FKF–FKL Spectral Analysis and Quantum Optimization for Intelligent and Resilient Logistics

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Abstract—
Modern supply chains require intelligent methods to manage disruptions, uncertain lead times, energy constraints, and complex logistics decisions. This study proposes an integrated framework combining FKF/FKL spectral analysis, digital twins, artificial intelligence, blockchain traceability, and quantum-inspired optimization for resilient and sustainable logistics. FKF/FKL transforms characterize multi-scale lead-time patterns, shifts, and operational perturbations, while digital twins provide synchronized representations of evolving supply-chain states. Quantum annealing and quadratic unconstrained binary optimization (QUBO) support selected problems such as unit-load-device configuration, packing, assignment, and disruption recovery, complemented by classical preprocessing and validation. Energy-aware mobility incorporates battery capacity, solar contribution, and route requirements into logistics decisions. AI enables prediction and risk assessment, while blockchain strengthens provenance and traceability and human-centric controls preserve operational authority. The resulting architecture integrates sensing, spectral analysis, prediction, optimization, verification, and recovery into a unified decision-support cycle for resilient logistics

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. INTRODUCTION

Modern supply chains are interconnected and exposed to disruptions, uncertain lead times, transport constraints, energy limits, and sustainability pressure **[29]**. Decision support must represent operational state, identify emerging disturbance, and select feasible recovery. Conventional optimization remains fundamental; IoT, digital twins, blockchain, AI, and selective quantum computing supply complementary layers **[7], [9], [11], [20]**.

IoT and intelligent transportation systems provide mobility and infrastructure telemetry **[20], [26]**. Artificial intelligence supports prediction and sustainable logistics decisions **[8]**. Digital twins maintain synchronized physical operational state and support recovery analysis **[7]**. Blockchain strengthens transparency, traceability, and provenance **[9]**. Lead-time traces contain shifts, scale variation, transients, and irregular patterns. The FKF transform and the complementary FKL transform supply the spectral layer for those traces **[13], [14], [15], [16], [17], [18], [19], [30], [31]**.

At the combinatorial layer, unit-load-device (ULD) configuration, packing, assignment, and disruption recovery are natural QUBO kernels. Quantum Computing for Logistics Optimization treats ULD configuration under disruption as an annealing problem after classical reduction **[25]**. Broader quantum-logistics surveys insist that industrial use stay selective and be scored against classical heuristics on identical instances **[11], [27]**. Energy-aware mobility folds battery capacity, solar contribution, and route demand into the feasible set **[12], [22], [24], [28]**. Industry 5.0 and the swipe controller keep human authority over critical release **[10], [21]**. Power-line-carrier anti-theft sensing distinguishes physical compromise from ordinary telemetry fault **[23]**.

II. Scope and Notational Convention

Throughout the formulation, notation is standardized to distinguish discrete operational decisions, continuous physical quantities, and spectral variables. Binary decision variables are written with a double subscript when they couple an object, vehicle, shipment, or task index with a slot, device, location, or planning period, consistent with assignment and logistics formulations discussed in [11], [20], [21], [25], and [27]. Continuous energy, power, battery, mobility, and spectral quantities use a single identifying subscript, supporting the energy and mobility representations developed in [12], [22], [24], and [28].

Time-dependent quantities are written with explicit arguments in parentheses, such as $E(t)$, $P(t)$, and $\ell(t)$, to distinguish temporal evolution from indexing. This convention is particularly important for FKF/FKL spectral analysis, where temporal behavior, lead-time shifts, scale-dependent dynamics, and resonance characteristics are treated explicitly [13–19], [30], [31]. Distributional and sequential formulations likewise retain explicit temporal dependence when representing irregular observations and expanding data windows [30], [31].

Penalty weights that convert hard equalities and inequalities into unconstrained QUBO terms are denoted by $\lambda$with a constraint-class subscript, such as λ_{assign}, λ_{energy}, $\lambda_{\text{capacity}}$, and $\lambda_{\text{recovery}}$. This notation separates physical model parameters from optimization penalties and facilitates the integration of QUBO and quantum-annealing formulations with digital-twin and resilience architectures [11], [25], [27], [29]. The resulting notation also supports the coupling of spectral state variables with IoT, AI, blockchain, human-centric control, and digital-twin layers [7], [9], [10], [20], [21], [23], [29].

Accordingly, the notation follows the hierarchy

binary decisions → continuous operational variables
→
time-dependent states → FKF–FKL spectral states
→
QUBO penalty terms

so that mathematical variables remain distinguishable across the physical, spectral, digital-twin, and optimization layers [7–31].

Table 1. Principal symbols used in 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}	Two-sided FKF and complementary FKL transforms
$\lambda_{asg}, \lambda_{cap}, \lambda_{dis}$	QUBO penalty weights
H_t, I_t, S_t	Hash digest, integrity bit, swipe release
ρ_t, π_t, Γ_n	Twin discrepancy, disruption risk, annealer gap

III. QUANTUM-ENABLED LOGISTICS AND UNIT-LOAD CONFIGURATION

Quantum Computing for Logistics Optimization establishes ULD configuration under disruption as a QUBO after classical pre-processing **[25]**. Quantum Computing in Transportation and Logistics requires identical-instance comparison with classical heuristics **[27]**. Navigating the Quantum Revolution in Logistics restricts the kernel to packing, assignment, and selected routing **[11]**.

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. Pre-processing removes dominated packings and maps geometrically infeasible pairs to a forbidden set F.

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

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

B. Primitive packing constraints

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

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

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

C. QUBO lift

Annealing engines accept an unconstrained quadratic form. Equalities and inequalities are transcribed with non-negative penalties. Let z collect assignment bits x and recovery bits y.

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

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

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

$$H_{asg} = \sum_i (\sum_j x_{ij} - 1)^2 \quad (9)$$

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

D. Disruption extension and benchmark

Let $D_t \subseteq J$ be slots unavailable at epoch t. The disruption Hamiltonian charges unrecovered outages and forbids pairs marked by event k, which is the configuration-under-disruption setting of **[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 implied by **[27]**. Feasibility after decoding is checked by substituting x back into (3)–(5).

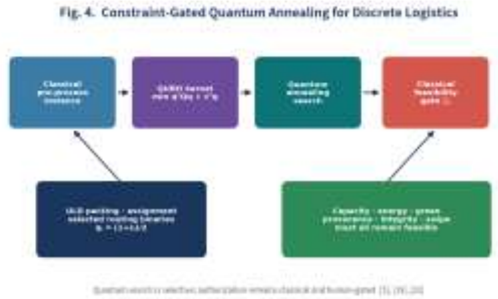

Fig. 1. Constraint-gated quantum annealing for ULD configuration after [11], [25], [27]

IV. SPECTRAL, TWIN, ENERGY, AND GOVERNANCE LAYERS

A. Two-sided FKF/FKL features

The spectral framework for supply-chain dynamics and resilience is the FKF representation **[15]**. Shift-invariant analysis of multi-echelon lead times prevents a mere delay from being read as a new mechanism **[14], [18]**. FKL supplies the complementary scale transform **[17]**. Residue-based resonance extraction isolates recurring hybrid-vehicle and multi-scale modes **[13]**. Distributional extension and sequential convergence authorize irregular traces and streaming updates **[16], [30], [31]**. Exponential modulation tracks intensity change in secure 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. Governed prediction–authorization loop using [7]–[10], [20], [21], [23], [26].

B. Twin, energy, provenance, and swipe

The digital-twin review supplies synchronized state and counterfactual ranking **[7]**. IoT/ITS telemetry updates the replica **[20], [26]**. Battery, solar-hybrid, formula-hybrid sizing, and solar-assisted mobility define the energy envelope **[12], [22], [24], [28]**. Green-logistics bibliometrics require those variables to act as constraints **[8]**. Blockchain integration binds observation windows **[9]**. PLC anti-theft contributes the integrity bit **[23]**. Industry 5.0 intelligent logistics and the swipe controller supply the human predicate **[10], [21]**.

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

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

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

$$G_t = 1\{\pi_t \leq \pi_{max}\} \cdot 1\{H_t = H_{t*}\} \cdot 1\{I_t = 1\} \cdot 1\{S_t = 1\} \quad (20)$$

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

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

Fig. 3. Graduated Industry 5.0 swipe authorization after [10], [21].

Fig. 4. Energy envelope after [12], [22], [24], [28].

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V. RESULTS PROTOCOL AND DISCUSSION

Future This reconstruction specifies a measurable protocol rather than an industrial claim. FKF/FKL features should be scored on multi-echelon lead-time traces for shift detection, resonance stability, and sequential convergence **[13], [14], [30], [31]**. Twins should be driven by IoT/ITS telemetry and reported through ρ_t **[7], [20], [26]**. QUBO kernels should be run on standardized ULD instances and compared with tabu, ALNS, and MIP under the same wall-clock budget, following **[25], [27]**.

Fig. 5. End-to-end sensing–spectral–twin–QUBO–swipe cycle

Multi-objective cases must include carbon, battery draw, and solar availability **[8], [12], [28]**. Provenance and integrity should be 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]**. The enclosing resilience agenda remains that of the digital-transformation review **[29]**.

Fig. 6. Progressive deployment from sensing to selective QUBO.

Integrated Architecture and Scope

The reconstructed architecture forms a citation-closed assembly of established technological and analytical instruments. Digital-twin technology provides the synchronization layer for representing evolving physical and operational states, while green-logistics and blockchain mechanisms introduce sustainability constraints, traceability, and verifiable operational records. Human-centric control and Industry 5.0 principles provide the authorization and intervention layer, ensuring that automated recommendations remain subject to appropriate operational oversight.

Quantum computing and quantum-annealing approaches provide optimization capabilities for selected combinatorial logistics problems, particularly packing, assignment, and disruption-aware ULD configuration. Energy and mobility models establish practical constraints associated with battery capacity, usable range, power availability, and solar-assisted operation. In parallel, FKF/FKL spectral methods provide the diagnostic layer for identifying multi-scale lead-time behavior, temporal translation, intensity variation, spectral perturbation, and resonance. IoT and intelligent transportation systems provide the sensing infrastructure, while secure communication mechanisms help distinguish genuine operational shortages from potential communication or system compromise.

The resulting architecture can therefore be viewed as a layered pipeline:

Sensing → Digital Twin → Spectral Diagnosis
→ Sustainability and Traceability →
Human Authorization → Optimization

This separation is important because prediction is not authorization. AI or spectral analysis may identify a probable disruption, while the digital twin may estimate its consequences and a quantum or classical optimizer may generate candidate recovery actions; none of these steps, by themselves, constitutes operational approval. Human-centric control and auditable authorization must remain distinct decision layers. The architecture should therefore be interpreted as an integrated analytical and decision-support framework rather than an assertion of autonomous industrial control.

Finally, although the individual components provide a coherent theoretical architecture, their combined industrial effectiveness cannot be assumed solely from their separate publications. Future empirical validation should use real multi-echelon operational traces, controlled disruption scenarios, common evaluation metrics, and identical-instance benchmarks for ULD and other logistics optimization problems. Comparative testing against established classical methods is also necessary before claiming measurable computational, economic, resilience, or sustainability advantages.

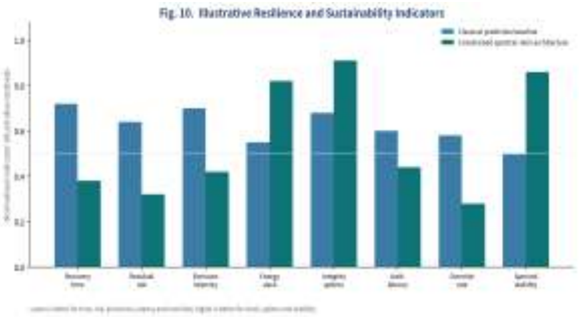

Fig. 7. Illustrative indicator language for the evaluation protocol

V. CONCLUSION

This study presents an integrated framework for intelligent, resilient, and sustainable supply-chain logistics by combining FKF/FKL spectral analysis, digital twins, artificial intelligence, blockchain traceability, quantum optimization, and human-centric decision control. The framework addresses the interconnected challenges of lead-time variability, disruption propagation, ULD configuration, transportation assignment, energy constraints, and operational traceability within a unified decision cycle.

FKF/FKL-based spectral representations provide a mechanism for analyzing multi-scale and irregular supply-chain dynamics, while digital twins enable synchronized monitoring and recovery-oriented simulation. AI supports prediction and risk assessment, and blockchain strengthens the provenance and traceability of critical operational events. Quantum annealing and QUBO formulations provide an additional optimization layer for selected combinatorial problems, particularly ULD configuration, packing, assignment, and disruption recovery, while classical preprocessing and validation ensure practical feasibility.

The integration of battery and solar-energy constraints further extends the framework toward sustainable mobility and energy-aware logistics. At the same time, human authorization and physical-integrity mechanisms ensure that intelligent automation remains controllable, auditable, and aligned with Industry 5.0 principles. Overall, the proposed architecture demonstrates that resilience is best achieved through coordinated analytical, computational, physical, and human layers rather than through a single technology. Future empirical validation on real logistics datasets and standardized optimization benchmarks will be essential for assessing scalability, computational advantage, sustainability benefits, and practical deployment.

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