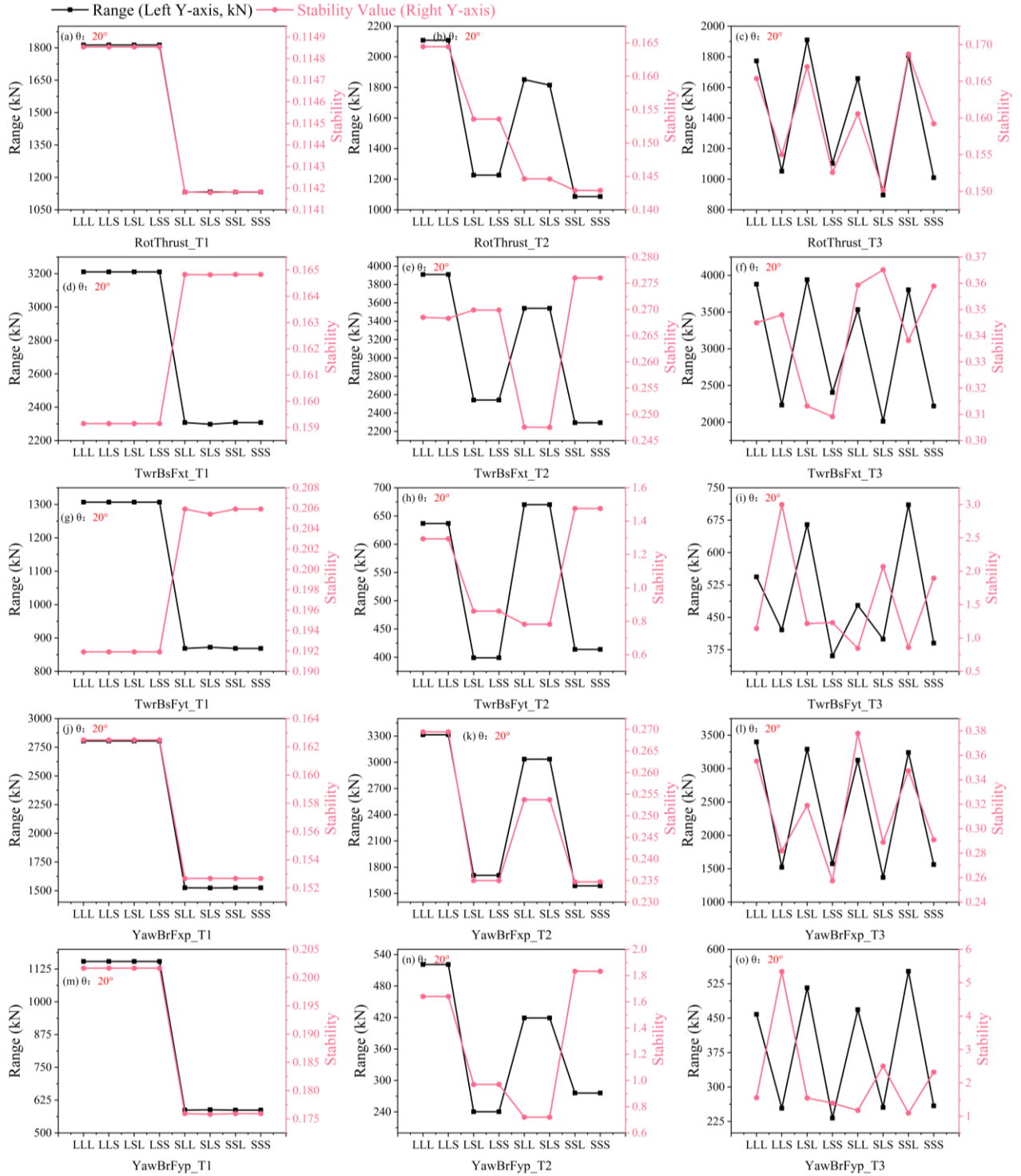


Fig. 23. Load stability metrics for eight layouts at 20° yaw, representing rotor thrust (RotThrust), tower-base shear forces (TwrBsFxt, TwrBsFyt), and yaw-bearing shear forces (YawBrFxp, YawBrFyp).

With the T1 yaw angle increased to 20°, stability responses exhibit new trends compared to those of 10° yaw conditions (Fig. 23). For hub thrust and the yaw-bearing X-direction, small-capacity T1 yields higher global stability

of the system, and additionally, small-capacity T2 and T3 further enhancing performance (Figs. 23b, c, k and l), supporting the recommendation of the SSS configuration. In the yaw-bearing Y -direction, small-capacity T1 maintains optimal stability, while large-capacity T2 significantly improves stability (Fig. 23n) and large-capacity T3 achieves peak performance (Fig. 23o), establishing the SLL configuration as optimal.

Tower-base optimization diverges from drivetrain optimization: the X -direction favors the LLL configuration, supported by large-capacity T1 and T2 as described in Figs. 23d-e and its marginal superiority in Fig. 23f. For the Y -direction, while large-capacity T1 enhances stability (Fig. 23g), small-capacity T2 performs better (Fig. 23h). For T3, negligible difference exists between the LSL and LSS configurations (Fig. 23i) and considering the larger range values of large-capacity turbines, both configurations are recommended.

Thus, the optimal solutions at a 20° yaw of angle of T1 are: SSS for hub thrust and yaw-bearing X -direction, SLL for yaw-bearing Y -direction, LLL for tower-base X -direction, and LSL/LSS for tower-base Y -direction being optimal due to their equivalent performance. Synthetically these findings, the SSS and SLL configurations demonstrate superior drivetrain stability, while the LLL, LSL, and LSS configurations provide robust substructure responses, collectively representing optimal configuration strategies.

4.1.4 Analysis of Fatigue Damage Equivalent Load (DEL) Characteristics of Tower and Yaw System under Multi-Turbine Array Layouts

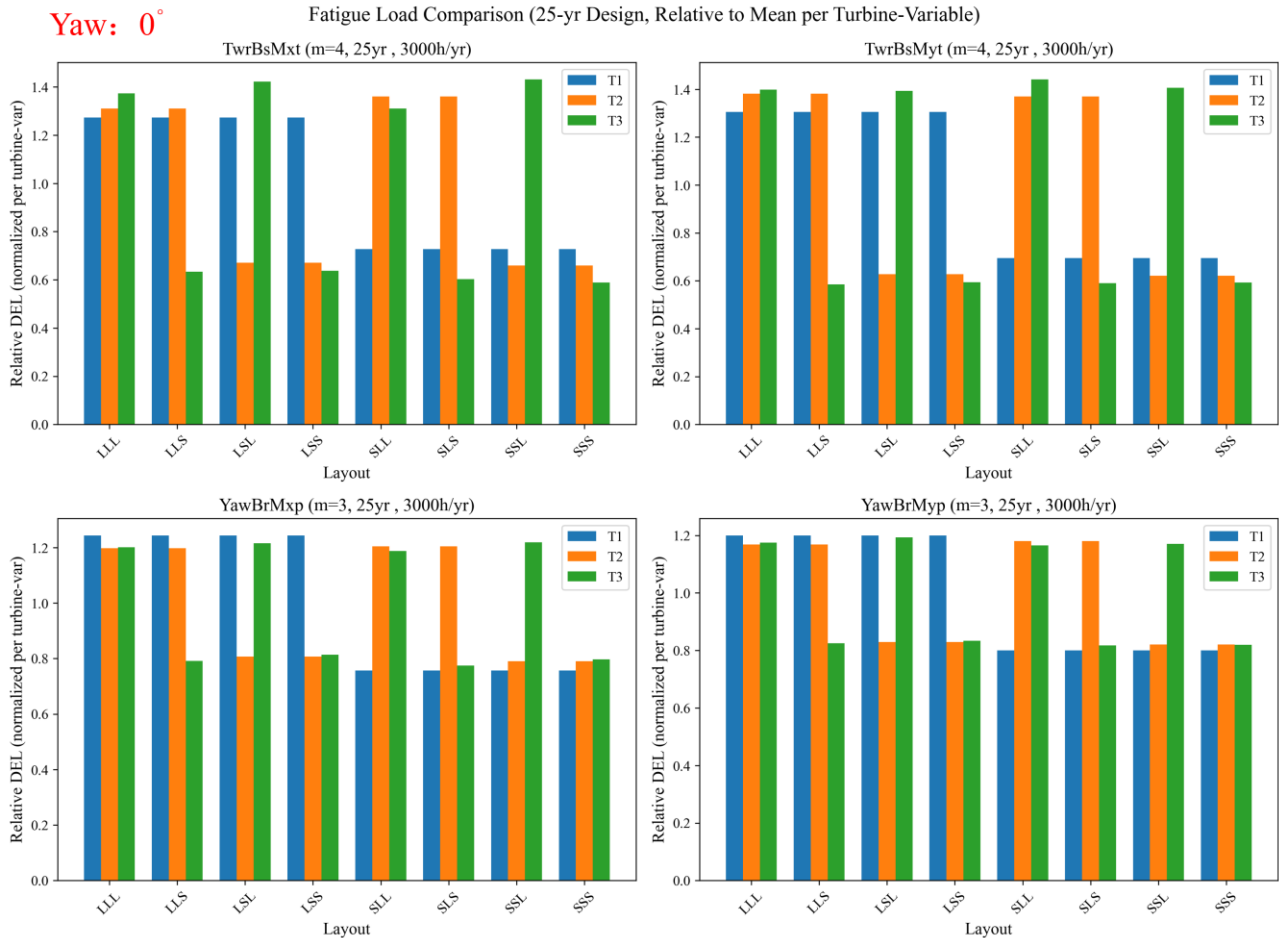


Fig. 24. Equivalent fatigue loads (DEL) for eight layouts at 0° yaw, representing tower-base bending moments (TwrBsMxt, TwrBsMyt) and yaw-bearing bending moments (YawBrMxp, YawBrMyp).

Yaw: 10°

Fatigue Load Comparison (25-yr Design, Relative to Mean per Turbine-Variable)

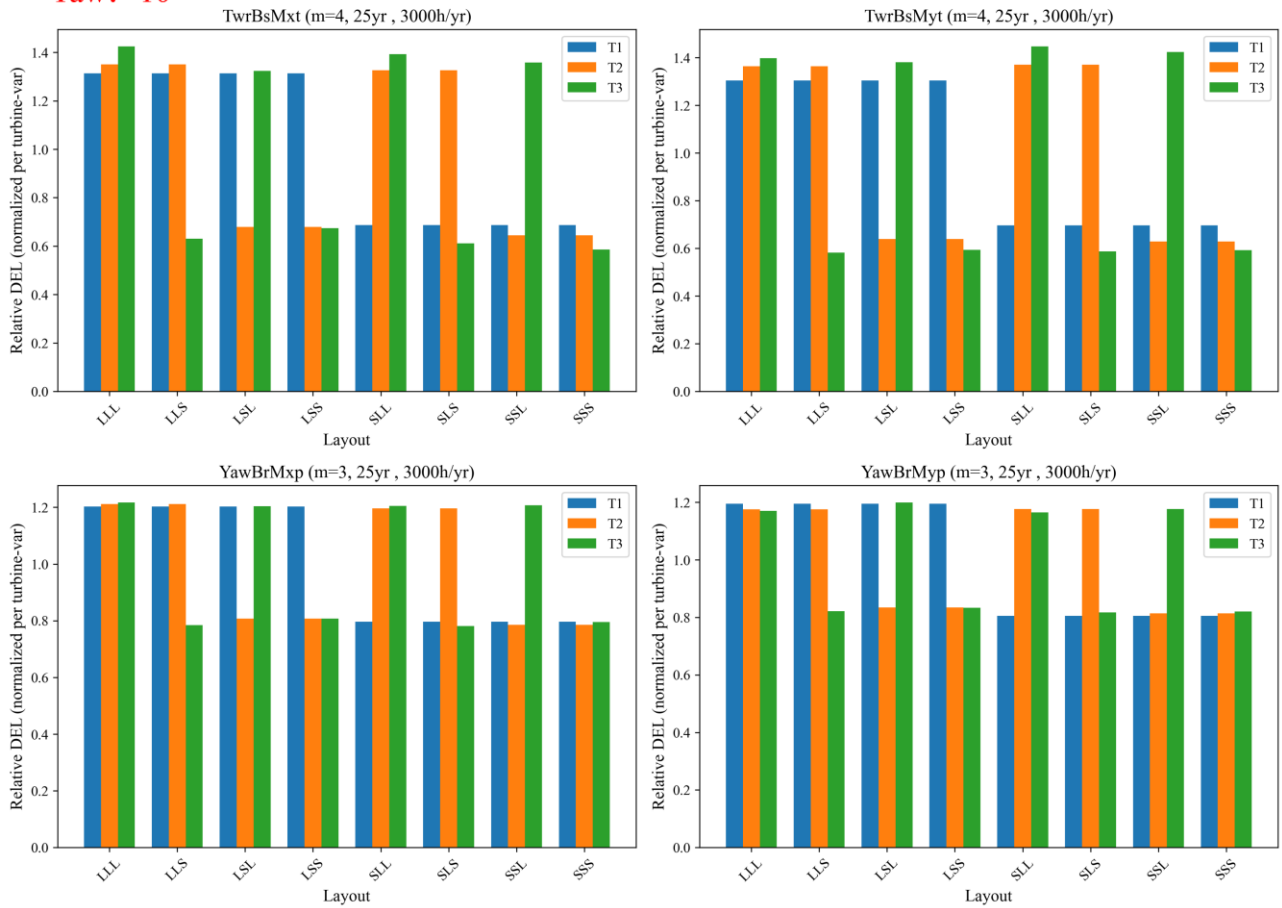


Fig. 25. Equivalent fatigue loads (DEL) for eight layouts at 10° yaw, representing tower-base bending moments (TwBsMxt, TwBsMyt) and yaw-bearing bending moments (YawBrMxp, YawBrMyp).

Yaw: 20°

Fatigue Load Comparison (25-yr Design, Relative to Mean per Turbine-Variable)

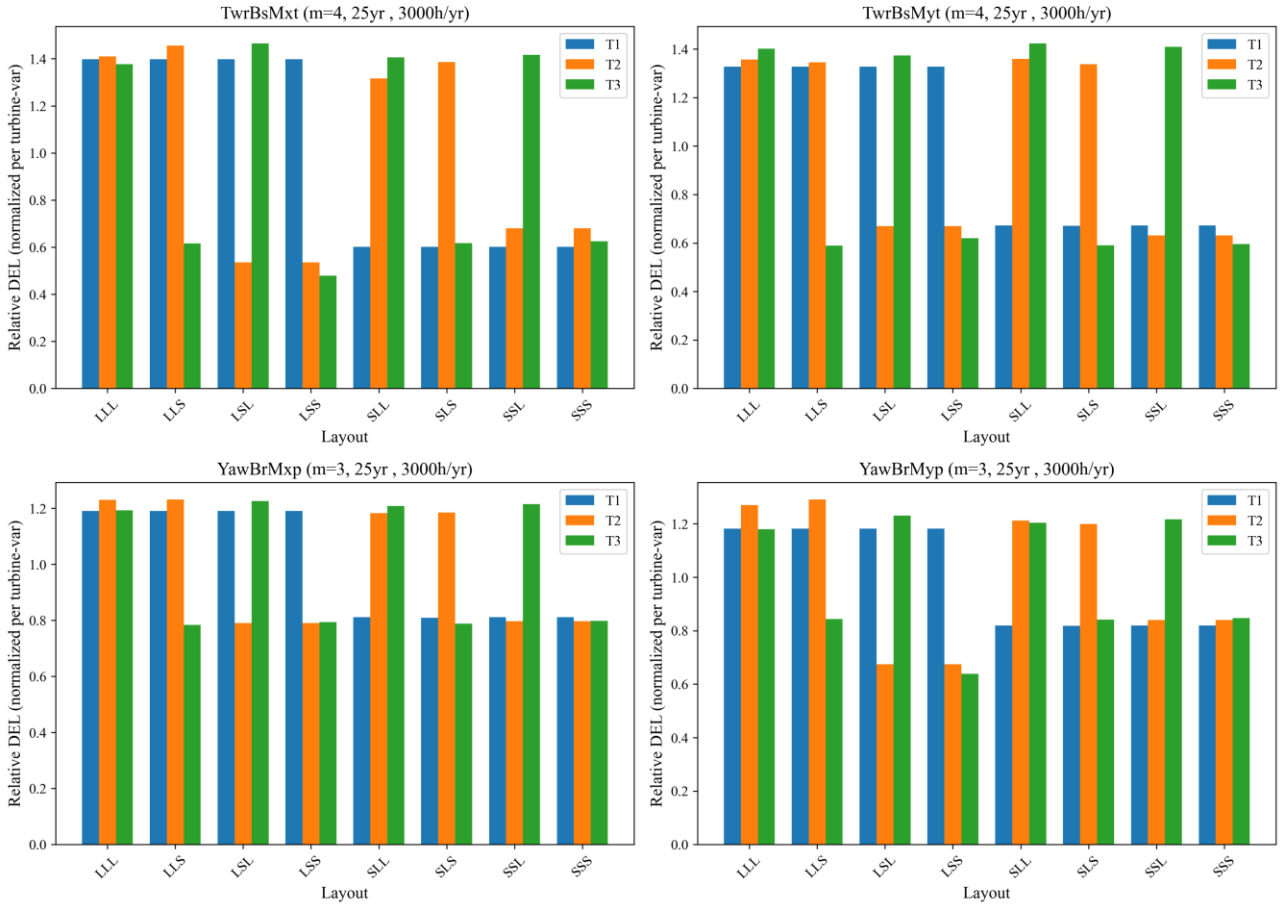


Fig. 26. Equivalent fatigue loads (DEL) for eight layouts at 20° yaw, representing tower-base bending moments (TwrBsMxt, TwrBsMyt) and yaw-bearing bending moments (YawBrMxp, YawBrMyp).

To further quantify the impact of different layout configurations, turbine positions, and yaw angles on the long-term fatigue damage equivalent load (DEL) of tower bases and yaw bearings, a quantitative analysis was conducted based on the raw DEL and normalized relative DEL data under three yaw conditions (0°, 10°, and 20°), as presented in Figs. 24–26. Across all operating conditions, the DEL exhibited a clear hierarchical distribution: the raw DEL of large turbines (L) was significantly higher than that of small turbines (S), indicating that turbine type is the dominant factor governing fatigue damage magnitude. The DEL of the three turbines in the all-large layout (LLL) was globally the highest, while the all-small layout (SSS) yielded the lowest values, with mixed layouts falling in between. From the perspective of turbine positional differences, the DEL values of the three large turbines in the LLL layout were comparable, with small variations. When small turbines were introduced, load differentiation became pronounced. For example, in the SSL layout, the tower-base bending moment DEL of the large turbine T3 far exceeded that of the two small turbines T1 and T2 in the same layout. In the LSS layout, the DEL of the two small turbines T2 and T3 decreased relative to their counterparts in the all-large layout, indicating a significant reduction in fatigue risk. When only one turbine was replaced by a small turbine (e.g., LLS, SLL), the DEL of the small turbine itself was substantially reduced, but because the remaining large turbines still sustained high loads, the overall average DEL reduction across the wind farm was limited. Layouts containing two or more small turbines (LSS, SLS, SSL), and especially the all-small SSS layout, achieved the lowest global DEL, confirming the effectiveness of deploying small turbines in suppressing fatigue accumulation. The influence of yaw angle manifested as follows: at 10° yaw, the DEL values of each layout exhibited only minor fluctuations, and the relative order remained essentially unchanged. At a large yaw angle of 20°, load differentiation intensified considerably. The tower-base lateral bending moment DEL of the upstream large turbine increased

substantially, while the corresponding DEL of downstream small turbines either decreased or remained stable, further widening the fatigue damage gap between large and small turbines. The raw DEL magnitudes of tower-base bending moments (TwrBsMxt, TwrBsMyt) were overall higher than those of yaw-bearing bending moments (YawBrMxp, YawBrMyp), and the variability of tower-base DEL with layout and yaw angle was more pronounced, indicating that the tower base is more sensitive to turbine spacing and yaw conditions. The normalized relative DEL further corroborated these findings: the relative DEL of the three turbines in the LLL layout generally exceeded 1.2, representing fatigue damage above the farm average, while that of layouts containing small turbines was mostly below 0.8, indicating below-average damage.

In summary, turbine type and layout configuration are the core variables governing the long-term fatigue damage of tower bases and yaw bearings. Large turbines exhibit significantly higher fatigue damage risk than small turbines. Increasing the yaw angle amplifies load differentiation among layouts, and the tower base is more susceptible to layout and yaw effects than the yaw bearing. In engineering practice, priority should be given to targeted damage monitoring for large turbines in all-large layouts, while adopting mixed layouts with multiple small turbines can effectively reduce the equivalent fatigue load over the 25-year design life of the entire wind farm.

4.2 Pareto-Front Identification-Assisted Supporting Methodology for Wind Farm Layout Arrangement

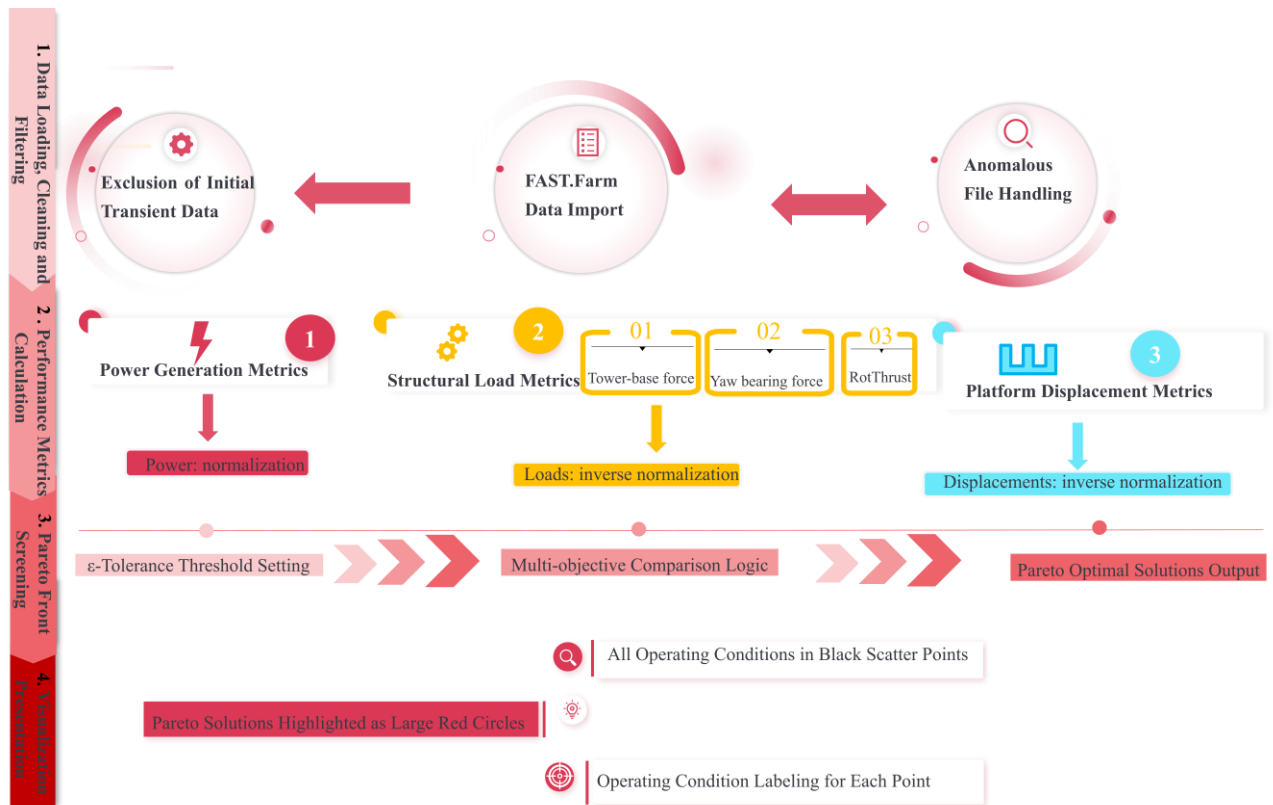


Fig. 27. Multi-objective optimization workflow

Existing stability metrics offer preliminary assessments of wind turbine performance but inadequately address multidimensional performance characteristics, which limits the comprehensive evaluation of configuration advantages. Therefore, additional key parameters must be incorporated to establish an automated Pareto-front based evaluation framework for a discrete set of wind turbine configurations (Fig. 27). Pareto front analysis with a tolerance parameter ϵ is employed to address non-ideal engineering conditions. Data from numerical simulations provide theoretical foundations for engineering applications. The workflow extracts steady-state phase data (post-300s simulation period) from Fast.Farm outputs, categorizing it into power generation (P), structural loads (F), and

displacement responses (D). Normalization via Eqs. (13-15) eliminates dimensional and magnitude disparities:

$$\tilde{P}_i = \frac{P_i - P_{min}}{P_{max} - P_{min}} \quad (13)$$

$$\tilde{F}_i = 1 - \frac{F_i - F_{min}}{F_{max} - F_{min}} \quad (14)$$

$$\tilde{D}_i = 1 - \frac{D_i - D_{min}}{D_{max} - D_{min}} \quad (15)$$

Multi-objective vectors $\mathbf{f}^{(i)} = [\tilde{P}_i, \tilde{F}_i, \tilde{D}_i]$ are constructed. Solution filtering applies ε -modified Pareto dominance:

$\mathbf{f}^{(i)}$ is Pareto-optimal if no $\mathbf{f}^{(j)}$ satisfies $\forall j \neq i, \nexists \mathbf{f}^{(j)} \succ_{\varepsilon} \mathbf{f}^{(i)}$ and $\mathbf{f}^{(j)} \succ_{\varepsilon} \mathbf{f}^{(i)} \Leftrightarrow (\forall k, f_k^{(j)} \geq f_k^{(i)} - \varepsilon) \wedge$

$(\exists k, f_k^{(j)} > f_k^{(i)} + \varepsilon)$ (Eqs. 16-17). This method identifies the non-dominated configurations that best balance

energy efficiency and structural safety under the multiple criteria considered, providing quantitative foundations for comparative design assessment.

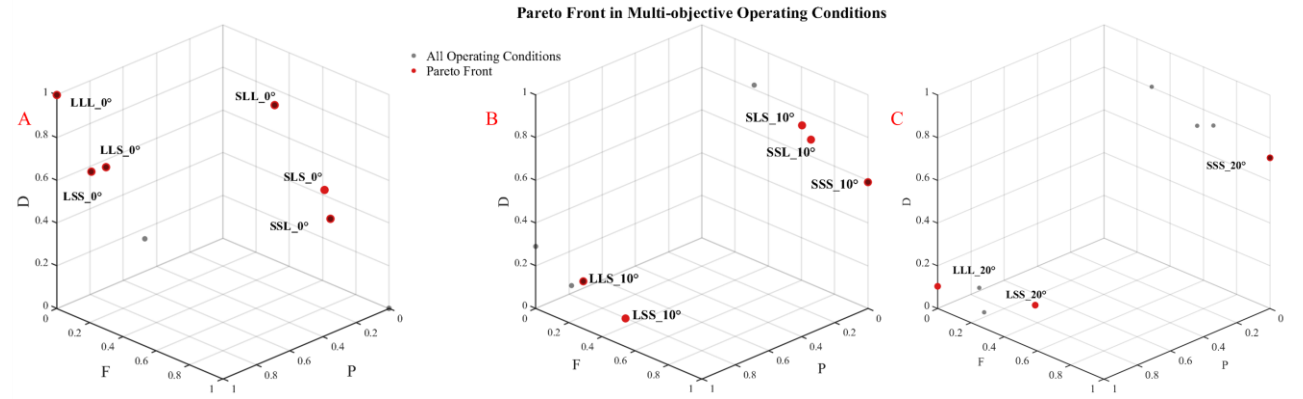


Fig. 28. Pareto-optimal solution sets for three layouts

The identified optimal solutions are marked with red dots in Fig. 28, while the remainder of the solution set is depicted as gray dots—with their specific arrangements not indicated. Fig. 28(A) shows six optimal configurations identified by the ε -Pareto front at 0° yaw angle of T1, where the LLS and LSS configurations align with the stability-based optima. Although discrepancies exist (with only two configurations being exclusive to one method), the partial solution overlap yields a Jaccard coefficient of 0.33—defined as the size of the intersection divided by the size of the union of the two optimal sets (Deng L et al., 2024)—with the two optimal sets denoted as sets A and B in Eq. (18). This value indicates a moderate consistency between the two methods and validates the applicability of the ε -Pareto approach under low yaw angles.

$$J(A, B) = |A \cap B| / |A \cup B| \quad (18)$$

At a 10° yaw of T1 (Fig. 28(B)), five non-dominated solutions (LLS, LSS, SLS, SSL, SSS) show strong alignment with the stability-based assessment: LSS excels in the stability of hub thrust and yaw-bearing X -direction performance, SSS dominates yaw-bearing Y -direction stability, and LLS optimizes tower-base X -direction responses. A Jaccard coefficient of 0.60 confirms high consistency between the ε -Pareto front method and the stability-based assessment method.

Table 4. Power output of the LSS layout under three turbulent inflow realizations

Variable	Mean (kW)	Std. Dev. (kW)	CoV (%)	Seed 1	Seed 2	Seed 3
GenPwr_T1	10 905.13	25.08	0.230	10 883.57	10 932.65	10 899.17

GenPwr_T2	5 431.07	72.80	1.340	5 499.63	5 354.67	5 438.91
GenPwr_T3	4 428.22	31.55	0.712	4 459.86	4428.03	4 396.77

1 **At a 20° yaw angle of T1 (Fig. 25(C)), three Pareto solutions (LLL,**
2 **LSS, SSS) match the stability-based optima, with SSS optimizing**
3 **drivetrain systems and LLL/LSS dominating tower-base substructures,**
4 **supported by a Jaccard coefficient of 0.60. Crucially, the LSS**
5 **configuration consistently emerges in Pareto sets across all yaw angles.**
6 **To verify whether this advantage is coincidental, a dedicated sensitivity**
7 **analysis using three independent turbulent inflow realizations (seeds)**
8 **was performed for the LSS layout. As shown in Table 4, the coefficient**
9 **of variation (CoV) of its total power output across the three seeds is**
10 **below 1.5% (0.23% for T1, 1.34% for T2, 0.71% for T3), and the CoV**
11 **of its key structural loads remains within 5%. It should be noted that**
12 **the CoV reported here is defined as the ratio of the inter-seed standard**
13 **deviation to the ensemble mean, quantifying the sensitivity of the results**
14 **to the specific turbulent inflow realization — distinct from the**
15 **time-domain CoV used elsewhere in this study. These results confirm**
16 **that the superiority of the LSS layout is robust against turbulent inflow**
17 **randomness, demonstrating exceptional operational adaptability,**
18 **structural stability, and significant practical deployment potential for**
19 **wind farm optimization.**

5. Conclusion

This study established a theoretical and practical framework for optimizing wind farm layouts and control strategies under complex wind conditions. To this end, the coupled effects of mean turbulent wind speeds (7.6–12.7 m/s), turbine configurations, and yaw misalignment on wake characteristics, system efficiency, and structural responses have been systematically quantified. The analysis identified the primary controlling factors for wake loss and energy compensation, thereby validating the effectiveness of the Pareto-front identification approach for screening turbine placement configurations within a discrete design space. The key conclusions are as follows:

1. Mechanisms governing the impacts of wind speed and turbine arrangement on wake loss are elucidated. Wake-induced power loss exhibits a strong inverse correlation with wind speed. It is most pronounced at low-to-medium wind speeds but diminishes significantly as operating conditions approach the rated capacity of the turbines. A comprehensive analysis demonstrates that installing smaller and lower-hub turbines upstream effectively reduces wake losses on larger and higher-hub downstream units (e.g., T2), thereby exhibiting robust energy regulation and compensation mechanisms across the turbine array.

2. The yaw control of the upstream turbine T1 alone induces prominent aerodynamic-structural effects on the downstream units, confirming the effectiveness of the first step in yaw-based wake steering. However, active yaw of downstream turbines is not considered in this study. Future work may explore adaptive downstream yaw strategies based on these findings to further enhance overall wind farm performance. Specifically, increasing the upstream yaw angle deflects the wake, which reduces wake impingement on T2 and enhances its power output at the expense of the yawed turbine's own efficiency. This dynamic confirms a power compensation mechanism within the array (i.e., $T1 \text{ loss} \approx T2 \text{ gain}$). Structurally, T2 exhibits the highest sensitivity to this wake deflection, as evidenced by its yaw, pitch, and surge responses that increase monotonically with the yaw angle. This trend is attributed to the asymmetric loading induced by the deflected wake. This aerodynamic-structural coupling persists under heterogeneous turbine configurations, underscoring the necessity for balanced yaw strategies that negotiate the trade-off between power gain and structural load risks.

3. The Pareto front optimization method is employed to identify optimal layouts that balance power efficiency, structural load response, and displacement control. Evaluations across multiple operating conditions (yaw angles of 0° , 10° , 20°) demonstrate that this method effectively screens a vast space of potential configurations to yield robust, high-performance solutions. Notably, the "LSS" layout consistently emerges as a non-dominated solution across all tested scenarios, exhibiting superior and stable performance in energy output, structural integrity, and operational adaptability. It is, therefore, recommended as a promising candidate for practical wind farm layout optimization under diverse wind conditions.

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Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work the author used DeepSeek in order to improve language and readability. After using this tool/service, the author reviewed and edited the content as needed and took full responsibility for the content of the published article.

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