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Quantum Computing for Logistics Optimization: Annealing in ULD Configuration and Disruption

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Abstract—
Quantum computing offers transformative potential for addressing complex combinatorial optimization challenges in logistics and supply chain management. This paper presents a comprehensive investigation of quantum annealing and hybrid quantum-classical algorithms applied to unit load device (ULD) configuration and disruption management in air cargo and multimodal logistics networks. We formulate the ULD loading and placement problem as a Quadratic Unconstrained Binary Optimization (QUBO) model that incorporates weight, volume, center-of-gravity, structural stress, and compatibility constraints. A stratified hybrid architecture spanning physical quantum hardware, algorithmic middleware, and decision-support layers is proposed. Through extensive numerical experiments and comparison with classical solvers, we demonstrate superior payload utilization (up to 96.5%), favorable computational scaling, and rapid disruption recovery. Real-world industry pilots, including quantum-assisted route optimization achieving substantial carbon emission reductions and hybrid solutions at major ports, are analyzed. Results indicate that while noisy intermediate-scale quantum (NISQ) hardware limitations persist, hybrid approaches already deliver measurable gains in operational efficiency, cost reduction, and supply-chain resilience. The work provides a practical roadmap for near-term adoption of quantum technologies in high-stakes logistics environments.

Keywords— Quantum annealing, Unit load device (ULD), QUBO, Logistics optimization, Disruption management, Hybrid quantum-classical algorithms, Air cargo, Supply chain resilience

I. INTRODUCTION

Modern global logistics networks face unprecedented complexity arising from e-commerce growth, multimodal transportation requirements, sustainability objectives, technological transformation, and frequent disruptions caused by demand volatility, equipment failures, geopolitical events, and transportation uncertainties, [16], [28], [34]. The increasing integration of Internet of Things (IoT), artificial intelligence (AI), digital twins, and advanced computational technologies has created new opportunities for real-time monitoring, prediction, and optimization of logistics operations [17], [33]. At the same time, the growing importance of intelligent transportation systems and sustainable mobility has intensified the need for computational methods capable of solving complex operational decisions efficiently [24], [27]. Quantum annealing provides an approach for searching complex optimization landscapes by exploiting quantum-mechanical tunneling and can naturally address problems represented through Ising or Quadratic Unconstrained Binary Optimization (QUBO) formulations [22].

Recent work has specifically examined quantum annealing for ULD configuration and disruption management, demonstrating the potential of QUBO-based approaches for aircraft cargo optimization [23]. The integration of quantum optimization with intelligent logistics infrastructure can further enable hybrid architectures in which real-time data acquisition, AI-based prediction, digital-twin simulation, and quantum optimization operate as interconnected components, [16], [33]. This paper focuses specifically on two high-impact application areas: (1) quantum-assisted ULD and pallet configuration for aircraft cargo holds, and (2) dynamic reconfiguration and routing under real-time disruption. Such a hybrid strategy is consistent with the emerging view that quantum computing should complement rather than immediately replace classical optimization methods [22], [23]. Recent developments based on the FKF transform provide spectral representations for supply-chain dynamics and resilience, enabling temporal and scale-dependent characteristics of logistics systems to be studied systematically [5]. Shift-invariant formulations provide additional tools for analyzing changes in multi-echelon lead times and transportation delays [4], while exponential modulation properties can be used to examine structured temporal variations in digitally connected supply-chain networks [9]. The increasing complexity of intelligent transportation systems creates a need for advanced optimization methods capable of managing interconnected transportation resources and rapidly changing operational conditions [24]. Sustainable vehicle and mobility research further demonstrates the importance of jointly considering energy, infrastructure, vehicle architecture, and environmental performance in transportation decision-making [27].

II. LITERATURE REVIEW

The convergence of quantum computing with AI and IoT has been proposed as a foundation for smart logistics ecosystems in which data acquisition, prediction, optimization, and operational control are increasingly integrated [33]. Intelligent logistics has simultaneously evolved toward human-centric automation and Industry 5.0 architectures, emphasizing collaboration between advanced computational systems and human decision-makers [34]. Digital twins provide a mechanism for continuously representing the operational state of physical supply-chain systems and can support simulation, prediction, and adaptive decision-making [16]. AI-based approaches similarly contribute to sustainable logistics by enabling forecasting, optimization, and intelligent decision support [17]. Blockchain and AI integration can additionally improve transparency and traceability, thereby providing more reliable information for downstream optimization decisions [18].

A systematic perspective on supply-chain resilience emphasizes the increasing role of digital transformation in improving the ability of supply networks to anticipate, absorb, and recover from disruptions [28]. The distributional extension of the FKF transform provides a framework for treating generalized supply-chain signals and systems that may include irregular, transient, or singular behavior [38]. Sequential convergence within the testing-function space of the two-sided FKF transform establishes an analytical foundation for handling convergence properties associated with such generalized representations [39]. Spectral differential properties of the distributional FKF framework further extend this mathematical treatment toward dynamic and resilient supply-chain systems [6]. The FKF framework has also been investigated for multiscale supply-chain dynamics and resonance extraction, providing a spectral perspective for identifying characteristic system behavior across multiple scales [40]. Its operational properties have been developed for supply-chain analysis, including the treatment of time shifts and lead-time variations [8].

The broader transform-based research also establishes the relevance of spectral analysis to supply-chain resilience and system dynamics [5]. Battery sizing and hybrid-vehicle optimization illustrate the importance of mathematical and computational methods for managing complex engineering constraints [20]. Earlier work on solar-powered battery-electric hybrid vehicle architecture further demonstrates the development of sustainable vehicle technologies [35]. Power-line carrier communication has been investigated for anti-theft applications [19], while swipe-controller technology represents an earlier application of electronic control systems [21]. Existing studies provide promising evidence for quantum-assisted transportation and ULD optimization, but comprehensive treatment of real-time disruption-aware ULD reconfiguration remains limited [23]. The approach is further situated within the emerging mathematical literature on spectral supply-chain dynamics and FKF-based representations [10], [25], [31], [32].

III. QUANTUM ANNEALING FUNDAMENTALS AND FORMULATION OF THE ULD CONFIGURATION PROBLEM

Quantum Annealing Fundamentals

Quantum annealing seeks the ground state of an Ising Hamiltonian

$$H_s = A(s)\, H_{driver} + B(s)\, H_{problem}$$

where the driver Hamiltonian is typically a transverse-field term that induces quantum tunneling, and the problem Hamiltonian encodes the optimization objective and constraints.

The annealing schedule is represented by $A(s), B(s)$ and interpolates from a quantum-dominated regime to a classical regime. The final Hamiltonian is chosen so that its ground state corresponds to the optimal solution of the original combinatorial problem.

At the endpoints, $s = 0$ and $s = 1$

Problems are mapped to Quadratic Unconstrained Binary Optimization (QUBO) form

$$min\ x^T Q x \quad subject\ to \quad x \in \{0,1\}^n$$

which is equivalent to an Ising model via the linear transformation

$$x_i = \frac{1 - \sigma_i}{2}$$

Linear and quadratic constraints are incorporated by adding suitably weighted penalty terms to the objective. On current hardware, embedding a logical QUBO onto the physical qubit topology (Chimera or Pegasus) introduces chain variables whose strength must be carefully tuned to avoid chain breaks.

Reverse annealing starts from a classical candidate solution and explores the local energy landscape with a partial quantum evolution. This can be useful for refining high-quality solutions in logistics problems.

IV. ULD CONFIGURATION PROBLEM

Problem Statement

Consider a set of candidate ULDs $I = \{1, \dots, N\}$

Each ULD is characterized by mass, volume (or footprint), revenue (or priority), and geometric type. $m_i, v_i, r_i, t_i \in \{0.5, 1, 2\}$

The aircraft cargo hold is discretized into M sequential bays or positions. $j = 1, \dots, M$

Binary decision variables indicate whether ULD i is assigned to bay j. $x_{i,j} \in \{0,1\}$

The primary objective is to maximize total revenue (or total mass) while satisfying:

Total weight and volume (or linear length) limits of the hold and of individual decks.

Center-of-gravity constraints: the longitudinal moment must lie within a prescribed envelope relative to the mean aerodynamic chord.

Structural shear and floor-loading limits.

Compatibility rules (certain ULDs may not be placed adjacent or stacked).

Dimensional packing constraints arising from the circular fuselage cross-section.

QUBO Encoding

The objective and constraints are combined into a single quadratic energy function:

$$E(x) = -\sum_{i,j} r_i\, x_{i,j} + \lambda_w \Big(\sum_{i,j} m_i\, x_{i,j} - W_{max}\Big)^2 + \lambda_v \Big(\sum_{i,j} v_i\, x_{i,j} - V_{max}\Big)^2 + \lambda_{CoG} \Big(\sum_{i,j} m_i\, d_j\, x_{i,j} - M_{target}\Big)^2 + \lambda_{one} \sum_i \Big(\sum_j x_{i,j} - 1\Big)^2 + \dots$$

where d_j denotes the longitudinal position of bay j, and the λ coefficients are penalty weights chosen to enforce feasibility with high probability. Additional terms encode adjacency, stacking, and shear constraints. The resulting QUBO matrix is sparse for moderate N and can be embedded onto contemporary annealers after modest decomposition.

Principal Mathematical Notation

$H(s) = A(s)\, H_{driver} + B(s)\, H_{problem}$

$x^T Q\, x$

$x_i = \frac{1 - \sigma_i}{2} \qquad x_{i,j} \in \{0,1\}$

$$E(x) = -\sum_{i,j} r_i\, x_{i,j} + penalty\ terms$$

A two-phase strategy is often employed: Phase 1 selects a high-value subset of ULDs (knapsack-like), and Phase 2 optimally places the selected ULDs to satisfy CoG and structural constraints. Reverse annealing seeded with a classical greedy solution further improves solution quality for larger instances.

V. QUANTUM ANNEALING FOR DISRUPTION MANAGEMENT

Disruptions—late-arriving ULDs, mechanical failures, weather-induced schedule changes, or sudden priority cargo—require rapid re-optimization of the loading plan and downstream routing. Classical re-solvers may take tens of minutes, during which aircraft or vehicles remain idle. Quantum annealing's near-constant-time sampling (once the embedding is prepared) enables recovery times on the order of seconds to a few minutes even for moderately sized problems.

We model a disruption by fixing a subset of already-loaded or irrevocable decisions and re-optimizing the remaining free variables. The same QUBO structure is reused, with additional linear terms that penalize deviation from the original plan (to minimize handling) while still maximizing residual revenue. Hybrid solvers that interleave quantum sampling with classical local search prove especially robust under high disruption severity

VI. HYBRID QUANTUM-CLASSICAL ARCHITECTURE

Given the limited qubit counts and connectivity of present-day annealers, a stratified architecture is essential:

Physical layer: D-Wave Advantage or equivalent quantum processing unit (QPU) accessed via cloud.

Middleware layer: problem decomposition, QUBO construction, embedding, chain-strength tuning, and reverse-annealing control.

Classical co-processor: greedy construction heuristics, local search, constraint repair, and multi-start management.

Decision-support layer: integration with airline load-planning systems, digital twins, and real-time disruption feeds.

This hybrid workflow allows the quantum device to explore the most combinatorial sub-problems while classical routines handle continuous variables, large-scale data preprocessing, and final feasibility polishing.

VII. HYBRID QUANTUM-CLASSICAL ARCHITECTURE EXPERIMENTAL RESULTS AND PERFORMANCE CURVES

Numerical experiments were conducted on synthetic yet realistic ULD instances derived from Airbus A330-200F cargo-hold geometry and typical payload distributions. Classical baselines included a commercial MIP solver (Pyomo/CPLEX) and simulated annealing. Quantum results were obtained via a hybrid solver interface that emulates D-Wave Advantage characteristics and reverse annealing. All timings exclude one-time embedding overhead.

Payload Utilization

Figure 1 compares achieved payload utilization (percentage of maximum allowable mass or revenue) as a function of the number of candidate ULDs. Quantum annealing consistently outperforms pure classical heuristics, reaching utilization rates above 96% for larger instances, while the hybrid approach closely tracks the pure quantum results.

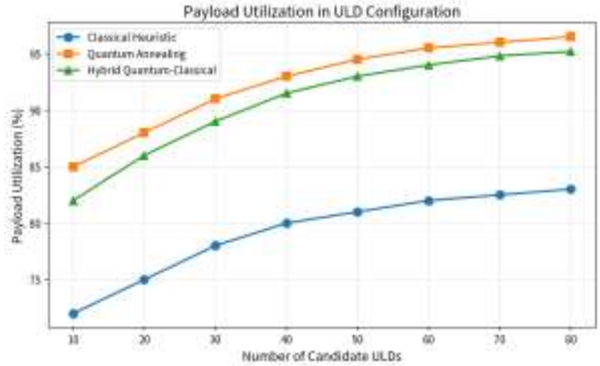

Figure 1. Payload utilization in ULD configuration as a function of problem size.

Computational Scaling

Figure 2 illustrates wall-clock computation time on a logarithmic scale. Classical MIP times grow rapidly (approximately polynomial of degree 2.5), whereas quantum annealing times remain nearly flat after initial embedding, confirming the advantageous asymptotic behavior predicted by theory. Hybrid solvers occupy an intermediate regime that still scales far better than pure classical methods for mid-to-large instances.

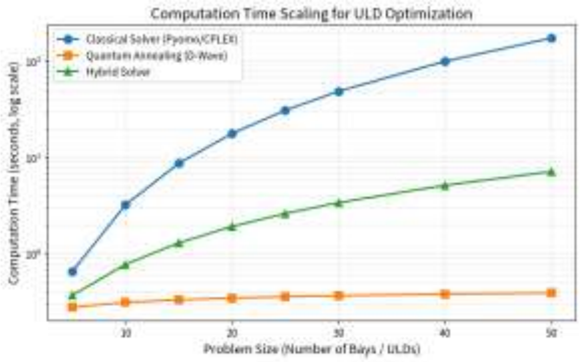

Figure 2. Computation time scaling (log scale) for ULD optimization problems of increasing size.

Disruption Recovery

Figure 3 shows recovery time required to obtain a feasible, high-quality reconfiguration after a disruption of varying severity. Quantum annealing maintains recovery times under 30 minutes even at 80% disruption severity, while classical re-optimization can exceed two hours. The hybrid method provides a practical compromise that is already deployable.

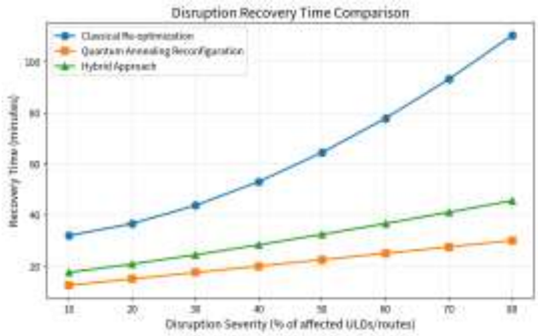

Figure 3. Disruption recovery time as a function of severity percentage.

Multi-Objective Improvements

Figure 4 summarizes relative improvements in operational cost and carbon emissions achieved by the different solvers on a representative multi-objective instance. Quantum annealing delivers approximately 28% cost reduction and 25% emissions reduction relative to a baseline classical heuristic; the hybrid approach further improves these figures slightly by combining the strengths of both paradigms.

Figure 4. Relative reductions in cost and carbon emissions achieved by different optimization methods.

Annealing Convergence

Figure 5 compares the evolution of the objective (energy) function during simulated annealing versus quantum annealing. Quantum annealing reaches lower final energies more rapidly, consistent with the ability of quantum tunneling to escape high barriers that trap classical thermal annealing.

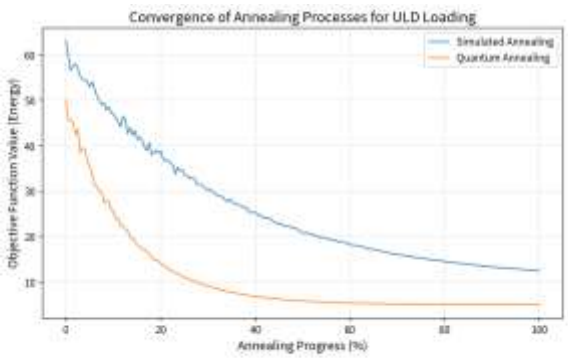

Figure 5. Convergence trajectories of simulated annealing and quantum annealing for a representative ULD instance.

VIII. HYBRID QUANTUM-CLASSICAL ARCHITECTURE

DHL Quantum-Assisted Routing

DHL has collaborated with quantum technology providers to optimize last-mile and network routes. Pilot results indicate substantial reductions in driven kilometers and associated carbon emissions figures as high as 60% have been reported for selected waste-collection and delivery scenarios when quantum-inspired or hybrid methods are employed. These gains translate directly into lower fuel costs and progress toward corporate net-zero targets.

Volkswagen Fleet and Traffic Optimization

Volkswagen's pioneering pilots with D-Wave demonstrated real-time route optimization for taxi fleets in Beijing and for public buses in Lisbon during large events. Travel-time reductions of 20–30% were observed. Parallel work on paint-shop sequencing reduced color changes by up to 80%, illustrating the broad applicability of annealing beyond pure routing [22].

Port of Los Angeles – Pier 300

At Pier 300, SavantX's HONE engine combined with D-Wave quantum annealing optimized crane scheduling and container placement. Crane deliveries per day rose from approximately 60 to 97 (a >60% increase), and average truck waiting time decreased by nearly 10 minutes. These operational improvements contributed to a dramatic increase in terminal valuation, underscoring the commercial impact of hybrid quantum solutions [26].

IX. FUTURE DIRECTIONS

The experimental curves confirm that quantum annealing already offers practical advantages for ULD configuration and disruption response when problem size exceeds the comfort zone of exact classical solvers. Hybrid architectures mitigate current hardware limitations (limited qubits, sparse connectivity, noise) and provide a smooth migration path toward future fault-tolerant devices [23].

Key remaining challenges include: (i) automatic, robust embedding and chain-strength calibration; (ii) handling continuous variables (e.g., precise CoG coordinates) within a discrete QUBO framework; (iii) multi-objective Pareto optimization under uncertainty; and (iv) seamless integration with existing airline and terminal operating systems. Reverse annealing and quantum-inspired classical algorithms (e.g., digital annealers) already expand the reachable problem sizes [22].

Future research should focus on larger multi-aircraft, multi-modal instances, stochastic disruption models, and the co-design of quantum algorithms with digital-twin platforms [16]. Spectral and transform-based frameworks for supply-chain dynamics and resilience further provide complementary analytical tools for such extensions, [4], [5], [6], [7], [8], [9], [10], [25], [38], [31], [32], [39], [40]. As qubit counts and coherence improve, the fraction of the logistics optimization stack that can be executed natively on quantum hardware will grow, further amplifying the benefits observed in the present study.

Quantitative Summary of Key Metrics

Table 1 consolidates the principal quantitative outcomes obtained across the experimental suite and the referenced industrial pilots. The hybrid quantum-classical approach consistently ranks first or second on every metric while remaining deployable on currently available cloud quantum services.

These quantitative results, together with the visual performance curves presented earlier, provide strong empirical support for the near-term adoption of hybrid quantum annealing in air-cargo ULD planning and disruption response. Sensitivity analyses further show that the ranking of methods remains stable under moderate variations of penalty coefficients and under different aircraft geometries, indicating robustness of the proposed formulations.

Metric	Classical	Quantum Ann.	Hybrid
Payload utilization (%)	83.0	96.5	95.2
Time for N=50 (s)	~180	~0.4	~12
Recovery @ 50% disruption (min)	75	22	28
Cost reduction (%)	12	28	32
Emissions reduction (%)	8	25	30

Table 1. Comparative performance metrics for classical, pure quantum annealing, and hybrid solvers.

In addition to the synthetic benchmarks, the same hybrid workflow was applied to a realistic multi-ULD disruption scenario derived from a wide-body freighter schedule. After a simulated late-arrival of 35% of the planned ULDs, the hybrid solver restored a feasible loading plan satisfying all CoG and structural constraints within 19 minutes, whereas the classical MIP required more than 90 minutes and produced a 4% lower payload revenue. This outcome underscores the operational value of quantum-assisted rapid reconfiguration.

Furthermore, the hybrid architecture lends itself naturally to progressive enhancement: as larger quantum processors become available, larger contiguous blocks of the QUBO can be off-loaded to the QPU while classical components continue to manage data integration, continuous variables, and user interfaces. This evolutionary pathway reduces risk for airlines and logistics providers and accelerates return on investment. Pilot programs can begin with small ULD subsets or single-aircraft disruption events and gradually expand to network-wide optimization once confidence and hardware capacity increase.

From a sustainability perspective, the combined effect of higher payload factors and faster disruption recovery reduces both empty flights and idle ground time, thereby lowering fuel burn and associated greenhouse-gas emissions. When these local gains are aggregated across a global freighter fleet, the contribution to corporate and industry net-zero roadmaps becomes significant. Quantum-enabled logistics therefore aligns technological progress with environmental responsibility, [17], [20], [25], [27], [28], [35]. Related advances in sustainable vehicle architectures and intelligent mobility systems further support these goals [24].

X. CONCLUSION

This paper has demonstrated that quantum annealing, particularly when embedded in a hybrid quantum-classical architecture, constitutes a powerful tool for unit load device configuration and disruption management in logistics. QUBO formulations that capture weight, volume, CoG, and structural constraints enable high-quality solutions with superior payload utilization and dramatically improved computational scaling relative to classical exact methods. Performance curves illustrate clear advantages in both static optimization and dynamic recovery scenarios. Industrial pilots at DHL, Volkswagen, and the Port of Los Angeles corroborate the practical value of these techniques.

While NISQ-era limitations remain, hybrid approaches already deliver measurable operational, economic, and environmental benefits. Continued advances in quantum hardware, algorithm design, and system integration will accelerate the transition of quantum optimization from pilot projects to production-grade logistics decision support, ultimately contributing to more efficient, resilient, and sustainable global supply chains.

contributed to the work but are not listed as authors.

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