

Quantum-Inspired Computing Approaches for Complex Optimization Problems in Industrial Engineering

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Abstract: Industrial engineering increasingly depends on solving large-scale optimization problems involving scheduling, routing, resource allocation, inventory control, energy management, and supply-chain coordination. Classical exact methods often become computationally expensive when problem size, uncertainty, and combinatorial complexity grow rapidly. Although practical quantum computers are still developing, quantum-inspired computing approaches have emerged as powerful alternatives that adapt principles from quantum mechanics to run on classical hardware. This paper investigates quantum-inspired computing approaches for complex optimization problems in industrial engineering. It examines methodologies including simulated annealing, tensor-network optimization, Ising formulations, quantum-inspired evolutionary algorithms, digital annealers, and hybrid classical-intelligent heuristics. Applications in production scheduling, facility layout, vehicle routing, maintenance planning, portfolio optimization, warehouse operations, and smart manufacturing are analyzed. Particular attention is given to solution quality, scalability, stochastic decision-making, real-time adaptability, and integration with Industry 4.0 data systems. Benefits include faster near-optimal solutions, improved operational efficiency, reduced energy consumption, and better responsiveness under uncertainty. Major challenges include formulation difficulty, parameter tuning, benchmarking inconsistency, interpretability, and transition barriers within traditional industrial workflows. A future roadmap is proposed involving hybrid quantum-classical ecosystems, AI-guided optimization engines, digital twins, and autonomous decision platforms. The paper concludes that quantum-inspired computing can deliver practical industrial value today by bridging the gap between conventional optimization and future quantum advantage, especially in environments where speed, flexibility, and complexity management are essential.

Keywords: Quantum-Inspired Computing, Optimization, Industrial Engineering, Scheduling, Smart Manufacturing

1. Introduction

Industrial engineering focuses on designing, improving, and optimizing systems involving people, machines, materials, information, and energy. Modern industries must continuously make decisions about production schedules, inventory levels, transportation routes, workforce allocation, machine maintenance, and supply-chain coordination. These decisions are increasingly complex because markets are volatile, product customization is rising, and global operations are deeply interconnected [1]. Many industrial decisions can be formulated as optimization problems. The objective may be minimizing cost, maximizing throughput, reducing energy use, balancing workloads, or improving service levels. However, real-world problems often involve thousands of variables, nonlinear constraints, uncertainty, and combinatorial explosion. Exact algorithms may become too slow for operational use, especially when decisions must be updated frequently [2]. Quantum computing promises new computational capabilities for certain optimization tasks, but fault-tolerant large-scale quantum machines are not yet widely available. In response, researchers and industry have developed quantum-inspired methods that borrow concepts from quantum mechanics while operating on classical computers. These methods

already provide practical benefits in logistics, manufacturing, and planning. This paper examines their role in solving complex optimization problems in industrial engineering.

2. Optimization Challenges in Industrial Engineering

Industrial systems generate diverse optimization tasks. A factory may need to schedule hundreds of jobs across multiple machines while respecting due dates, setup times, and maintenance windows. A warehouse must assign storage locations and picker routes efficiently. A supply chain must decide inventory positions under uncertain demand. Many of these problems are NP-hard, meaning computation grows rapidly with scale. Even when mathematical formulations are elegant, solving them exactly may be infeasible for large instances. Furthermore, data change continuously due to disruptions, urgent orders, machine failures, or traffic delays [3]. As a result, industries often need high-quality solutions quickly rather than mathematically perfect solutions too late. This requirement has driven interest in heuristics, metaheuristics, AI, and now quantum-inspired approaches.

3. Foundations of Quantum-Inspired Computing

Quantum-inspired computing does not require actual quantum hardware. Instead, it adapts ideas such as superposition-like representation, probabilistic search, tunneling analogies, Ising energy minimization, and high-dimensional state encoding into classical algorithms or specialized processors. The central advantage is exploration efficiency. Instead of searching one candidate solution path at a time, these methods use structured probabilistic states or parallel update rules that explore many possibilities effectively. They often excel in rugged solution landscapes with many local optima [4]. Quantum-inspired methods should be viewed as part of a broader advanced optimization toolkit rather than as magical replacements for all classical methods.

4. Simulated Annealing and Digital Annealers

Simulated annealing is one of the earliest physics-inspired optimization techniques. It mimics the cooling of materials, allowing occasional uphill moves to escape local minima before gradually converging toward strong solutions. It has been widely used in scheduling, layout design, and routing. Modern digital annealers extend this idea using specialized architectures that solve large binary optimization problems rapidly. Many industrial problems can be transformed into quadratic unconstrained binary optimization forms, allowing efficient exploration of candidate solutions [5]. Applications include portfolio planning, semiconductor layout, traffic coordination, and production sequencing where solution speed is valuable.

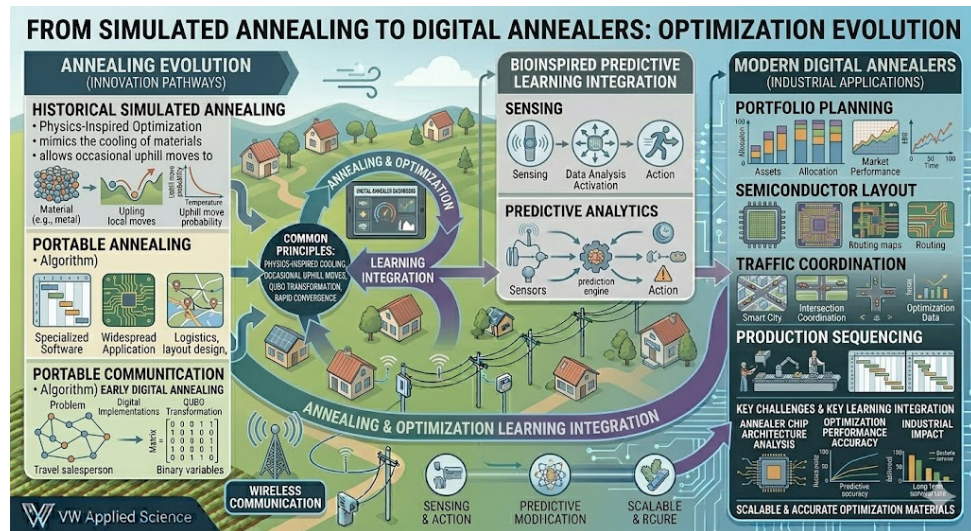


Fig 1

5. Ising Models for Industrial Problems

The Ising model originated in statistical physics to represent interacting spins. In optimization, variables are mapped to binary states, and constraints/objectives become energy terms. The goal is to find the lowest-energy configuration corresponding to the best solution. Industrial engineering problems such as job-shop scheduling, vehicle routing, assignment, and network design can often be encoded in Ising form. Once formulated, various solvers including annealers, metaheuristics, or hybrid algorithms can be applied [6]. The challenge is not only

solving the Ising model but constructing efficient encodings that avoid excessive penalty terms or oversized variable counts.

6. Quantum-Inspired Evolutionary Algorithms

Evolutionary algorithms imitate natural selection through mutation, crossover, and selection. Quantum-inspired variants represent populations probabilistically, allowing richer diversity and faster adaptation. Candidate solutions are sampled from encoded probability amplitudes and updated iteratively toward stronger regions of the search space. These methods have shown promise in assembly line balancing, facility layout planning, supplier selection, and multi-objective optimization [7]. Because industries often face conflicting goals such as cost versus quality or speed versus energy use, flexible multi-objective search is especially useful.

7. Production Scheduling Applications

Scheduling is a core industrial engineering challenge. Manufacturers must assign jobs to machines while minimizing tardiness, changeover time, idle capacity, and bottlenecks. In dynamic factories, schedules may need revision every hour. Quantum-inspired methods can rapidly generate near-optimal schedules under changing conditions. They are effective where classical exact solvers struggle with large combinatorial spaces. Hybrid systems may combine mathematical programming for constraints with annealing-based search for sequencing decisions [8]. When integrated with live shop-floor data, these methods support responsive manufacturing operations.

8. Logistics and Vehicle Routing

Transportation and logistics networks depend on efficient routing. Delivery fleets must minimize travel time, fuel use, lateness, and capacity violations while adapting to traffic and demand uncertainty. Vehicle routing problems grow quickly with the number of stops and constraints. Quantum-inspired solvers can improve route construction and re-optimization in near real time. Applications include last-mile delivery, warehouse shuttle movement, cold-chain logistics, and spare parts distribution [9]. As e-commerce expands, fast routing optimization becomes increasingly valuable.

9. Supply Chain and Inventory Optimization

Supply chains require balancing inventory availability against holding cost and obsolescence risk. Decisions span procurement, safety stock, warehouse placement, replenishment timing, and disruption recovery. Quantum-inspired approaches can analyze many demand scenarios simultaneously and search large policy spaces efficiently. They are useful for stochastic inventory planning and network redesign under uncertain conditions. When connected with digital supply-chain platforms, optimization engines can respond quickly to port delays, supplier outages, or sudden demand spikes.

10. Smart Manufacturing and Industry 4.0 Integration

Industry 4.0 systems generate large volumes of operational data from sensors, enterprise systems, robotics, and quality platforms. Optimization no longer occurs in isolation; it must interact with real-time data streams. Quantum-inspired solvers can be embedded into manufacturing execution systems, digital twins, and predictive maintenance platforms. For example, a factory digital twin may simulate different schedules, energy tariffs, and machine availability scenarios, then use advanced optimization to select the best response [10]. This creates autonomous decision loops where sensing, analysis, and execution are tightly connected.

11. Energy and Sustainability Optimization

Industrial facilities face growing pressure to reduce emissions and energy cost. Optimization problems include load shifting, equipment dispatch, process parameter tuning, renewable integration, and waste heat recovery. Quantum-inspired methods can help schedule energy-intensive operations during low-tariff periods, allocate renewable power efficiently, and optimize plant-wide resource flows. Better decisions reduce both cost and environmental footprint. As carbon accounting becomes stricter, intelligent optimization will be central to sustainable operations.

12. Challenges and Limitations

Despite strong promise, several limitations remain. Problem formulation can be difficult, especially when translating real industrial constraints into binary or energy-based models. Poor formulations may erase computational advantages. Parameter tuning is another challenge. Annealing schedules, penalty weights, and search settings strongly affect results. Benchmarking is often inconsistent because studies use different datasets and metrics. Organizational barriers also matter. Many firms rely on legacy planning systems and may hesitate to adopt unfamiliar optimization tools without clear return on investment [11].

13. Future Directions

The future likely involves hybrid ecosystems combining classical optimization, machine learning, and quantum-inspired search. AI can predict demand or machine failures, while advanced solvers optimize responses. As quantum hardware matures, some workflows may shift gradually toward true quantum-classical integration. Meanwhile, digital twins will provide realistic simulation environments for continuous optimization testing. User-friendly platforms that hide mathematical complexity from practitioners will accelerate industrial adoption.

14. Conclusion

Quantum-inspired computing offers a practical and timely pathway for solving complex optimization problems in industrial engineering. By adapting principles from quantum mechanics to classical systems, these approaches can generate high-quality solutions for scheduling, routing, inventory control, energy management, and smart manufacturing. Their value lies not in replacing all traditional methods but in expanding the toolkit available for fast and flexible decision-making under complexity. With better formulations, integration platforms, and demonstrated business outcomes, quantum-inspired optimization is positioned to become an important driver of next-generation industrial efficiency.

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