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Review

Optimization of wind turbine blade designs using computational fluid dynamics and structural analysis: a review

Sudheer Choudari[1]*, Surender Kumar Yadav[2], Jaishree Chauhan[3], Phaneender Aedla[4], Pasupula Kalidass Anjani[5], Rajendra Kumar Ganiya[6], Md. Abdul Raheem Junaidi[7], Saurabh Sanjay Joshi[8]

[1]Department of Civil Engineering, Centurion University of Technology and Management, Andhra Pradesh, India
[2]Department of Mechanical Engineering, Sanskaram University, Haryana, Uttar Pradesh, India
[3]Department of Mechanical Engineering, Institute of Engineering and Technology, MLSU, Udaipur, India
[4]Department of Energy, Climate & Catastrophe Risk, SP Jain School of Global Management, India
[5]Department of Management Studies, Sona College of Technology, Salem, India
[6]Department of Computer Science and Engineering, Koneru Lakshmaiah Education Foundation, Vaddeswaram, Guntur, A.P, India
[7]Mechanical Engineering Department, Muffakham Jah College of Engineering and Technology, Hyderabad, Telangana, India
[8]Department of Civil and Environmental Engineering, KIT's College of Engineering (Empowered Autonomous), Kolhapur, Maharashtra, India

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*Corresponding author
Email address:
sudheer.13031@gmail.com

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ABSTRACT

Wind turbine blade optimization requires coordinated improvement of aerodynamic efficiency, structural reliability, fatigue life, manufacturability, and computational cost. This systematic literature review synthesizes studies on wind turbine blade design optimization using computational fluid dynamics and structural or aeroelastic analysis, with attention to design variables, modeling approaches, coupling strategies, optimization methods, validation practices, and limitations. The review protocol was registered with the OSF Registries under DOI 10.17605/OSF.IO/VAR9T. Following a PRISMA-guided process, 233 records were identified from Scopus, Web of Science, ScienceDirect, IEEE Xplore, Google Scholar, and manual reference checks. After removing 25 duplicates, 208 records were screened, 34 full texts were assessed, and 14 studies were included for qualitative synthesis. The literature clustered into three streams: CFD-based aerodynamic shape optimization, especially airfoil, blade-tip, chord, twist, and sweep refinement; aeroelastic or multidisciplinary optimization balancing annual energy production with loads, fatigue, and control constraints; and structural or composite optimization addressing mass, stiffness, stress, deflection, buckling, laminate design, and manufacturability. Many studies used hybrid workflows combining selective high-fidelity CFD with reduced-order, beam, cross-sectional, or surrogate models. Integrated aero-structural optimization appears most practical, but comparisons remain limited by inconsistent load cases, incomplete validation, limited reporting of uncertainty, and insufficient treatment of manufacturability.

1. Introduction

Wind energy will also continue to grow as an alternative source of low-carbon electricity, and this growth will increasingly rely on larger, lighter, and more efficient wind turbine rotors. Since the rotor blade is the primary component that converts wind kinetic energy into mechanical energy, blade design greatly influences annual energy production (AEP), aerodynamic and structural loads, fatigue life, noise, and, ultimately, energy costs. The modern blades should thus be extremely aerodynamically efficient while also meeting strict structural requirements under widely varying inflow conditions. This is an inherently multiphysics design challenge in which gains in aerodynamic performance may lead to higher loads, deflections, and fatigue damage unless structural design and aeroelastic behavior are addressed simultaneously.

One of the most effective strategies for dealing with these competing requirements has been optimization. The shape and local geometry of the blade can be optimized to increase energy capture and control flow separation, especially in regions such as the tip, where the 3D effect is strong. Aerodynamic shape optimization methods have been developed using adjoint techniques to compute gradients for rotating blade designs and to systematically optimize the blade geometry based on aerodynamic requirements [1,2]. A shape-to-performance mapping of these methods is being complemented by data-driven methods, such as invertible neural networks, that have been investigated for the shape control of airfoils, enabling rapid mapping of shape parameters to performance behavior and accelerating design exploration [3]. However, to improve aerodynamics, the design must also be evaluated for structural viability and operational reliability, as an optimized design based solely on aerodynamic criteria may lead to excessive stresses, deflections, or reduced fatigue life.

Aerodynamic design is therefore necessitated by structural analysis and optimization. Blade structures are typically composite and must comply with stiffness, strength, buckling, and manufacturability constraints whilst remaining lightweight. Structural optimization has been used at various scales, including topology optimization to optimize material use in offshore composite blades subject to structural constraints [4] and multi-material and thickness optimization of still critical areas, such as the blade root load transfer, which is most critical there [5]. The mass of composite wind turbine designs has also been reduced through genetic algorithm-based structural optimization, which has shown that heuristic optimization can be important for searching discrete or highly constrained design spaces [6]. In the modeling level, the development of high-fidelity structural solvers (e.g., BeamDyn in the FAST/OpenFAST framework) has enhanced the quality of large deflections, anisotropic composite behavior, and structural dynamics -functionalities that are relevant where structural constraints are incorporated in the blade optimization [7]. Structural optimization and cross-sectional aeroelastic analysis, complementary tools, can also be used to efficiently analyze slender composite structures and quickly explore structural design variables [8].

The reason integrating CFD and structural analysis is of significant interest is that wind turbine blades are aeroelastic: aero-loads act on the blade, and deformation feeds back into aero-loading. This is even more relevant as blades are fitted with high-performance control systems, and load reduction and capturing energy are clear design aims. Aero-servo-elastic co-optimization research demonstrates how distributed aerodynamic control devices can be optimized alongside blade design to enhance performance while accounting for fatigue and actuation constraints [9]. Design Conceptual design of a flexible, rail-carryable blade identifies further real-world constraints (e.g. manufacturability and logistics) that affect aeroservoelastic performance and therefore define the space of feasible optimization [10]. Besides, as recent studies indicate, model fidelity may have a pronounced impact on the conclusions of control co-design and aeroelastic optimization, especially in offshore and floating problems, where system dynamics are complex [11]. Alternative methods eliminate computation by reducing the number of design load cases and incorporating turbulence, making aeros-structural optimization more manageable and ensuring the variability of inflows is not neglected. Smaller-scale and built-environment turbine experimental and CFD modeling studies also underscore the importance of combining simulation and validation for obtaining plausible optimization results [12].

Although this has occurred, the research arena is still disjointed. Many studies may focus on single-discipline optimization (e.g., aero shape optimization or structural mass reduction), whereas others introduce coupled strategies with varying fidelity, coupling strategies, and validation. Consequently, researchers and practitioners continue to struggle to compare approaches and identify best practices, as well as to assess trade-offs among computational cost, accuracy, and real-world dependability. The synthesis of existing evidence on wind turbine blade optimization using CFD and structural analysis is therefore presented in this SLR, with particular emphasis on integrating and validating the aerodynamic and structural approaches.

2. Methodology

2.1 PRISMA-guided review design

This systematic literature review (SLR) was conducted in accordance with the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) to provide a clear and repeatable process of choosing studies to be a part of the research carried out on the optimization of the design of wind turbine blades using the tools of computational fluid dynamics (CFD) and structural analysis/finite element analysis (FEA). All scope, data sources, screening steps, and eligibility criteria for the review process were identified prior to study selection, in line with the review protocol.

2.2 Protocol registration

To ensure transparency about who was involved in the review, the review design, and the project documentation used, the review record was registered with OSF Registries as an OSF Preregistration. The registration DOI for the OSF is 10.17605/OSF.IO/VAR9T, and the OSF project can be found here: https://osf.io/4nb58/. The registration record is licensed under a CC0 1.0 Universal license.

2.3 Data sources and search strategy

A thorough review of the literature was conducted to identify peer-reviewed publications on the aerodynamic, structural, and multidisciplinary optimization of wind turbine (WT) blade designs. The databases searched were Scopus, Web of Science, ScienceDirect, IEEE Xplore, and Google Scholar because they are the most comprehensive sources of information on research in engineering, renewable energy, fluid mechanics, structural mechanics, and optimization. Manual reference checking (backward snowballing) was also conducted to identify additional pertinent studies. The keywords searched included wind turbine blades, optimization, CFD, structural analysis, and aeroelastic design. The main Boolean search string was: (“wind turbine blade” OR “wind turbine rotor blade”) AND (optimi OR (“shape optimization” OR “structural optimization” OR “multidisciplinary design optimization”) OR aeroelastic) AND (CFD OR “computational fluid dynamics” OR FEA OR FEM OR “finite element analysis” OR “structural analysis”).

Studies conducted in English and with understandable methodology at the blade, structural, or aero-structural optimization levels were considered. This search identified 233 records, of which 220 were from databases and 13 from manual reference checking.

2.4 Structured inclusion and exclusion criteria

The eligibility criteria were defined before full-text assessment and were applied consistently during the PRISMA-based screening process. Studies were included when they addressed wind turbine blade design optimization using CFD-based aerodynamic analysis and structural analysis or load-related evaluation, as shown in Table 1. Studies were excluded when they were unrelated to blade design optimization, lacked CFD or structural assessment, were not optimization-oriented, or did not provide sufficient methodological information for extraction and synthesis.

2.5 Duplicate removal

All retrieved records were exported to a reference-management spreadsheet. Duplicate records were identified using title, author names, year, DOI, and source title. When DOI information was unavailable, titles and author lists were manually compared. Twenty-five duplicate records were removed, leaving 208 unique records for title and abstract screening.

2.6 Screening of titles and abstracts

The 208 records were initially filtered based on titles and abstracts to evaluate their relevance to optimizing blade design and CFD and/or structural analysis. At this step, the studies that clearly did not address the optimization of wind turbine blades, simply the control of the turbine or the design of a wind farm, no CFD/structural analysis of the same was carried out, etc., were eliminated. After title and abstract screening, 170 records were excluded, and 38 records were retained for full-text review.

2.7 Full-text retrieval and eligibility assessment

The remaining 38 reports were searched in full text, but 4 could not be retrieved. In line with that, 34 full-text articles underwent eligibility assessment against predetermined inclusion and exclusion criteria aligned with the goals and objectives of this review.

Table 1. Inclusion and exclusion criteria used for PRISMA-based study selection

Criteria	Inclusion criteria	Exclusion criteria
Study focus	Studies focused on optimization of wind turbine blade design, including aerodynamic, structural, aeroelastic, or multidisciplinary optimization.	Studies not focused on wind turbine blade design optimization, such as wind farm layout, turbine control only, general renewable energy studies, or non-blade components.
Aerodynamic analysis	Studies using computational fluid dynamics (CFD), aerodynamic simulation, or validated aerodynamic modelling to evaluate blade performance.	Studies without CFD-based or equivalent aerodynamic analysis.
Structural analysis	Studies including structural analysis, finite element analysis (FEA/FEM), beam or shell modelling, composite material modelling, load analysis, fatigue analysis, buckling, stress, or deflection assessment.	Studies without structural, FEA/FEM, load, fatigue, stress, or deflection assessment.
Optimization method	Studies applying a clear optimization method, such as gradient-based optimization, genetic algorithm, particle swarm optimization, NSGA-II, surrogate-assisted optimization, machine learning-assisted optimization, or multidisciplinary design optimization.	Studies limited to performance analysis, validation, modelling, or simulation only, without an optimization process.
Design variables	Studies considering blade geometry, airfoil shape, chord, twist, blade-tip configuration, thickness, layup, material distribution, structural configuration, or control-related blade design variables.	Studies that do not define or evaluate blade-related design variables.
Document type	Peer-reviewed journal articles, conference papers, and technically relevant research papers with sufficient methodological detail.	Editorials, commentaries, book chapters, patents, non-technical reports, duplicate records, inaccessible full texts, or papers with insufficient methodological information.
Language	Studies published in English.	Non-English studies, unless a complete English version was available.
Availability	Full-text articles available through databases, institutional access, open-access repositories, or author/public sources.	Reports for which full text could not be retrieved after reasonable search attempts.
Relevance to thesis	Studies providing extractable information on CFD model, structural model, optimization objective, constraints, validation method, or design outcome.	Studies lacking enough methodological or outcome detail for qualitative synthesis.

The inclusion criteria were that the study focuses on optimization of wind turbine blade design (geometry and/or structural configuration), CFD-based aerodynamic analysis, and structural modeling (e.g., FEM/FEA, beam/shell models) and/or load or fatigue analysis. The studies were filtered out by the fact that they were not focused on blade design optimization (n = 7), lacked CFD-based aerodynamic analysis (n = 5), lacked structural/FEA or load/fatigue analysis (n = 4), were not optimization (i.e. not analysis/validation) (n = 3) or lacked sufficient methodological information to access (n = 1). Overall, 20 studies were eliminated during the eligibility process.

2.8 Included studies and synthesis approach

The 14 studies that passed the PRISMA selection process met the eligibility criteria and were included in the final qualitative synthesis. Data from the included studies were extracted using predefined categories, including author and year, blade-design variables, CFD modeling approach, structural or finite element analysis method, aeroelastic or multidisciplinary coupling strategy, optimization algorithm, objective functions, constraints, validation method, main findings, and reported limitations. When information was not clearly available in a study, it was recorded as "not reported" rather than inferred.

The extracted information was organized using a structured thematic synthesis approach. The studies were classified based on their main methodological approach to the problem, as CFD-based aerodynamic shape optimization, aeroelastic or multidisciplinary design optimization, and structural/composite blade optimization. The studies within each group were compared based on modeling options, optimization goals, constraints, validation methods, and reported design results. This enabled a systematic comparison of the optimization methods employed in the design of a wind turbine blade across aerodynamic, structural, and coupled aero-structural approaches.

2.9 Risk-of-bias and quality assessment

The risk of bias was evaluated using a checklist for CFD, structural analysis, and wind-turbine blade optimization studies. The checklist considered the following: Is the CFD model clearly explained in the study? Does the study report on convergence verification? Does the study report on the turbulence modeling approach? Does the study report on the structural model? Do the material assumptions in the study clearly explain the model? Do the load cases in the study clearly report on these? Are the validation details clearly reported? Does the study report on the treatment of uncertainties? Does the study report on the details of reproducibility? Studies that had a clear description of the modeling and validation procedures and reproducible solver or design settings were rated as having a low–moderate risk of bias. Studies that were not fully reported, lacked instrument validation, did not describe validation assumptions, or lacked sufficient details on how the study was reproduced were assigned a moderate risk of bias. This assessment was conducted to evaluate the methodological quality of the included studies and to inform the judicious comparisons of their findings, but not to assign numerical weights to the studies.

3. Results

3.1 Study Selection (PRISMA)

In selecting the studies (Figure 1), the PRISMA framework was used to identify, screen, and select relevant studies within the scope of this study, covering wind turbine blade design optimization using CFD and structural analysis. In total, 220 records were retrieved from electronic scientific databases (Scopus, Web of Science, IEEE Xplore, ScienceDirect, and Google Scholar), and 13 records were manually checked from scientific journals. 25 duplicate records were removed, leaving 208 unique records for title and abstract screening. During screening, 170 records were excluded because they were outside the scope of the review, did not focus on wind turbine blade optimization, or lacked relevant CFD or structural analysis content. Consequently, 38 reports were sought for full-text assessment.

Of the 38 reports assessed for eligibility, 20 were excluded based on predefined criteria. The exclusion reasons were: not focused on blade design optimization (n = 7), no CFD-based aerodynamic analysis (n = 5), no structural/FEA or load/fatigue assessment (n = 4), simulation or validation study without an optimization process (n = 3), and insufficient methodological detail for extraction (n = 1). Finally, 14 studies met all eligibility criteria and were included in the qualitative synthesis.

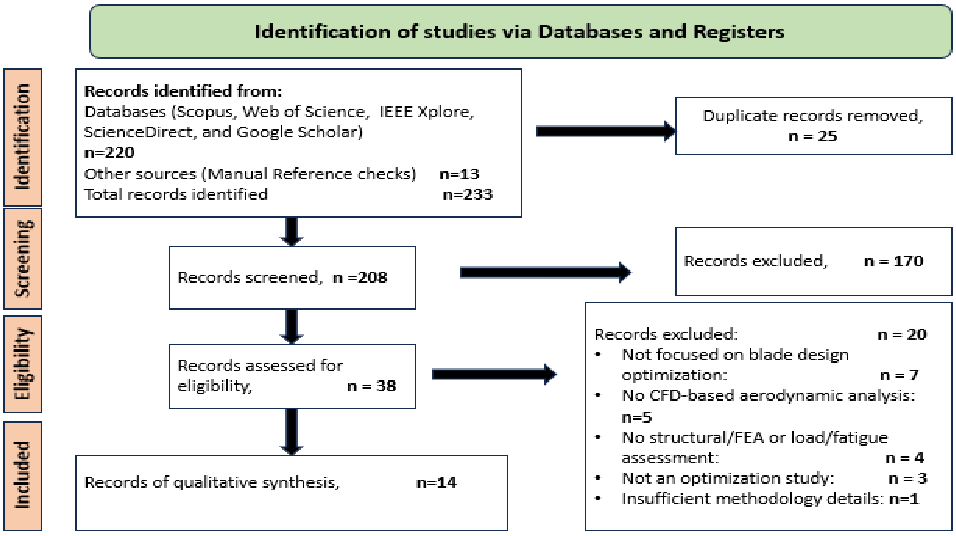

Figure 1. PRISMA flow diagram of study selection and screening process

These studies formed the basis for analyzing blade parameterization, CFD modeling approaches, structural evaluation methods, coupling strategies, and optimization algorithms in aero-structural wind turbine blade design optimization.

3.2 Characteristics of the included studies

The 14 included studies (Table 2) fall into three main methodological streams: (i) high-fidelity CFD-based aerodynamic shape optimization, particularly blade-tip and airfoil refinement; (ii) aeroelastic or multidisciplinary design optimization, where aerodynamic performance is optimized while considering structural, fatigue, load, or control-related constraints; and (iii) structural or composite optimization, where blade mass, stiffness, stress, deflection, buckling, laminate design, or manufacturability are the primary concerns. Several studies combine multiple streams, especially when aerodynamic gains are evaluated alongside structural feasibility. The most common CFD applications in the included studies are localized aerodynamic refinements, such as tip shaping, airfoil improvement, and blade geometry optimization. Structural optimization is commonly performed using beam, shell, composite cross-section, or blade-level aeroelastic models. Figure 2 summarizes the principal geometric and structural blade-design variables reported across the included optimization studies, including chord distribution, twist angle, airfoil selection, sweep, tip-shape configuration, and composite thickness/layup.

3.3 Aerodynamic (CFD) blade shape optimization trends

One subset of the studies included uses CFD-based shape optimization to boost aerodynamic efficiency or minimize losses in key regions of the blade, especially at the tip. In relation to the geometric variables shown in Figure 2, CFD-based studies most commonly optimized airfoil shape, blade-tip configuration, chord, twist, and sweep, whereas structural studies focused more strongly on spar-cap thickness, laminate layup, shear-web configuration, and material distribution. To illustrate this, we can consider the case of curved-tip design optimization, in which 3D CFD can inform geometry refinement to optimize aerodynamic performance and load behavior in the tip region [14].

The systematic aerodynamic refinement using high-fidelity CFD-based optimization of the blade shape also enables systematic aero-flow refinement through flow-field assessment, particularly for geometric modifications that are closely coupled to performance quantities [15]. Additionally, access to open-source, high-fidelity CFD functionality for performing geometry-resolved simulations of realistic atmospheric flows also supports the methodological basis for further CFD-based optimization and validation experiments [16]. Taken together, these papers point to the ongoing trade-off between fidelity to the real world and the cost of a simulation, and close attention is likely to be paid to the selection of turbulence modeling, mesh approach, and the extent to which optimization is carried out (local tip/airfoil refinement or global planform optimization) [14].

3.4 Aeroelastic and multidisciplinary optimization trends

Some of these incorporated works have explicitly combined aerodynamic and structural performance through aeroelastic tailoring and multidisciplinary design optimization (MDO). High-fidelity MDO models have sought to enhance rotor-level performance by integrating aerodynamic models with structural tailoring, whose significance lies in incorporating the effects of deformation and load redistribution into the optimization [17]. Aeroelastic optimization also studies the use of active aerodynamic devices (i.e., trailing-edge flaps) to maximize energy generation whilst meeting the loading requirement [18,19]. Aero-servo-elastic co-optimization at the system level integrates blade design with a distributed network of aerodynamic control devices to achieve improved performance under more realistic operating conditions, often subject to fatigue and actuation limits [20]. There is also more extensive conceptual research on flexible and transportable blades that confirms the existence of real-world limitations (e.g., manufacturability and logistics) as any factor that can affect aeroservoelastic performance and hence dictate attainable optimization directions [10].

Table 2. Methodological classification of the 14 included studies according to their dominant focus in wind turbine blade optimization

Feature	Number of studies	Interpretation
CFD-based aerodynamic shape optimization	3/14	These studies mainly focused on aerodynamic blade-shape refinement, curved tip design, high-fidelity CFD, or blade-flow performance assessment.
Aeroelastic / aero-servo-elastic / MDO optimization	4/14	These studies integrated aerodynamic performance with structural response, load reduction, fatigue constraints, active control, or multidisciplinary optimization.
Structural / composite blade optimization	4/14	These studies mainly focused on structural modelling, beam-based analysis, laminate design, stiffness, strain, mass reduction, or section-level optimization.
Flexible / transportable blade concept evaluation	1/14	This study focused on the feasibility of flexible, rail-transportable blade design under aeroservoelastic and practical constraints.
Machine-learning-based airfoil design	1/14	This study used machine-learning-based airfoil shape control to support rapid blade-design exploration and surrogate-ready prediction.
Open-source segmented blade design tool	1/14	This study focused on developing a reproducible segmented blade design tool and standardized design outputs.
Total included studies	14/14	All included studies were classified once according to their dominant methodological focus.

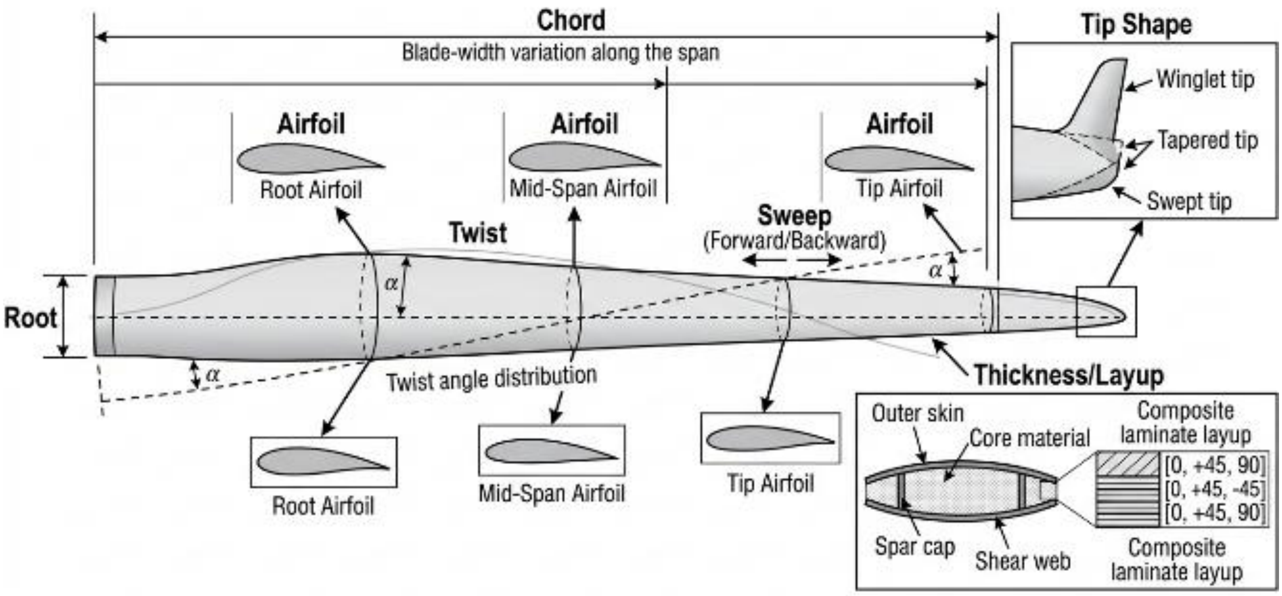

Figure 2. Blade-design parameterization schematic showing key geometric and structural design

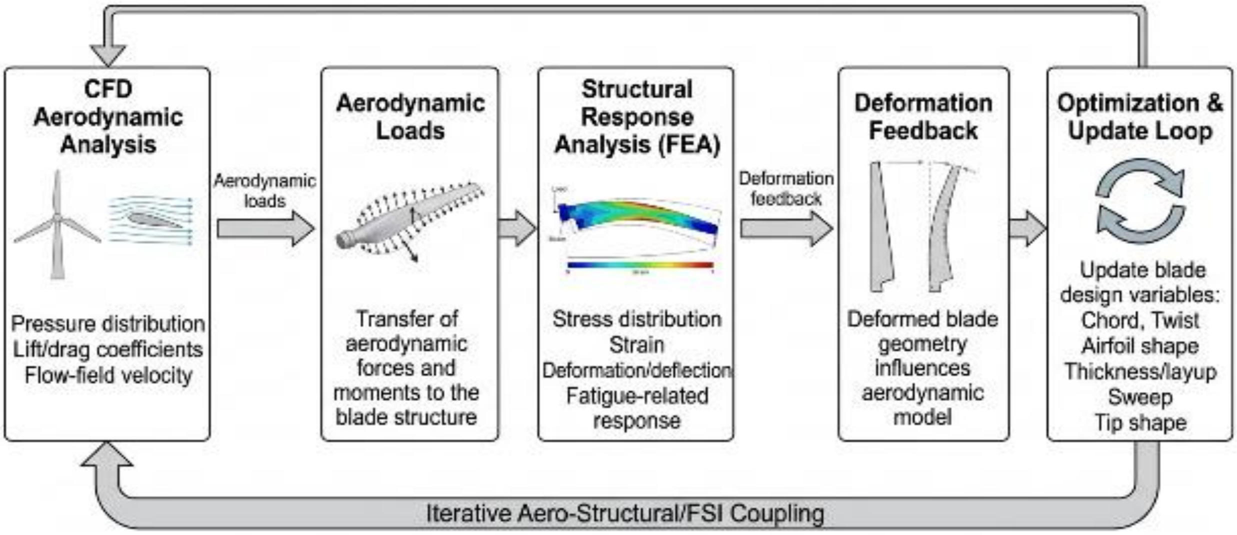

Figure 3. Aero-structural/FSI coupling workflow showing CFD analysis, load transfer, structural response, deformation feedback, and iterative optimization

On the whole, the evidence presented implies that multi-objective formulations (e.g. AEP improvement with load reduction and/or mass minimization) and the utilization of reduced-order structural models (beam/cross-sectional models) are becoming increasingly important in controlling the cost of aeroelastic/MDO studies [17]. Figure 3 illustrates the iterative aero-structural or fluid–structure interaction workflow commonly used in coupled blade-optimization studies, where CFD-derived aerodynamic loads are transferred to the structural model, deformation feedback is evaluated, and blade-design variables are updated through an optimization loop.

3.5 Structural optimization trends

The structural optimization of the included set is based on the design of composite blades, the parameterization of cross-sections, and the concepts of manufacturable layups.

Comparisons of cross-sectional approaches using beam models show that the adopted structural representation can affect structural design and sensitivity to structural optimization, thereby promoting more reliable structural decision-making in blade optimization processes [21]. More complex composite parameterizations, such as multi-parametric laminate designs, are being explored to expand the design space without compromising optimization tractability or manufacturability knowledge [22]. Tools and methods that aid the integration of cross-sectional aeroelastic analysis and structural optimization are also helpful for effectively analyzing thin composite structures and actively searching for stiffness-mass compromise [8]. High-fidelity structural solvers are also employed in aeroelastic structures, enhancing structural modeling fidelity and enabling more accurate prediction of deflection and dynamic response of large, flexible blades [7]. In these structural investigations

(Table 3), common targets include minimizing mass and meeting safety constraints, such as stress, buckling, and stiffness/deflection limits [16,18].

3.6 Risk of bias assessment

The included studies showed an overall moderate risk of bias (Table 4). This rating was based on recurring limitations in reporting and reproducibility, particularly incomplete descriptions of CFD mesh convergence checks, turbulence model selection, structural model assumptions, load case coverage, validation procedures, uncertainty treatment, and the availability of sufficient modeling details for replication. Open-source tools, well-described solver parameters, and well-documented structural modeling procedures were considered to reduce the risk of bias in the studies. Open-source tools, well-described solver parameters, and well-documented structural modeling procedures were considered to be low to moderate risk of bias in the studies.

Table 3. Summary of included studies and key outputs relevant

Included study (APA short)	Main data/source	Method focus	Key output relevant
Madsen et al. (2022) [13]	3D CFD simulations of curved blade-tip geometries	CFD-driven curved tip shape optimization	Quantified tip-shape aerodynamic improvements and load/feasibility implications
McWilliam et al. (2018) [14]	Aeroelastic simulations with active flaps	Aeroelastic design optimization for AEP maximization	AEP gains with associated load/operational constraint impacts (energy–load trade-off)
Werthen et al. (2024) [15]	Beam-based cross-sectional structural modelling for composites	Structural design/optimization using beam cross-section approaches	Structural KPI sensitivity (stiffness/strain/stress proxies) across modelling approaches
Mangano et al. (2023) [16]	High-fidelity aero + structural simulations within MDO	Aeroelastic tailoring using high-fidelity MDO	Pareto trade-offs (performance vs loads/structural limits) supporting multi-criteria comparison
Werthen et al. (2025) [17]	Multi-parametric composite (double-double laminate) modelling	Composite laminate parameterization and optimization	Mass–performance–feasibility outcomes for manufacturable composite blade designs
Madsen (2020) [18]	High-fidelity CFD simulations across blade-shape variants	CFD-based blade shape optimization	Aerodynamic performance deltas (Cp/AEP proxies) tied to optimized geometry changes
Wang et al. (2017) [7]	BeamDyn solver results in FAST/OpenFAST framework	High-fidelity blade structural dynamics modelling/solver	Standardized structural response outputs (deflection/strain/dynamics) for design evaluation
Feil et al. (2020) [8]	Cross-sectional aeroelastic analysis + structural optimization tool outputs	Section-level aeroelastic/structural optimization	Section property KPIs (mass/stiffness matrices) enabling consistent structural indexing
Abbas et al. (2023) [9]	Aero-servo-elastic simulations with distributed control devices	Aero-servo-elastic co-optimization	Co-optimized performance/AEP improvement with fatigue/load/actuation constraints
Bortolotti et al. (2021) [10]	Conceptual design + aeroservoelastic performance evaluation	Flexible/transportable blade concept evaluation	System feasibility metrics + aeroservoelastic performance indicators under constraints
Jasa et al. (2022) [3]	Invertible neural networks (INNs) with blade/airfoil design data	ML-based airfoil shape control for blade design	Data-driven shape-to-performance mapping enabling surrogate-ready KPI prediction
Anderson et al. (2022) [19]	Open-source segmented blade design tool development	Tool-based segmented blade design methodology	Standardized segmentation variables and outputs improving reproducibility/KPI extraction
Sharma et al. (2024) [20]	ExaWind open-source CFD (hybrid RANS/LES) simulations	High-fidelity geometry-resolved CFD in atmospheric flows	High-fidelity flow and load outputs supporting fidelity-aware aerodynamic KPI assessment
Barlas et al. (2016) [21]	Aeroelastic optimization study of a 10 MW blade with trailing-edge flaps	Aeroelastic optimization with active trailing-edge flaps	Quantified performance improvement with load mitigation trade-offs (multi objective outputs)

Table 4. Risk of bias assessment for included studies

Author (Year)	Methodology	Overall Risk of Bias
Madsen et al. (2022) [13]	CFD-driven curved tip shape design; supports aerodynamic KPI extraction (tip efficiency, load implications) for index-based comparison.	Moderate
McWilliam et al. (2018) [14]	Aeroelastic optimization with active flaps for AEP-focused KPI plus load-related constraints; suitable for energy–load trade-off indexing.	Moderate
Werthen et al. (2024) [15]	Beam-model cross-sectional approaches for composite blade optimization; supports structural KPI consistency checks (stiffness/strain proxies) for index integration.	Low–Moderate
Mangano et al. (2023) [16]	High-fidelity multidisciplinary design optimization (MDO) for aeroelastic tailoring; produces Pareto trade-offs enabling multi-criteria index weighting.	Moderate
Werthen et al. (2025) [17]	Multi-parametric composite optimization (double-double laminates); strengthens manufacturability-aware structural KPIs for composite index use.	Moderate
Madsen (2020) [18]	High-fidelity CFD-based blade shape optimization; provides CFD performance deltas for aerodynamic index scoring.	Moderate
Wang et al. (2017) [7]	BeamDyn high-fidelity blade solver; supports standardized extraction of structural response KPIs (deflection/strain/dynamics) for index integration.	Low–Moderate
Feil et al. (2020) [8]	Cross-sectional aeroelastic analysis + structural optimization tool; provides section-property KPIs (mass/stiffness matrices) that map directly to index components.	Low–Moderate
Abbas et al. (2023) [9]	Aero-servo-elastic co-optimization with distributed aerodynamic control; supports control-enabled performance KPIs (AEP vs loads/fatigue indicators).	Moderate
Bortolotti et al. (2021) [10]	Conceptual design of transportable blades with aeroservoelastic evaluation; enables feasibility/constraint compliance KPIs for index scoring.	Moderate
Jasa et al. (2022) [3]	Invertible neural networks for airfoil shape control; provides ML-based surrogate mapping for index-ready performance prediction but may depend on dataset representativeness.	Moderate
Anderson et al. (2022) [19]	Open-source segmented blade design tool; improves method transparency and repeatable KPI extraction across segmented configurations.	Low–Moderate
Sharma et al. (2024) [20]	Open-source ExaWind hybrid RANS/LES CFD; strengthens fidelity-aware aerodynamic/load KPIs for index integration in atmospheric flows.	Low–Moderate
Barlas et al. (2016) [21]	Aeroelastic optimization of 10 MW blade with active trailing-edge flaps; supports multi objective KPI integration (energy gains with load mitigation).	Moderate

Studies that used a customized workflow, did not validate these methods, or did not provide full reporting of CFD/structural assumptions were considered to have a moderate risk of bias. The results of the included studies were thus deemed appropriate for qualitative comparison, while the observed performance gains and optimization results should be viewed with caution due to differences in model fidelity, validation, and reporting across studies.

4. Discussion

This literature review identifies three critical elements for wind turbine blade optimization: clearly defined design goals, reliable aerodynamic and structural models, and a balance between performance improvement and structural feasibility. The aerodynamic refinement employed is often high-fidelity and is generally added to areas of the blade where changes in flow behavior are highly sensitive to the geometry, typically near the blade tip. Optimized tip geometry has been shown to improve aerodynamic performance, as suggested by tip-focused CFD studies.

These benefits, however, must be considered alongside structural feasibility and load effects, as an aerodynamically efficient design can also increase stress, deflection, or fatigue risk [22]. In fact, CFD benchmarking studies indicate that the reference case, mesh verification, and turbulence model selection are crucial, as modeling choices affect predictions of stall, separation, tip-vortex behavior, and rotor loading [23]. The reviewed studies also emphasize the role of structural model selection. Reduced-order structural models are used in many optimization workflows due to their computational efficiency and ability to be evaluated repeatedly in design optimization. However, aero-servo-elastic and beam modeling have been compared, and significant differences in blade deflection, stiffness behavior, stress margins, and dynamic response can be observed depending on the modeling assumptions [24]. These differences may affect an optimized design's ability to meet structural requirements. Thus, before using structural solvers and modeling assumptions in an optimization loop, they should be verified, particularly if the results are used to inform design comparisons or final design decisions.

One of the common problems that emerges in the studies reviewed is the trade-off between model accuracy and computational cost. However, high-fidelity CFD can capture complex three-dimensional flow features such as separation, tip vortices, and inflow effects, but it can be costly when used directly in iterative optimization [25]. In view of this, many studies employ hybrid approaches, using CFD to explore a smaller number of designs but using lower-cost aerodynamic, structural, or aeroelastic models to explore a larger design space. Integrated aerodynamic and aero-structural optimization studies have demonstrated that this approach can enhance design efficiency while maintaining adequate structural detail for engineering interpretation [26]. However, care is needed when interpreting reported performance gains, as a given blade design may yield different results when evaluated with varying model fidelities.

There are some methodological limitations. First, due to the high computational cost and the complexity of the workflow, fully coupled 2-way fluid–structure interaction (FSI) is not yet widely adopted in blade optimization studies. Sequential coupling is used in many studies: the aerodynamic loads are applied to a structural model, and the deformation is calculated for the model alone. This is a practical method, but it can underestimate the aerodynamic loading and blade-deformation feedback, which are significant for aeroelastic performance, fatigue prediction, and load assessment [25]. Second, structural optimization studies are often incomplete with respect to realistic considerations in composite manufacturing, including layup rules, ply-thickness transitions, producible laminate architectures, and manufacturable material distributions. While topology optimization can help consider structural ideas that are as mass-efficient as possible, the resulting structural layouts may not be readily transferable to real composite blade designs [27]. Third, across the various studies, load cases are not always consistent, limiting comparability. Some studies examine a limited number of operating conditions, while others consider more comprehensive aeroelastic or fatigue conditions. Finally, while the effects of atmospheric uncertainty and of turbulence, manufacturing tolerances, and uncertainty in the material properties are important in determining the loads and performance of blades, they are frequently not reported.

Hence, in the future, more attention should be given to scalable design optimization workflows that include multiple disciplines, transparent validation processes, and uncertainty treatment, to realistic loading cases, as well as manufacturability-aware composite structural design. Several methods have been proposed to reduce the number of costly CFD evaluations while retaining selected high-fidelity evaluations, such as surrogate modeling and Bayesian optimization. Likewise, aero-structural optimization can be used to more faithfully inform design decisions by considering aerodynamic performance, structural response, and loading simultaneously, in a single workflow [26]. Such enhancements would provide more consistent and predictable results for optimization and be applicable to real-world wind turbine blade design.

5. Conclusion

Based on the aforementioned systematic literature review, it can be seen that there are three main streams of work for the optimization of wind turbine blades: CFD-based aerodynamic optimization of shape, aeroelastic/aero-structural optimization, and structural/composite optimization. They are then predominant since they are directly connected to the essentials of blade performance and reliability, i.e., energy capture, load mitigation, mass reduction, and lifetime, and they represent the pragmatic trade-offs between computational cost and model fidelity. Hybrid processes are preferred among synthesis processes for selectively applying high-fidelity CFD models (e.g., tip or airfoil refinement), while stiffness or aeroelastic models are used as feasibility evaluation models for stiffness, strength, and fatigue problems in optimization loops. The literature presents the best-performing strategies, in which the blade design is treated as a multi-objective problem, striking a clear balance between AEP gains and deflection, stress, buckling, and fatigue constraints. Surrogate-assisted optimization and reduced-order aeroelastic models are more efficient and enable exploration of more physical trends during design. The most useful practical tips for researchers and industry are: always take model fidelity into account when designing the question; validate aerodynamic and structural models before optimizing; and consider realistic load cases and manufacturability requirements to ensure that the optimized designs can be deployed and are reliable under operational conditions.

Ethical issue

The authors are aware of and comply with best practices in publication ethics, specifically regarding authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with research ethics policies. The authors adhere to publication requirements that the submitted work is original and has not been published elsewhere.

Data availability statement

The manuscript contains all the data. However, additional data will be provided by the corresponding author upon reasonable request.

Conflict of interest

The authors declare no potential conflict of interest.

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