Layered Spectral–Quantum Decision Architecture for Constrained Logistics Resilience

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Abstract—
Resilient logistics now has to absorb irregular lead times, energy ceilings, unit-load conflicts, and contested custody at the same time. This article assembles a layered decision architecture in which two-sided FKF/FKL spectra diagnose multi-echelon traces, a digital twin carries the synchronized state, and a QUBO / quantum-annealing kernel proposes unit-load-device recoveries that remain inside an energy-aware, human-gated feasible set. Shift-invariant and exponentially modulated identities keep clock offset and intensity drift from being misread as structural change; distributional pairing on a testing-function space and sequential convergence allow bursty Internet of Things packets to update the twin without a regime reset. Hash-chain provenance and a power-line-carrier integrity bit separate physical compromise from ordinary telemetry faults. Industry 5.0 swipe authorization remains a distinct layer: prediction is not release. The paper specifies professional equations, a constraint-gated Hamiltonian, an evaluation protocol against classical heuristics, and indicator language for later yard trials. Adjacent artificial-intelligence and digital-twin studies in engineered materials and processing are cited only as methodological parallels, not as logistics evidence.

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

I. MOTIVE, EXPOSURE, AND DECISION LAYERS

Interconnected freight networks now fail in several coordinates at once: delayed scans, depleted batteries, blocked unit-load slots, and disputed custody [29,32]. A usable support system must therefore represent the live state, name the disturbance class, and emit only those recoveries that remain physically and organizationally feasible. Classical search stays the baseline; Internet of Things streams, digital twins, blockchain records, artificial intelligence, and selective quantum kernels are added as complementary layers rather than replacements [7,9,11,20].

Mobility infrastructure and intelligent transportation systems deliver the latency and location packets that a twin can ingest [20,26]. Predictive scores for disruption and green-mode choice come from the sustainable-logistics evidence base [8]. Synchronized replicas support counterfactual recovery ranking [7,33]. Hash-chain provenance hardens transparency when echelons disagree [9]. Multi-echelon lead-time traces still mix translation, scale drift, transients, and missing samples. Residue-based resonance extraction isolates recurring hybrid-vehicle modes [13], while shift-invariant FKF analysis keeps a pure delay from being read as a new mechanism [14,18]. The joint spectral framework and the complementary FKL transform supply the two-parameter state [15,17]. Spectral differentials, distributional pairing, and sequential convergence on a testing-function space authorize irregular atoms and expanding windows [16,30,31]. Exponential modulation follows intensity drift on secured digital traces [19].

On the combinatorial side, unit-load-device packing, assignment, and disruption repair admit a QUBO lift after classical reduction [25]. Broader quantum-logistics surveys require identical-instance scoring against heuristics before any advantage is claimed [11,27]. Energy-aware mobility folds battery capacity, plug-in-hybrid sizing, and solar-assisted contribution into the feasible set [12,22,24,28]. Industry 5.0 practice and the swipe controller keep release authority with a designated operator [10,21]. Power-line-carrier anti-theft sensing distinguishes a missing heartbeat from an ordinary radio gap [23]. Methodological parallels in digital-twin textile processing and other AI-for-engineering reviews are acknowledged only for instrumentation style [4,5,6].

II. RELATED INSTRUMENTS AND SYMBOL DISCIPLINE

A. Prior Layers That This Architecture Reuses

Resilience under digital transformation is treated here as an agenda rather than a finished metric [29]. Ripple-effect analytics and digital supply-chain twins motivate keeping a live discrepancy between replica and plant [32,33]. Green-logistics bibliometrics insist that carbon and energy enter as constraints, not as after-action reports [8]. Blockchain–AI integration supplies the provenance pattern later written as a hash recursion [9]. Those sources set the governance question; they do not by themselves diagnose a lead-time trace.

Shift-invariant FKF analysis is what stops a pure delay from being labelled a new mechanism [14,18]. Residue-based resonance extraction isolates recurring hybrid-vehicle and multi-scale modes [13]. The spectral framework paper supplies the joint Fourier–Kontorovich–Lebedev representation used below [15]. Distributional differentials, testing-function pairing, and sequential convergence of the two-sided transform authorize irregular atoms [16,30,31]. Exponential modulation tracks intensity change on secured digital traces [19]. FKL moments remain the slow-scale complement [17]. Together they form the diagnostic layer that the twin is allowed to commit.

B. Indexing, Time Arguments, and Penalty Marks

Binary decisions that couple an object to a slot or an event to a recovery window carry two indices, matching assignment practice in quantum-logistics notes [11,20,21,25,27]. Continuous energy, mobility, and spectral quantities keep a single identifying subscript [12,22,24,28]. Time-dependent maps are written with an explicit argument so that a lead-time shift is never confused with an item index [13–19,30]. Penalty weights that lift equalities into an unconstrained Hamiltonian are marked λ with a constraint-class subscript, keeping physics distinct from solver tuning [11,25,27,29]. The working hierarchy is therefore binary decisions → continuous operational variables → time-dependent states → FKF–FKL spectral states → QUBO penalty terms.

III. UNIT-LOAD RECOVERY AS A GATED QUADRATIC PROGRAM

Unit-load-device configuration under disruption is written as a QUBO only after a classical filter has removed dominated packings [25]. Transportation-and-logistics surveys require that any annealer run be compared with tabu, ALNS, or MIP on the same instances and wall-clock budget [27]. The kernel itself is restricted to packing, assignment, and selected recovery routing rather than to an undifferentiated quantum supply chain" [11]. That restriction is what keeps the Hamiltonian small enough for present hardware.

A. Filtered Variables

Let I be the cargo set after aggregation, J the ULD slots, and K the disruption events that survive the filter. Geometrically impossible pairs are stored in a forbidden set F and never instantiated as decision bits.

$$x_{ij} \in \{0,1\}, \quad x_{ij} = 1 \ iff\ item\ i\ occupies\ slot\ j. \qquad (1)$$

$$y_k \in \{0,1\}, \quad y_k = 1 \ iff\ event\ k\ is\ recovered\ in\ the\ window. \qquad (2)$$

B. Primitive Packing Laws

Each item occupies exactly one admissible slot, and both weight and a second resource stay inside device limits. These identities are checked after decoding; they are not optional scoring terms.

$$\sum_{j \in J} x_{ij} = 1 \quad for\ all\ i \in I. \qquad (3)$$

$$\sum_{i \in I} w_i x_{ij} \le C_j \quad for\ all\ j \in J. \qquad (4)$$

$$\sum_{i \in I} a_i x_{ij} \le A_j \quad for\ all\ j \in J. \qquad (5)$$

C. Unconstrained Lift

Annealing engines accept a quadratic form without explicit equalities. The assignment vector x and the recovery vector y are stacked as z, and each hard law is squared and weighted.

$$min_{z \in \{0,1\}^n} \ Q(z) = z^T Q z + c^T z. \qquad (6)$$

$$H(z) = H_{obj}(z) + \lambda_{asg} H_{asg}(z) + \lambda_{cap} H_{cap}(z) + \lambda_{dis} H_{dis}(z). \qquad (7)$$

$$H_{obj} = \sum_{i,j} c_{ij} x_{ij} + \sum_{k \in K} \rho_k (1 - y_k). \qquad (8)$$

$$H_{asg} = \sum_i \left(\sum_j x_{ij} - 1\right)^2. \qquad (9)$$

$$H_{cap} = \sum_j \left(\sum_i w_i x_{ij} + \sum_m 2^m s_{jm} - C_j\right)^2. \quad (10)$$

D. Disruption Charge and Identical-Instance Gap

Let $D_t \subseteq J$ be the slots declared unavailable at epoch t. The disruption Hamiltonian charges unrecovered outages and forbids pairs tagged by event k, which is the configuration-under-disruption setting used in the ULD annealing note [25].

$$H_{dis} = \sum_k \rho_k (1 - y_k) + \sum_{k,i,j} \delta_{kij} x_{ij} (1 - y_k). \quad (11)$$

$$\Gamma_n = \frac{|E_Q - E_C|}{|E_C|}. \quad (12)$$

A distribution of Γ_n over a fixed testbed not a single anecdote is the evaluation unit required by the transportation quantum survey [27]. Feasibility after decoding is verified by substituting x back into (3)–(5). Figure 1 records the gate that must precede every anneal.

Fig. 1. Constraint-gated recovery of unit-load assignments

Fig. 1. Constraint-gated recovery of unit-load assignments after classical reduction.

IV. SPECTRAL DIAGNOSIS, TWIN STATE, ENERGY, AND RELEASE

A. Two-Sided FKF/FKL Features

Joint Fourier–Kontorovich–Lebedev coordinates are the spectral state the twin is allowed to store [15]. A mere translation of the operational clock must change phase only [14,18]. FKL carries the slow scale [17]. Residue calculus isolates recurrent hybrid-vehicle modes [13]. Distributional extension and sequential convergence of expanding windows in the testing-function space license irregular and streaming traces [16,30,31]. Exponential modulation follows intensity drift on secured digital networks [19].

$$\mathcal{F}_{FKF}[f](\xi,\eta) = \int_0^{\infty} \int_{-\infty}^{\infty} f(t,r)\, e^{-i\xi t}\, K_{i\eta}(r)\, dt\, dr. \quad (13)$$

$$\mathcal{F}_{FKL}[f](\eta) = \int_0^{\infty} f(r)\, K_{i\eta}(r)\, \frac{dr}{r}. \quad (14)$$

$$\mathcal{F}_{FKF}[f(t-\tau,r)] = e^{-i\xi\tau}\, \mathcal{F}_{FKF}[f(t,r)]. \quad (15)$$

$$R_k = Res_{z=z\_k}\, \mathcal{F}_{FKF}[f](z,\eta). \quad (16)$$

Fig. 2. Closed sensing–diagnosis–authorization loop

Fig. 2. Closed sensing–diagnosis–authorization loop used by the twin.

B. Replica Error, Battery Envelope, Hash, and Swipe Predicate

The digital-twin reviews supply synchronized state and counterfactual ranking [7,33]. IoT and ITS packets refresh that replica [20,26]. Battery chemistry, solar-hybrid architecture, formula-hybrid sizing, and solar-assisted mobility define the energy envelope that green logistics treats as a constraint [8,12,22,24,28]. Blockchain integration binds each observation window [9]. PLC anti-theft contributes the integrity bit [23]. Industry 5.0 logistics and the swipe controller supply the human predicate [10,21].

$$\rho_t = \frac{\|\hat{x}_t - x_t\|_2}{1 + \|x_t\|_2}. \quad (17)$$

$$SOC_{t+1} = SOC_t + \frac{\left(\eta_c P_{c,t} - \frac{P_{d,t}}{\eta_d}\right)\Delta t}{B}. \quad (18)$$

$$H_t = SHA-256(H_{t-1} \parallel M_t). \quad (19)$$

$$G_t = 1_{\{\pi_t \le \pi_{max}\}} \cdot 1_{\{H_t = H_t*\}} \cdot 1_{\{I_t = 1\}} \cdot 1_{\{S_t = 1\}}. \quad (20)$$

$$r_t = y_t - \hat{y}_t, \quad z_{t+1} = z_t + K_t r_t. \quad (21)$$

$$J_g = \alpha D_t + \beta C_t + \gamma E_t. \quad (22)$$

Equation (20) is the only predicate that turns a recommended recovery into an authorized dispatch. Spectral or AI alerts may raise π_t; they do not flip S_t.

Fig. 3. Graduated human release under Industry 5.0

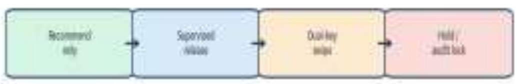

Fig. 3. Graduated human release under Industry 5.0.

Fig. 4. Energy envelope used as a hard logistics constraint

Fig. 4. Energy envelope treated as a hard logistics constraint.

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V. MEASUREMENT PROTOCOL AND INTERPRETIVE READING

What follows is a measurable protocol, not an industrial performance claim. FKF/FKL features should be scored on multi-echelon lead-time traces for shift detection, resonance stability, and sequential window behaviour in the testing-function space [13,14,30,31]. Twins should be driven by IoT/ITS telemetry and reported through ρ_t [7,20,26,33]. QUBO kernels should run on standardized ULD instances and be compared with tabu, ALNS, and MIP under one wall-clock budget [25,27]. Multi-objective cases must include carbon, battery draw, and solar availability [8,12,28].

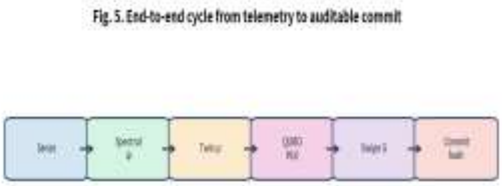

Fig. 5. End-to-end cycle from telemetry to auditable commit.

Provenance and integrity are logged as hash continuity and PLC uptime [9,23]. Human-in-the-loop metrics are authorization latency, override rate, and residual risk after swipe [10,21]. Adjacent AI studies on pavement imaging, village-scale water models, geopolymer mechanics, and textile digital twins are useful only as reminders that engineered sensing stacks can be instrumented with the same commit discipline [4,5,6]. The enclosing resilience agenda remains that of the digital-transformation review and the ripple-effect literature [29,32].

Fig. 6. Staged adoption from sensing to selective annealing.

Prediction is not authorization. A spectral residue or an AI score may identify a probable disruption; the twin may estimate its consequence; a quantum or classical solver may list recoveries; none of those steps releases a unit load. Human-centric control and the hash-backed swipe remain distinct layers, which is why Figure 5 ends on commit rather than on anneal.

VI. CONCLUSION

The reconstructed architecture is an assembly of coordinated layers, not a claim of autonomous yard control. Digital twins keep the operational replica aligned with the physical network. Green logistics and hash-chain provenance impose sustainability and inspectable custody. Industry 5.0 practice and the swipe controller keep release in human hands. Two-sided FKF/FKL spectra classify translation, intensity drift, and residue-based resonance on irregular lead-time traces. Quantum annealing is reserved for those unit-load kernels that survive classical reduction. Battery, plug-in-hybrid, and solar-assisted models bound the work that may be dispatched. Power-line-carrier anti-theft sensing and intelligent-transportation packets close the physical loop. Combined industrial effectiveness still has to be measured on shared traces and identical-instance benchmarks.

Table I. Principal symbols used in the reconstructed equations

Symbol class	Interpretation
x_{ij}, y_k, s_j, m	Binary assignment, recovery, and slack bits
w_i, C_j, a_i, A_j	Item weight, slot capacity, second resource and limit
E(t), SOC(t), B	Energy, state of charge, battery size
$F_{FKF}, F_{FKL} \in$	Two-sided FKF and complementary FKL transforms
$\lambda_{asg}, \lambda_{cap}, \lambda_{dis}$	QUBO penalty weights by constraint class
H_t, I_t, S_t	Hash digest, integrity bit, swipe release
ρ_t, π_t, Γ_n	Twin discrepancy, disruption risk, annealer gap

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