Hybrid Quantum–Classical Simulation of Manufacturing Systems for

Predictive Bottleneck Analysis and Process Optimization

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***Abstract*—Hybrid quantum–classical simulation offers a novel computational paradigm for addressing the increasing complexity of modern manufacturing systems. As production lines evolve into highly interconnected, data-rich environments, conventional simulation and optimization techniques often struggle to capture nonlinear interactions, dynamic bottlenecks, and stochastic fluctuations in real time. This study proposes a hybrid framework that integrates quantum-inspired state encoding, variational quantum optimization, and classical discrete-event simulation to model and predict bottleneck behavior with enhanced efficiency. By leveraging quantum subroutines—particularly Variational Quantum Eigensolvers (VQEs) and Quantum Approximate Optimization Algorithms (QAOA)—the framework accelerates combinatorial scheduling searches and dynamic resource allocation tasks. Classical processors, in turn, handle high-fidelity system modeling and domain-specific constraints. Preliminary experimental simulations demonstrate that the hybrid approach can identify emergent bottlenecks earlier than purely classical methods and improve process throughput by up to 18% in benchmark scenarios. These results highlight the transformative potential of hybrid quantum–classical systems for next-generation smart factories, enabling more resilient, adaptive, and energy-efficient manufacturing operations.**

The increasing complexity of modern manufacturing systems—characterized by multi-stage workflows, fluctuating demand, interconnected cyber-physical components, and tight scheduling constraints—has intensified the need for advanced computational tools capable of real-time decision support [8]. Traditional simulation and optimization methods, while effective for small to medium-scale problems, often struggle to efficiently capture and process the combinatorial explosion associated with large production networks [5]. As manufacturing transitions toward Industry 4.0 and intelligent factories, predictive analytics and adaptive optimization have become essential for reducing inefficiencies, lowering operational costs, and ensuring system resilience [3].

Bottleneck prediction, in particular, remains a persistent challenge. Bottlenecks frequently shift due to variations in demand, machine performance, workforce allocation, and material flow—creating a dynamic environment where static models rapidly lose accuracy [7]. Identifying these constraints early is crucial: unresolved bottlenecks propagate delays, decrease throughput, and inflate operational expenses. Classical discrete-event simulations (DES) offer valuable insights but can become computationally prohibitive when dealing with high-dimensional

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