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REVIEW

Recent Advances and Future Directions in Centrifugal Slurry Pump Design Optimization: A Lifecycle-Oriented Review

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ABSTRACT: Slurry transport is a critical multiphase-flow process in mining, metallurgy, and dredging applications, where hydraulic efficiency, particle-induced wear, cavitation erosion, and structural vibration are strongly coupled. This topic-focused review synthesizes recent advances in centrifugal slurry pump design optimization from the perspectives of wear-resistant surface engineering, hydraulic design, structural dynamics, intelligent optimization algorithms, and multiphysics simulation. Unlike earlier reviews that primarily addressed hydraulic performance, erosion wear, flow visualization, or numerical modeling in isolation, the present work adopts a lifecycle-oriented perspective. Representative studies are critically evaluated according to reported efficiency improvements, wear-rate and material-loss reduction, cavitation and net-positive-suction-head-related performance changes, validation strategies, uncertainty sources, and practical engineering feasibility. Particular attention is devoted to the integration of computational fluid dynamics with the discrete element method, fluid-structure interaction, cavitation-erosion coupling, particle-size effects, surrogate-assisted optimization, and digital-twin-enabled monitoring frameworks. The reviewed literature indicates that high-fidelity simulations and intelligent algorithms have significantly enhanced design exploration and predictive capability. However, their large-scale engineering deployment remains limited by challenges associated with model validation, data availability, computational cost, interpretability, and generalization under variable slurry conditions. Finally, digital-twin-enabled lifecycle optimization is discussed as a promising conceptual pathway rather than a fully validated industrial solution, highlighting the need for reduced-order modeling, robust sensing strategies, uncertainty-aware data assimilation, and staged experimental validation to support reliable real-world implementation.

KEYWORDS: Slurry pump; design optimization; wear-resistant materials; hydraulic model; intelligent algorithms; multiphysics simulation

1 Introduction

Slurry pumps are key hydraulic machines for transporting abrasive solid–liquid mixtures used in mining, metallurgy, and thermal power generation, and related process industries [1–4]. In these applications, the conveyed media typically contain tailings, fly ash, ore particles, or other high-hardness solids, which subject the pump to coupled hydraulic, erosive, and structural loads during long-term operation. The main wetted components of a slurry pump, including the impeller, volute, shaft, sealing system, and inlet–outlet passages, are shown in Fig. 1. Owing to the strong interaction among solid particles, carrier fluid, and wetted walls, slurry pumps commonly operate under highly abrasive, erosive, and hydraulically unsteady conditions. Mining operations are increasingly required to improve resource efficiency, reduce environmental impacts, and adopt more sustainable production and management practices [5,6]. Within slurry-transport systems, hydraulic performance degradation and abrasive wear of wetted components, particularly impellers and volutes, can increase energy consumption, maintenance requirements, and lifecycle costs [7,8].

Specifically, complex particle trajectories and particle–wall interactions intensify turbulent energy dissipation in blade passages [9–11]; cavitation–erosion coupling accelerates surface damage of wetted components [12,13]; and fluctuations in slurry concentration and particle-size distribution weaken the adaptability of conventional fixed-parameter designs [14,15]. Therefore, slurry-pump design optimization is not associated with pump efficiency and service life, but also directly affects the continuity and economic performance of key industrial processes such as mineral recovery, slurry transport, and backfilling.

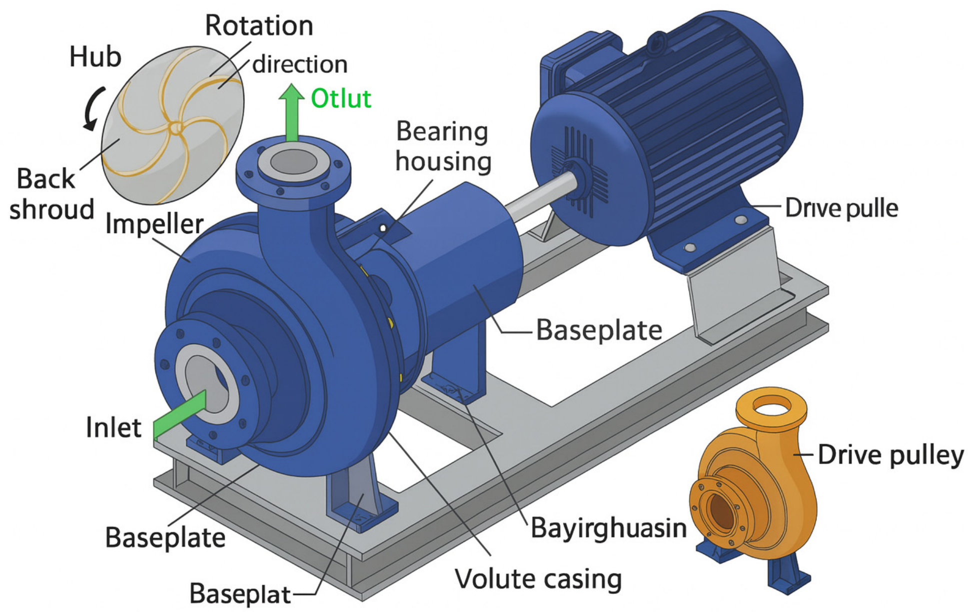


Figure 1: Construction and composition of slurry pump. Construction and main wetted components of a centrifugal slurry pump, including the impeller, volute, shaft, sealing system, inlet passage, and outlet passage.

To address these operational challenges, slurry pump design has gradually shifted from empirical, single-parameter modification toward multiphysics-informed and data-supported optimization frameworks [16–19]. This transition reflects the increasing integration of computational fluid dynamics, particle-scale modeling, materials engineering, and intelligent optimization algorithms. For example, coupled Computational Fluid Dynamics–Discrete Element Method (CFD–DEM) simulations can resolve the effects of particle-size distributions and particle motion on turbulent kinetic energy dissipation within impeller passages, thereby providing quantitative guidance for blade-profile optimization [20]. Wang et al. [21] employed the Non-dominated Sorting Genetic Algorithm II (NSGA-II) to design a bi-convex blade structure, which broadened the high-efficiency operating range while maintaining rated head, thereby improving pump adaptability under variable operating conditions. At the materials level, high-energy laser cladding of tungsten carbide–reinforced nickel-based composite, namely NiBSi–WC/W_2C, on cast-iron impellers has been reported to improve wear resistance in quartz-sand slurry media, indicating the potential of a material–structure synergistic optimization.

Building upon these optimization methodologies, designs are now evaluated from a comprehensive life-cycle perspective delivering benefits in two primary dimensions. Techno-economically, optimizing flow passage profiles reduces energy consumption per ton of ore transported, yielding substantial annual electricity savings in large concentrators. Environmentally, extending service intervals for wetted components mitigates CO_2 emissions from spare-part manufacturing, aligning with global low-carbon strategies. Current research is evolving from single-attribute optimization toward intelligent sensing and autonomous adjustment. For example, Zhang et al. [22]. developed a digital twin-based adaptive control system that dynamically adjusts pump speed via real-time slurry concentration monitoring, maintaining efficiency with minimal fluctuation under highly variable conditions. These optimization efforts also need to be evaluated from a lifecycle perspective. Reducing flow-passage losses can lower the energy consumption per unit of transported ore, whereas extending the service intervals of wetted components can reduce maintenance frequency and the environmental burden associated with spare-part manufacturing. Recent studies therefore increasingly combine hydraulic optimization, wear monitoring, and adaptive operation rather than treating efficiency and durability as independent objectives. Research in this field provides dual core value: continuously optimizing slurry pumps reduces per-unit material handling energy consumption and operational costs [23–28], as shown in Fig. 2, while improving reliability and sustainability. Recent years have witnessed accelerated research progress in understanding slurry pump erosion and reliability, particularly through advanced experimental techniques and predictive modeling. While this review aims to synthesize key developments, it is acknowledged that the rapidly evolving nature of the field means some very recent contributions were not fully covered in earlier versions. The following sections have therefore been augmented to reflect emerging insights from the past five years into erosion mechanisms, novel coating strategies, and data-driven wear prediction models. Accordingly, this topic-specific review organizes recent progress into five technical directions that together define the current optimization landscape for centrifugal slurry pumps:

- **Wear-Resistant Material Surface Modification**. Novel surface engineering techniques (laser cladding, thermal spraying such as HVOF, composite diffusion coatings) for enhancing wear, corrosion, and cavitation resistance of slurry pump wetted components. Cutting-edge advances, underlying wear mechanisms, and implementation challenges are highlighted.
- **Hydraulic Model Parameter Optimization**. High-fidelity multiphase flow simulations (e.g., CFD–DEM) and optimization strategies for key flow components (impellers, volutes). Emphasis is on multi-objective trade-offs among efficiency, NPSHr (Net Positive Suction Head required), uniform wear distribution, and broad operational adaptability.
- **Intelligent Algorithm-Assisted Design**. Applications of evolutionary algorithms and machine learning in multi-objective slurry pump optimization. This includes genetic algorithms, surrogate modeling with neural networks, and hybrid data-driven frameworks for design space exploration.
- **Structural Dynamics and Vibration Characterization**. Vibration behavior of pumps under solid–liquid two-phase flow excitation, methods for fatigue life prediction, and strategies for improving structural reliability of pump casings and impellers. This encompasses modeling fluid–structure interactions and mitigating flow-induced vibrations.
- **Multiphysics Co-Simulation & Intelligent Systems**. Coupled simulations integrating fluid dynamics, structural mechanics, and wear processes in slurry pumps (e.g., FSI simulations and wear-performance coupling). The principles, representative case studies, and emerging trends in intelligent slurry pump systems that integrate digital twins, condition monitoring, and adaptive control technologies are systematically reviewed.

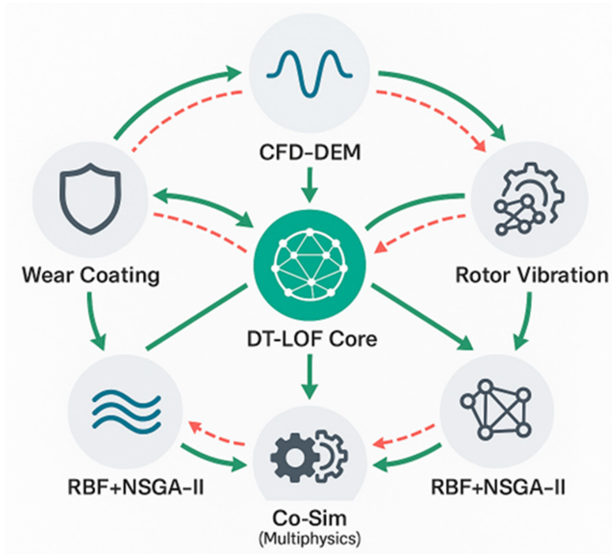


Figure 2: Lifecycle flowchart of centrifugal slurry pump design, operation, monitoring, maintenance, and degradation.

Within the topic of centrifugal slurry pump design optimization, the distinctive contribution of this review is to provide a lifecycle-oriented synthesis of material design, hydraulic geometry, structural dynamics, multiphysics modeling, intelligent optimization, and operational maintenance, rather than to present these topics as separate review themes. Previous reviews have provided valuable summaries of hydraulic performance and erosion wear in centrifugal slurry pumps [29], as well as recent developments in erosion mechanisms and flow visualization, whereas the present review further emphasizes the coupling among these aspects during design, operation, monitoring, maintenance, and degradation. Digital twin technology is discussed as a potential integration platform for connecting sensing data, reduced-order modeling, predictive maintenance, and adaptive decision support, rather than as an already validated pump design model. To clarify the contribution of this review relative to previous studies, a structured comparison with representative slurry-pump-focused reviews is provided in Table 1.

To avoid a purely descriptive summary, representative studies are evaluated using explicit comparative criteria, including reported performance improvement, wear or material-loss reduction, cavitation-related changes, validation methods, uncertainty sources, and engineering feasibility. Where sufficient information is available, the reported results are discussed in terms of efficiency-improvement ranges, wear-rate reduction, material-loss reduction, cavitation or net-positive-suction-head-related changes, and validation approaches such as numerical convergence tests, laboratory measurements, prototype tests, or field monitoring. When direct cross-study normalization is not justified because of differences in pump geometry, operating conditions, slurry concentration, particle-size distribution, material system, testing duration, or validation method, the comparison basis is stated and the reported result is interpreted as qualitative or condition-dependent evidence rather than as a direct benchmark.

Accordingly, the novelty of this review lies in its integrative synthesis of material surface engineering, hydraulic geometry, flow-induced vibration, multiphysics modeling, intelligent optimization, and lifecycle operation. Within this framework, the discussion of digital twins is positioned as a prospective integration platform for sensing, reduced-order modeling, predictive maintenance, and adaptive decision-making, rather than as a validated pump design model. Therefore, the digital-twin-related discussion in this review should be understood as a conceptual synthesis of future research directions, not as an experimentally validated optimization model developed in the present work.

Table 1: Structured comparison between representative slurry-pump-focused reviews and the present lifecycle-oriented synthesis.

Comparison Item	Representative Slurry-Pump Reviews	Present Review
Main scope	Duan et al. [1] further summarized hydraulic performance and erosion wear characteristics. while Hydraulic performance and erosive wear were systematically reviewed by Tarodiya and Gandhi [7], Banka and Rai [29] focused on erosion and flow visualization developments.	Material design, hydraulic geometry, structural dynamics, multiphysics modeling, intelligent optimization, and operational maintenance are organized within a lifecycle-oriented framework.
Evaluation logic	Previous reviews mainly summarized mechanisms, performance trends, and technical progress within specific research directions.	Representative studies are further discussed in terms of performance improvement, wear or material-loss reduction, cavitation-related changes, validation methods, uncertainty sources, and engineering feasibility.
Digital twin role	Digital twin technology was not the central organizing framework in the representative slurry-pump-focused reviews listed above.	Digital twin technology is discussed as a conceptual platform linking sensing data, reduced-order modeling, predictive maintenance, and adaptive decision support.
Critical gap highlighted	Existing reviews identified important challenges in hydraulic degradation, erosion wear, and experimental or numerical characterization	This review further highlights material–flow mismatch, model validation gaps, computational cost, data limitations, and transferability to industrial slurry conditions.

In the following sections, the reviewed literature is organized according to a lifecycle-oriented logic. Section 2 summarizes recent technological progress in surface modification, hydraulic design, structural dynamics, intelligent algorithm-assisted optimization, and multiphysics co-simulation. Section 3 then synthesizes the main contradictions, methodological limitations, and digital-twin-oriented research directions that emerge from these studies. This structure is intended to separate technical progress from critical synthesis and to reduce repetition between the review and discussion sections.

2 Recent Technological Progress in Slurry Pump Optimization

Recent studies have improved the understanding of slurry pump erosion, reliability, and performance degradation through experimental measurements, predictive modeling, and coupled numerical simulation. This section applies the comparative evaluation logic introduced above to recent studies on slurry pump optimization. For material-related studies, attention is given to coating hardness, porosity, bonding strength, wear-rate reduction, material-loss reduction, and experimental validation. For hydraulic and cavitation-related studies, the discussion focuses on efficiency variation, head or net-positive-suction-head changes, particle-size effects, cavitation criteria, and validation methods. For structural dynamics, intelligent algorithms, and multiphysics simulation, the evaluation further considers vibration response, predictive accuracy, convergence behavior, data requirement, uncertainty sources, and engineering feasibility. The ordering of the subsections follows the physical pathway from component protection to system-level operation. Surface modification first addresses material durability at the wetted boundary. Hydraulic optimization then determines flow distribution, particle trajectories, and cavitation risk. Structural dynamics links unsteady hydraulic excitation to vibration and fatigue. Intelligent algorithms provide tools for design-space exploration, while multiphysics co-simulation connects these domains through coupled numerical and data-supported models.

2.1 Surface Modification for Wear-Resistant Wetted Components

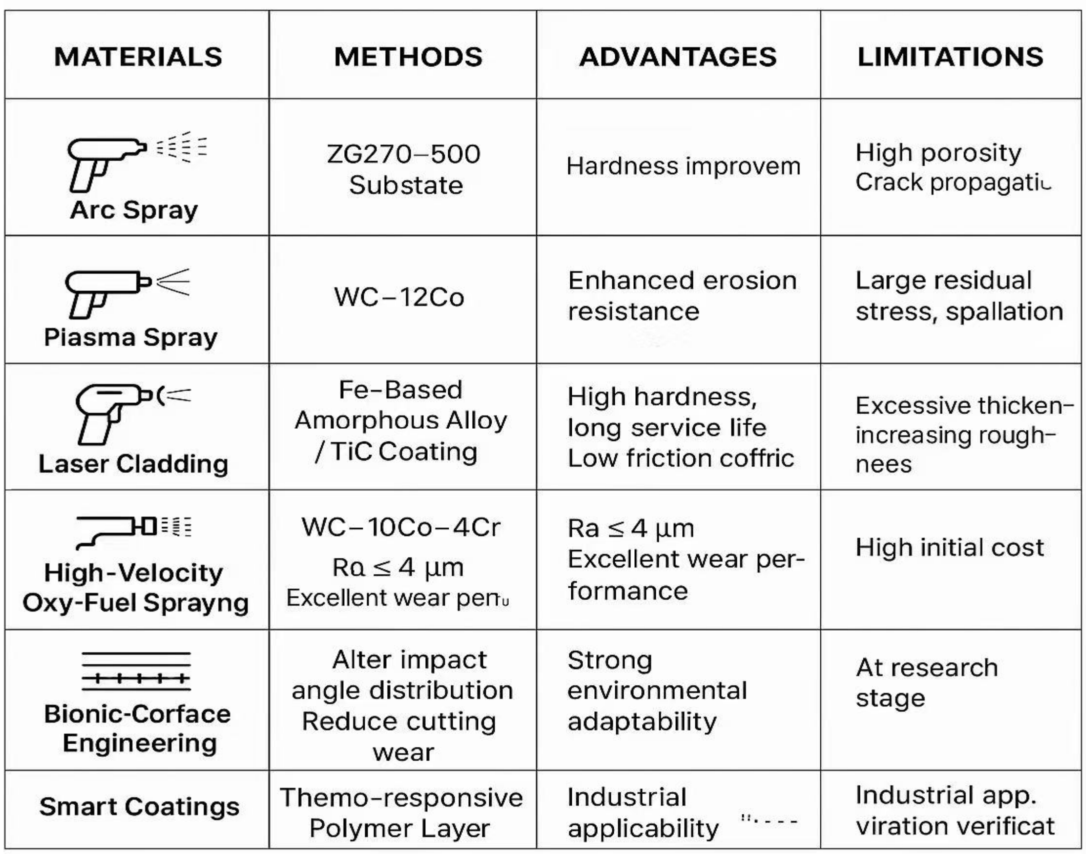
Surface modification provides a material-level route for improving the wear resistance and service durability of slurry pump wetted components. This subsection focuses on coating composition, preparation method, hardness, porosity, bonding strength, surface morphology, and erosion resistance under slurry transport conditions. High-performance wear-resistant materials for pump wetted parts form the physical foundation for efficiency and long-term reliability [30–32]. Surface modification technologies have evolved from early single-material hard facing to advanced multifunctional composite coatings that combine wear, corrosion, and fatigue resistance. This technological evolution has proceeded in tandem with deeper investigations into coating failure mechanisms, interface bonding characteristics, and the evolution of service performance under dynamic loads.

Early thermal spray techniques (e.g., arc spraying) could raise the Rockwell hardness of ZG270-500 cast steel substrates; however, in high-hardness media (quartz sand), sprayed layers suffered from porosity-induced microcrack propagation, leading to premature failure. Furthermore, although subsequent plasma-sprayed WC−12Co coatings improved erosion resistance, their application was constrained by weak interface bonding strength in the heat-affected zone, leading to spallation under high-pressure cyclic loads [33]. More recently, Shen et al. [34] employed reverse modeling to analyze erosion in static slurry-pump components, further demonstrating that geometry reconstruction and component-specific flow-field interpretation can improve the localization of high-risk wear regions.

To overcome these bonding and porosity bottlenecks, laser surface and high-velocity deposition techniques have demonstrated significant advantages. For example, Pei et al. [35] deposited nanocrystalline TiC/amorphous carbon composite coatings using closed-field magnetron sputtering, achieving low-friction, highly wear-resistant surfaces. An nc-TiC/a-C:H coating with low Ti content exhibited frictional stability and wear resistance. 3D surface morphology showed its wear track depth was markedly smaller than coatings with higher Ti content, with a friction coefficient of ~0.04 and an extremely low wear rate of 4.8×10^{-17} $m^3 \cdot N^{-1} \cdot m^{-1}$, while maintaining excellent surface integrity−making it suitable for heavy-duty abrasive environments (e.g., hydraulic machinery). Li et al. [36] applied plasma cladding to form cermet coatings on pulverizer fan impellers and found the cladding layer's microhardness to be several times higher than the 16Mn steel substrate, with greatly improved wear resistance. Using coaxial powder feeding, Fe-based amorphous alloy composite coatings on Cr27 high-chrome iron achieved a microhardness of up to 1250 HV with porosity below 0.5% under the reported coating preparation conditions. These coatings significantly extended impeller service life in fine magnetite slurry transport. However, a trade-off exists wherein excessive cladding thickness can increase passage surface roughness (Ra), inducing local turbulence. In this regard, High-Velocity Oxy-Fuel (HVOF) spraying showed unique advantages [37–39]. Nanostructured WC−10Co−4Cr coatings via HVOF coatings maintained a surface roughness of Ra $\leq$ 4 μm and reduced the reported wear rate under the tested particle concentration and slurry medium, clearly outperforming conventional coatings. An economic analysis by Noon et al. [40] indicated that although HVOF retrofitting increased initial pump cost, it substantially reduced maintenance costs over the pump's life, confirming the overall benefits of surface modification technologies.

Recent work has further refined thermal spray and cladding techniques for erosion resistance. For these coating studies, comparison is based not only on reported wear-rate reduction, but also on coating preparation method, substrate material, slurry medium, particle characteristics, test duration, and validation approach, because these factors strongly affect the measured erosion resistance. For instance, Singh et al. [41] systematically compared HVOF-sprayed WC−10Co−4Cr coatings reinforced with yttria and zirconia, demonstrating that microstructural refinement through nano-additives can reduce wear rates by over 30% in high-concentration slurries. Meanwhile, Tran et al. [42] developed a Gaussian process-based machine learning framework ("WearGP") for localized erosion prediction, enabling coating designs tailored to specific particle impact patterns. These studies, among others published in Powder Technology and Wear, highlight the ongoing convergence of materials science and computational modeling in developing next-generation erosion-resistant surfaces.

Fig. 3. Summary of surface modification technologies for slurry pump wetted components. Source: compiled by the authors based on reviewed coating and erosion studies. Current research hotspots focus on integrating bionic surface engineering and "smart" coatings. Inspired by tubercle structures on humpback whale flippers, micro-groove arrays on impeller surfaces have been designed to alter particle impact angle distributions. a groove spacing of 20 μm was reported to reduce the proportion of 45° particle-impact angles under the tested slurry condiction, significantly decreasing cutting wear in regions prone to that wear mode. Even more forward-looking are temperature-responsive coatings; for example, incorporating a PNIPAM-NFC additive improved water-vapor barrier properties of a biodegradable polymer coating, suggesting environmental adaptability [42]. It is noteworthy that surface modifications must act synergistically with flow field optimization. Na et al. [43] verified via discrete phase simulations that when impeller surface hardness exceeds a threshold, the optimal particle impact angle range shifts from 25°–50° to 35°–60°. This finding, as shown in Fig. 3, imposes new mechanical matching requirements on graded coating design to ensure that harder surfaces still operate in tandem with flow dynamics.



MATERIALS	METHODS	ADVANTAGES	LIMITATIONS
Arc Spray	ZG270–500 Substate	Hardness improvem	High porosity Crack propagati
Piasma Spray	WC–12Co	Enhanced erosion resistance	Large residual stress, spallation
Laser Cladding	Fe-Based Amorphous Alloy / TiC Coating	High hardness, long service life Low friction coffric	Excessive thicken- increasing rough- nees
High-Velocity Oxy-Fuel Sprayng	WC–10Co–4Cr Ra ≤ 4 μm Excellent wear pen	Ra ≤ 4 μm Excellent wear per- formance	High initial cost
Bionic-Corface Engineering	Alter impact angle distribution Reduce cutting wear	Strong environmental adaptability	At research stage
Smart Coatings	Themo-responsive Polymer Layer	Industrial applicability	Industrial app. viration verificat

Figure 3: Summary of surface modification technologies for slurry pump wetted components, including laser cladding, thermal spraying, composite coatings, bionic surface textures, and responsive coatings [10,41,42].

2.2 Hydraulic Model Parameter Optimization

In slurry pump hydraulic optimization, coordinated improvements in impeller blade design and volute matching have become central to boosting energy conversion efficiency. Peng et al. [44] found via CFD–DEM simulation that increasing the impeller outlet blade angle from 25° to 35° reduced solid particle slip velocity, significantly decreasing turbulence energy dissipation caused by flow separation. Zhang et al. [45] used a genetic algorithm to optimize the impeller leading-edge profile, which shrank the low-pressure region on the blade suction side and greatly increased the critical cavitation inception head—confirming that blade camber and curvature strongly influence flow stability. Notably, the ratio of volute base-circle diameter to impeller outer diameter (the K value) exerts a decisive effect on secondary flow recirculation. Specifically, adjusting K from 1.05 to 1.12, the vortex core intensity in the outlet section dropped significantly and the high-efficiency region of the pump's performance curve broadened.

Recent validated studies on centrifugal pumps also provide useful foundations for slurry pump hydraulic optimization. For hydraulic optimization studies, reported efficiency or head improvement is interpreted together with pump geometry, flow rate, particle-size distribution, slurry concentration, cavitation criterion, and validation method, because these parameters determine whether the reported improvement can be transferred to other operating conditions. Dehghan and Shojaeefard [46] combined experimental measurements and numerical simulations to optimize volute geometry and demonstrated that volute design directly affects pump head and hydraulic efficiency at the best efficiency point. Dehghan et al. [47] further proposed an energy-saving-oriented criterion for identifying cavitation onset in centrifugal pumps, providing a useful reference for interpreting cavitation-related performance degradation. Although slurry pumps involve additional particle-laden flow and erosion mechanisms, these studies indicate that impeller optimization should be discussed together with volute matching, local pressure distribution, cavitation inception, and net positive suction head required. These factors jointly influence hydraulic performance, cavitation risk, and erosion-prone regions under slurry transport conditions. In addition, Wang et al. [48] examined the performance prediction of an optimized high-efficiency centrifugal pump, providing a useful reference for evaluating whether hydraulic-geometry optimization can be translated into reliable head and efficiency predictions.

Particle-size effects further complicate this optimization. Fine particles tend to modify turbulence, suspension uniformity, and near-wall concentration gradients, whereas coarse particles increase slip velocity, impact energy, and localized cutting wear. Under cavitating conditions, bubble collapse can remove protective surface films and intensify solid-particle impact damage, making cavitation-induced erosion and solid-particle erosion mutually reinforcing rather than independent mechanisms. Therefore, future hydraulic optimization should report particle-size distribution, concentration range, cavitation criterion, and validation method together with efficiency and wear metrics.

A dedicated issue in hydraulic optimization is cavitation-erosion coupling, which should be interpreted as a coupled damage process rather than as the linear superposition of cavitation erosion and particle-induced erosion. Cavitation inception first depends on the local pressure field, vapor volume fraction, turbulence intensity, and NPSHr margin. Once bubbles collapse near blade leading edges, volute tongues, or coating defects, the resulting micro-jets and shock waves can remove passive films, roughen coated surfaces, and create micro-pits that trap or redirect solid particles. These changes increase local impact angle variability and accelerate cutting or deformation wear. Conversely, particle impacts and material loss can increase roughness and promote earlier cavitation inception by disturbing the near-wall pressure field. Therefore, reliable modeling requires not only a cavitation model and an erosion law, but also validation against pressure fluctuation, vapor distribution, surface morphology, and post-test material-loss patterns.

Reported cavitation-erosion results should be compared cautiously because inception criteria, particle-size distribution, coating hardness, slurry concentration, and test duration strongly affect the measured damage rate.

Unsteady flow simulations have revealed multi-scale mechanisms underlying such parameter optimizations [49–51]. Using an RNG k–ε turbulence model for liquid–solid flow, previous studies reported that increasing the blade wrap angle from 95° to 110° reduced the solid concentration gradient inside the impeller passages and improved the alignment between the impeller outlet flow angle and the volute diffuser angle, thereby reducing head fluctuations under the investigated conditions [52]. Additionally, discrete phase simulations by Chen et al. [53] showed that a helical blade with a 30° spiral angle yielded a lower particle collision frequency under the simulated operating condition compared to other designs. The configuration reduced the boundary layer separation zone, providing quantitative guidance for balancing solids dewatering with throughput. The study also found a nonlinear effect of blade incidence angle vs. flow approach angle on local wear: when the mismatch exceeded approximately 7°, the reported leading-edge wear rate increased markedly under the investigated condition.

Multi-objective optimization algorithms have improved the efficiency of design parameter tuning by enabling systematic exploration of trade-offs among hydraulic performance, wear resistance, and operating constraints [54–56]. Pareto-front analysis using NSGA-II identified a Pareto-optimal design interval for the impeller outlet width-to-volute throat area ratio, within which hydraulic efficiency and wear resistance can be balanced under the investigated operating conditions. An economic evaluation by Noon et al. [40] found that optimizing impeller–volute clearance via design of experiments reduced pump life-cycle costs: each decrement in the impeller–volute gap led to a proportional drop in peak shear stress in the volute vortex core. Recent studies have advanced beyond single-parameter optimization to iterative co-optimization strategies. For example, iteratively co-optimizing the impeller blade load distribution and volute velocity circulation yielded higher specific energy efficiency in a 300ZJ slurry pump under certain slurry concentrations compared to a traditional design. However, achieving adaptability across wide operating ranges remains challenging, especially when solids concentration fluctuations exceed a threshold. Fixed-geometry optimized designs still suffer excessive efficiency decay under extreme conditions. This underscores the need for intelligent variable-geometry impeller designs in the future.

2.3 Structural Dynamics and Vibration Control

In the realm of slurry pumps structural dynamics, the coupling between rotor vibrations and two-phase flow excitation has opened new opportunities for design optimization [57–60]. Cheng et al. [61] experimentally confirmed that increasing the rotational speed from 1200 to 1800 rpm intensified boundary-layer separation under the reported test condition, which raised fluctuations in blade impact loads and shifted the second-order natural frequency—directly undermining rotor balance. Fluid–structure coupling simulations show that high solid-content slurries can raise the peak equivalent dynamic stress at the impeller leading edge by several times compared to water, while also shifting the main vibration frequency band to lower frequencies. This correlates with resonance risks when certain blade-passing harmonics coincide with volute tongue pressure pulsations. Zhou et al. [62] further investigated the effects of particle concentration on the dynamics of a single-channel sewage pump under low-flow-rate conditions, indicating that solid concentration should be treated as a coupled hydraulic and dynamic variable when assessing vibration-sensitive pump operation.

To elucidate the mechanisms driving these instabilities, unsteady flow simulations have been employed to capture complex dynamic interactions. Tarodiya and Gandhi [63] performed unsteady CFD simulations of a centrifugal slurry pump handling multi-size particulate slurry using a sliding-mesh granular Eulerian–Eulerian model. Their results showed that particle-size distribution significantly affected particle transport within the impeller and casing passages through particle-kinetic effects, indicating strong phase-dependent flow behavior during solid–liquid slurry-pump operation.

Recent advances in multi-body dynamic modeling provide a useful pathway for precise vibration control [64–66]. A six-DOF rotor model including bearing stiffness and seal damping revealed that reducing the impeller–volute gap increases fluid–structure coupling stiffness proportionally, but also lowers modal damping, explaining the nonlinear growth of vibration amplitude at high slurry concentrations. Lv et al. [67] further noted via slip-flow theory that fine-particle slip alters the impeller outlet velocity triangle, shifting the phase of aerodynamic excitation forces—necessitating updated rotor Campbell diagram analyses to avoid resonance.

Campbell diagram analysis is useful for linking hydraulic excitation with structural reliability in slurry pumps. By comparing natural frequencies with rotating speed, blade-passing frequency, and their harmonics, Campbell diagrams can help identify critical speed ranges and potential resonance zones. This analysis is particularly relevant for slurry pumps because particle loading and concentration fluctuations may change excitation forces and modal frequencies, thereby affecting the safe operating window. When combined with fluid–structure interaction analysis and measured vibration spectra, Campbell diagrams can provide a clearer basis for vibration-aware pump optimization and resonance avoidance.

Contemporary design strategies increasingly incorporate dynamic stress, modal characteristics, and critical-speed analysis to mitigate structural vibration and resonance risks in slurry pumps; representative advances are summarized in Table 2 [68]. Topology optimization of the impeller (through parameter inversion techniques) can shift the first natural frequency outside the range of 0.75–1.25 times operating speed, thereby reducing vibration intensity below industry limits. Experiments show that adding 45° guide vanes on the impeller hub effectively suppresses wake vortex shedding and dramatically reduces pressure pulsation amplitudes. Moreover, the integration of smart materials for vibration control has shown initial success: arranging piezoelectric actuators on the bearing housing enables active modal tuning, though the damping effectiveness is observed to diminish at certain excitation frequencies. These advances lay the foundation for next-generation slurry pumps with self-sensing and self-adjusting vibration control capabilities.

Table 2: Summary of improvements in the dynamics of slurry pumps.

Mechanism	Findings	Optimization Strategies
Rotor-two-phase coupling	- Increasing impeller speed (1200⟶1800 rpm) intensifies boundary-layer separation and shifts second-order natural frequency, undermining rotor balance. - Slurry with high solid content raises equivalent dynamic stress several-fold and shifts main vibration frequency band to lower frequencies, risking resonance with volute tongue pulsations.	- Topology optimization shifts the first natural frequency outside the 0.75–1.25× operating speed range, reducing vibration intensity below industry limits.
Special dynamic mechanisms	- 'Pendulum effect': liquid-phase fluctuations exceed those of the solid phase, causing periodic impact loads that reduce hub bolt fatigue life. - As particle size increases, vibration energy density within a frequency band rises several-fold due to turbulence modulation by large particle clusters. - Critical whirling speed under two-phase flow is lower than design value in water; von Kármán vortex shedding behind the impeller back-plate induces stress concentrations.	- Adding 45° guide vanes on the impeller hub suppresses wake vortex shedding and significantly reduces pressure pulsation amplitudes.

Table 2: *Cont.*

Mechanism	Findings	Optimization Strategies
Multi-body dynamic modeling	- A six-DOF rotor model including bearing stiffness and seal damping shows that reducing impeller-volute gap increases coupling stiffness but lowers modal damping, leading to nonlinear growth of vibration amplitude at high slurry concentrations. - Slip-flow theory shows fine-particle slip alters the impeller outlet velocity triangle, shifting the phase of aerodynamic excitation forces and requiring updated Campbell diagram analysis.	- Combine structural parameter optimization with dynamic matching to avoid resonance and maintain rotor stability.
Smart materials & active control	- Arranging piezoelectric actuators on the bearing housing enables active modal tuning. - Damping effectiveness diminishes at certain excitation frequencies.	- Develop self-sensing, self-adjusting vibration control systems for next-generation slurry pumps.

2.4 Intelligent Algorithm-Assisted Design

In recent years, intelligent design approaches that combine evolutionary algorithms with deep learning have driven a significant shift in slurry pump optimization paradigms [69–72]. Radial Basis Function (RBF) neural networks have been used to construct surrogate models that overcome the limitations of traditional response surfaces in high-dimensional, nonlinear design problems. Using RBF-based surrogate modeling, complex nonlinear relationships between impeller geometry parameters (e.g., blade wrap angle, outlet width) and performance outputs (head, efficiency, etc.) can be predicted with low error [73]. Experiments indicate that optimizing such parameters with an RBF surrogate requires only about one-fifth the training samples of a traditional design-of-experiments approach to achieve comparable accuracy, saving significant computational effort.

The NSGA-II genetic algorithm has shown remarkable advantages for exploring the Pareto optimal front. Its fast non-dominated sorting and crowding-distance mechanisms yield a highly converged set of solutions for impeller profile design within relatively few iterations. Cui et al. [71] established a Kriging surrogate model and applied NSGA-II to optimize the blade wrap angle, rear-cover inlet angle, and blade outlet width of an oil slurry pump, with the average wear rate and hydraulic efficiency selected as optimization objectives. The optimized impeller exhibited a 14.12% reduction in average wear rate and a 3.05% improvement in efficiency. However, the robustness and transferability of such surrogate-assisted Pareto-optimal solutions under different particle-size distributions, slurry concentrations, and off-design operating conditions still require further validation.

For clarity, the typical NSGA-II-based pump optimization workflow can be summarized as follows: parameterize impeller or volute geometry, generate an initial population, evaluate each candidate using CFD or experimental response data, rank candidates through non-dominated sorting, preserve diversity using crowding distance, and update the population through selection, crossover, and mutation until a Pareto front is obtained. In slurry pump applications, the Pareto front should be interpreted together with manufacturability, cavitation margin, wear distribution, and off-design robustness rather than only head and efficiency. For slurry pump optimization, the more important issue is not the generic evolutionary loop itself, but how the loop is coupled with pump-specific design variables, CFD or experimental objective evaluation, cavitation constraints, wear-distribution metrics, manufacturability, and off-design robustness. Therefore, the manuscript retains a concise textual workflow and emphasizes the pump-specific interpretation of the Pareto front rather than adding a schematic that would duplicate standard NSGA-II descriptions. In addition, the algorithmic results should not be interpreted as universally optimal designs. Their validity depends on the fidelity of CFD or experimental training samples, the selected objective functions, and the extent to which constraints such as cavitation margin, manufacturability, material degradation, and off-design operation are included during optimization.

To overcome the limits of any single optimization method, data-driven hybrid algorithm frameworks are emerging [74,75]. For example, one approach couples Particle Swarm Optimization (PSO) with a Deep Belief Network (DBN): by combining PSO's global search ability with DBN's feature extraction, this hybrid achieved a synergistic improvement in efficiency and accuracy for optimizing the impeller–volute clearance [76,77]. Case studies demonstrated that this framework optimized multi-variable design problems in approximately half the computational cost required by conventional genetic algorithm, while exhibiting reduced variance in the objective convergence.

Current efforts focus on enhancing algorithm generalization and robustness. By incorporating transfer learning, optimization models can maintain stable performance across different operating conditions [78]. For instance, a domain-adversarial neural network (DANN) transfer learning framework achieved high prediction accuracy with only a small number of samples from new operating conditions, supporting adaptive pump design over a wide range of working scenarios. A core challenge, however, is that real-world deployment of these algorithms is limited by access to high-quality training data, especially the lack of wear monitoring data under extreme conditions severely weakens model extrapolation ability. Addressing this data bottleneck is crucial for these intelligent design methods to reach their full potential in practical engineering.

Beyond academic studies, intelligent algorithms have demonstrated verifiable benefits in industrial pump optimization [79]. For example, He et al. [80] applied a genetic algorithm coupled with a 3D parameterized impeller model (constrained by manufacturing tolerances) to retrofit a large circulating water pump in a thermal power plant. The optimized design achieved a ~3.2 percentage-point increase in average efficiency across the operating range, which was subsequently validated in a full-scale factory acceptance test. The annual energy savings were estimated at ~450 MWh. In the mining sector, Gan et al. [81] reported a surrogate-model-assisted optimization for a series of slurry pumps in a tailings transport circuit. Using a deep belief network trained on CFD simulation data, engineers rapidly evaluated over 2000 design variants of the volute and impeller outlet geometry. The selected design, when prototyped and tested in a closed-loop slurry pump test rig, showed a ~15% reduction in peak wear rate at the volute tongue compared to the baseline, while maintaining the required head. These cases highlight the transition from purely maximizing hydraulic efficiency to incorporating wear reduction in multi-objective pump design within real industrial projects.

While intelligent algorithms have accelerated design exploration, their practical deployment is constrained by several factors. First, most surrogate models (e.g., RBF, DNN) are data-hungry and require extensive high-fidelity simulation or experimental data for training—a resource-intensive process. Second, these models often act as "black boxes," offering limited physical interpretability, which hinders engineers' trust and ability to extract mechanistic insights. Third, generalization remains a critical issue: models trained under specific operating conditions (e.g., a fixed particle size distribution) often perform poorly when applied to off-design or highly variable slurry properties, a phenomenon exacerbated by the scarcity of open, standardized wear datasets. Furthermore, multi-objective optimization algorithms such as NSGA-II may converge to locally optimal fronts when objective landscapes are highly nonlinear or constrained by dynamic operational boundaries. Overcoming these barriers will require advances in physics-informed neural networks, transfer learning across operational domains, and collaborative benchmarking initiatives. Although intelligent algorithms can accelerate design-space exploration, their engineering use remains constrained by data availability, interpretability, and generalization. Surrogate models, including radial basis function networks and deep neural networks, require training data from high-fidelity simulations or experiments, and their prediction accuracy depends strongly on the coverage and quality of these samples. When the training set is limited to a fixed particle-size distribution, slurry concentration, or operating range, the resulting model may lose accuracy under off-design or highly variable slurry conditions. In addition, many data-driven models exhibit black-box behavior, which makes it difficult to identify the physical mechanism linking geometric parameters, particle impact, cavitation margin, and wear evolution [82]. Multi-objective algorithms such as NSGA-II may also produce condition-dependent Pareto fronts when the objective functions, constraints, or CFD-based samples do not include cavitation margin, manufacturability, material degradation, and off-design robustness. Therefore, future applications should combine intelligent algorithms with physics-informed constraints, uncertainty reporting, transferability tests, and benchmark datasets covering variable slurry properties and wear mechanisms.

2.5 Multiphysics Co-Simulation and Digital Twin-Oriented Modeling

Multiphysics co-simulation provides a useful approach for analyzing the coupled effects of fluid motion, particle transport, structural response, and material wear in slurry pump optimization. For example, CFD–DEM simulations can be used to examine how particle size and concentration affect flow stratification, slip velocity, and erosion-prone regions, while FSI analysis can link pressure pulsation and particle-induced loading to structural stress and vibration response. However, the predictive value of these models depends on whether their numerical accuracy, coupling stability, and experimental validation are sufficiently demonstrated. Therefore, CFD–DEM and FSI results should be interpreted together with mesh independence, time-step sensitivity, particle-contact parameter calibration, turbulence-model selection, erosion-law assumptions, and comparison with measured hydraulic performance, pressure fluctuation, vibration spectra, or wear patterns. For instance, Li et al. [83] combined CFD–DEM simulations with two-phase performance and wear experiments to investigate particle motion and component wear in a centrifugal pump. Their results showed that the instantaneous wear rates of the impeller, volute, and wear plate varied periodically with impeller rotation and generally increased with particle mass concentration. These findings highlight the importance of particle–fluid and particle–wall interactions in wear-oriented slurry-pump design. Structural responses under particle-laden two-phase loading should be evaluated separately using fluid–structure interaction and modal analyses.

Despite its theoretical capability to resolve particle–fluid interactions, the direct application of fully resolved CFD–DEM to industrial-scale centrifugal pumps remains computationally prohibitive. Computational challenges and simplification strategies in industrial CFD–DEM applications. The challenge arises from the enormous number of particles (often $>10^8$) and the need for transient multiphase flow solutions over meaningful operational durations. To render simulations feasible, researchers and engineers typically adopt simplification strategies that trade off some accuracy for tractability. Coarse-graining (CG) is widely used, wherein groups of real particles are represented by larger, computationally "cheaper" parcels with scaled-up properties. CG can reduce particle counts by orders of magnitude, but it inevitably smears out local particle-size effects and may misrepresent polydisperse slurry behavior. Geometric simplification is another common approach: complex pump geometries are often reduced to 2D or periodic sector models, and detailed surface textures (e.g., coating roughness) are homogenized. While this lowers mesh counts and accelerates convergence, it can overlook critical secondary flows and localized wear patterns that depend on full three-dimensional geometry. Hybrid Euler–Lagrange coupling offers a middle ground: discrete particles are tracked only in regions of high erosion risk (e.g., near impeller leading edges), while the bulk slurry is treated as a continuous phase. This method balances detail with speed but requires careful interface treatment to avoid momentum-transfer errors at phase boundaries. Importantly, these simplifications have not been comprehensively validated across the wide range of operating conditions encountered in practice. Consequently, while CFD–DEM methods provide valuable qualitative insights, their quantitative predictive accuracy for long-term wear in full-scale pumps remains an open challenge, urging the development of more efficient yet physically faithful modeling frameworks. For this reason, the convergence behavior of coupled simulations should be reported explicitly, including mesh resolution near blade leading edges and volute tongues, time-step independence for particle–wall collision events, and sensitivity to particle restitution coefficient, friction coefficient, and size distribution. When available, numerical predictions should be validated against pump head and efficiency curves, pressure fluctuation measurements, vibration acceleration signals, post-test wear depth, surface morphology, or material-loss distribution. Without these validation steps, the simulated erosion zones and stress concentrations are more appropriately regarded as qualitative indicators of high-risk regions rather than direct quantitative predictions of service life.

To address these predictive limitations, cross-scale wear prediction models have been developed to link particle-impact information with macroscopic material-loss estimates [84]. By combining the Discrete Element Method (DEM) with Archard's wear law, researchers have created algorithms that map microscopic particle impacts to macroscopic material loss. For example, Hawash et al. [85] compared numerical wear predictions with experimental observations and showed that the predicted wear distribution was consistent with the main erosion-prone regions under the tested conditions. Simulations indicated that with each increment in flow rate, the cumulative energy of particle impacts increases proportional to the square of particle slip velocity. Moreover, when a vortex core's location aligns with an impeller mode shape (resonance condition), local wear rates spike, revealing the critical role of fluid–structure vibration coupling in wear evolution. Nevertheless, the transferability of such models remains limited when slurry concentration, particle-size distribution, material hardness, or operating duration differs from the calibrated test condition.

The complexity of such multi-field coupling has spurred the advanced numerical solution strategies [86,87]. Adaptive mesh refinement can increase mesh density in boundary layers by orders of magnitude, achieving particle tracking accuracy on the order of millimeters. For cases of abrupt changes in solid concentration, hybrid implicit–explicit solvers with adaptive time-stepping have been developed to improve computational efficiency. On the structural side, Dynamic Mode Decomposition (DMD) helps rapidly identify dominant flow patterns from complex internal flows, enabling analysis of specific flow-induced vibration modes. Xue et al. [88] discovered that pressure oscillation modes from a rotating stall vortex manifest as a primary nodal-circle mode and a secondary one-nodal-diameter rotating mode, corresponding to low-order "wet modes" of the pump's back cover. Such numerical strategies should be accompanied by convergence assessment, because locally refined meshes or adaptive time-stepping may change predicted particle trajectories, collision frequency, wall shear stress, and pressure-pulsation phase. For FSI-based analyses, the stability of data transfer at the fluid–structure interface should also be checked, since inconsistent temporal resolution between the fluid and structural solvers can introduce artificial phase shifts or energy-transfer errors.

Research is currently transitioning from one-way coupling toward fully coupled multi-physics systems that encompass thermal and intelligent dimensions. Thermo–fluid–structural simulations using conjugate heat transfer models have found that frictional heating of slurry can create steep temperature gradients on the impeller surface, inducing thermal stresses that constitute a large portion of the total stress. Coupled with flow-induced vibrations, this led to crack growth rates in blade resonance regions increasing several-fold under high-concentration conditions. To resolve cross-scale data transfer issues, machine-learning surrogate models are being introduced into the co-simulation loop: by training deep neural networks to link macro-scale flow parameters with micro-scale wear features, the efficiency of iterative cross-scale computation is improved. These advances lay a foundation for developing full-condition digital twin systems for slurry pumps [89]. To synthesize the findings presented throughout this section, Table 3 summarizes the key mechanisms, discoveries, and corresponding optimization measures.

Table 3: Mechanism–discovery–optimization measures.

Mechanism	Key Findings	Optimization Measures
Fluid–particle interaction (CFD–DEM coupling)	Larger particle diameters intensify volute vortex cores and steepen velocity gradients at the impeller outlet, distorting the flow field.	Regulate particle size distribution and adjust volute/impeller geometry to reduce harmful stratification.
Fluid–structure dynamic coupling	Two-way FSI showed that fine-particle slurries induce several-fold increases in impeller leading-edge stresses, shifting vibration frequencies lower. This provides fatigue load spectra.	Use vibration-resistant impeller designs, fatigue life prediction, and damping structures to suppress resonance.
Cross-scale wear prediction (DEM + Archard's law)	Microscopic particle impacts mapped to macroscopic wear; experimental validation showed prediction errors well below industrial limits. Local wear spikes occurred when vortex cores matched impeller mode shapes.	Apply predictive wear-resistant coatings, redesign inlet regions, and monitor vortex–mode alignment to prevent localized erosion.
Adaptive numerical strategies	Adaptive mesh refinement improved particle tracking resolution to millimeter scale; hybrid implicit–explicit solvers enhanced efficiency under concentration fluctuations.	Use adaptive meshing/time-stepping in CFD–DEM solvers to ensure accuracy with reduced computational cost.
Dynamic Mode Decomposition (DMD)	Identified dominant flow-induced vibration modes; rotating stall vortices produced low-order "wet modes" of the back cover.	Target reinforcement of back-cover regions and mitigate stall oscillations via impeller outlet angle optimization.
Thermo–fluid–structural coupling	Conjugate heat transfer showed slurry frictional heating induces thermal stresses comparable to mechanical stresses, accelerating crack growth in resonance regions.	Introduce thermal barrier coatings and optimize cooling/ventilation paths in slurry regions.
Machine-learning assisted co-simulation	Surrogate models linked macro-flow features with micro-wear evolution, improving iterative computation efficiency and enabling real-time analysis.	Incorporate ML-based digital twins to support predictive maintenance and full-condition monitoring.

The boundary between material-oriented wear analysis and system-level multiphysics modeling should also be clarified. Section 2.1 primarily concerns coating composition, microstructure, hardness, porosity, bonding strength, and wear/corrosion resistance, whereas this section focuses on the predictive workflow linking CFD-DEM, FSI, erosion laws, surrogate models, and digital twins. Overall, the credibility of multi-physics modeling in slurry pump optimization depends on both numerical verification and experimental validation. Numerical verification should include grid convergence, time-step sensitivity, coupling stability, and sensitivity analysis of particle and material parameters. Experimental validation should compare simulated results with measured pump performance, pressure fluctuation, vibration spectra, erosion morphology, wear depth, or material-loss distribution. If these procedures are not reported, CFD–DEM, FSI, and wear-coupled simulations should be treated as mechanistic or qualitative guidance rather than as direct evidence for long-term quantitative prediction.

3 Discussion

3.1 Core Challenges in Integrated Optimization

The reviewed literature reveals three recurring contradictions. These contradictions are identified by comparing not only reported performance gains, but also validation basis, operating range, uncertainty sources, and feasibility of transferring laboratory or simulation results to industrial slurry conditions. First, high-fidelity CFD-DEM/FSI models improve physical resolution but remain difficult to deploy in real-time optimization without reduced-order or surrogate models. Second, surface coatings that improve erosion resistance may alter roughness, wetting behavior, or local flow separation, creating a trade-off between material durability and hydraulic efficiency. Third, intelligent algorithms can efficiently search high-dimensional design spaces, but their reliability depends on training-data quality, interpretable constraints, uncertainty reporting, and validation under variable particle-size distributions, slurry concentrations, and operating conditions.

Although recent studies have reported progress in coating design, hydraulic optimization, vibration control, intelligent algorithms, and multiphysics simulation, these advances remain only partially connected at the system level. The reviewed literature reveals three recurring contradictions that limit integrated slurry pump optimization. First, high-fidelity CFD–DEM and FSI models improve the physical resolution of particle-laden flow, erosion, and vibration mechanisms, but their computational cost, parameter sensitivity, and validation requirements still limit direct use in real-time design or operation. Second, wear-resistant coatings can improve erosion resistance, but they may also change surface roughness, wetting behavior, and near-wall flow separation, which creates a trade-off between material durability and hydraulic efficiency. This trade-off becomes more complex under cavitating slurry conditions, where bubble collapse can accelerate surface damage and particle impacts can modify the local roughness that controls cavitation inception. Third, intelligent algorithms can accelerate design-space exploration, but their engineering reliability depends on training-data quality, interpretable constraints, uncertainty reporting, and validation under variable slurry conditions.

Despite the progress reviewed in the preceding section, achieving fully integrated optimization of slurry-pump materials, geometry, and operating control remains a fundamental challenge. Recent studies have begun to jointly optimize impeller geometry, hydraulic performance, and erosion resistance [90]. However, a broader framework that simultaneously integrates material selection, geometric design, and operating or control strategies remains underdeveloped [91]. Innovations in individual areas (e.g., surface coatings that extend impeller life, intelligent algorithms that improve efficiency) have mostly been pursued in isolation. Studies show that when surface hardness is raised beyond a certain point, the optimal particle incidence angle requires adjustment. However, current hard coatings are frequently applied to design on traditional flow parameters, resulting in a mismatch between material performance and flow characteristics that is especially detrimental under low fluctuation conditions [92].

Within the domain of fluid–structure coupling, a pronounced disconnect exists regarding the coordinating of dynamic parameters. For example, Dong et al. [93] investigated transient solid–liquid flow in a centrifugal pump under variable operating conditions and showed that flow regulation changes the pressure and turbulence-energy distributions, causing particles to migrate toward the middle and trailing regions of the blade suction surface and thereby intensifying suction-side wear. An even greater inconsistency exists between control optimization and material performance: when intelligent algorithms optimize impeller geometry, the erosion-rate coefficients used remain static empirical values, without dynamically linking to the coating's hardness gradient over time. This temporal discrepancy often leads to "optimized" designs exhibiting a shorter actual service life than predicted models suggest.

Furthermore, the fragmented nature of current multiphysics research impedes major breakthroughs in cross-scale analysis. For instance, CFD–DEM models can precisely simulate fine particle trajectories, but they lack spatial resolution for nanoscale hardness gradients on material surfaces, resulting in high wear prediction error. Likewise, slight shifts in impeller modal frequencies can change surface residual stress distributions, yet current vibration control schemes assume uniform material properties. This lack of cross-scale understanding hinders co-optimization of bio-inspired surface engineering and structural dynamics. Specifically, micro-groove surface arrays designed to optimize particle impact angles may inadvertently shift the main frequency band of flow-induced vibrations, thereby creating new resonance risks.

Bottlenecks in the engineering application of intelligent algorithms highlight the absence of collaborative mechanisms [94,95]. Transfer learning can achieve high cross-condition prediction accuracy, but current training sets do not integrate key parameters like material crack growth rates. Moreover, many multi-objective optimizations treat head, efficiency, and lifespan as independent goals, ignoring nonlinear couplings between them. Experiments show that optimizing impeller outlet width to improve efficiency can simultaneously increase local stress concentration factors several-fold. These conflicts are difficult to reconcile under the current fragmented research paradigm. Consequently, overcoming these barriers requires establishing a fully coupled database linking material properties, flow characteristics, and structural responses, and developing a multidisciplinary digital twin optimization platform for slurry pumps.

3.2 Methodological Limitations

The methodological limitations of current slurry pump optimization arise mainly from scale mismatch, dynamic operating conditions, and insufficient validation of coupled models [96–98]. Long-term wear experiments can capture progressive material loss but often miss short-time particle-impact events, whereas numerical simulations can resolve transient flow and collision processes but usually cover much shorter physical durations. This mismatch makes it difficult to establish a direct causal link between simulated particle impacts, measured wear morphology, and long-term service degradation. Traditional pump experiments rely on test rigs to collect steady-state performance and long-term wear data, but their time resolution cannot capture millisecond-scale particle impact events. Conversely, numerical simulations can resolve microsecond-level flow details, but computational limits force the simulated physical time to be compressed to minutes, breaking the cross-scale causality for some wear mechanisms. For example, Romano et al. [99] found that while a RANS-based impeller flow simulation had mean velocities closely matching PIV measurements, it failed to capture transient fine-particle trajectories. This discrepancy revealing a decoupling between simulated turbulence fluctuations and actual particle motions.

Intrinsic limitations also persist in the are handled of dynamic parameters, particularly regarding the prevalence of quasi-steady assumptions to simplify fluid–structure coupling [100,101]. For instance, blade wear models often discretize impact angle into fixed bins, whereas experiments show that even under small concentration fluctuations, particle incidence angles vary widely over short timescales-behavior that current Archard-law-based models linearize away. The time-varying nature of material properties is also ignored; for example, laser-clad coatings experience sharply accelerated microhardness decay after prolonged service, but optimization algorithms still treat hardness as constant, leading to large life prediction errors. In an online monitoring study, Zhang et al. [102] observed that a traditional DEM model's error in predicting dynamic stress at the blade leading edge grew exponentially over runtime, exceeding allowable thresholds after extended operation. Data fusion in coupled multi-field modeling remains another urgent challenge [103,104]. Current CFD-DEM-FFT combined simulations can simultaneously analyze flow fields, particle motion, and vibration spectra, but time-space synchronization between solvers is not yet well controlled. Studies show that if the fluid domain uses a millisecond-level timestep while the structural domain uses a much smaller timestep, large energy-transfer errors can occur, distorting the phase of pressure pulsations at the fluid-structure interface. In terms of spatial-scale integration, no effective mechanism yet maps micron-scale coating surface features to meter-scale pump structures. For example, the drag-reduction effect of micro-pitted textures may be overly smoothed in full-scale flow simulations, causing the turbulence-suppression benefits to appear only weakly in the model.

Uncertainty analysis is also insufficient in many coupled slurry pump simulations. Model outputs may be affected by turbulence closure, drag law selection, particle-contact parameters, wall roughness treatment, erosion-law coefficients, material hardness evolution, and the coupling scheme used between the fluid and structural solvers. Therefore, future multiphysics studies should report parameter sensitivity, validation error, convergence behavior, and uncertainty bounds together with predicted wear or vibration results. This would allow simulation results to be compared more transparently across different pump geometries, slurry conditions, and material systems.

Methodological dilemmas also confront the application of intelligent algorithms in engineering practice [105–107]. For intelligent optimization, data dependency and generalization remain major methodological limitations. Models trained under a narrow range of slurry concentration, particle-size distribution, or wear mechanism may not remain accurate when transferred to off-design conditions. The lack of open benchmark datasets and standardized validation protocols further limits direct comparison among algorithmic studies. Therefore, future studies should report training-data coverage, validation error, uncertainty bounds, and transferability tests together with optimized hydraulic or wear-related performance. NSGA-II has shown promise for impeller optimization, but its fitness function is often simplified to a static weighted sum of objectives, without incorporating time-varying operational constraints. Experimental data indicate that when solid concentration increases gradually, a fixed-parameter optimized design loses performance several times faster than a design optimized with dynamic modeling. Transfer learning can improve generalization across conditions, but if the wear mechanisms in the training data differ too greatly from those in the target domain, predictive accuracy plummets. Fundamentally, current algorithm architectures struggle with emergent behaviors from multidisciplinary coupling. Existing surrogate-assisted optimization frameworks may have difficulty preserving strongly nonlinear interactions among different disciplines when the corresponding disciplinary models are constructed and updated separately. In nonlinear multidisciplinary analyses, these interactions can produce complex system-level responses that cannot be adequately represented by a straightforward combination of independent surrogate models [108–110]. Overall, these methodological limitations show that the main challenge is not only to improve individual models, but also to establish a validated connection among particle-laden flow, material degradation, structural response, and operational decision-making. Without such connection, optimized designs may remain condition-dependent and difficult to transfer from laboratory or simulation settings to industrial slurry transport systems.

3.3 Conceptual Digital Twin-Based Lifecycle Optimization Framework

Based on the contradictions and methodological limitations discussed above, digital-twin-enabled lifecycle optimization is considered here as a conceptual integration route rather than as a validated engineering solution. Its role is to organize sensing, reduced-order modeling, uncertainty-aware updating, and maintenance decision-making within a staged framework. While fully autonomous, CFD–DEM-driven digital twins remain a future vision, several sensor-driven, reduced-order digital twin systems have already been piloted in industry. For example, a major mining company implemented a cloud-based digital twin for its 300ZJ slurry pumps transporting iron-ore concentrate. The system integrates real-time pressure, vibration, and motor power sensor data with a physics-informed LSTM model to predict the remaining useful life of the impeller. In a 12-month field trial, this pilot successfully predicted two impeller failures roughly 800 h in advance, reducing unplanned downtime by an estimated 40%. Another pilot in a phosphate slurry pipeline uses a hybrid digital twin for operational optimization. A one-dimensional hydraulic network model, calibrated by periodic CFD simulations, runs in real time alongside the pipeline's SCADA control system to recommend pump speeds and valve settings that minimize specific energy consumption under varying slurry densities. After deployment, the pipeline twin reported a 5–7% reduction in energy use during non-peak hours, verified by meter data. These examples illustrate that current industrial digital twins tend to prioritize specific high-value functions (predictive maintenance, energy optimization) over full multiphysics fidelity, adopting a pragmatic, modular approach to integration. To address the methodological gaps identified above, a conceptual Digital Twin-based Lifecycle Optimization Framework is discussed as a long-term research roadmap. This framework is not presented as a validated model, but as an organizing structure for connecting material degradation, hydraulic performance, structural response, sensing data, reduced-order modeling, and maintenance decision-making. Its practical implementation depends on the availability of reliable monitoring data, computationally efficient surrogate models, and staged validation under representative slurry transport conditions. Rather than representing a validated model, this conceptual framework outlines a real-virtual iterative optimization pathway across material, structure, flow, and control domains. Its core consists of a three-tier architecture:

- **Bottom layer**: Offline high-fidelity multiphysics simulations are used to generate physically informed reference data, while reduced-order or surrogate models provide a more practical basis for near-real-time inference.
- **Middle layer:** Sensor-based parameter updating is used to assimilate pressure, flow rate, vibration, motor power, slurry concentration, temperature, and wear-related monitoring signals into reduced-order or surrogate models.
- **Top layer:** A decision-support module combines remaining-useful-life prediction and multi-objective optimization to assist speed adjustment, inspection scheduling, and maintenance planning.

As shown in Fig. 4, the proposed framework should be interpreted as a modular implementation pathway rather than a real-time full-fidelity CFD–DEM system. The data layer collects pressure, flow rate, vibration, motor power, slurry concentration, temperature, and wear-related monitoring signals. The model layer combines offline CFD–DEM or FSI simulations with reduced-order or surrogate models to support near-real-time inference. The decision layer uses multi-objective optimization and remaining-useful-life prediction to support operational adjustment and maintenance planning. The validation layer compares digital-twin predictions with bench tests, field monitoring, historical failure records, and post-maintenance inspection. Future validation should compare reduced-order or surrogate-model predictions with experimental measurements of particle trajectories, coating degradation, and local flow separation before such a framework can be deployed for closed-loop optimization. To enable dynamic performance optimization, the system integrates a piezoelectric sensor array and fiber Bragg grating network to continuously collect impeller surface strain and fluid pressure data. An improved Kalman filter could be used to update reduced-order model parameters when reliable sensor data are available. Such data assimilation may support faster responses to abrupt condition changes, such as sudden spikes in slurry concentration, but its practical effectiveness depends on sensor robustness, sampling frequency, and model calibration quality.

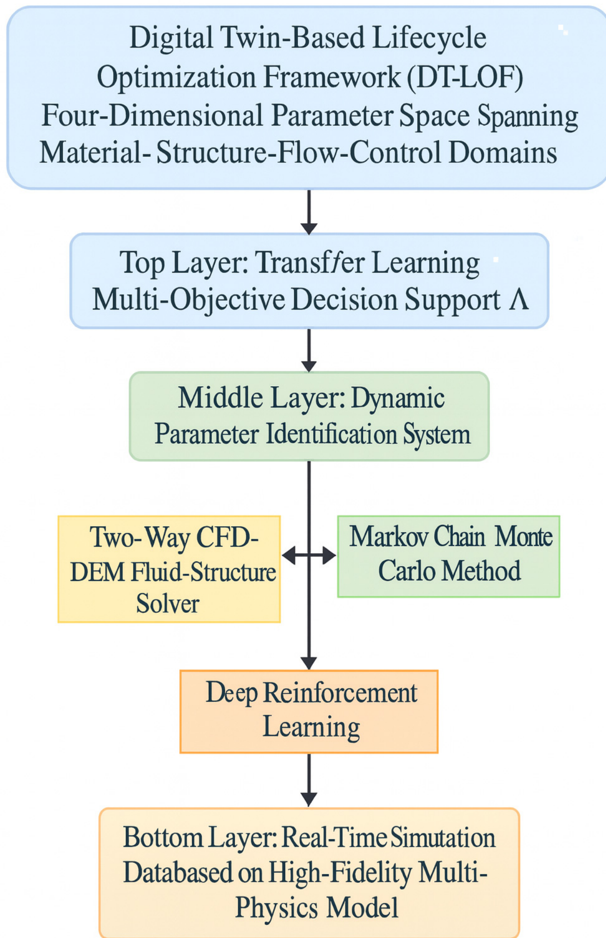


Figure 4: Conceptual digital-twin-based lifecycle optimization framework for centrifugal slurry pumps, including sensing, modeling, updating, prediction, optimization, and maintenance decision support.

The algorithmic choices in the framework should follow the time scale and data availability of each layer. Offline CFD–DEM and FSI simulations are suitable for resolving particle trajectories, coating degradation, and vibration coupling, but they remain too expensive for direct closed-loop control. Reduced-order or surrogate models are more appropriate for near-real-time inference after calibration with high-fidelity simulations or experimental data. Kalman-filter-type updating is suitable when continuous sensor streams are available and model states can be corrected recursively, whereas sequence models such as long short-term memory networks are more suitable for remaining-useful-life prediction when long-term degradation histories are available. Multi-objective evolutionary algorithms should mainly be used for offline design-space exploration or maintenance-planning optimization, where head, efficiency, cavitation margin, wear rate, and service life can be treated as competing objectives.

Extending beyond real-time operational adjustments, the framework addresses lifecycle management through an LSTM-based remaining life prediction model. When trained on datasets covering coating failure, fatigue crack growth, and other degradation modes, an LSTM-based model could support probabilistic remaining-life prediction, provided that sufficient long-term monitoring data and independent validation are available. In parallel, the digital twin is combined with adaptive manufacturing: In future implementations, wear monitoring data could be used to support maintenance planning, such as identifying coating repair needs or scheduling inspection intervals. For engineering deployment, such a framework should be evaluated on representative slurry pump systems by comparing efficiency fluctuation, wear evolution, and maintenance cost against baseline operation.

The proposed roadmap emphasizes cross-disciplinary collaborative innovation by establishing a joint platform spanning fluid dynamics, materials science, and control engineering. It prioritizes breakthroughs in the coupled design of bionic surface microstructures and adaptive flow controllers. For example, blade leading-edge profiles inspired by humpback whale tubercles are optimized to proportionally reduce fine-particle cutting wear. In tandem, a NiTi–Al_2O_3 graded functional coating with shape-memory effect is developed, with a phase transition temperature tailored to frictional heating characteristics, enabling autonomous healing of surface erosion damage. Implementing this innovation pathway will propel slurry pump design from isolated optimizations toward system-level intelligent evolution, providing a model for the digital transformation of heavy industrial equipment.

For engineering deployment, validation should proceed in stages. The offline model should first be verified through mesh convergence, time-step sensitivity, and comparison with controlled experiments. Bench-scale tests should then be conducted under specified slurry concentration and particle-size distributions to evaluate hydraulic performance, vibration response, and wear evolution. Hardware-in-the-loop tests or supervisory-control-data replay can be used to examine inference speed and decision stability before field monitoring is performed. Only after these validation steps can the framework support reliable lifecycle decision-making under industrial slurry transport conditions.

4 Conclusions

This review synthesizes recent progress in centrifugal slurry pump optimization by connecting hydraulic design, material wear mechanisms, structural dynamics, intelligent algorithms, and digital-twin concepts within a lifecycle-oriented perspective. Rather than treating these topics as independent research streams, the review emphasizes their coupling across design, operation, monitoring, maintenance, and degradation stages. The reviewed literature indicates that flow-field design affects particle impact and cavitation behavior, surface modification changes wear resistance and local roughness, and structural vibration can feed back into both hydraulic stability and component reliability.

Hydraulic and wear-related optimization studies show that computational fluid dynamics coupled with discrete element methods, discrete-phase wear models, and cavitation simulations can improve the interpretation of particle motion, erosion distribution, and performance degradation under slurry transport conditions. Fine and coarse particles affect this process through different mechanisms. Fine particles tend to influence turbulence modulation, suspension uniformity, and near-wall concentration gradients, whereas coarse particles increase slip velocity, particle-impact energy, and localized cutting wear. Therefore, reported efficiency gains, wear-rate reductions, and cavitation-related material-loss changes should be interpreted together with pump geometry, operating conditions, slurry concentration, particle-size distribution, material system, cavitation criterion, unit definition, and validation method, rather than being treated as directly comparable benchmarks.

Cavitation–erosion interaction remains a critical issue in hydraulic optimization. Cavitation inception is governed by the local pressure field, vapor volume fraction, turbulence intensity, and net positive suction head required, while bubble collapse near blade leading edges, volute tongues, or coating defects can remove passive films, roughen surfaces, and generate micro-pits. These surface changes can modify particle impact angles and intensify cutting or deformation wear. Conversely, particle-induced material loss can increase local roughness and promote earlier cavitation inception. Reliable cavitation–erosion analysis therefore requires not only a cavitation model and an erosion law, but also validation against pressure fluctuation, vapor distribution, surface morphology, and post-test material-loss patterns.

Structural dynamics and multiphysics modeling provide another basis for lifecycle-oriented optimization. Rotor-flow coupling, fluid–structure interaction analysis, modal assessment, Campbell diagram interpretation, and wear-coupled simulation can help identify vibration-sensitive operating ranges, resonance risks, and erosion-prone regions. Nevertheless, many existing models still rely on quasi-steady assumptions, simplified material properties, limited uncertainty analysis, or insufficient validation against measured vibration spectra, pressure fluctuations, erosion morphology, wear depth, and material-loss distribution. Stronger connections are therefore needed among pressure pulsation, modal response, fatigue-life assessment, cavitation–erosion evolution, and field monitoring.

Intelligent algorithms offer useful tools for design-space exploration, performance prediction, and remaining-useful-life estimation. Multi-objective evolutionary algorithms, surrogate models, transfer learning, and sequence models can reduce computational cost and support data-assisted decision-making. Their engineering value, however, depends on the quality and coverage of training data, the interpretability of model outputs, the treatment of uncertainty, and validation under variable slurry concentration, particle-size distribution, wear mechanism, and operating condition. Without such validation, algorithm-derived optimal designs may remain condition-dependent, and their generalization capability may be overestimated.

Overall, the reviewed evidence suggests that lifecycle-oriented slurry pump optimization is promising but not yet fully mature. The main barriers are the lack of standardized long-duration datasets, insufficient validation of coupled erosion and vibration models, limited interpretability of machine-learning-assisted optimization, and the difficulty of transferring laboratory or simulation-based conclusions to variable industrial slurries. The reviewed evidence also indicates that reported efficiency gains, wear reductions, and cavitation-related improvements should be interpreted together with validation methods, slurry conditions, particle-size distributions, and material systems, rather than being treated as directly comparable benchmarks. Future work should prioritize benchmark datasets, uncertainty-aware model validation, particle-size-resolved cavitation–erosion experiments, and modular digital twins based on reduced-order models and robust sensor data [111,112]. In this sense, the proposed digital-twin-oriented lifecycle framework should be interpreted as a research roadmap for organizing future studies rather than as a validated industrial solution.

Future research should prioritize dynamic coupled modeling and cross-scale correlation mechanisms. Existing methods remain limited in temporal and spatial integration: long-term rig tests may miss millisecond-scale particle-impact events, while short simulations may fail to represent progressive material degradation. In addition, surrogate-model and transfer-learning approaches should be evaluated under changing wear mechanisms, particle-size distributions, slurry concentrations, and operating conditions to avoid overestimating their generalization capability.

Future digital-twin research should proceed through modular implementation and staged validation. Remaining-useful-life prediction models, including sequence-learning methods, may also support probabilistic maintenance decisions when sufficient long-term monitoring data and independent validation are available. Reduced-order models, robust sensing, uncertainty-aware data assimilation, and interpretable remaining-life prediction are needed before digital twins can support reliable closed-loop operation. Advanced optimization strategies may improve the tractability of high-dimensional design problems, but their practical value for slurry pump applications still requires systematic benchmarking and engineering validation.

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