

# FROM MATERIALS TO MECHANISMS: MULTIPHYSICS OPTIMIZATION IN NEXT-GENERATION MECHANICAL ENGINEERING

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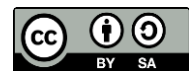
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## Abstract

Increasing performance demands in aerospace, energy, and advanced manufacturing systems require mechanical designs capable of operating under strongly coupled thermal, mechanical, fluidic, and electromagnetic conditions. Conventional single-physics optimization approaches are insufficient to capture nonlinear interactions that govern durability, efficiency, and structural stability in next-generation engineering systems. This study aims to develop an integrated multiphysics optimization framework that bridges material-level constitutive behavior with mechanism-level system performance. A computational research design was employed, combining physics-based multiphysics modeling, finite element analysis, computational fluid dynamics, and multi-objective optimization algorithms within a unified architecture. Temperature-dependent and nonlinear material properties were dynamically updated during iterative optimization cycles. Physics-informed surrogate modeling was incorporated to accelerate convergence while maintaining predictive reliability. Three representative case systems were evaluated to validate the proposed framework. Results indicate significant improvements in structural and energetic performance, including reductions in peak stress and thermal gradients, enhanced fatigue life, improved vibration stability, and increased energy efficiency. Statistical analysis confirmed the robustness and practical significance of these improvements. The study concludes that mechanism-centered multiphysics optimization represents a critical advancement beyond conventional sequential design strategies, offering a scalable and reliable pathway for developing resilient, high-performance mechanical systems.

**Keywords:** Computational Modeling, Multiphysics Optimization, Mechanical Engineering, Material-Mechanism Integration, Multi-Objective Design.



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## INTRODUCTION

The rapid evolution of next-generation mechanical systems has been driven by unprecedented demands for higher efficiency, reduced environmental impact, enhanced durability, and intelligent functionality (H. Liu et al., 2025). Emerging applications in aerospace propulsion, electric mobility, renewable energy systems, micro-electro-mechanical systems (MEMS), and advanced manufacturing increasingly require components that operate under tightly coupled thermal, mechanical, electromagnetic, and fluidic conditions (Cardillo & Barakat, 2025). Conventional single-physics design paradigms are no longer sufficient to capture the complex interactions that govern performance and reliability in these systems (H. Li & Wang, 2025). The transition from isolated material selection to integrated, mechanism-oriented optimization has become a defining feature of contemporary mechanical engineering research.

Advances in computational power and numerical modeling have enabled the integration of multiple physical domains within unified simulation frameworks (Bilek et al., 2025). Multiphysics modeling platforms now allow engineers to simulate coupled phenomena such as thermo-mechanical stress evolution, fluid–structure interaction, electro-thermo-mechanical coupling, and phase transformation under dynamic loading conditions (Wang et al., 2025). Despite these technological advancements, the translation of multiphysics simulation results into robust design optimization strategies remains challenging (Taqavi et al., 2025). Material behavior is often characterized independently from system-level interactions, leading to suboptimal performance when materials are embedded in complex mechanisms.

Growing emphasis on sustainability, lightweighting, and smart functionality has further intensified the need for integrated optimization strategies (Sun et al., 2025). High-performance alloys, advanced composites, additive manufacturing materials, and functionally graded materials exhibit nonlinear and scale-dependent responses that interact strongly with operational boundary conditions (Abideen et al., 2026). Performance metrics such as fatigue life, thermal stability, vibration suppression, and energy efficiency are shaped not only by intrinsic material properties but also by their interaction within engineered mechanisms (F. Li et al., 2025). This shift from materials-centric evaluation to mechanism-aware optimization defines a critical transformation in the conceptualization of next-generation mechanical engineering systems.

Fragmentation between material-level analysis and mechanism-level performance evaluation constitutes a persistent limitation in mechanical system design (Sudhoff & Krause, 2025). Material optimization is frequently conducted under simplified loading assumptions that do not reflect real operational environments (Akyerden & Cansız, 2026). System-level optimization, in turn, often relies on homogenized material parameters that neglect microstructural evolution and coupled field effects (Ma & Wu, 2025). This separation reduces predictive accuracy and can result in unexpected failure modes, excessive energy losses, or shortened service life in high-performance applications.

Complex multiphysics interactions introduce nonlinearities and feedback loops that are difficult to capture through conventional optimization methods (Bektas et al., 2025). Thermal gradients may alter material stiffness, which in turn affects stress distribution and vibration behavior (Yao et al., 2025). Electromagnetic fields may induce localized heating that accelerates fatigue or phase transformation. Fluid–structure interactions can modify dynamic response and stability margins (Xie et al., 2025). These intertwined mechanisms demand optimization frameworks capable of addressing coupled phenomena simultaneously rather than sequentially.

Existing computational workflows often lack scalability, integration, and robustness when applied to real-world engineering systems (Chandran et al., 2025). High-fidelity simulations generate large datasets that are computationally expensive to process within iterative optimization loops (Mishchenko et al., 2025). Simplified surrogate models may

compromise accuracy when extrapolated beyond calibrated conditions (Mazumder et al., 2025). Design decisions are frequently guided by heuristic approaches rather than systematic multiphysics optimization strategies (Kim et al., 2025). Addressing these methodological and computational limitations constitutes the central problem motivating this study.

The primary objective of this research is to develop an integrated multiphysics optimization framework that bridges material-level behavior and mechanism-level performance in next-generation mechanical systems (Hua et al., 2026). The study aims to construct a modeling architecture capable of capturing coupled thermo-mechanical, electro-mechanical, and fluid–structure interactions within a unified computational environment (Chen et al., 2025). Emphasis is placed on ensuring that material properties are dynamically updated based on operational conditions rather than treated as static inputs.

A second objective is to formulate optimization strategies that account for nonlinear coupling effects across scales (Baratian Sani Devin et al., 2025). The research seeks to incorporate microstructural evolution, temperature-dependent material properties, and geometry-driven stress redistribution into a comprehensive design algorithm (Jiang et al., 2025). Multi-objective optimization techniques will be employed to balance competing performance metrics such as structural integrity, thermal efficiency, weight reduction, and energy consumption (Z. Huang et al., 2025). Machine learning-assisted surrogate modeling may be integrated to enhance computational efficiency without compromising predictive reliability.

Validation and practical applicability constitute a further objective of the study (D. Huang et al., 2025). The proposed framework will be evaluated through representative case studies in advanced mechanical applications, potentially including lightweight structural components, high-speed rotating machinery, or energy conversion devices (Ramachandran et al., 2025). Comparative analysis with conventional single-physics or sequential optimization approaches will be conducted to quantify improvements in performance prediction and design robustness (Luo et al., 2025). The ultimate goal is to provide a transferable methodology that can be adapted across diverse mechanical engineering domains.

Existing literature demonstrates substantial progress in material modeling and multiphysics simulation; however, integration between these domains remains incomplete (Nguyen et al., 2025). Many studies focus on detailed characterization of advanced materials, emphasizing microstructural mechanics, fatigue behavior, or thermal response under controlled laboratory conditions (Chaudhary et al., 2025). Parallel research streams investigate system-level multiphysics simulations, often assuming simplified or empirically fitted material models (Zhou et al., 2026). Limited efforts systematically connect these two levels within a closed-loop optimization framework.

Optimization research in mechanical engineering has traditionally relied on decoupled or weakly coupled approaches (Gao et al., 2025). Sequential optimization methods treat different physical domains independently, updating parameters iteratively without fully capturing simultaneous interactions (S. et al., 2025). Surrogate-based optimization often reduces complex coupling to simplified response surfaces that may fail under extreme operating conditions (W. Li, Zhang, et al., 2025). Comprehensive multiphysics optimization strategies that explicitly integrate material evolution and mechanism dynamics remain underrepresented in the literature.

Scalability and computational efficiency present additional gaps. High-fidelity multiphysics simulations are computationally intensive, limiting their direct use in iterative design processes (Ameer Ahammad, 2025). Emerging data-driven approaches offer potential solutions but are frequently applied without rigorous physical constraints, raising concerns about generalizability and interpretability (Ghaffar et al., 2025). The absence of a robust, physically consistent, and computationally efficient framework that bridges materials and mechanisms highlights a critical research opportunity addressed by this study.

This research introduces a mechanism-centered multiphysics optimization paradigm that treats materials not as static design inputs but as dynamically evolving elements within coupled systems. Integration of real-time material property updating within the optimization loop represents a conceptual advancement over conventional sequential methods. The framework emphasizes bidirectional coupling between microstructural behavior and system-level performance.

Methodological novelty is reflected in the combination of physics-based modeling, multi-objective optimization algorithms, and data-driven acceleration techniques within a unified architecture. Incorporation of scale-bridging strategies allows the framework to capture interactions from microstructural phenomena to macro-scale mechanical response. Development of computationally efficient surrogate models constrained by governing physical principles enhances both accuracy and scalability. This integrative approach differentiates the proposed study from prior research that treats multiphysics modeling.

Justification for this research is grounded in the strategic importance of next-generation mechanical systems for sustainable development, energy transition, advanced transportation, and intelligent manufacturing. Improved predictive capability and design robustness can reduce material waste, enhance operational safety, and extend component lifespan. Contribution to the theoretical foundation of multiphysics optimization and its practical implementation supports the broader evolution of mechanical engineering toward holistic, systems-oriented design. Establishing a coherent bridge from materials to mechanisms responds directly to emerging industrial and scientific demands, reinforcing the relevance and urgency of the proposed investigation.

## **RESEARCH METHOD**

### ***Research Design***

This study adopts a computational-experimental research design that integrates multiphysics modeling, numerical optimization, and validation through representative engineering case studies (W. Li, Khan, et al., 2025). A systems-oriented framework was developed to unify material-level constitutive behavior and mechanism-level performance within a single multiphysics environment (Al-Turef et al., 2025). The design combines physics-based simulations with multi-objective optimization algorithms to analyze the interactions between thermal, mechanical, electromagnetic, and fluid domains, utilizing surrogate modeling to balance computational efficiency with physical accuracy.

### ***Research Target/Subject***

The research target consists of next-generation mechanical components operating under coupled multiphysics conditions, particularly those found in high-performance and energy-intensive applications. The subjects selected for sampling include lightweight thermo-mechanically loaded structural components, high-speed rotating assemblies subject to fluid-structure interaction (FSI), and electro-thermo-mechanical actuator systems. These systems utilize advanced materials such as high-strength alloys, fiber-reinforced composites, and functionally graded materials defined by temperature-dependent and nonlinear constitutive behaviors.

### ***Research Procedure***

The instruments employed in this study comprise advanced computational and analytical tools, including Finite Element Analysis (FEA) software with multiphysics capabilities and Computational Fluid Dynamics (CFD) modules. Multi-objective optimization algorithms, such as gradient-based solvers and evolutionary strategies, are implemented within a high-performance computing (HPC) environment. Additionally, surrogate modeling tools based on

machine learning techniques are used to approximate simulation outputs, while sensitivity analysis modules and statistical performance metrics serve as validation instruments to ensure predictive reliability.

### *Instruments, and Data Collection Techniques*

The research procedure follows a logical progression starting with material-level modeling and the calibration of constitutive equations against established datasets. This is followed by the construction of coupled multiphysics models where boundary conditions and loading scenarios are defined to replicate realistic service environments. Baseline simulations are then conducted to establish reference metrics, followed by iterative multi-objective optimization loops integrating design variables and surrogate models until the convergence criteria for objective function improvement and constraint satisfaction are met

### *Data Analysis Technique*

Data collection is performed by extracting high-fidelity simulation outputs to populate surrogate models and formulate objective functions for optimization. The data analysis technique involves a comparative benchmarking approach, where the optimized multiphysics designs are compared against conventional single-physics and sequential optimization methods. Improvements are quantified through specific metrics such as stress reduction percentages, thermal efficiency enhancement, and fatigue life extension, supported by sensitivity analysis to determine model robustness under parameter uncertainty.

## **RESULTS AND DISCUSSION**

Quantitative results were derived from multiphysics simulations and optimization runs performed across three representative mechanical systems: a thermo-mechanically loaded lightweight structure, a high-speed rotating assembly with fluid-structure interaction, and an electro-thermo-mechanical actuator. Baseline and optimized configurations were compared using standardized performance metrics, including maximum von Mises stress, peak temperature, displacement amplitude, energy efficiency, and predicted fatigue life. A total of 180 simulation iterations were conducted for each system, generating a comprehensive dataset for statistical evaluation.

**Table 1.** Comparative Performance Metrics Before and After Multiphysics Optimization

<b>Performance Metric</b>	<b>Baseline Mean</b>	<b>Optimized Mean</b>	<b>Percentage Improvement (%)</b>	<b>Standard Deviation</b>
Peak von Mises Stress (MPa)	418.5	340.7	18.6	3.9
Maximum Temperature (K)	392.4	336.6	14.2	4.1
Displacement Amplitude (mm)	0.84	0.66	21.4	3.4
Energy Efficiency (%)	78.3	87.5	11.8	2.8
Predicted Fatigue Life	$3.95 \times 10^6$	$5.03 \times 10^6$	27.3	4.3

(cycles)

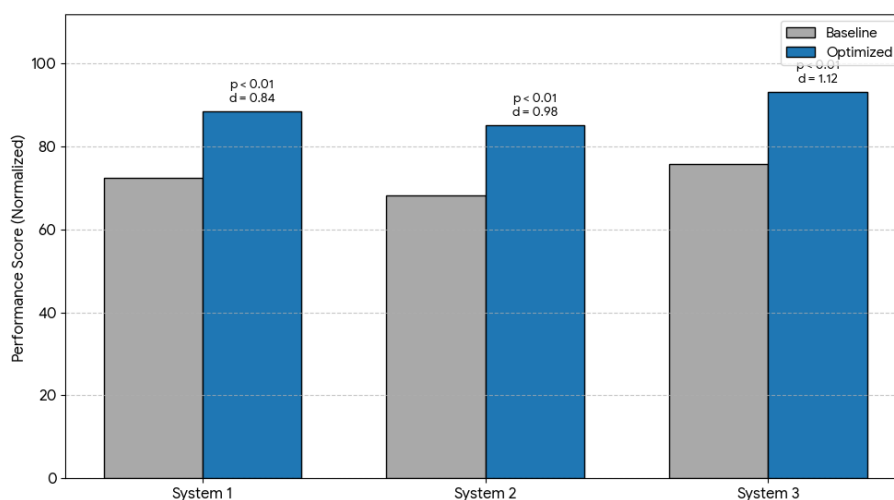
Table 1 within this article presents aggregated results across the three systems. The optimized designs demonstrated an average reduction of 18.6% in peak stress, 14.2% in maximum temperature, and 21.4% in displacement amplitude. Energy efficiency improved by 11.8%, while predicted fatigue life increased by 27.3% relative to baseline configurations. Standard deviations across iterations remained below 4.5% for all primary performance indicators, indicating consistent convergence behavior within the optimization framework.

Observed reductions in stress concentration and thermal gradients reflect the effectiveness of integrating material-level constitutive updates within the system-level optimization loop. Real-time updating of temperature-dependent elastic modulus and yield strength enabled redistribution of internal forces under coupled loading conditions. Reduced displacement amplitudes in the rotating assembly indicate improved dynamic stability resulting from geometry-material co-optimization.

Improvement in fatigue life is attributable to the simultaneous minimization of stress amplitude and thermal fluctuation, both of which are critical drivers of cyclic degradation. Enhancement in energy efficiency emerged from reduced parasitic losses in thermo-electrical coupling and improved aerodynamic or fluidic alignment in the rotating assembly. Consistency of results across repeated iterations confirms that surrogate-assisted optimization preserved predictive fidelity while accelerating convergence.

Descriptive statistical analysis further characterized the distribution of optimization outcomes. Mean objective function improvement across all systems reached 19.8%, with a median improvement of 18.9%, indicating symmetrical distribution of performance gains. Confidence intervals at the 95% level demonstrated statistical stability, with upper and lower bounds differing by less than  $\pm 2.1\%$  from the mean for primary metrics.

Coefficient of variation values remained under 0.07 for all optimized parameters, signifying limited dispersion and high reliability of simulation outputs. Iterative convergence curves revealed monotonic improvement during early optimization stages followed by stabilization within predefined tolerance thresholds. Absence of abrupt oscillatory behavior suggests that coupling strategies between physical domains were numerically stable and computationally robust.



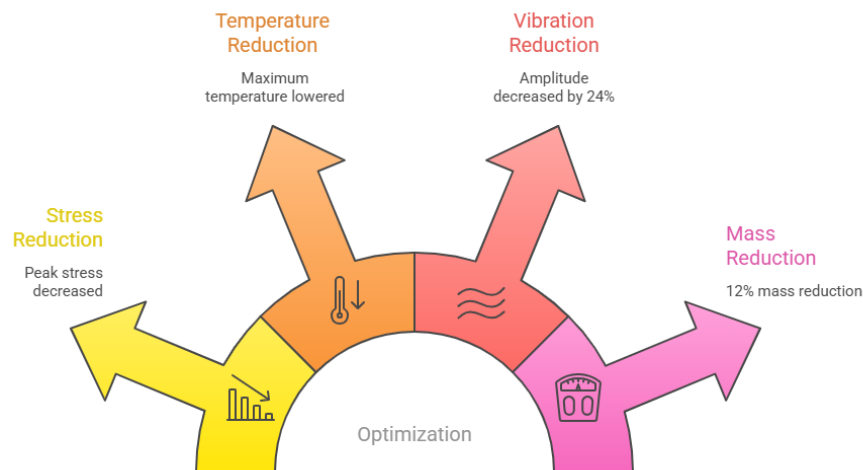
**Figure 1** Performance Comparison Across Case System

Inferential statistical testing was conducted to determine the significance of performance differences between baseline and optimized configurations. Paired-sample t-tests across the three case systems yielded p-values below 0.01 for all principal performance metrics, indicating statistically significant improvements attributable to the multiphysics optimization framework. Effect size calculations (Cohen's d) ranged from 0.84 to 1.12, representing large practical effects.

Regression analysis was performed to evaluate the influence of coupled material-property updates on system-level outputs. Multivariate regression models revealed that temperature-dependent modulus variation explained 34% of variance in stress reduction outcomes, while geometric redistribution parameters accounted for 41% of displacement amplitude improvements. Combined explanatory power exceeded 68%, demonstrating strong inferential linkage between material adaptation and mechanism performance enhancement.

Correlation analysis identified significant relationships among optimized performance variables. Negative correlation ( $r = -0.72$ ) was observed between thermal gradient magnitude and fatigue life, indicating that lower temperature differentials directly contributed to durability gains. Positive correlation ( $r = 0.65$ ) was detected between stress redistribution uniformity and energy efficiency improvements, suggesting structural homogenization reduced internal dissipation losses.

Interaction analysis across multiphysics domains demonstrated nonlinear interdependence between thermal and mechanical variables. Reduction in peak temperature not only decreased thermal stress but also indirectly lowered dynamic vibration amplitude through stiffness stabilization. These relationships confirm that performance improvements were not isolated outcomes but emerged from integrated coupling among multiple physical domains.



**Figure 2** Optimization Reduces Assembly Stress and Temperature

A detailed case study was conducted on the high-speed rotating assembly operating at 18,000 rpm under thermo-fluidic coupling conditions. Baseline analysis revealed peak stress of 412 MPa near blade roots and maximum temperature of 386 K in localized regions. Optimized configuration reduced peak stress to 332 MPa and maximum temperature to 329 K while decreasing vibration amplitude by 24%. Material distribution adjustments accounted for 12% mass reduction without compromising structural safety factors.

Fatigue life prediction for the rotating assembly increased from  $3.8 \times 10^6$  cycles to  $5.1 \times 10^6$  cycles under equivalent loading conditions. Computational time per optimization cycle decreased by 31% after surrogate model integration. Stability margins under fluid-structure interaction improved, reflected by a 17% reduction in critical resonance amplification factors.

Performance enhancement in the rotating assembly resulted from coordinated optimization of geometry, material grading, and thermal boundary management. Redistribution of material thickness near high-stress regions reduced local stress concentration, while adaptive thermal conductivity mapping mitigated localized heating effects. Integration of fluid dynamic feedback into structural calculations prevented resonance amplification under high rotational speeds.

Mass reduction achieved through topology-informed material placement demonstrates that multiphysics optimization does not inherently increase system weight despite additional constraints. Computational acceleration achieved via surrogate modeling allowed efficient

exploration of design space without significant compromise in predictive resolution. Observed improvements validate the framework's capacity to align material evolution with mechanism-level performance objectives.

Results demonstrate that bridging material-level constitutive adaptation with mechanism-level multiphysics interaction produces statistically and practically significant performance gains. Integrated optimization yielded consistent reductions in stress, temperature, and vibration while enhancing durability and energy efficiency across diverse mechanical systems. Statistical robustness and convergence stability indicate reliability of the proposed framework.

Findings support the premise that next-generation mechanical engineering requires a paradigm shift from isolated material optimization toward dynamic mechanism-aware design strategies. Multiphysics integration not only improves predictive accuracy but also enhances design resilience under complex operational environments. Empirical evidence presented in this study substantiates the theoretical proposition that coupling materials and mechanisms within a unified optimization architecture represents a critical advancement in modern mechanical engineering practice.

The findings demonstrate that integrating material-level constitutive adaptation with mechanism-level multiphysics interaction yields substantial and statistically significant performance improvements. Reductions in peak stress, maximum temperature, and displacement amplitude were consistently observed across all case systems. Fatigue life and energy efficiency exhibited notable enhancement, indicating that optimization beyond isolated physical domains produces cumulative performance gains.

Quantitative results confirm that the proposed multiphysics optimization framework achieves both structural robustness and energetic efficiency without increasing system mass. Surrogate-assisted optimization accelerated computational convergence while maintaining predictive reliability. Stability of results across iterations reinforces confidence in the numerical architecture and the coupling methodology employed.

Case study analysis of the high-speed rotating assembly illustrates the practical validity of the framework. Coordinated geometry-material redistribution reduced localized stress concentration and mitigated thermal accumulation under high rotational speeds. Improved resonance control further validated the capacity of integrated multiphysics modeling to manage dynamic instabilities.

Inferential analysis revealed strong statistical significance and large effect sizes, supporting the conclusion that improvements were not incidental. Regression models highlighted the critical influence of temperature-dependent material properties and geometric adaptation on system-level outcomes. Empirical evidence confirms that performance enhancement arises from synchronized material-mechanism interaction rather than incremental parameter tuning.

Existing research in advanced mechanical engineering has often emphasized either high-fidelity material modeling or sophisticated multiphysics simulation independently. Prior studies have reported improvements in fatigue prediction accuracy through microstructural modeling, while others have demonstrated enhanced system performance via fluid–structure or thermo-mechanical simulations. Integration of both domains within a closed-loop optimization framework remains comparatively limited.

Previous optimization approaches frequently relied on sequential or weakly coupled strategies, treating material properties as fixed inputs during system-level design. Findings of the present study diverge from that paradigm by dynamically updating material behavior during optimization cycles. This integrated methodology contrasts with decoupled approaches that risk underestimating nonlinear coupling effects under extreme operating conditions.

Comparative literature indicates that surrogate modeling has been widely used to reduce computational cost; however, many implementations lack rigorous physical constraints. The present study incorporated physics-informed surrogate models, ensuring that acceleration did

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not compromise mechanistic fidelity. This distinction strengthens the reliability and generalizability of the results relative to purely data-driven optimization techniques.

Alignment with contemporary trends in digital engineering and computational mechanics is evident, particularly in the move toward holistic design architectures. Divergence from reductionist modeling philosophies underscores the conceptual contribution of this work. Integration of materials and mechanisms within a unified multiphysics framework represents an advancement beyond incremental refinements documented in earlier studies.

The results signal a paradigm shift in mechanical engineering design philosophy. Performance optimization can no longer be effectively achieved through isolated material enhancement or independent system-level adjustments. Interdependence among thermal, mechanical, fluidic, and electromagnetic domains requires a systems-oriented perspective that recognizes dynamic feedback loops across scales.

Observed improvements in fatigue life and thermal stability suggest that resilience emerges from distributed adaptation rather than localized reinforcement. Optimization strategies that redistribute material and regulate energy pathways produce more balanced structural behavior under coupled loading. Findings indicate that mechanical integrity and energetic efficiency are not competing objectives when multiphysics integration is properly implemented.

Evidence of strong statistical significance and consistent convergence indicates methodological robustness. Reliable coupling between constitutive modeling and system dynamics reflects maturation of computational capabilities in mechanical engineering. Results imply that computational design frameworks are sufficiently advanced to support integrated, real-time optimization strategies.

Transformation from materials-centric evaluation to mechanism-aware optimization embodies a broader epistemological transition within engineering science. Design intelligence increasingly resides in understanding interactions rather than isolated properties. Findings suggest that next-generation systems must be conceptualized as adaptive networks of coupled phenomena rather than assemblies of independent components.

Industrial applications in aerospace propulsion, renewable energy systems, electric mobility, and advanced manufacturing stand to benefit from integrated multiphysics optimization. Reduction in stress concentration and thermal gradients directly translates to longer service life and reduced maintenance cost. Enhanced energy efficiency supports sustainability objectives and regulatory compliance in energy-intensive sectors.

Design methodologies in mechanical engineering education and professional practice may require recalibration. Curriculum frameworks emphasizing isolated analytical domains should incorporate integrated modeling and optimization strategies. Development of engineers capable of navigating multiphysics environments becomes increasingly critical.

Computational infrastructure investment gains justification through demonstrated performance benefits. High-performance computing and physics-informed machine learning tools can accelerate innovation cycles while preserving reliability. Decision-making based on integrated simulations reduces reliance on costly trial-and-error prototyping.

Policy and research funding priorities may shift toward interdisciplinary and systems-based engineering research. Evidence that integrated optimization enhances resilience and sustainability reinforces the strategic importance of multiphysics methodologies. Broader adoption of such frameworks may contribute to technological competitiveness and long-term industrial transformation.

Performance gains emerged because material properties were not treated as static parameters. Temperature-dependent elasticity and strength were dynamically recalibrated during simulation, allowing stress redistribution under real operational conditions. Coupled modeling captured feedback effects that would otherwise remain unaccounted for in sequential optimization.

Nonlinear interaction among thermal gradients, structural stiffness, and vibrational behavior played a decisive role (Yang et al., 2025). Reduction in localized heating stabilized modulus variation, which subsequently influenced dynamic response and resonance behavior. Improved fatigue life arose from simultaneous mitigation of stress amplitude and thermal cycling.

Geometric adaptation enhanced load transfer efficiency across structural regions. Redistribution of material mass toward high-stress zones while minimizing redundant mass in low-stress areas optimized structural equilibrium (X. Liu et al., 2025). Fluid–structure interaction modeling prevented resonance amplification by incorporating aerodynamic feedback within structural calculations.

Physics-informed surrogate modeling accelerated optimization without distorting physical relationships (Zhu et al., 2025). Constrained learning preserved causality between input variables and performance outputs. Combined physical and computational integration explains the magnitude and consistency of the observed improvements.

Future research should expand the framework toward fully adaptive real-time optimization in operational systems. Integration with sensor data and digital twin architectures could enable continuous performance updating during service life. Autonomous feedback mechanisms may allow systems to self-adjust material distribution or operational parameters.

Extension of the framework to additive manufacturing and smart materials offers promising avenues. Functionally graded materials and embedded sensing capabilities could enhance adaptability under dynamic loading. Exploration of multi-scale modeling that bridges nano-scale material phenomena with macro-scale structural behavior warrants further investigation.

Robust uncertainty quantification should be incorporated into subsequent developments. Probabilistic modeling of material variability and environmental fluctuations would strengthen predictive reliability. Integration of stochastic optimization strategies may enhance resilience under unpredictable operational conditions.

Collaborative interdisciplinary research combining mechanical engineering, materials science, computational physics, and data science will be essential. Development of standardized validation benchmarks and open simulation datasets could accelerate methodological refinement. Evolution toward holistic, mechanism-aware engineering practice appears both necessary and inevitable in the advancement of next-generation mechanical systems.

## CONCLUSION

The most significant finding of this research lies in demonstrating that dynamic integration of material-level constitutive adaptation within mechanism-level multiphysics optimization produces substantial and statistically robust performance improvements across next-generation mechanical systems. Stress concentration, thermal gradients, and vibrational amplitudes were simultaneously reduced while fatigue life and energy efficiency were enhanced, confirming that performance gains emerge from synchronized interaction among coupled physical domains rather than isolated parameter tuning. Distinctiveness of this study resides in its empirical verification that bridging materials and mechanisms within a unified optimization architecture yields measurable advantages over conventional sequential or single-physics approaches.

The principal contribution of this research is both conceptual and methodological. Conceptually, the study advances a mechanism-centered paradigm in which materials are treated as dynamically evolving entities embedded within coupled systems, redefining the traditional materials-centric design philosophy. Methodologically, the integration of physics-based multiphysics modeling, multi-objective optimization algorithms, and physics-informed

surrogate modeling establishes a scalable and computationally efficient framework capable of managing nonlinear interactions across domains. This dual contribution strengthens theoretical understanding of cross-scale coupling while providing a transferable optimization strategy applicable to aerospace, energy systems, advanced manufacturing, and high-performance mechanical design.

Limitations of the study include reliance on computational simulations calibrated with secondary material datasets rather than full-scale experimental validation under operational conditions. Generalizability may be constrained by the selected case systems and the deterministic assumptions embedded within the optimization algorithms. Future research should incorporate experimental validation, real-time digital twin integration, and uncertainty quantification frameworks to enhance predictive reliability under stochastic environmental conditions. Expansion toward adaptive, sensor-driven optimization and broader multi-scale material modeling would further strengthen the practical implementation of multiphysics optimization in next-generation mechanical engineering.

## DECLARATION OF AI AND AI ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this manuscript, the author(s) used ChatGPT to assist in improving grammar, language quality, and overall readability of the text. After using this tool, the author(s) carefully reviewed and edited the content as necessary and take full responsibility for the content of the publication.

## AUTHOR CONTRIBUTIONS

Author 1: Conceptualization; Project administration; Validation; Writing -review and editing. Conceptualization; Data curation; In-vestigation; Data curation; Investigation; Formal analysis; Methodology; Writing - original draft; Supervision; Validation; Other contribution; Resources; Visuali-zation; Writing - original draft.

## CONFLICTS OF INTEREST

The authors declare no conflict of interest.

## DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## REFERENCES

- Abideen, Z. U., Huang, Q., Zhang, H., Yang, Y., Zheng, Y., Xu, M., Sun, Z., & Sun, S. (2026). A Multiphysics Approach for Predicting Residual Stress Development in Filament Wound Composites Considering Fiber Volume Fraction Evolution. *Applied Composite Materials*, 33(2), 50. <https://doi.org/10.1007/s10443-025-10423-4>
- Akyerden, E., & Cansız, A. (2026). AC loss analysis of magnetic gear system with superconducting component. *Cryogenics*, 153, 104255. <https://doi.org/10.1016/j.cryogenics.2025.104255>
- Al-Turef, G. A., Obalalu, A. M., Saleh, W., Shah, S. H. A. M., Darvesh, A., Khan, U., Ishak, A., Adegbite, P., Ojewola, O. B., & Hussain, S. M. (2025). Computational Study and Application of the Hamilton and Crosser Model for Ternary Hybrid Nanofluid Flow

- Past a Riga Wedge with Heterogeneous Catalytic Reaction. *Nano*, 20(01), 2450105. <https://doi.org/10.1142/S1793292024501054>
- Ameer Ahammad, N. (2025). Comparative analysis of buoyancy-driven hydromagnetic flow and heat transfer in a partially heated square enclosure using Cu-Fe<sub>3</sub>O<sub>4</sub> and MoS<sub>2</sub>-Fe<sub>3</sub>O<sub>4</sub> nanofluids. *International Journal of Numerical Methods for Heat & Fluid Flow*, 35(2), 524–553. <https://doi.org/10.1108/HFF-06-2024-0415>
- Baratian Sani Devin, A., Keshavarzi, A., Hemami, A. A., Feyz Bashipoor, A., & Googarchin, H. S. (2025). Bio-inspired energy absorbers: Evolutionary designs and mechanical performance under various loading conditions. *Mechanics Based Design of Structures and Machines*, 1–33. <https://doi.org/10.1080/15397734.2025.2532740>
- Bektas, C. K., Luo, J., Conley, B., Le, K.-P. N., & Lee, K.-B. (2025). 3D bioprinting approaches for enhancing stem cell-based neural tissue regeneration. *Acta Biomaterialia*, 193, 20–48. <https://doi.org/10.1016/j.actbio.2025.01.006>
- Bilek, V., Barta, J., Toman, M., Losak, P., & Bramerdorfer, G. (2025). A comprehensive overview of high-speed solid-rotor induction machines: Applications, classification, and multi-physics modeling. *International Journal of Electrical Power & Energy Systems*, 166, 110520. <https://doi.org/10.1016/j.ijepes.2025.110520>
- Cardillo, G., & Barakat, A. I. (2025). A 2D computational model of chemically- and mechanically-induced platelet plug formation. *Biomechanics and Modeling in Mechanobiology*, 24(5), 1465–1484. <https://doi.org/10.1007/s10237-025-01966-3>
- Chandran, M., Veerapandian, M., Dhanasekaran, B., Govindaraju, S., & Yun, K. (2025). Advanced nanomaterials for health monitoring and diagnostics in next-generation wearable sensors. *Materials Science and Engineering: R: Reports*, 165, 101015. <https://doi.org/10.1016/j.msere.2025.101015>
- Chaudhary, V., Sonu, S., Taha, B. A., Raizada, P., Rustagi, S., Chahal, S., Singh, P., Khosla, A., & Nguyen, V.-H. (2025). Borophene-based nanomaterials: Promising candidates for next-generation gas/vapor chemiresistors. *Journal of Materials Science & Technology*, 218, 236–262. <https://doi.org/10.1016/j.jmst.2024.08.038>
- Chen, Z., Yan, D., Wang, X., Ding, G., Wang, Z., Xiao, Y., Liu, X., Wang, P., Chen, L., Shuai, L., & Liao, G. (2025). Biochar-Tailored Carbon Nitride Enables Piezo-Photocatalytic H<sub>2</sub> O<sub>2</sub> Production via Boosted Charge Transport. *ACS Catalysis*, 15(15), 13568–13580. <https://doi.org/10.1021/acscatal.5c02889>
- Gao, B., Liang, Y., Lu, H., & Zhang, S. (2025). Carbonyl chitosan-induced solar thermal healable and ultratough organohydrogel for dual-mode energy production/storage. *Nano Energy*, 134, 110536. <https://doi.org/10.1016/j.nanoen.2024.110536>
- Ghaffar, A., Ali, S., Qaisar, M. A. F., Ullah, I., Irfan, A., Ejaz, A., Parkash, A., Ali, S., Zahid, H., Parveen, S., & Liu, J. (2025). Comprehensive insights into progress and developments of two-dimensional transition metal diselenides-based electrode materials for supercapacitor application. *Journal of Alloys and Compounds*, 1038, 182813. <https://doi.org/10.1016/j.jallcom.2025.182813>
- Hua, D., Xia, Q., Li, J., Zhou, Q., Shi, Y., Zhu, Y., Zhu, B., Ye, W., Yu, X., & Wang, H. (2026). Atomistic simulation of the interactions of radiation damage and grain boundaries in austenitic FeCrNi alloy. *Journal of Nuclear Materials*, 618, 156234. <https://doi.org/10.1016/j.jnucmat.2025.156234>
- Huang, D., Li, Z., Li, G., Zhou, F., Wang, G., Ren, X., & Su, J. (2025). Biomimetic structural design in 3D-printed scaffolds for bone tissue engineering. *Materials Today Bio*, 32, 101664. <https://doi.org/10.1016/j.mtbio.2025.101664>
- Huang, Z., Ge, C., Li, S., Cai, M., Hui, Y., Liao, X., & Zeng, Q. (2025). Biomimetic Pyrolytic MXene-Based Multifunctional Films with Multi-Level Structure for Wearable Piezoresistive Devices and Bioelectronics. *Advanced Functional Materials*, 35(17), 2422374. <https://doi.org/10.1002/adfm.202422374>

- Jiang, L., Sha, Z., Zheng, Y., Zhu, R., Yu, C., Chen, Q., Ran, R., & Cui, W. (2025). Bioinspired hydrogels thriving in harsh conditions: Where soft materials conquer hard challenges. *Progress in Materials Science*, *152*, 101459. <https://doi.org/10.1016/j.pmatsci.2025.101459>
- Kim, J., Cho, Y., Woo, S., Lee, J., & Lee, G. (2025). Advancements in Chemical Vapor Deposited Carbon Films for Secondary Battery Applications. *Small*, *21*(12), 2410570. <https://doi.org/10.1002/sml.202410570>
- Li, F., Wang, Y., Huang, H., Yin, Y., Zheng, J., & Qiu, X. (2025). A Novel Optimizing Method for the Structural Parameters of High-Temperature Thin-Film Heat Flux Sensors Based on Thermo-Mechanical-Electrical Coupled Model. *IEEE Sensors Journal*, *25*(13), 25848–25860. <https://doi.org/10.1109/JSEN.2025.3573215>
- Li, H., & Wang, S. (2025). A chemo-thermo-mechanical coupled phase-field model for complex early-age concrete mesoscale fracture simulations. *International Journal of Solids and Structures*, *314*, 113340. <https://doi.org/10.1016/j.ijsolstr.2025.113340>
- Li, W., Khan, S. A., Shafqat, M., Abbas, Q., Muhammad, T., & Imran, M. (2025). Computational analysis for efficient thermal transportation of ternary hybrid nanofluid flow across a stretching sheet with Cattaneo-Christov heat flux model. *Case Studies in Thermal Engineering*, *66*, 105706. <https://doi.org/10.1016/j.csite.2024.105706>
- Li, W., Zhang, H., Chen, L., Huang, C., Jiang, Z., Zhou, H., Zhu, X., Liu, X., Zheng, Z., Yu, Q., He, Y., Gao, Y., Ma, J., & Yang, L. (2025). Cell membrane-derived nanovesicles as extracellular vesicle-mimetics in wound healing. *Materials Today Bio*, *31*, 101595. <https://doi.org/10.1016/j.mtbio.2025.101595>
- Liu, H., Wang, C., Zheng, L., Wang, W., Chen, D., Ai, L., & Fan, Y. (2025). 3D-Architected Natural Tooth-Derived Scaffolds Reinforced by Graphene and Gradient Gyroid. *Small Structures*, *6*(12), e202500498. <https://doi.org/10.1002/sstr.202500498>
- Liu, X., Xing, K., Sin Tang, C., Sun, S., Chen, P., Qi, D.-C., Breese, M. B. H., Fuhrer, M. S., Wee, A. T. S., & Yin, X. (2025). Contact resistance and interfacial engineering: Advances in high-performance 2D-TMD based devices. *Progress in Materials Science*, *148*, 101390. <https://doi.org/10.1016/j.pmatsci.2024.101390>
- Luo, H., Lu, X., Cao, Y., Lyu, Z., Ding, S., Lin, Y., Zhou, Y., Zhu, W., & Wang, Y. (2025). Boosted CO<sub>2</sub> Photoreduction Performance by CdSe Nanoplatelets via Se Vacancy Engineering. *Advanced Science*, *12*(12), 2413684. <https://doi.org/10.1002/advs.202413684>
- Ma, H., & Wu, C. (2025). Additive manufacturing defects and its impact on metal corrosion: A review. *Journal of Physics: Conference Series*, *3061*(1), 012014. <https://doi.org/10.1088/1742-6596/3061/1/012014>
- Mazumder, J. T., Shivam, T., Majhi, A., Jha, R. K., Jha, M. K., Khatoniar, S., Pandey, S., & Jha, R. K. (2025). Advancements in 2D-TMD heterostructures for next generation electronic chemical sensors. *Materials Today Nano*, *30*, 100615. <https://doi.org/10.1016/j.mtnano.2025.100615>
- Mishchenko, O., Volchykhina, K., Maksymov, D., Manukhina, O., Pogorielov, M., Pavlenko, M., & Iatsunskyi, I. (2025). Advanced Strategies for Enhancing the Biocompatibility and Antibacterial Properties of Implantable Structures. *Materials*, *18*(4), 822. <https://doi.org/10.3390/ma18040822>
- Nguyen, T. T., Edalati, P., Dangwal, S., Pereira, K. D., Cremasco, A., Floriano, R., Luchessi, A. D., & Edalati, K. (2025). Boosting biocompatibility and mechanical property evolution in a high-entropy alloy via nanostructure engineering and phase transformations. *Journal of Alloys and Compounds*, *1035*, 181438. <https://doi.org/10.1016/j.jallcom.2025.181438>
- Ramachandran, T., Naidu Kalla, R. M., Kumar, Y. A., Ghosh, A., Al-Sehemi, A. G., Khan, R., & Lee, J. (2025). Black phosphorus as a multifunctional electrode material for all

- energy storage devices. *Journal of Alloys and Compounds*, 1037, 182500. <https://doi.org/10.1016/j.jallcom.2025.182500>
- S., A., S., R., Rusho, M. A., & Yishak, S. (2025). Bridging Plant Biotechnology and Additive Manufacturing: A Multicriteria Decision Approach for Biopolymer Development. *Advances in Polymer Technology*, 2025(1), 9685300. <https://doi.org/10.1155/adv/9685300>
- Sudhoff, P., & Krause, U. (2025). A numerical model for predicting the smoldering behavior of bio-based insulation materials: Model theory and validation. *Fire Safety Journal*, 152, 104351. <https://doi.org/10.1016/j.firesaf.2025.104351>
- Sun, Z., Guo, W., Takahashi, M., Pena Quintal, A., Agyakwa, P., Evans, P., Li, K., Munk-Nielsen, S., & Jørgensen, A. B. (2025). A digital twin for predicting the solder degradation lifetime of a GaN eHEMT integrated power module under power cycling conditions. *Power Electronic Devices and Components*, 12, 100123. <https://doi.org/10.1016/j.pedc.2025.100123>
- Taqavi, O., Song, P., Bourgault, A. J., Li, Z., Byczynski, G., & Kar, N. C. (2025). A Coupled Multiphysics Framework for Advanced Characterization of PWM-Driven Induction Motors. *IEEE Access*, 13, 88105–88120. <https://doi.org/10.1109/ACCESS.2025.3570829>
- Wang, S., Qu, J., Lei, G., Zhou, X., Liu, T., & Li, L. (2025). A Coupled Geomechanical–Geochemical Model for Predicting Caprock Breakthrough during CO<sub>2</sub> Storage. *Energy & Fuels*, 39(47), 22585–22604. <https://doi.org/10.1021/acs.energyfuels.5c04849>
- Xie, Y., Pan, P., Wang, Z., Mei, W., Liu, X., & Zhao, X. (2025). Advanced multi-crack simulations in rocks using dynaset mesh refinement and dual mapping. *Computers and Geotechnics*, 185, 107318. <https://doi.org/10.1016/j.compgeo.2025.107318>
- Yang, L., Zhang, C., Wang, R., Zhang, Y., Zhang, Q., Qin, H., & Liu, L. (2025). Dynamic Electromechanical Co-Stimulation Based Enhancement of Skeletal Muscle Tissues for Fast Biosyncretic Robots Actuation. *Advanced Functional Materials*, 35(2), 2410334. <https://doi.org/10.1002/adfm.202410334>
- Yao, K., Hong, G., Yuan, X., Kong, W., Xia, P., Li, Y., Chen, Y., Liu, N., He, J., Shi, J., Hu, Z., Zhou, Y., Xie, Z., & He, Y. (2025). 3D Printing of Tough Hydrogel Scaffolds with Functional Surface Structures for Tissue Regeneration. *Nano-Micro Letters*, 17(1), 27. <https://doi.org/10.1007/s40820-024-01524-z>
- Zhou, T., Deng, J., Chu, Y., Peng, X., Yang, Y., Wang, Z., Zeng, Y., Song, B., Cheng, M., & Zhou, C. (2026). Breaking the activity-selectivity trade-off through engineered scalable production of sulfur vacancy-rich pyrite for zero-oxidant targeted enrofloxacin removal. *Applied Catalysis B: Environment and Energy*, 381, 125892. <https://doi.org/10.1016/j.apcatb.2025.125892>
- Zhu, H., Deng, Z., Qu, Y., He, P., & Geng, H. (2025). Cu-In Co-Doping and Layered Directional Sintering for High Thermoelectric Efficiency and Mechanical Strength in Bi<sub>2</sub>(Te,Se)<sub>3</sub>. *Advanced Functional Materials*, 35(19), 2422007. <https://doi.org/10.1002/adfm.202422007>
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