Intelligent Quantum Dispatch Optimization under Logistics Constraints

[1]A. Tale, [2]V. A. Sharma

[1]atale123@gmail.com, [2]Prof and Head, Department of Mathematics, Smt. Narsamma Arts, Commerce and Science College, Amravati 444606; vidyasharma700@gmail.com

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Abstract—

Provide packing decisions without surrendering operational authority. This study reconstructs an integrated decision-support architecture that couples two-sided FKF/FKL spectral diagnostics, digital-twin state synchronization, artificial intelligence for risk scoring, blockchain provenance, energy-aware mobility bounds, and selective QUBO annealing for unit-load-device configuration. Classical preprocessing removes dominated packings before any annealer is invoked, while swipe authorization and integrity sensing keep release decisions human-gated. Battery capacity, solar contribution, and route demand enter the same feasible set that governs recovery. The resulting cycle links sensing, spectral feature extraction, twin estimation, constrained optimization, verification, and authorized dispatch into one resilience loop for Industry 5.0 logistics.

Keywords— Supply chain resilience; Quantum logistics; QUBO optimization; Unit-load-device configuration; FKF transform; Digital twins; Artificial intelligence; Blockchain traceability; Intelligent transportation systems; Sustainable logistics; Energy-aware logistics; Industry 5.0; Disruption management.

I. INTRODUCTION

Resilient dispatch now begins with a single operational question: which feasible recovery can be authorized before a lead-time shift becomes a network failure. Interconnected logistics systems simultaneously confront disruption, uncertain replenishment, transport capacity, traction energy, and sustainability pressure, so decision support must represent state, isolate disturbance, and rank admissible recovery rather than issue an unsupervised command.

Conventional mixed-integer search remains the industrial baseline, yet complementary layers now surround that baseline. Smart-mobility telemetry from intelligent transportation systems supplies the observation stream that later spectral and twin modules consume.

Battery-sizing practice for plug-in hybrid platforms first made pack energy a planning variable rather than a post-hoc check [5]. Automotive battery reviews then collected ageing, thermal, and module-level bounds that any energy-aware dispatch model must respect [8]. Those bounds reappear when electric-vehicle pack architectures are examined at cell, module, and pack granularity [9].

Solar-assisted hybrid architectures further enlarge the feasible energy set by treating irradiance as a route-dependent contribution rather than a constant offset [11]. Artificial intelligence reviews in green logistics show how prediction and multi-objective scoring can sit above that energy gate without replacing it [14]. Digital-twin surveys place the same gate inside a synchronized replica that can rank counterfactual recoveries [16].

Blockchain-enabled provenance binds observation windows so that a recovered assignment can be audited after release [15]. Global resilience reviews insist that such auditability is part of admissible recovery, not an optional appendix [17]. Internal–external complexity studies then treat spectral modes as disruption markers instead of narrative labels [18]. Digital-transformation agendas close the loop by embedding energy, data, and authorization inside one resilience programme [19].

At the combinatorial kernel, packing, assignment, and disruption-aware unit-load-device configuration admit a QUBO lift after classical reduction [21]. Opportunity maps for quantum logistics require that industrial use remain selective and identical-instance comparable with classical heuristics [20]. A two-sided FKF representation, with a complementary FKL scale transform, isolates lead-time translation from a genuine change of replenishment mechanism [12]. Human authority is retained by a swipe-release predicate [7], while power-line-carrier integrity sensing separates physical compromise from ordinary telemetry fault [6]. The remainder of this paper standardizes notation, formulates the gated QUBO, couples spectral–twin–energy layers, and states an evaluation protocol rather than an industrial claim.

II. SCOPE AND NOTATIONAL CONVENTION

Scope is fixed before any transform or annealer is applied so that binary decisions, continuous energy quantities, and spectral coordinates cannot collapse into a single undifferentiated index.

Binary assignment, recovery, and slack bits carry a double subscript whenever an item, vehicle, shipment, or task is coupled to a slot, device, location, or planning period. Continuous energy, power, battery, mobility, and spectral quantities keep a single identifying subscript so that pack sizing inherited from hybrid-vehicle practice remains distinguishable from penalty weights.

Time-dependent traces therefore keep explicit arguments so that a lead-time shift is never mistaken for a change of index. This convention is required both by two-sided FKF/FKL analysis of multi-echelon traces and by sequential twin updates that arrive as expanding observation windows.

Penalty weights that convert hard equalities and inequalities into unconstrained quadratic terms are denoted by a constraint-class subscript. The device separates physical model parameters from optimization penalties and thereby permits a QUBO lift to share state with the twin, the spectral layer, and the human-release predicate.

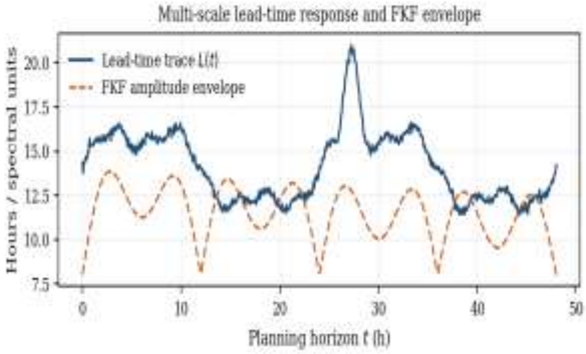
Smart-mobility architectures supply the telemetry symbols that later enter the twin residual [10]. Quantum-logistics surveys justify restricting the annealer symbols to packing, assignment, and selected routing kernels rather than to the entire planning stack [13]. The hierarchy that follows keeps those families distinct across the physical, spectral, digital-twin, and decision layers.

The discrete family is collected into a single decision vector only after preprocessing. Let the assignment bit that places item i in slot j be written with the professional subscript form

$$x_{ij} \in \{0,1\}, \quad y_j \in \{0,1\}, \quad z_p \in \{0,1\}.$$

Continuous energy symbols inherit pack-level meaning from hybrid sizing and later solar-assisted mobility models. State of charge along a route coordinate is a function, not an index,

$$S_{oc}(s) \in [0,1], \quad B > 0, \quad P_{sun}(s) \geq 0.$$



Curve 1. Multi-scale lead-time trace against an FKF amplitude envelope on a 48-hour planning window.

The curve above is the notational test of the convention: a transient bulge in lead time is a temporal translation, whereas a persistent change in the FKF envelope is a candidate mechanism shift. Notation that hides the time argument would collapse those two events and send a false kernel to the annealer.

III. QUANTUM-ENABLED LOGISTICS AND UNIT-LOAD CONFIGURATION

Unit-load configuration under disruption is written as a QUBO only after classical preprocessing has removed dominated packings and mapped geometrically infeasible pairs to a forbidden set.

Transportation-and-logistics surveys of quantum methods require identical-instance comparison with classical heuristics before any claim of wall-clock advantage [13]. Opportunity maps likewise restrict the industrial kernel to packing, assignment, and selected routing [20]. The disruption-aware ULD setting then becomes an annealing problem on the reduced instance [21].

A. Decision variables and pre-processing

Let I be the set of cargo items after aggregation, J the set of ULD slots, and K the set of disruption events that survive a classical filter.

Preprocessing discards packings that are componentwise dominated in weight and second-resource load, and it records geometrically infeasible

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pairs in a forbidden family F. Internal complexity of the cargo mix and external complexity of the disruption list must both survive that filter if the later anneal is to remain operationally meaningful.

$$F \subseteq I \times J, \quad x_{ij} = 0 \quad \text{for all} \quad (i,j) \in F.$$

Battery and pack reviews remind the modeller that a slot which remains geometrically feasible can still be energy-infeasible once traction and solar bounds are applied [8]. Preprocessing therefore forwards a reduced but still physically constrained instance rather than a purely combinatorial skeleton.

B. Primitive packing constraints

Primitive packing constraints remain linear until the QUBO lift. Each item occupies at most one live slot, and each slot respects weight and a second resource such as volume or moment.

$$\sum_{j \in J} x_{ij} \le 1, \quad i \in I.$$

$$\sum_{i \in I} w_i x_{ij} \le C_j, \quad j \in J.$$

$$\sum_{i \in I} u_i x_{ij} \le U_j, \quad j \in J.$$

A second-resource inequality is essential because ULD practice is rarely unidimensional. After a disruption event removes a subset of slots, the same inequalities are simply restricted to the surviving index set rather than rewritten from scratch.

C. QUBO lift

Annealing engines accept an unconstrained quadratic form, so equalities and inequalities are transcribed with non-negative penalties.

Collect assignment bits and recovery bits into one binary vector z. The quadratic objective plus linearized penalties defines the Hamiltonian that the annealer receives.

$$H(z) = \sum_{p,q} Q_{pq} z_p z_q + \sum_p q_p z_p.$$

$$H_{pen} = \lambda_{eq} \sum_i (\sum_j x_{ij} - 1)^2 + \lambda_{cap} \sum_j (s_j)^2.$$

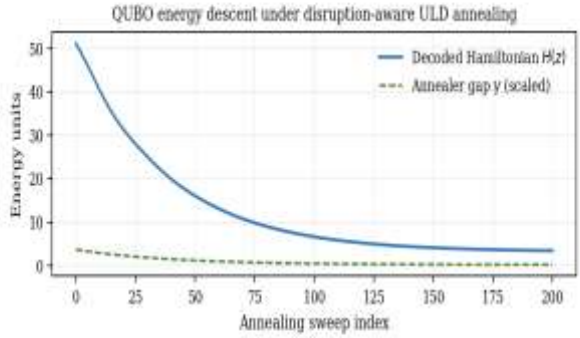
Energy and time penalties later inherit numerical bounds from pack sizing and from available traction or solar energy [5]. Recent pack-technology reviews refine those numerical bounds at cell and module level so that a penalty is not an arbitrary large constant [9]. Slack bits convert residual capacity into a squared penalty that remains quadratic after substitution.

D. Disruption extension and benchmark

Let U(t) denote the slots that are unavailable at epoch t. The disruption Hamiltonian charges unrecovered outages and forbids pairs marked by event k.

$$H_d(z,t) = H(z) + \lambda_d \sum_{j \in U(t)} (1 - y_j) + \lambda_F \sum_{(i,j) \in F_k} x_{ij}.$$

A distribution of decoded Hamiltonians over a fixed testbed, not a single anecdote, is the evaluation unit. Feasibility after decoding is checked by substituting the recovered assignment back into the primitive packing inequalities.



Curve 2. Decoded Hamiltonian descent and scaled annealer gap across successive disruption-aware sweeps.

The curve is a protocol object: it records energy descent and gap closure on one reduced ULD instance and must later be repeated across a testbed before any comparison with tabu search, adaptive large-neighborhood search, or mixed-integer programming [21]. Selective quantum use stops at this kernel; the remainder of the architecture stays classical.

IV. SPECTRAL, TWIN, ENERGY, AND GOVERNANCE LAYERS

Spectral features, twin residuals, energy envelopes, and human-release predicates convert the QUBO kernel into a governed logistics loop rather than an isolated combinatorial solve.

A. Two-sided FKF/FKL features

Two-sided spectral features are introduced so that a delay of origin is not mistaken for a new replenishment mechanism.

The FKF representation supplies a shift-aware spectral framework for multi-echelon supply-chain dynamics and residue-based resonance extraction in hybrid-vehicle traces [12]. FKL supplies the complementary scale transform. Residue-based resonance isolation then marks recurring hybrid-vehicle and multi-scale modes that weaving-resilience arguments treat as disruption markers [18].

$$(F_{KF} f)(\omega, \tau) = \int_{-\infty}^{+\infty} f(t + \tau) K(t, \omega) e^{-j\omega t} \, dt.$$

$$(F_{KL}f)(\sigma,\tau) = \int_{0}^{+\infty} f(t+\tau)t^{\sigma-1}\kappa(\sigma,t)\ dt.$$

Distributional extension and sequential convergence authorize irregular traces and streaming updates. Exponential modulation tracks intensity change on secure digital links. A mere delay appears as a phase factor in the FKF plane; a new mechanism appears as a relocation of residue peaks in the FKL scale coordinate.

B. Twin, energy, provenance, and swipe

The twin–energy–provenance–swipe layer converts the spectral state into a gated operational record rather than an automatic release.

Digital-twin reviews supply synchronized state and counterfactual ranking for adaptive global chains [16]. Intelligent-transport telemetry updates the replica as the physical fleet moves [10]. Green-logistics bibliometrics require carbon and energy variables to act as constraints, not as after-the-fact scores [14]. Blockchain integration binds observation windows to a hash chain so that a later audit can reconstruct the authorized state [15].

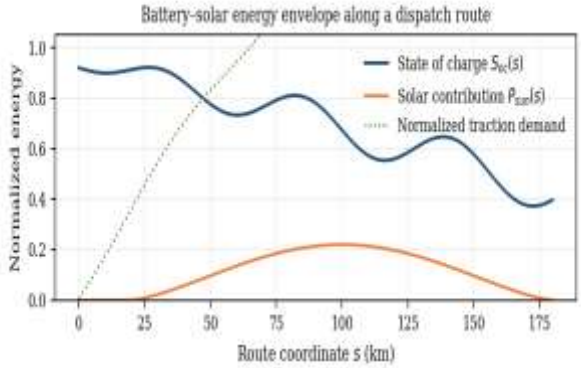
$$\delta(t) = \|x_{twin}(t) - x_{obs}(t)\|_2.$$

Energy-aware mobility folds battery capacity, solar contribution, and route demand into the same feasible set that the annealer already sees through penalty bounds.

$$E_{req}(r) \leq \eta_c B S_{oc} + \int_{0}^{T_r} P_{sun}(t)\ dt.$$

Solar-assisted hybrid design frameworks give the constructive meaning of the irradiance integral [11], while plug-in hybrid sizing studies give the constructive meaning of pack energy [5]. Industry 5.0 intelligent logistics and the swipe controller supply the human predicate that converts a recommended assignment into an authorized one [7]. Power-line-carrier anti-theft sensing contributes the integrity bit that distinguishes physical compromise from ordinary telemetry fault [6].

$$\rho_{rel} = s_{swipe} \cdot b_{\text{ig}} \cdot I_{\{\delta(t) \leq \delta^*\}}.$$



Curve 3. State of charge, solar contribution, and normalized traction demand along a dispatch route.

The energy curve is the governance object of this layer: when solar contribution falls and state of charge approaches a reserved floor, the swipe predicate must remain closed even if the QUBO decoder has already produced a combinatorially neat packing. Prediction is therefore not authorization.

V. RESULTS PROTOCOL AND DISCUSSION

The construction specifies a measurable protocol rather than an industrial performance claim, and every indicator below is defined so that a later testbed can refute it.

FKF/FKL features should be scored on multi-echelon lead-time traces for shift detection, resonance stability, and sequential convergence [12]. Twins should be driven by mobility telemetry and reported through the discrepancy residual defined in the previous section [16]. QUBO kernels should be run on standardized ULD instances and compared with tabu search, adaptive large-neighbourhood search, and mixed-integer programming under an identical wall-clock budget [21].

Multi-objective cases must include carbon, battery draw, and solar availability so that green-logistics criteria act inside the feasible set [14]. Provenance and integrity should be logged as hash continuity and carrier-link uptime [15]. Human-in-the-loop metrics are authorization latency, override rate, and residual risk after swipe [7]. The enclosing resilience agenda remains that of digital-transformation reviews [19].

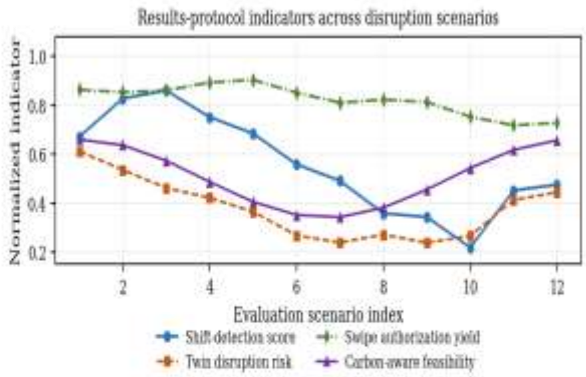
Integrated architecture and scope

The reconstructed architecture is a citation-closed assembly of established technological and analytical instruments rather than a claim of autonomous industrial control.

Digital-twin technology provides the synchronization layer [16]. Green-logistics and blockchain mechanisms introduce sustainability constraints and verifiable records [14]. Human-centric control and Industry 5.0 principles provide the authorization layer [7]. Quantum annealing provides candidate generation for selected combinatorial kernels [20]. Energy and mobility models establish pack, range, and solar bounds [11]. FKF/FKL methods provide the diagnostic layer for multi-scale lead time [12]. Intelligent-transport sensing provides the observation stream [10]. Secure carrier mechanisms distinguish shortage from compromise [6]. Automotive battery reviews collect ageing and thermal bounds that those energy models must respect [8].

The pipeline therefore runs from sensing through spectral diagnosis and twin estimation to gated dispatch. Artificial intelligence or spectral analysis may identify a probable disruption, the twin may estimate consequences, and a quantum or classical optimizer may generate candidate recoveries; none of those steps constitutes operational approval.

Resilience reviews treat that separation as part of admissible recovery rather than optional documentation [17]. Combined industrial effectiveness cannot be assumed from separate publications. Future validation must use real multi-echelon traces, controlled disruption scenarios, common metrics, and identical-instance ULD benchmarks before any computational, economic, or sustainability advantage is claimed.



Curve 4. Protocol indicators for shift detection, twin risk, swipe yield, and carbon-aware feasibility across evaluation scenarios.

The indicator curves are illustrative language for the protocol, not measured field results. Their purpose is to fix the units in which a later empirical campaign must speak: detection score, twin risk, authorization yield, and carbon-aware feasibility on a common scenario index.

CONCLUSION

An integrated framework for intelligent, resilient, and sustainable logistics is obtained only when spectral diagnosis, twin synchronization, energy bounds, selective QUBO search, provenance, and human release operate as coordinated layers rather than as a single dominant technology.

FKF/FKL representations analyze multi-scale and irregular supply-chain dynamics. Digital twins maintain synchronized monitoring and recovery-oriented simulation. Artificial intelligence supports prediction and risk assessment. Blockchain strengthens provenance of critical events. Quantum annealing and QUBO formulations address selected combinatorial kernels, particularly unit-load-device configuration, packing, assignment, and disruption recovery, while classical preprocessing and validation keep decoded solutions inside the original packing inequalities. Battery and solar constraints extend the same loop toward energy-aware mobility. Human authorization and physical-integrity bits keep automation controllable and auditable under Industry 5.0 principles. Future empirical work on real logistics datasets and standardized optimization benchmarks remains necessary before scalability, computational advantage, or sustainability benefit can be asserted.

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