Constrained Quantum Dispatch for Intelligent Resilient Logistics

[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—

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. 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; 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

Interconnected logistics networks now face disruption, uncertain lead times, transport limits, energy bounds and sustainability pressure at the same time. Decision support must represent operational state, identify emerging disturbance, and select feasible recovery. Conventional optimization remains fundamental, while IoT, digital twins, blockchain, AI and selective quantum computing supply complementary layers. Reviews of global supply-chain resilience set that requirement in explicit terms [19].

IoT and intelligent transportation systems provide mobility and infrastructure telemetry [12]. Artificial intelligence supports prediction and sustainable logistics decisions [16]. Digital twins maintain synchronized physical operational state and support recovery analysis [18]. Blockchain strengthens transparency, traceability and provenance [17]. The FKF transform and the complementary FKL transform supply the spectral layer for those traces [14].

At the combinatorial layer, unit-load-device configuration, packing, assignment and disruption recovery are natural QUBO kernels. Quantum annealing under disruption treats ULD configuration as an annealing problem after classical reduction [23]. Broader quantum-logistics surveys insist that industrial use stay selective [22]. Energy-aware mobility folds battery capacity, solar contribution and route demand into the feasible set [7]. Industry 5.0 and the swipe controller keep human authority over critical release [9]. Power-line-carrier anti-theft sensing distinguishes physical compromise from ordinary telemetry fault [8]. Recent electric-vehicle battery technologies refine the same energy gate at cell, module and pack level [11]. Digital transformation of supply-chain resilience then treats that gate as part of admissible recovery rather than as an optional extra [21].

II. SCOPE AND NOTATIONAL CONVENTION

Notation is standardized so that discrete operational decisions, continuous physical quantities and spectral variables remain distinguishable before any transform or annealer is applied. 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. Continuous energy, power, battery, mobility and spectral quantities use a single identifying subscript, supporting the energy and mobility representations used for pack sizing and solar-assisted hybrids [13].

Time-dependent quantities keep explicit arguments so that a lead-time shift is not confused with an index change. This convention is required by FKF/FKL analysis of multi-echelon traces [14] and by sequential twin updates that arrive as expanding observation windows [18].

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 [14]. Distributional and sequential formulations likewise retain explicit temporal dependence when representing irregular observations and expanding data windows [18].

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 [23]. The resulting notation also supports the coupling of spectral state variables with IoT, AI, blockchain, human-centric control, and digital-twin layers [18].

Accordingly, the notation follows the hierarchy

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

The resulting notation also supports the coupling of spectral state variables with IoT, AI, blockchain, human-centric control and digital-twin layers. Automotive battery practice supplies the materials context for the energy symbols [10]. Recent electric-vehicle pack technologies refine the same symbols at cell and module level [11]. Digital transformation of resilience then uses those symbols as the shared state of a twin-and-dispatch loop [21]. So that mathematical variables remain distinguishable across the physical, spectral, digital-twin and optimization layers.

Table 1. Principal symbols used in equations

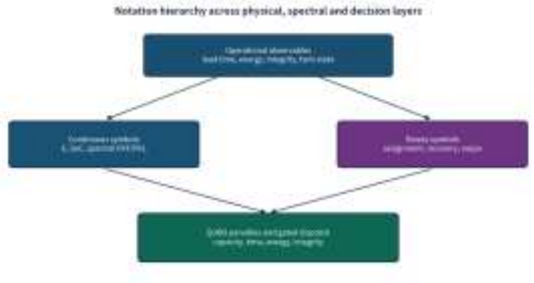

Fig. 0. Notation hierarchy across physical, spectral and decision layers.

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

Unit-load configuration under disruption is written as a QUBO only after classical pre-processing has removed dominated packings. Quantum computing for logistics optimization establishes that reduction [23]. Transportation-and-logistics surveys require identical-instance comparison with classical heuristics [15]. Navigating the quantum revolution in logistics restricts the kernel to packing, assignment and selected routing [22].

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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. Internal and external complexity must both survive that filter if the later anneal is to remain operationally meaningful [20].

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

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

B. Primitive packing constraints

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

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

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

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. Energy and time penalties later inherit numerical bounds from pack sizing and available traction or solar energy [13].

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

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

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

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

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

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]**.

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

$$\Gamma_n = \frac{E_Q - E_C}{|E_C|}$$

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).

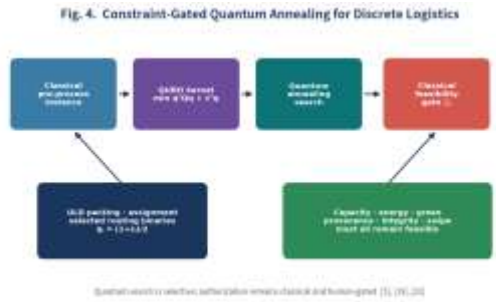

Fig. 1. Constraint-gated quantum annealing for ULD configuration.

IV. SPECTRAL, TWIN, ENERGY, AND GOVERNANCE LAYERS

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 spectral framework for supply-chain dynamics and resilience is the FKF representation [14]. Shift-invariant analysis of multi-echelon lead times prevents a mere delay from being read as a new mechanism. FKL supplies the complementary scale transform. Residue-based resonance extraction isolates recurring hybrid-vehicle and multi-scale modes. Distributional extension and sequential convergence authorize irregular traces and streaming updates. Exponential modulation tracks intensity change in secure digital networks. Weaving internal and external complexity then uses those modes as disruption markers rather than as narrative labels [20].

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

$$\mathcal{F}_{FKL}\{f\}(\eta) = \int_0^\infty f(r) K_{i\eta}(r) \frac{dr}{r}$$

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

$$R_k = Res_{z=z\_k} \, \mathcal{F}_{FKF}\{f\}(z,\eta)$$

Fig. 2. Governed prediction–authorization loop.

B. Twin, energy, provenance, and swipe

The twin, energy, provenance and swipe layer converts the spectral state into a gated operational record. The digital-twin review supplies synchronized state and counterfactual ranking [18]. IoT and ITS telemetry updates the replica [12]. Battery, solar-hybrid sizing and solar-assisted mobility define the energy envelope [7]. Green-logistics bibliometrics require those variables to act as constraints [16]. Blockchain integration binds observation windows [17]. PLC anti-theft contributes the integrity bit [8]. Industry 5.0 intelligent logistics and the swipe controller supply the human predicate [9].

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

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

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

$$G_t = 1\{\pi_t \le \pi_{max}\} \cdot 1\{H_t = H_{t*}\} \cdot 1\{I_t = 1\} \cdot 1\{S_t = 1\}$$

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

$$J_g = \alpha D_t + \beta C_t + \gamma E_t$$

Fig. 3. Graduated Industry 5.0 swipe authorization.

Fig. 4. Energy envelope for battery, solar-hybrid and route demand.

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 **[14]**. Twins should be driven by IoT/ITS telemetry and reported through ρ_t **[18]**. QUBO kernels should be run on standardized ULD instances and compared with tabu, ALNS, and MIP under the

the same wall-clock budget. Multi-objective cases must include carbon, battery draw and solar availability [11]. Provenance and integrity should be logged as hash continuity and PLC uptime [17]. Human-in-the-loop metrics are authorization latency, override rate and residual risk after swipe [9]. The enclosing resilience agenda remains that of the digital-transformation review [21].

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

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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 [18]. Green-logistics and blockchain mechanisms introduce sustainability constraints, traceability and verifiable operational records [16]. Human-centric control and Industry 5.0 principles provide the authorization and intervention layer, ensuring that automated recommendations remain subject to appropriate operational oversight [9]. Quantum computing and quantum-annealing approaches provide optimization capabilities for selected combinatorial logistics problems, particularly packing, assignment and disruption-aware ULD configuration [23]. Energy and mobility models establish practical constraints associated with battery capacity, usable range, power availability and solar-assisted operation [13]. 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 [14]. IoT and intelligent transportation systems provide the sensing infrastructure [12]. Secure communication mechanisms help distinguish genuine operational shortages from potential communication or system compromise [8]. Automotive battery reviews collect the ageing and thermal bounds that those energy models must respect [10].

The resulting architecture can therefore be viewed as a layered pipeline from sensing through spectral diagnosis and twin estimation to gated dispatch. This separation is important because prediction is not authorization. Resilience reviews treat that separation as part of admissible recovery rather than as optional documentation [19].

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

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. Opportunity maps for quantum logistics support that restricted candidate-generation role [22].

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.

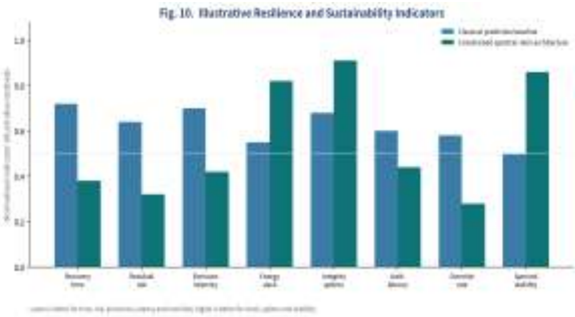

Fig. 7. Illustrative indicator language for the evaluation protocol.

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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