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A Gated FKF–FKL Spectral Digital Twin for Constrained, Green, and Quantum-Enabled Logistics

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Abstract—
Resilient logistics increasingly operate as cyber-physical systems in which sensor observations, mobility constraints, energy availability, authorization, provenance, and optimization must agree before an operational decision is committed. This reconstruction develops a gated digital-twin architecture that places an FKF–FKL spectral layer upstream of an integrity-aware dispatch layer. The spectral component separates translation, exponential intensity modulation, slow-scale FKL behavior, and residue-associated resonance; the operational component admits only observations and actions that satisfy freshness, human authorization, physical-integrity, and energy-reserve conditions. The framework therefore treats constrained resilience as a feasible-set problem rather than as a post hoc score. Digital-twin state is linked to green-logistics mode selection and blockchain-style hash-chain provenance, while quantum annealing and QUBO formulations are restricted to admissible unit-load-device configurations. IoT and intelligent transportation telemetry provide the observation stream, Industry 5.0 supplies the human-authority principle, and hybrid-electric or solar-assisted mobility supplies an energy envelope. The resulting formulation is deliberately interpretive: it unifies published instruments without claiming field validation, and it provides a reproducible mathematical structure for subsequent calibration and industrial trials.

Keywords— constrained resilience; digital twins; green logistics; blockchain traceability; FKF/FKL transforms; sequential convergence; multi-echelon lead time; quantum logistics; quantum annealing; QUBO; ULD; IoT; intelligent transportation; Industry 5.0; human-centric automation; sustainable mobility; battery sizing; solar-assisted mobility; power-line communication; anti-theft; anomaly diagnosis.

I. INTRODUCTION

Digital Supply-chain digitalization has moved the operational problem from isolated optimization toward synchronized cyber-physical decision making. Digital twins are increasingly positioned as mechanisms for representing changing network state and testing recovery alternatives, while sustainable logistics and blockchain traceability add environmental and evidentiary constraints to the same decision loop [4]–[6], [30].

A central difficulty is that telemetry is not equivalent to state. Multi-echelon lead-time streams can contain timestamp displacement, amplitude drift, missing observations, communication delay, unauthorized holds, and physical-integrity failures. If these effects are interpreted directly as structural disruption, a twin may amplify measurement artifacts into unnecessary recovery actions. The FKF transform is used here as a spectral coordinate system in which temporal translation, modulation, and resonance can be separated, while the FKL transform supplies complementary scale information [10]–[13], [18]–[20]. The second difficulty is admissibility. A spectrally interesting event should not automatically become a dispatch command. Freshness, authorization, custody, and available energy must constrain the actions that reach the optimizer. IoT and intelligent transportation systems provide latency-aware telemetry; swipe-based control records grant and hold states; power-line-carrier communication provides a physical-integrity signal; and hybrid-electric, plug-in-hybrid, and solar-assisted architectures bound the energy available for movement [7], [9], [21]–[25], [27], [29].

The final layer is computational choice. Quantum logistics studies indicate practical value in selected combinatorial problems rather than unrestricted end-to-end optimization. Accordingly, QUBO and quantum annealing are used only after classical spectral and integrity screening, with unit-load-device configuration as a representative decision problem [8], [26], [28]. This ordering keeps human authority and physical custody ahead of optimization.

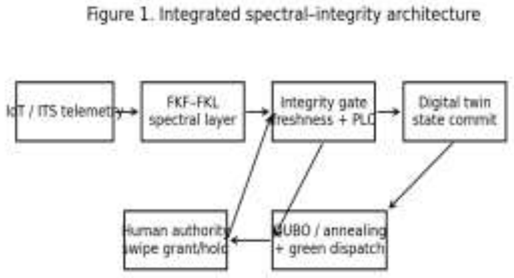

Figure 1. Reconstructed architecture linking spectral analysis, integrity controls, the digital twin, and constrained dispatch.

II. REVIEW OF THE ENABLING KNOWLEDGE BASE

Resilience, Digital Twins, and Sustainable Visibility

Resilience research establishes flexibility, redundancy, and recovery capability as system-level properties; digital-twin research translates these ideas into synchronized state representation and disruption analysis [4], [30]. Green-logistics research adds environmental performance to the operational objective, while blockchain-oriented studies provide traceability and transparency for observations whose provenance may otherwise be disputed [5], [6].

The present reconstruction combines these strands through a single state-transition principle: a digital twin should commit a decision only when its observational evidence and operational permissions are mutually consistent. This makes sustainability and provenance active constraints rather than descriptive attributes.

FKF/FKL Analysis of Multi-Echelon Dynamics

The FKF construction combines Fourier behavior in time with the Kontorovich–Lebedev/Macdonald-function coordinate, allowing oscillatory and positive-scale behavior to be inspected jointly [11], [12], [18]. The time-shift identity is important for lead-time analysis because a reporting translation should modify phase without fabricating a new structural mode [19].

Exponential modulation offers a second confound-separation mechanism: multiplying a signal by an exponential factor corresponds to a spectral displacement in the Fourier variable [20]. Distributional extension broadens the transform to generalized observations, and the two-sided construction is compatible with irregular or incomplete telemetry when interpreted through a testing-function space [32]. Sequential convergence then provides a principled way to distinguish incremental window growth from a genuine change in the limiting spectral object [33].

$$FFKF_{[\ell_t]}(\omega,\nu) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \ell(t)e - i\omega tKi\nu_{(et)}dt \quad (1)$$

Mobility, Energy, and Human-Centred Automation

Smart mobility and intelligent transportation systems determine whether telemetry is timely enough to support a live decision. Industry 5.0 reframes automation around human agency, so algorithmic recommendations remain subordinate to authorized operational personnel [21], [22], [27]. The swipe-controller concept provides a concrete grant/hold abstraction, while PLC anti-theft communication extends integrity checking into physically constrained environments [7], [24].

Energy-aware logistics requires more than a nominal battery capacity. Battery sizing, hybrid-electric architectures, and solar-assisted mobility motivate an available-energy envelope that accounts for committed work and reserve requirements [9], [23], [25], [29]. This envelope becomes a feasibility condition for green mode switching and recovery dispatch.

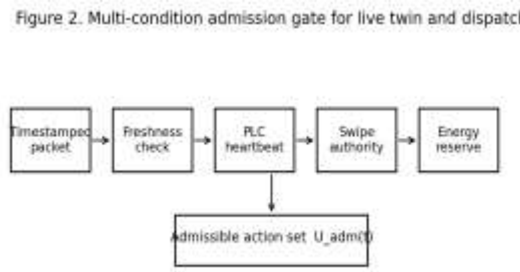

Figure 2. New integrity gate: only fresh, physically valid, human-authorized, energy-feasible actions enter the live twin or optimizer.

Quantum Logistics as a Downstream Decision Layer

Quantum-computing literature emphasizes the near-term relevance of hybrid and NISQ-era workflows, where classical preprocessing reduces the combinatorial core before quantum resources are applied [28]. QUBO formulations translate constrained binary decisions into quadratic objectives through penalty construction, making them suitable for annealing-based search [8], [26].

For unit-load-device planning, the proposed workflow does not claim that quantum annealing replaces logistics expertise. Instead, it receives a reduced set of eligible assets, slots, and recovery options after spectral and integrity screening. This ordering preserves interpretability and limits the quantum subproblem to decisions that are physically and organizationally executable.

III. MATHEMATICAL RECONSTRUCTION OF THE GATED TWIN

State Representation and Observation Freshness

Let asset a at observation time t be represented by position, velocity, available energy, and a binary integrity state. The state is intentionally compact because the digital twin should expose the variables that control feasibility rather than reproduce every raw sensor channel.

$$m_{a,t} = (p_{a,t}, v_{a,t}, E_{b,a,t}, \sigma_{a,t}) \quad (2)$$

The observation latency is measured from the timestamp carried by the packet to its receipt. A maximum-latency threshold defines whether an observation can update the live state.

$$L_{a,t} = t_{recv} - t_{stamp} \quad (3)$$

$$L_{a,t} \leq L_{max} \quad (4)$$

A stale observation is not discarded from the audit record; it is simply prevented from altering the live twin. This distinction allows distributional spectral analysis to retain irregular evidence while operational control remains freshness constrained.

Human Authorization and Physical Custody

Authorization is represented by binary grant and hold processes on an explicit control clock. Their mutual exclusion prevents a single request from being simultaneously executable and suspended.

$$g_{r,t} + h_{r,t} \leq 1 \quad (5)$$

$$A_{open}(t_r) = \int t_0^{t_1}(g_r(\tau) - h_r(\tau))d\tau \quad (6)$$

Human override is retained as a first-class condition. If an authorized operator grants an action, the machine recommendation cannot erase that authority; conversely, a human hold can prevent execution even when a solver reports a low-cost alternative. This realizes the human-centric principle of Industry 5.0 [22].

Physical custody is monitored separately from authorization. A PLC heartbeat and sealed-path checksum define a binary integrity state, so a missing heartbeat is treated as a custody failure rather than merely as a communication anomaly [24].

$$\iota_{a,t} = 1 \; if \; |s_{a,t} - s^*(a,t)| \leq \varepsilon_{PLC}; \; otherwise \; 0$$
(7)

$$\sigma_{a,t} = 1(L_{a,t} \leq L_{max}) \cdot \iota_{a,t} \quad (8)$$

Integrated Feasibility Gate

The operational gate joins freshness, integrity, authorization, and energy reserve into a single admissible set. Only actions satisfying every condition are exposed to the dispatch layer.

$$U_{adm,t} = \{ u : E_{work,u} \leq E_{avail,t} - E_{reserve}, \sigma_{a,t} = 1, g_{u,t} = 1 \} \quad (9)$$

This formulation converts constrained resilience into a feasibility statement. A recovery plan is resilient only when the required work remains executable under the simultaneous limits imposed by energy, custody, latency, and human authority.

IV. SPECTRAL–OPERATIONAL COUPLING

After admission, the twin compresses each window into spectral features rather than carrying the full telemetry stream into every decision. Dominant FKF magnitude, characteristic frequency, and low-order FKL moments form a compact representation of the current lead-time regime.

Translation-Invariant Features

A pure temporal displacement should be treated as an observational transformation. For a shift τ_0, the FKF spectrum acquires phase while its magnitude envelope is preserved, which supports shift-invariant comparison of multi-echelon lead-time traces [19].

$$FFKF_{[\ell(t-\tau_0)]}(\omega, \nu) = e - i\omega\tau_0 FFKF_{[\ell(t)]}(\omega, \nu)$$
(10)

This property is operationally useful because delayed reporting, synchronized shipment holds, and clock offsets can be screened before a structural alarm is raised. The twin therefore compares invariant envelopes first and phase-dependent quantities second.

Exponential Drift and Residue Signatures

Amplitude drift is represented by exponential modulation rather than by declaring a new logistics mechanism. If the input is multiplied by e raised to αt, the Fourier coordinate shifts into the complex plane [20].

$$FFKF_{[e\alpha^t \ell(t)]} = FFKF_{[\ell]}(\omega + i\alpha, \nu) \quad (11)$$

Residue-based resonance is then examined after translation and modulation effects have been compensated. A compact normalized spectral displacement may be written as follows.

$$\Delta_{spec}(\omega) = \frac{||FFKF_{[\ell]}||K_L - ||FFKF_{[\ell]}|K_L}{||FFKF_{[\ell]}||K_L + \varepsilon_0} \quad (12)$$

The exact threshold for resonance is intentionally left for calibration. The theoretical role of the residue is diagnostic: persistent concentration across convergent

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windows is stronger evidence of a structural mechanism than a single large packet.

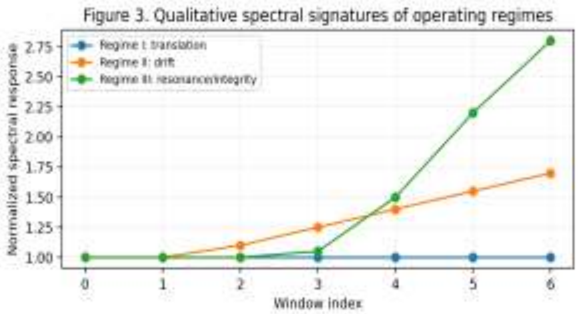

Figure 3. Qualitative spectral regimes used by the reconstructed twin: translation, intensity/energy drift, and persistent resonance or integrity failure.

Three Decision Regimes

Regime I represents gated translation. Freshness, authorization, and PLC integrity are valid, while the spectral envelope remains stable. The twin therefore updates phase-related state without initiating a new-mechanism recovery action.

Regime II represents intensity or energy drift. Exponential modulation changes amplitude, while FKL moments may move as the operating scale changes. If the feasible set remains nonempty, green mode selection can shift toward solar-assisted or plug-in-hybrid mobility without rebuilding the entire dispatch problem [23], [25], [29].

Regime III represents integrity failure or persistent resonance. A stale packet, missing physical heartbeat, human hold, or concentrated residue can remove an action from the live feasible set. If resonance persists through sequentially convergent windows, the remaining admissible alternatives can be passed to a QUBO or hybrid annealing workflow [26], [28], [33].

V. PROVENANCE, SUSTAINABILITY, AND DECISION INTEGRITY

Every accepted window should carry a provenance record that binds the spectral feature vector to freshness, authorization, and physical-integrity bits. Hash-chain construction can then make retrospective modification detectable, while the green-logistics layer can learn only from states that satisfy the integrity gate [6].

This coupling matters because an anomalous or stolen asset should not become training data for a predictive model merely because its telemetry contains a strong spectral feature. Freezing downstream learning when integrity fails prevents spurious modes from being absorbed into the digital representation.

VI. GREEN AND ENERGY-AWARE LOGISTICS

Available-Energy Envelope

Energy is treated as a dispatch resource with a protected reserve rather than as a static vehicle specification. Battery-management and sizing studies motivate a state-dependent estimate of usable energy, while solar-assisted and hybrid architectures provide additional, path-dependent supply [9], [23], [25], [29].

$$E_{commit}(t,H) \le E_{avail}(t) - E_{reserve}(t) \quad (13)$$

The resulting envelope can be attached directly to logistics work. If a proposed ULD movement, route, or recovery action consumes more energy than the remaining envelope permits, it is excluded before optimization. This prevents a mathematically attractive schedule from becoming an infeasible green-logistics plan.

Sustainable Mode Switching

Sustainable logistics is represented as a constrained choice among operational modes rather than as an independent reporting metric. Solar contribution, battery state, route length, and required reserve can jointly determine whether a hybrid-electric or plug-in-hybrid leg is feasible [23], [29].

Because the spectral layer identifies whether the underlying lead-time change is translation, drift, or resonance, mode switching can be targeted. A drift caused by energy scarcity should not be confused with a custody failure, and a custody failure should not trigger unnecessary energy-intensive repositioning.

VII. QUANTUM-CONSTRAINED ULD RECONFIGURATION

Binary Decision Structure

The downstream optimization stage receives only eligible assets and slots. Binary variables can represent assignment of an admissible unit-load device to a recovery position, while penalties enforce exclusivity and operational feasibility. The QUBO is therefore a reduced representation of the gated logistics problem rather than a replacement for the upstream decision logic [8], [26], [28].

$$minimize\ Q(x) = x^T Q x + \lambda_1 P_1(x) + \lambda_2 P_2(x) \quad (14)$$

The penalty weights should be calibrated so that hard constraints dominate soft cost terms. In a hybrid workflow, classical preprocessing removes stale, unauthorized, or physically compromised candidates before the binary graph is embedded or annealed.

Hybrid Quantum–Classical Workflow

A practical sequence is: acquire IoT/ITS observations; compute FKF/FKL features; test freshness and physical integrity; apply human authorization; estimate energy feasibility; construct the reduced ULD problem; solve classically or by annealing; and write the selected state back to the twin with provenance. This ordering reflects the selective role assigned to quantum logistics in the cited work [8], [26], [28].

Quantum annealing is thus treated as an optional search engine inside a controlled architecture. If the admissible set is empty, the correct response is not to weaken the gate simply to obtain a solution; the twin should report infeasibility and preserve the evidence for diagnosis.

VIII. ANOMALY DIAGNOSIS AND CONSTRAINED RESILIENCE

The framework distinguishes four diagnostic classes: observational confound, energy drift, authorization conflict, and physical or spectral disruption. The distinction is useful because each class requires a different response, ranging from waiting for a fresh packet to reconfiguring the logistics plan.

A resilience score can subsequently combine service recovery, energy margin, integrity, and spectral persistence. The score should be computed after the gate, not used to bypass it, so that resilience remains physically and organizationally constrained.

From Parallel Technologies

The technologies are often presented as separate innovations: digital twins synchronize state, blockchain records provenance, green logistics reduces environmental burden, IoT supplies observations, Industry 5.0 protects human agency, and quantum computing addresses selected combinatorial problems [4]–[8], [21], [22], [28], [30]. The reconstruction instead treats them as stages of one decision grammar.

The FKF/FKL layer answers whether a change is observationally explainable; the integrity gate asks whether it is operationally admissible; the digital twin records the resulting state; the sustainability layer tests resource consequences; and the quantum or classical optimizer selects among the remaining feasible actions. This division of responsibility reduces the risk that one technology is asked to compensate for another technology's failure.

Distributional Reasoning for Bursty Telemetry

IoT streams are rarely smooth laboratory signals. Packet loss, asynchronous sampling, and short-lived bursts make classical pointwise assumptions fragile. The distributional extension places observations in duality with testing functions, while sequential convergence of expanding windows provides a route for online analysis [32], [33].

The practical implication is conservative interpretation. A single packet can contribute evidence without automatically redefining the operating regime. Only when the transformed sequence demonstrates stable, persistent displacement should the twin promote the event from an observation to a structural diagnosis.

Human Authority as a Mathematical Constraint

Human-centric automation is often described at the policy level, but the present architecture makes it explicit in the feasible set. Grant and hold states are binary, mutually exclusive, and auditable; operator intervention is not a dashboard annotation but a constraint on executable actions [7], [22].

This approach also improves explainability. When a QUBO solution is rejected, the twin can identify whether the reason was freshness, custody, authorization, energy, or a spectral rule. The operator therefore sees a constraint-based explanation instead of an opaque optimization failure.

Provenance and Trustworthy Learning

Hash-chain provenance provides a compact integrity mechanism for committed observation windows. Each record can include the feature vector, timestamps, grant state, PLC state, and selected action, with the digest of the previous record incorporated into the next commitment [6].

The resulting chain does not make the physical system automatically trustworthy; rather, it makes retrospective alteration easier to detect. That distinction is important when digital-twin outputs become training data, regulatory evidence, or inputs to recovery optimization.

IX. IMPLEMENTATION BLUEPRINT

A deployable implementation can be organized into five services: telemetry ingestion, spectral processing, integrity and authorization, twin-state management, and optimization. Each service should expose explicit interfaces so that a failure in one layer cannot silently bypass another.

The telemetry service records raw and timestamped observations. The spectral service computes FKF/FKL features and convergence diagnostics. The integrity service evaluates latency, PLC heartbeat, and authorization. The twin service commits only admitted states and provenance. The optimizer consumes the resulting feasible action set and returns a classical or quantum-assisted recommendation.

This modularity also supports staged validation. An initial study can calibrate latency and energy thresholds, a second can test spectral discrimination on archived traces, and a later instrumented yard trial can measure recovery performance. The cited sources support the component architecture, but they do not by themselves establish industrial performance for the combined system [4]–[13], [18]–[30], [32], [33].

Evaluation Logic and Research Directions

Evaluation should begin with classification of events whose causes are known. Translation experiments can test whether magnitude remains stable under time displacement; controlled exponential scaling can test modulation compensation; synthetic or archived resonant traces can test residue persistence; and packet-drop experiments can test distributional stability [10]–[13], [19], [20], [32], [33].

Operational evaluation should then measure gate behavior. Relevant quantities include false admission of stale packets, false rejection of fresh packets, unauthorized-action rate, integrity-detection delay, energy-feasibility violations, and the fraction of ULD decisions requiring quantum search. These metrics connect the mathematical framework to implementable logistics controls.

Integration with Smart Mobility and IoT

Smart mobility infrastructure can supply the latency and connectivity information required by the freshness gate, while IoT devices provide position, velocity, energy, and custody observations [21], [27]. Power-line-carrier communication is particularly relevant where metallic structures or local radio conditions complicate wireless integrity monitoring [24].

The next step is therefore not simply to add more sensors. It is to synchronize sensing semantics: every observation should carry a timestamp, source identity, integrity state, and relationship to the physical asset. This makes the spectral layer and provenance layer operate on the same atomic evidence.

Research Opportunities in Quantum Logistics

Quantum logistics research can focus on adaptive subproblem selection. Rather than sending every dispatch problem to an annealer, the twin can estimate classical difficulty, feasible-set size, and disruption severity, then choose between classical heuristics, exact optimization, or quantum annealing [8], [26], [28].

This hybrid policy also offers a natural experimental benchmark. The same gated ULD instances can be solved by a classical baseline and an annealing workflow, with solution quality, runtime, constraint violations, and energy overhead compared under identical inputs. Such benchmarking is more defensible than reporting quantum output without a classical reference.

X. LIMITATIONS

The reconstructed framework is conceptual and mathematical. It does not report a field deployment, statistically validated thresholds, or a measured quantum advantage. The cited publications provide the component technologies and theoretical properties, but the integrated architecture remains a research hypothesis requiring empirical verification.

A second limitation is that green and energy models are represented through feasibility envelopes rather than detailed electrochemical or traffic simulations. Battery temperature, degradation, charging queues, route topology, and solar variability can materially change the available-energy estimate. These effects should be incorporated when the model is tested with real vehicles.

XI. CONCLUSION

This proposes a constrained digital-twin architecture in which FKF/FKL spectral reasoning, integrity-aware telemetry, human authority, sustainable mobility, provenance, and quantum logistics occupy distinct but connected roles. The central principle is that spectral evidence can inform resilience only after operational admissibility has been established.

By combining distributional FKF analysis and sequential convergence with freshness, PLC integrity, swipe authorization, energy reserve, and QUBO-based ULD reconfiguration, the framework converts a collection of technologies into an auditable decision pipeline. Its principal next step is experimental validation using synchronized logistics traces, calibrated energy models, and matched classical–quantum benchmarks.

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