

Hybrid Optimization Framework for Rotor Design in Hydraulic Turbomachinery: Enhancing Hydraulic Performance through Simulation, Artificial Intelligence, and Experimental Validation

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INTRODUCTION & AIM

Impellers are critical components in hydraulic turbomachinery, as they directly influence energy efficiency, structural reliability, and cavitation resistance, factors which are essential to the sustainability of water systems. Traditional CFD-FEM simulations and statistical optimization have advanced rotor design but remain limited when applied independently. Recent developments in Artificial Intelligence and evolutionary algorithms enable faster, multi-objective optimization; however, a unified and reproducible framework integrating these approaches is still lacking. This research aims to develop a Hybrid Optimization Framework that bridges high-fidelity simulations, AI-based predictive models, and evolutionary methods (NSGA-II, RSM, BBD) to enhance hydraulic performance and reduce design time.

METHOD

A six-stage systematic workflow was applied to build a reproducible hybrid optimization framework for hydraulic rotors.

1. Literature screening – Q1–Q2 studies from Scopus, WoS, IEEE Xplore (2015–2025).
2. Search strategy – Boolean queries combining CFD, FEM, optimization, and AI/ML.
3. Filtering criteria – Inclusion of works with validated CFD/FEM or experimental results.
4. Data management – Structured database of optimization methods, components, and metrics.
5. Classification – Grouped into CFD-based, surrogate modeling, evolutionary, AI/ML, and hybrid approaches.
6. Analysis & integration – Quantitative synthesis of efficiency, structural, and cavitation performance leading to the hybrid framework.

This structured process ensures rigor, comparability, and scalability for water-based turbomachinery design.

RESULTS & DISCUSSION

Depending on the specific objective, different numerical strategies are applied. Figure 1 outlines a modular simulation workflow that integrates CFD and FEM, which allowing for the appropriate selection of RANS, URANS/LES, or nonlinear FEM models based on the flow complexity, structural requirements, and computational constraints. This approach reflects the current state-of-the-art trend, where hybrid frameworks facilitate iterative cycles by balancing accuracy, cost, and experimental validation.

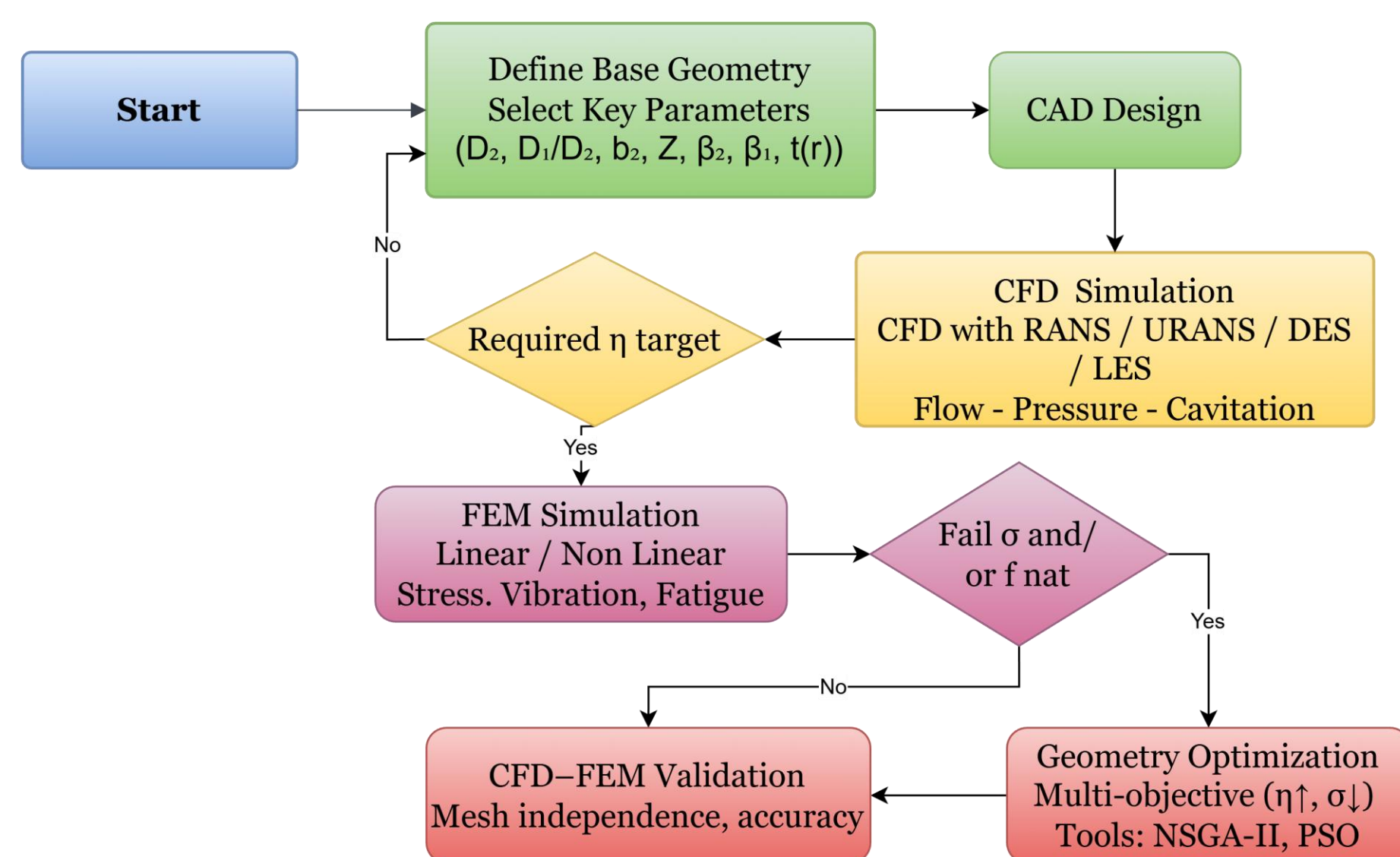


Figure 1. CFD–FEM Workflow

The proposed workflow (Figure 1) integrates CFD and FEM simulations to iteratively refine geometry, efficiency (η), and stress (σ) targets. It enables mesh-independent validation and multi-objective optimization through NSGA-II and PSO, improving prediction accuracy and reducing computational cost.

Hybrid statistical-AI methods enhance efficiency by balancing flow improvement and power reduction. RSM-DOE, Taguchi, and ANOVA methods explore key design variables, while ANN, XGBoost, and Genetic Algorithms accelerate convergence, yielding up to 25% gain in hydraulic efficiency (Figure 2).

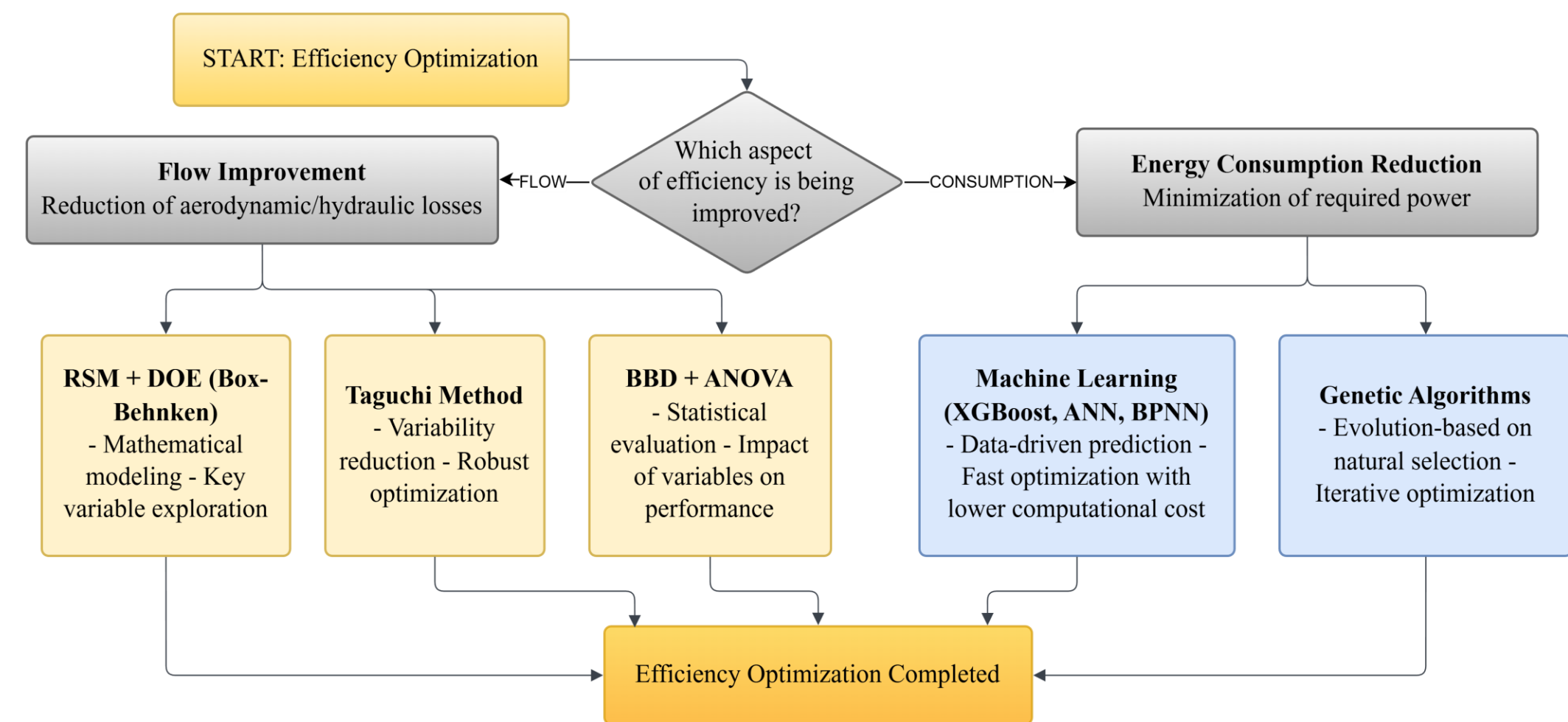


Figure 2. Efficiency Optimization

Stress and vibration reduction are achieved via NSGA-II/MOGA, Kriging surrogate models, LHS sampling, PSO and Genetic Algorithms improve modal stability and redesign geometry, resulting in over 30% mass reduction and extended fatigue life (Figure 3).

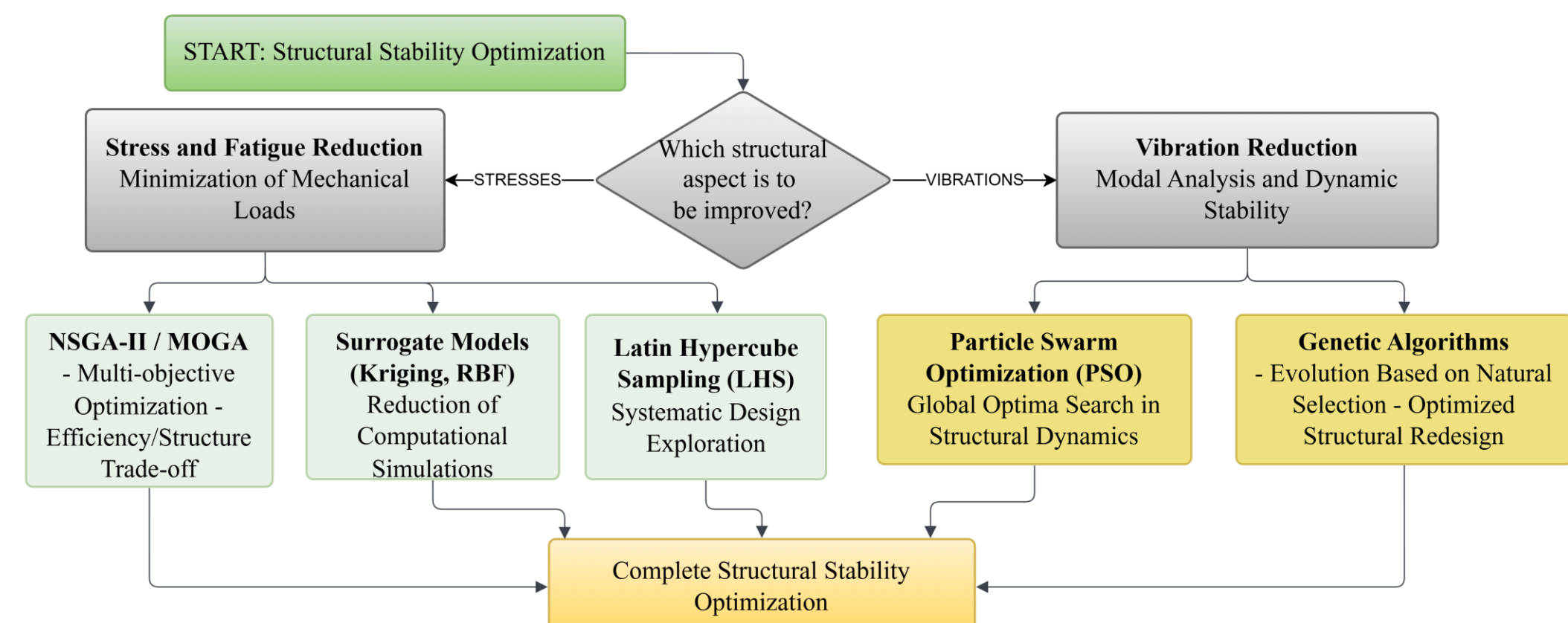


Figure 3. Structural Stability Optimization

Erosion and flow-induced cavitation are mitigated using hybrid AI-evolutionary approaches (SAGB + GA + Taguchi). These combined methods optimize aerodynamic profiles and anti-cavitation configurations, reducing pressure fluctuations and cavitation risk by up to 40% (Figure 4).

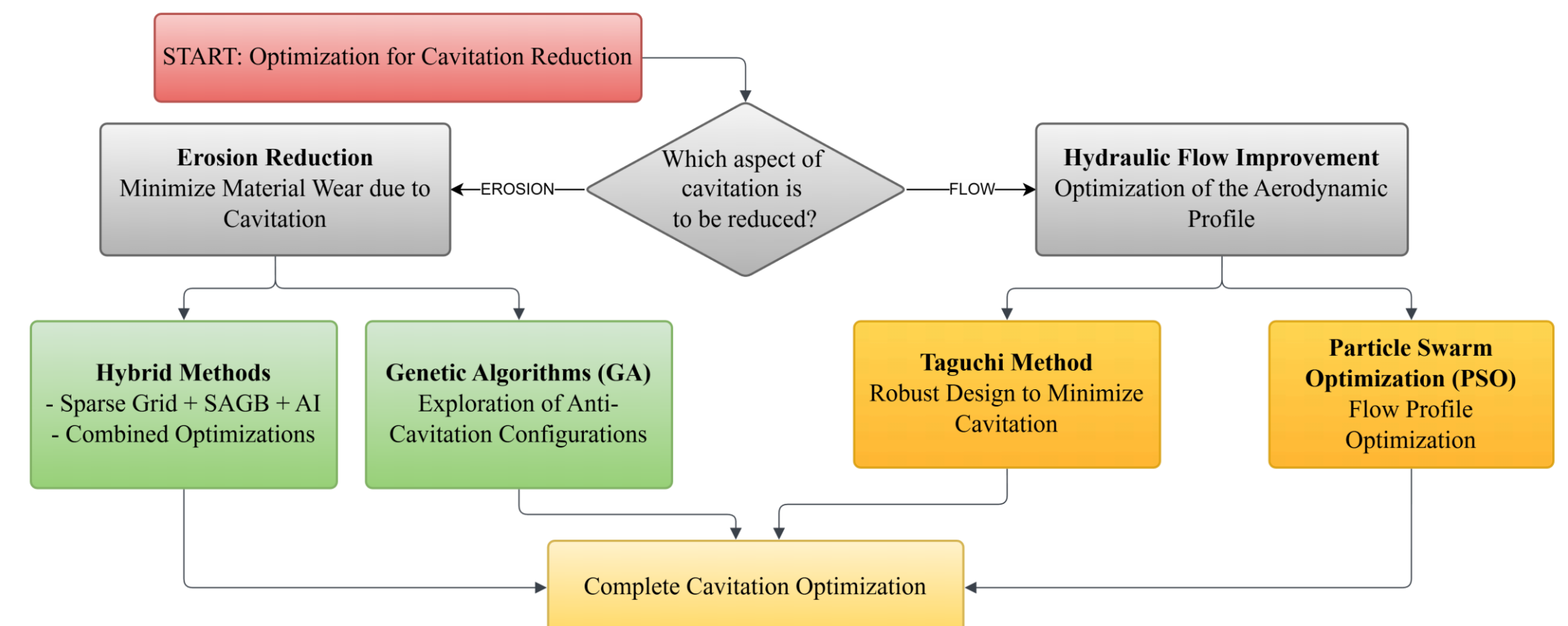


Figure 4. Cavitation Optimization

CONCLUSION

The proposed Hybrid Optimization Framework effectively integrates CFD-FEM simulations, AI predictive modeling, and evolutionary algorithms to enhance the design of hydraulic rotors. This modular and reproducible methodology bridges physics-based and data-driven approaches, balancing accuracy and computational cost. Its adaptability enables application across hydropower, water treatment, and fluid-transport systems, providing a scalable route toward more efficient and sustainable turbomachinery design.

FUTURE WORK / REFERENCES

Future efforts will focus on the experimental validation of the optimized rotors through additive manufacturing and hydraulic bench testing, ensuring agreement between numerical and physical performance. Integration of digital twins and physics-informed AI models will further enhance prediction accuracy and real-time optimization. The framework will be extended to cross-flow turbines and micro-hydropower systems, promoting sustainable energy conversion and data-driven water management solutions.