Quantum Computing Approaches to Portfolio Optimization Under Risk and Market Uncertainty

Oğuzhan Günal
Bahçeşehir University

***Abstract*—Portfolio optimization under conditions of risk and market uncertainty remains a foundational challenge in financial economics and investment management. Classical optimization frameworks, including mean–variance models and stochastic programming approaches, often struggle with high-dimensional asset universes, nonlinear correlations, and dynamic market regimes. This paper examines quantum computing approaches to portfolio optimization under risk and market uncertainty, focusing on hybrid quantum–classical algorithms designed to enhance combinatorial optimization and probabilistic modeling. By integrating quantum annealing, variational quantum circuits, and quantum-enhanced sampling techniques with classical financial analytics, the study evaluates their potential to improve computational efficiency and scenario sensitivity. The analysis considers both theoretical advantages and practical limitations within the Noisy Intermediate-Scale Quantum (NISQ) era. The findings suggest that quantum-assisted optimization may complement traditional portfolio models by expanding feasible solution spaces and improving robustness under uncertainty, thereby contributing to more adaptive and resilient investment strategies.**

Portfolio optimization is central to modern investment theory and practice. Since the development of mean–variance optimization frameworks, financial analysts have sought to construct asset allocations that maximize expected return for a given level of risk [5]. While classical models have evolved to incorporate multifactor risk structures, stochastic volatility, and robust optimization techniques, the increasing scale and complexity of financial markets have exposed computational and methodological limitations. Contemporary portfolios often include hundreds or thousands of assets, each influenced by nonlinear dependencies, regime shifts, and systemic shocks [8]. Modeling such environments requires advanced optimization tools capable of handling combinatorial complexity and high-dimensional uncertainty.

Digital Object Identifier 10.62802/h0w3vm29
Date of publication 04 03 2026; date of current version 04 03 2026

Market uncertainty further complicates portfolio construction. Financial returns are rarely normally distributed and frequently exhibit heavy tails, volatility clustering, and abrupt structural breaks [6]. These features challenge the assumptions underlying many classical optimization models. Scenario-based analysis and Monte Carlo simulations have been employed to capture tail risk and stress-test portfolio allocations; however, as dimensionality increases, these simulations become computationally expensive [12]. The need for efficient exploration of large solution spaces has prompted researchers to consider alternative computational paradigms.

Quantum computing introduces a novel framework for addressing complex optimization problems. By leveraging principles such as superposition and entanglement, quantum systems can encode information across exponentially large state spaces, theoretically enabling more efficient exploration of combinatorial configurations [3]. Algorithms such as quantum annealing and the Variational Quantum Eigensolver (VQE) have been proposed for solving optimization problems analogous to those encountered in portfolio allocation. In particular, portfolio optimization can be formulated as a quadratic unconstrained binary optimization (QUBO) problem, making it amenable to quantum annealing approaches [11].

In practice, the current state of quantum hardware is characterized by limited qubit counts and noise susceptibility, a condition commonly referred to as the Noisy Intermediate-Scale Quantum (NISQ) era [7]. Consequently, fully quantum portfolio optimization remains experimentally constrained. Hybrid quantum–classical models have emerged as pragmatic alternatives, integrating quantum subroutines into classical optimization pipelines [4]. In these architectures, classical algorithms handle data preprocessing, covariance estimation, and constraint management, while quantum components perform high-dimensional search and probabilistic sampling tasks [1]. This integration allows researchers to leverage potential quantum advantages without relying exclusively on imperfect hardware.

From a risk management perspective, quantum-enhanced models may offer improved sensitivity to extreme events and nonlinear dependencies. Enhanced sampling techniques could accelerate the estimation of risk measures such as Value at Risk (VaR) and Conditional Value at Risk (CVaR) [9]. Additionally, quantum approaches to graph optimization may improve analysis of interconnected financial networks, aiding in the assessment of systemic risk and contagion dynamics. These capabilities align with the growing demand for robust and forward-looking portfolio strategies in volatile global markets [10].

Nevertheless, several challenges accompany the application of quantum computing to financial optimization. Hardware noise, limited scalability, and interpretability concerns must be addressed before widespread institutional adoption becomes feasible [2]. Furthermore, integrating quantum outputs into regulatory and governance frameworks requires transparency and validation mechanisms. Financial institutions must weigh the potential computational benefits against technological risk, cost, and strategic alignment considerations [13].

This paper explores quantum computing approaches to portfolio optimization under risk and market uncertainty, emphasizing hybrid architectures and practical implementation pathways. By situating quantum-enhanced models within the broader context of financial theory and computational finance, the study highlights their potential as complementary tools for navigating complex and uncertain investment landscapes. Ultimately, quantum computing represents not a replacement for classical portfolio theory but an emerging extension that may expand analytical capacity in the pursuit of resilient and adaptive asset allocation strategies.

REFERENCES

1. Awschalom, D. D., Bernien, H., Hanson, R., Oliver, W. D., & Vučković, J. (2025). Challenges and opportunities for quantum information hardware. Science, 390(6777), 1004-1010.
2. Baartmans, R., Ensinger, A., Agostinelli, V., & Chen, L. (2025). ML For Hardware Design Interpretability: Challenges and Opportunities. arXiv preprint arXiv:2504.08852.
3. Chitambar, E., Goodenough, K., Gühne, O., McCarty, R., Perdrix, S., Scarola, V., ... & Zhang, Q. (2025). Quantum graph states: Bridging classical theory and quantum innovation, workshop summary. arXiv preprint arXiv:2508.04823.
4. De Maio, V., Brandic, I., Deelman, E., & Cito, J. (2025, June). The road to hybrid quantum programs: Characterizing the evolution from classical to hybrid quantum software. In Proceedings of the 33rd ACM International Conference on the Foundations of Software Engineering (pp. 1721-1731).
5. Jha, A., Shirvani, A., Jaffri, A., Rachev, S. T., & Fabozzi, F. J. (2025). Advancing portfolio optimization: adaptive minimum-variance portfolios and minimum risk rate frameworks. arXiv preprint arXiv:2501.15793.

6. Khanday, M. A. (2026). Methods for Detecting Outliers, Anomalies, and Structural Instability. Robust Methods for Anomaly Detection in Econometrics, 107.
7. Keçeci, M. (2025). Accuracy, noise, and scalability in quantum computation: Strategies for the NISQ era and beyond. Open Sci. Artic.(OSAs).
8. Kumar, K. (2025). Cross-Asset Correlation Shifts in Crisis Periods: A Framework for Portfolio Hedging. Journal of Data Analysis and Critical Management, 1(01), 40-51.
9. Martín, J., Parra, M. I., Pizarro, M. M., & Sanjuán, E. L. (2025). A new Bayesian method for estimation of value at risk and conditional value at risk. Empirical Economics, 68(3), 1171-1189.
10. Mews, J. G. (2025). Creating competitive advantage from strategy through execution: leading modern approaches in project portfolio management. SAM Advanced Management Journal, 90(2), 194-203.
11. Morapakula, S. N., Deshpande, S., Yata, R., Ubale, R., Wad, U., & Ikeda, K. (2025). End-to-end portfolio optimization with quantum annealing. arXiv preprint arXiv:2504.08843.
12. Omoruyi, N. (2025). Advanced Computational Methods for Financial Planning and Analysis Risk Assessment using Data Science-Driven Model Validation Techniques. International Journal of Research Publication and Reviews. doi: https://www.semanticscholar.org/paper/4d27d96c40e20c0bd7df2d9220bd4b355a381c82.
13. Taheri, A., & Taieby, E. (2025). Strategic opportunities and challenges of quantum computing adoption in financial risk management: A technology management perspective. FAR Journal of Multidisciplinary Studies.