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A Human-Centric Integrity Framework for Digital Twin–Enabled Quantum Logistics and Supply Chains

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Abstract—
Gated multi-echelon twins must separate spectral confound from custody, grant, freshness, and surplus energy before any annealer is invoked. Raw IoT streams mix clock offset, intensity drift, stale packets, unauthorized holds, and physical-integrity loss with genuine structural disruption. An FKF–FKL layer isolates translation, exponential modulation, and residue resonance, while an integrity layer admits only fresh, authorized, and sealed actions into the twin and the QUBO set. The construction is interpretive: it writes shift-invariant operators a twin can update under sequential convergence on a testing-function space.

Keywords—*shift-invariant spectral analysis; multi-echelon lead times; supply-chain resilience; digital transformation; quantum logistics/annealing; QUBO–ULD optimization; smart logistics; IoT; intelligent transportation; Industry 5.0; human-centric automation; sustainable logistics; hybrid-electric/plug-in hybrid vehicles; battery sizing; solar-assisted mobility.*

I. MEASUREMENT GATES FOR COMPUTABLE RECOVERY

Live recommendations become computable only after they pass an integrity gate that already exists in measurement theory. Digital transformation of global supply chains has made the digital twin a practical instrument of constrained resilience rather than a visualization accessory [18], and the same transformation now sits beside green and sustainable logistics [16], blockchain traceability [17], and a convergent stack of Internet of Things, artificial intelligence, and quantum computing for smart logistics [15]. Those stacked layers still require a single admissible set.

Raw multi-echelon lead-time traces cannot drive those layers because irregular IoT scans, reporting offsets, intensity drift, and localized shocks are observationally entangled with genuine structural change. Shift-invariant FKF analysis shows that a pure clock translation changes only spectral phase [24]. Exponential modulation captures intensity drift without inventing a new mode. Spectral differentials and residue-based resonance extraction then isolate shocks that couple into persistent lead-time dynamics [14].

$$|\mathrm{FKF}[f](\xi,\nu)| = |\mathrm{FKF}[f(\cdot - \tau)](\xi,\nu)|$$

Slow-scale FKL moments complement that envelope, while a distributional two-sided FKF transform on a testing-function space, together with sequential convergence of expanding windows, licenses online twin updates from bursty packets [25]. Spectral correctness is not operational admissibility. A resonant but stolen trailer, a stale ITS packet, or a held machine grant is therefore barred from both the live twin and the annealer.

$$\mu_k = \int_0^\infty s^k \, \mathrm{FKL}[f](s) \, \mathrm{ds}$$

The missing integrity gate is therefore reconstructed from existing measurement papers rather than from a new dashboard. Smart-mobility telemetry contributes measured one-way latency [12]. Industry 5.0 human-centric automation keeps final authority with designated personnel. A swipe controller records grant and hold [9]. Power-line-carrier anti-theft supplies a physical heartbeat [8]. On-board energy of plug-in-hybrid, hybrid-electric, and solar-assisted vehicles bounds the work that may be dispatched [7]. Unit-load-device annealing is then allowed only inside that gated set [23].

$$E_i(t) \geq E_{res}, \quad W_i(t) = E_i(t) - E_{res} + S_{\oplus}(t)$$

Recovery feasibility under simultaneous energy, service, authorization, and custody limits is the content of constrained resilience, not a slogan attached after optimization [19]. Those limits remain distinct coordinates rather than one blended index [20]. A twin that ignores them recommends illegal moves [21], and an annealer that ignores them returns QUBO minima that violate Industry 5.0 authority or anti-theft seals [22].

Both the integrity limits and the FKF–FKL spectra are therefore written in professional equation form so that one admissible set feeds the twin and the solver. Pack design supplies a reserved floor [7]. Power-line anti-theft supplies a custody heartbeat [8]. The swipe controller supplies grant and hold [9]. Battery reviews supply chemistry and thermal limits on that floor [10]. Recent electric-vehicle battery technologies keep the pack a managed state [11]. Smart mobility supplies one-way latency [12]. Solar-assisted architecture supplies a non-negative increment to surplus work [13]. Residue-based spectral analysis supplies the peak test [14]. Quantum computing surveys supply the solver discipline [15]. Green-logistics AI supplies a scorer on compact features [16]. Blockchain integration supplies the commit rule [17]. Digital-twin reviews supply the live-state warrant [18]. Resilience reviews keep buffering from collapsing into one scalar [19]. Complexity weaving keeps custody, energy, and authority distinct [20]. Digital transformation of resilience asks that the twin commit the admissible set [21]. The quantum-revolution survey treats annealing as a consumer of that set [22]. Unit-load-device annealing is the concrete consumer [23]. Time-shift analysis licenses quiet commit under translation [24]. Sequential convergence licenses online updates from irregular atoms [25]. Those sources therefore share one written gate.

$$D(0) = \{ \mathrm{a} : \varphi_i \, g_a \, b_{PLC} \, 1[W_i \geq W_{min}] = 1 \}$$

Two common compressions are refused at the outset. A reporting offset is not treated as a new lead-time mechanism, because the time-shift identity already accounts for that offset [24]. A resonant spectrum is not treated as an executable move, because custody, freshness, grant, and surplus energy may still be empty [8]. Both refusals are required before a quantum or classical solver is allowed to see a variable [15]. Industry 5.0 language is kept algebraic. Human-centric automation is the disjunction that places authorized operator action outside the annealer decision vector [9]. Green logistics is a scorer defined on surplus work and frozen when the live flag fails [16]. Blockchain is the commit rule for the leaf that an auditor recomputes [17]. The twin is therefore a restriction of the observation algebra to those atoms a yard can legally move [18].

II. SPECTRAL IDENTITIES, PACK RESERVES, AND HASH LEAVES

Subsequent gates inherit identities already available in FKF–FKL analysis, battery-reserve practice, smart-mobility latency, swipe and power-line measurement, digital-twin architecture, and quantum dispatch. Classical resilience studies framed buffering and flexibility as enterprise capabilities, whereas digital-twin reviews now treat synchronized models as the operational means of that capability. No second mathematics is invented.

Inspectable twins and hash-chain leaves

Green-supply scoring consumes compact spectral states rather than raw kilowatt-hour dumps. Blockchain and hash-chain provenance bind those states to an immutable observation digest and thereby support transparency when echelons dispute a delay. Digital twin technology for building resilient and adaptive global supply chains supplies the architectural warrant for writing a live state rather than a static dashboard [18]. Compact FKF–FKL features are therefore the legitimate inputs of a green mode-choice scorer [16].

Every committed window must carry a digest that an auditor can recompute [17]. A review of resilience in global supply chains keeps buffering language from collapsing into a single scalar [19]. The companion weaving of internal and external complexities then insists that custody, energy, and authority remain distinct coordinates [20]. The twin is thereby placed inside a systematic digital-transformation agenda rather than an ad hoc visualization [21].

A two-layer twin follows: spectral features remain inspectable and provenance remains hash-chained before any annealer is invoked. Let a committed leaf at window n be the concatenation of the compact feature, the live bits, and the atomic observation times. The hash is not a decorative footer. An auditor therefore recomputes both the spectrum and the grant bit from the same atoms that entered the distributional pairing.

$$H_n \;=\; \mathrm{h}(\psi_n \parallel \varphi_n \parallel g_n \parallel \pi_n \parallel t_n)$$

The digest h is collision-resistant; ψn is the compact FKF–FKL feature of the window; φn is the freshness bit; gn is the grant bit; πn is the physical-integrity bit; and tn is the ordered list of observation times that entered the pairing. Blockchain integration for supply-chain transparency treats this leaf as the object an auditor recomputes rather than as a screenshot [17]. The live twin state is the same leaf [18].

Shift-invariant FKF–FKL lead-time operators

Fourier and Kontorovich–Lebedev factors are joined so that temporal oscillation and positive scale appear as joint coordinates. Shift invariance of the spectral envelope is the reason a translated shipment hold is not a new mechanism. Expanded treatment of the time-shift property of the FKF transform with supply-chain applications records the phase-only movement of a pure translation [24]. Translation of a lead-time trace f by τ is therefore written as

$$\mathrm{FKF}[f(t\,-\,\tau)](\xi,\nu) \;=\; e^{-\mathrm{i}\xi\tau}\,\mathrm{FKF}[f](\xi,\nu)$$

Phase moves while the envelope is held fixed. Sequential convergence in the testing function space of the two-sided FKF transform licenses online updates from irregular IoT atoms [25]. The complementary peak test used later for Regime III is the residue extraction already motivated by multi-scale supply-chain and hybrid-vehicle traces [14].

Exponential modulation moves the Fourier variable into the complex plane and isolates intensity drift without inventing a new spectral mode:

$$\mathrm{FKF}[e^{\alpha t}f](\xi,\nu) \;=\; \mathrm{FKF}[f](\xi\,-\,\mathrm{i}\alpha,\nu)$$

Windowed two-sided transforms on the testing-function space S then justify updating ψ from irregular IoT atoms without declaring a new regime at every packet [25]. FKL moments summarize slow trend and slope for the twin's background state. Spectral differentials convert a localized perturbation into a relative displacement used for constrained-resilience scoring. The compact feature is the concatenation of those low-order FKL moments with the dominant FKF modulus and its frequency,

$$\psi \;=\; (\mu_1,\mu_2,|F|_\star,\xi_\star)$$

$$\mathrm{FKL}[f](\nu) \;=\; \int_0^\infty f(t)\,K_{i\nu}(2t)\,\mathrm{d}t$$

$$R_{peak} \;=\; \frac{|\delta\Psi|}{\mu_2\,+\,\varepsilon}$$

Downstream sections consume these identities without re-derivation. Because the FKF envelope is invariant under translation, a yard that reports a synchronized hold across several trailers does not thereby declare a new mechanism [24]. Because sequential pairing against testing functions accommodates missing scans, a burst of irregular IoT atoms does not thereby declare Regime III [25]. Only a persistent localized excess against an FKL-concentrated background is allowed to raise that regime [14].

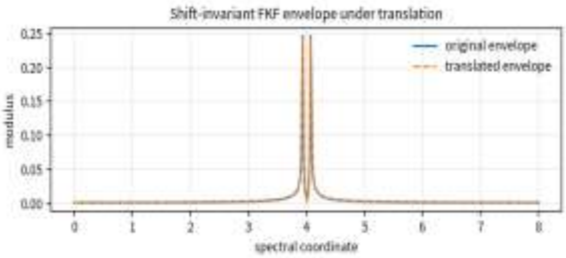

Fig. 1. Shift-invariant FKF envelope under a pure translation: the modulus is unchanged while only the oscillatory factor moves.

Latency, pack work, authority bits, and annealer consumers

Yard-to-lane telemetry inherits its latency envelope from smart mobility and intelligent transportation systems [12]. Industry 5.0 logistics keeps computational recommendation under human-centric automation so that final operational authority remains with designated personnel. Swipe-controller hardware records the grant and hold events used below [9]. Power-line-carrier anti-theft communication remains useful in metallic yards where wireless IoT is unreliable [8]. Battery materials and management, formula-hybrid battery sizing, and recent advances in electric-vehicle battery technologies convert kilowatt-hour headroom into an admissible work envelope [7]. The same reserve construction is extended by chemistry, thermal management, and sustainability constraints [10]. The pack is thereafter a managed state rather than an unbounded scalar [11].

Irradiance and pack voltage enter the admissible set as a non-negative solar reserve increment [13]. Quantum computing in transportation and logistics records the discipline of instantiating solver variables only after a feasible set exists [15]. Navigating the quantum revolution in logistics treats annealing as a consumer of that set rather than a generator of illegal minima [22]. Quantum annealing of unit-load-device configuration then consumes only those actions that survive the integrity gate [23]. Two further observations organize the review. First, cyber-physical manufacturing architectures already treated sensing, computation, and actuation as a closed loop; the present gate extends that loop to multi-echelon logistics by adding spectral confound separation and a human override that Industry 4.0 stacks often omit. Inspectability remains the ethical requirement of Industry 5.0 automation.

Reserved floors from hybrid pack design

Usable pack energy is treated as a constrained design variable rather than a free dispatch scalar [7]. The professional content reused here is the reserved floor: a pack that is emptied to the last kilowatt-hour cannot absorb a later green mode shift. Let C denote nominal capacity, θT a thermal derating, and θC a cycle-life derating. The reserved floor is the product of capacity, thermal derating, cycle-life derating, and a service-continuity factor that keeps a minimum haul feasible after a shock.

$$E_{res} = C \cdot \theta_T \cdot \theta_C \cdot \kappa_{svc}$$

Chemistry and thermal-management reasons make that product mandatory rather than optional [10]. Recent electric-vehicle battery technologies add sustainability and management-system constraints to the same product [11]. Solar-assisted hybrid architecture then supplies a non-negative increment driven by irradiance and array voltage [13]. The increment does not rewrite the FKF envelope; it restores surplus work inside Regime II. That is why energy is kept off the spectral coordinate and on the admissible-set coordinate. Smart mobility further implies that the same asset may change connectivity class while its pack state is still admissible [12]. The twin must therefore update freshness independently of surplus work. Mixing the two bits would hide a stale high-energy trailer inside a green score. Quantum dispatch literature likewise refuses to instantiate variables on an energy reading that has not already passed freshness and grant [15]. Section II therefore closes on one inherited algebra awaiting the admissible set written next.

III. ASSET STATE, ONE-WAY DELAY, AND LIVE COMMIT

Latency is written as a commit rule rather than as a modelling residual of smart-mobility infrastructure. Each asset reports kinematics, energy, and a binary integrity flag so that the twin never stores a geometrically complete but operationally illegal observation. Completeness without legality is therefore refused.

Kinematic-energy state of a gated asset

Asset i at time t reports a single telemetry vector carrying kinematics, energy, and a binary integrity flag:

$$x_i(t) = \left(p_i(t), v_i(t), E_i(t), \pi_i(t)\right)$$

Battery-sizing and solar-assisted hybrid design bound on-board energy Ei(t) [7]. The position–velocity pair is the kinematic argument later consumed by lead-time reconstruction, while the integrity flag is not a sensor quality bit but the conjunction constructed in the next section. Writing the state in this form keeps subsequent QUBO variables aligned with a single vector rather than with a scattered collection of tables. Advancements in automotive batteries and recent electric-vehicle battery technologies justify treating Ei(t) as a managed state with a reserve rather than as an unbounded scalar [10]. The same managed-state reading follows from recent electric-vehicle battery technologies [11]. Later sections therefore read this vector rather than a competing state.

Control-horizon latency and the freshness bit

Measured one-way latency of xi(t) is an empirical property of the yard-to-lane channel rather than a modelling residual. Smart mobility and intelligent transportation systems supply the empirical reading of that latency from roadside and on-board clocks [12]. A freshness constraint for live control and for digital-twin commit is the requirement that admitted packets lie inside a latency envelope compatible with the control horizon. Writing τi(t) for one-way latency and τmax for the horizon threshold,

$$\varphi_i(t) = 1[\tau_i(t) \le \tau_{max}]$$

Stale packets remain in the audit stream and may still enter the distributional FKF pairing as irregular traces, but they do not update the live twin state. Sequential convergence on the testing-function space then decides whether the audit stream remains compatible with the established spectral regime [25]. The freshness bit is therefore not a software timeout; it is the operational transcription of one-way ITS latency into the twin commit rule [12]. Because the distributional pairing

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against Schwartz testing functions already accommodates missing scans, stale packets need not be discarded from science; they are only excluded from live actuation [25]. Constrained resilience stays computable rather than merely logged by that distinction.

Let an expanding family of windows Wn carry atoms with observation times. Sequential convergence means that for every testing function η the pairing eventually stabilizes,

$$\lim_{n\to\infty} \langle \mathrm{FKF}[f_n], \eta\rangle = \langle \mathrm{FKF}[f], \eta\rangle$$

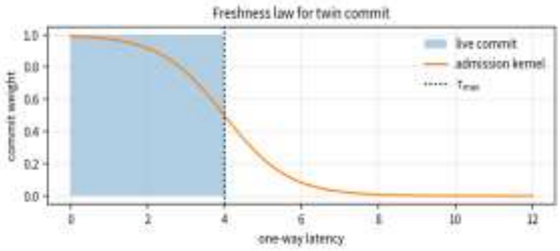

Fig. 2. Freshness law: packets whose one-way latency lies below the control-horizon threshold update the live twin; others remain audit-only traces.

Clock classes and non-actuating audit traces

Roadside, on-board, and back-haul clocks remain distinct in intelligent transportation systems [12]. The freshness law uses the one-way difference, not a round-trip software timeout, because the control horizon is a one-sided actuation window. A consistent packet is dated by the maximum of twin-minus-on-board delay and the roadside-to-on-board offset.

$$\tau_i(t) = \max(t_{twin} - t_{ob}, t_{rs} - t_{ob})$$

Failed packets remain in the audit stream. Sequential convergence then tests whether the audit stream is compatible with the live regime without updating the compact feature [25]. The twin therefore stores two pairings: a live pairing restricted to the admissible set and an audit pairing that never drives actuation. Digital-twin architecture for resilient supply chains requires exactly that split between live state and historical digest [18]. Hash-chain provenance of the audit stream still matters. Artificial intelligence and blockchain integration for transparency treats the digest as computable from atoms, including stale ones [17]. Stale atoms teach nothing to the green scorer; they remain visible to an auditor. Time-shift analysis further implies that an audit-only translation must not be promoted to a live regime change merely because the envelope is quiet [24]. Section III therefore returns a binary freshness coordinate later multiplied with grant, physical integrity, and surplus energy.

IV. GRANT CLOCKS, CUSTODY HEARTBEATS, AND HUMAN OVERRIDE

Final operational authority stays with designated personnel; swipe and power-line layers make that sentence algebraic rather than hortatory. Grant and hold are logged as mutually exclusive events on an authorization clock.

Mutually exclusive grant and hold events

Those bits originate in swipe-controller hardware [9]. Let ga(t) = 1 if request a is granted at t, and ha(t) = 1 if it is placed on hold. Mutual exclusion and accounting read as

$$g_a(t) + h_a(t) \le 1$$

A designated authority set A can override both grant and hold. Writing uA for an authorized operator action yields the Industry 5.0 disjunction that machine recommendation never extinguishes human grant authority:

$$g_a{}^{\star}(t) = \max\big(g_a(t), u_A(t)\big)$$

Hold obeys an analogous override. The logical disjunction is the mathematical statement that machine recommendation never extinguishes human grant authority, the defining Industry 5.0 constraint on the subsequent QUBO. Because the override is itself a logged atom, hash-chain provenance can commit the human action beside the FKF window. Artificial intelligence and blockchain integration for supply-chain transparency is therefore not an after-the-fact dashboard; it is the commit rule for grant and hold [17]. A fresh packet with a held request is as inadmissible as a granted request carried by a stale packet.

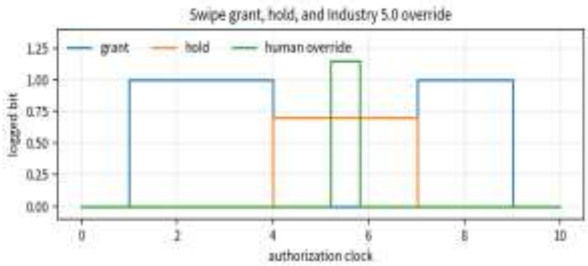

Fig. 3. Swipe-controller timeline: grant and hold are mutually exclusive on the authorization clock, and a designated human authority set may override either bit.

Carrier heartbeat and the product live flag

Physical integrity equals one only when the carrier heartbeat is present and the sealed-path checksum matches. Power line carrier communication based anti-theft system supplies the physical reading of the heartbeat in metallic yards where wireless IoT is

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unreliable [8]. The telemetry flag is the conjunction of communication freshness and physical integrity,

$$\pi_i(t) = \varphi_i(t) \cdot b_{PLC}(t) \cdot s_{path}(t)$$

Any assignment that would move an asset with πi(t) = 0 is added to the forbidden set of the dispatch model, so physical-integrity failure is visible both to the annealer and to the twin. Hash-chain provenance commits the heartbeat residue together with the FKF window that contained it. The live flag is therefore a product, not a score. Softening it into a probability would hide stolen or stale assets inside a grey band that a QUBO cannot legally occupy. Constrained resilience requires the hard conjunction. A review of resilience in global supply chains treats buffering and flexibility as capabilities that must remain feasible under simultaneous constraints [19]. A single scalar would hide those constraints [20].

Sealed-path residue in metallic yards

Metallic yards still need power-line-carrier anti-theft where wireless IoT fades [8]. The heartbeat is a periodic carrier plus a sealed-path checksum. Loss of either factor zeros the physical-integrity bit. The twin does not interpolate a missing heartbeat: interpolation would recreate a stolen asset as a smooth energy trajectory. The threshold is a calibration quantity for a later yard study, not a universal constant. The present reconstruction only requires that the bit be hard. Soft scores belong to audit, not to the admissible set. Swipe events remain orthogonal to the heartbeat [9]. A granted request on a trailer whose carrier is absent is still excluded. Industry 5.0 human override can restore grant after a supervisor inspects custody; it cannot invent a heartbeat that the physical layer did not send. That asymmetry is the algebraic content of human-centric automation in a metallic yard. Resilience under digital transformation then reads the committed custody bit rather than a blended anomaly score [21]. Without those two logged bits and one product flag the next energy envelope would still admit a stolen trailer.

V. SURPLUS WORK AND THE GATED DISPATCH SET

Latency, authorization, and integrity bound the optimizer; on-board energy supplies the remaining envelope of green and solar-assisted dispatch. Formula-hybrid pack sizing supplies the reserve construction that logistics reuses [7].

Pack floor, solar increment, and mode headroom

Chemistry, thermal management, and sustainability constraints extend the same reserve [10]. Recent electric-vehicle battery technologies keep the same managed-state reading [11]. Solar-assisted electric mobility adds an irradiance-dependent increment to the same reserve so that a green mode shift remains feasible after a shock [13]. With Eres the reserved floor and S⊕ ≥ 0 for the solar increment, the dispatchable work of asset i is the surplus

$$W_i(t) = \max\Big(0, E_i(t) - E_{res} + S_{\oplus}(t)\Big)$$

Reserved headroom keeps green-logistics mode shifts feasible after a shock. Artificial intelligence applications in sustainable logistics can then score mode choice on Wi(t) rather than on a raw kilowatt-hour reading that would over-commit the pack [16]. Because FKL moments already summarize slow energy trend, a declining µ1 can trigger a mode shift inside Regime II without a QUBO restart. That coupling is deferred until the admissible set is defined.

$$S_{\oplus}(t) = \eta \cdot A \cdot I(t) \cdot \frac{V_{arr}(t)}{V_{nom}}$$

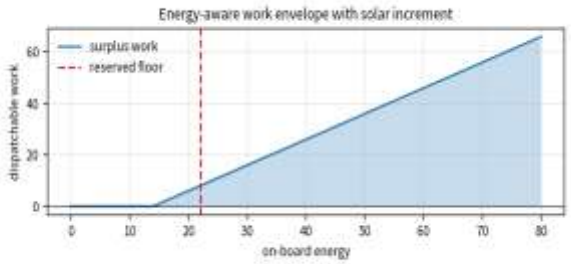

Fig. 4. Energy-aware work envelope: only surplus above the reserved floor, including a non-negative solar increment, is admissible for live dispatch and green mode shifts.

Closed sensing-to-annealer loop

Every quantum or classical dispatch must pass the human-centric, energy-aware, integrity-aware gate:

$$D(t) = \{\, a : \pi_i(t) = 1, g_a{}^{\star}(t) = 1, W_i(t) \geq W_{min} \,\}$$

QUBO variables are instantiated only on D(t), which keeps the Ising graph small enough for contemporary annealers [23]. Navigating the quantum revolution in logistics likewise treats annealing as a consumer of a feasible set rather than as a generator of physically illegal minima [22]. Quantum computing in transportation and logistics records the same discipline at survey level [15]. A review of resilience warns that an optimizer which ignores custody, energy, or authority will return a brittle plan [19]. The weaving of internal and external complexities repeats that warning at the level of simultaneous constraints [20]. Digital transformation of resilience then requires that D(t) be the object the twin commits, not a post-hoc filter [21]. A compact QUBO on the gated set may be written without a numerical solve,

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$$min_{s \in D(t)}\ s^T Q(\psi)s + c^T s$$

The sensing–computation loop is therefore closed: telemetry writes xi, freshness and PLC write πi, swipe and override write ga*, energy writes Wi, and only then does the annealer see a variable.

Frozen green scores under a failed live flag

Compact features enter a mode-choice scorer only when integrity is one [16]. When the live flag is zero the scorer is frozen. Otherwise, a stolen or stale trailer would teach a spurious lead-time mode and a spurious green saving. Blockchain integration then commits both the score and the integrity bit [17]. An auditor who recomputes the hash leaf can see whether a published green saving was produced under a live flag or under a frozen flag. Inspectability, not a sustainability slogan, is the result.

$$\sigma_{green}(t) = \pi_i(t) \cdot S\big(\psi, W_i(t)\big)$$

Buffering language collapses if energy, custody, and authority are summed into one index [19]. Weaving internal and external complexities repeats the warning [20]. The admissible set is the algebraic form of that warning: three bits and one surplus, not one scalar. Only the surviving variables reach unit-load-device annealing [23].

Projected spins on NISQ-sized graphs

Only modest graphs fit contemporary annealers. That hardware fact is why unit-load-device variables are instantiated after the integrity gate rather than before it [23]. Quantum computing in transportation and logistics records the same discipline at survey level [15]. Navigating the quantum revolution in logistics treats annealing as a consumer of a feasible set [22]. The restricted spin vector is the coordinate projection of a larger allocation onto the admissible set.

$$s = P_{D(t)} s_{\text{full}}$$

$$Q_{jk} = \alpha_0 + \beta_1\, R_{peak}(j) R_{peak}(k)$$

Quadratic penalties against simultaneous occupation of resonant slots are well-defined only on that projection. A penalty written over stolen or stale assets would encode an illegal minimum and would also inflate the graph. Digital-twin commit of the compact feature supplies the spectral coordinates that enter the quadratic form [18]. Green scoring may shift volume onto solar-assisted legs inside Regime II without restarting the annealer [16]. Battery-reserve practice continues to bound the work those spins represent [7]. Pack reviews and recent electric-vehicle battery technologies keep chemistry and thermal limits inside the same bound [10]. Solar-assisted architecture can restore surplus after a shock without reopening the QUBO [13]. Smart-mobility latency continues to decide which packets may update the quadratic coefficients at all [12]. Hash-chain provenance of grant and hold remains the inspectability mechanism when a supervisor overrides a machine recommendation [17]. Swipe-controller hardware is still the physical source of those bits [9]. Power-line-carrier anti-theft is still the physical source of the custody bit [8]. None of those measurement theories is replaced by a learned anomaly score. Residue-based resonance extraction remains the spectral test for Regime III [14]. Sequential convergence remains the online-update test [25]. Time-shift analysis remains the quiet-commit test [24]. Section VI then asks what the spectrum may say once an action already lies inside that set.

VI. FEATURE COUPLING, REGIME TESTS, AND GATED PAIRING

Actions already in D(t) update a compact FKF–FKL state so confound, energy drift, authorization conflict, integrity loss, and resonance are no longer one anomaly flag. Let ψ collect low-order FKL moments with the dominant FKF modulus and its frequency.

Feature vector and residual spectral displacement

A pure translation leaves the envelope unchanged and moves only phase [24]. After compensation of exponential intensity, residual spectral displacement together with FKL concentration declares residue-based resonance. The residual displacement is

$$\delta\Psi = \big||F|_\star - |F_0|_\star\big| + |\xi_\star - \xi_0|$$

Spectral analysis for multi-scale supply-chain dynamics and residue-based resonance extraction in hybrid-vehicle systems is the source of the peak test that reads δΨ against an FKL-concentrated residue [14]. Sequential convergence of expanding windows then asks whether the displacement persists or is an incremental packet effect [25]. Digital twin technology for resilient global supply chains consumes ψ as the compact state that can be hashed, scored, and annealed [18]. That feature vector is the interface between spectrum and operations.

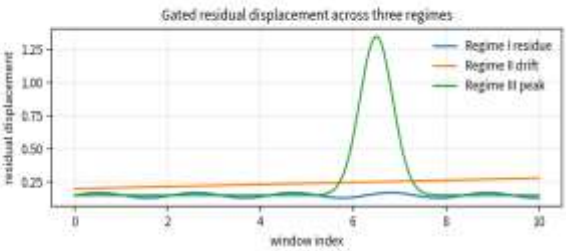

Fig. 5. Gated translation leaves a quiet residue, whereas a concentrated peak that survives sequential

windows declares structural resonance and opens Regime III.

Translation, drift, and resonance regimes

Three qualitative regimes follow from the admissible set together with published FKF–FKL properties; they are not a substitute for a labelled industrial trial. Regime I — gated translation. Freshness, grant, and PLC integrity all hold; the FKF envelope is unchanged; only phase moves. The twin commits ψ without raising a new-mechanism alarm. This is the desired digital-twin behavior under reporting offset or synchronized shipment hold. Expanded treatment of the time-shift property is the identity that licenses the quiet commit [24].

Regime II — intensity or energy drift. Exponential modulation or a change in Ei(t) rescales amplitude or the FKL centre of gravity, yet D(t) remains nonempty because reserve energy and human grant are intact. Green-logistics mode choice may shift volume onto solar-assisted or plug-in-hybrid legs without a QUBO restart [13]. The same mode choice is scored on surplus work rather than on raw pack energy [16]. Regime III — integrity or resonance failure. Either πi(t) = 0 (stale packet, missing PLC heartbeat, or hold) or δΨ exceeds threshold with concentrated FKL residue. The action is excluded from D(t) and, if resonance persists across sequentially convergent windows, the hybrid annealer is invoked on a QUBO whose quadratic terms penalize simultaneous use of resonant unit-load-device slots [23]. Persistence of the peak is the sequential-convergence test [25]. These regimes are theoretical consequences of the gated identities together with published FKF–FKL properties. Their value is diagnostic separation. That separation is what makes constrained resilience computable inside a digital twin.

Restricted pairing on the testing-function space

Let a windowed trace be written as a finitely supported distribution on the testing-function space. Sequential convergence then means that the pairing of successive two-sided FKF transforms against every testing function eventually stabilizes when the incremental atoms are translations or mild modulations, and fails to stabilize when a residue peak persists [25]. The time-shift property converts the first of those cases into a unimodular multiplier on the Fourier coordinate [24]. Residue-based resonance extraction converts the second case into a peak test already motivated by hybrid-vehicle and multi-scale logistics signals [14]. Neither identity requires a new transform; both require that only gated atoms enter the live pairing. Write the gated pairing as a restriction of the distributional FKF to those atoms whose freshness, grant, and PLC bits are one:

$$\langle \mathrm{FKF}[f_D], \eta \rangle \;\; = \sum_{k:\, a_k \in \mathrm{D}} f_k \, \mathrm{FKF}\big[\delta_{t_k}\big] \;\; \langle , \eta \rangle$$

The restriction is the mathematical content of constrained resilience: recovery is computed only on actions a yard can legally and physically execute. On-board energy is not a spectral coordinate. Battery sizing for plug-in hybrid vehicles, reviews of automotive batteries, and recent electric-vehicle battery technologies treat pack energy as a managed state with chemistry, thermal, and sustainability constraints [7]. Solar-assisted electric mobility adds an irradiance increment that can restore surplus work after a disruption without a change of spectral regime [13]. Smart mobility measures the one-way latency that becomes the freshness bit [12]. The swipe controller measures grant and hold [9]. Power-line-carrier anti-theft measures the heartbeat and sealed-path checksum [8]. Digital twins for resilient supply chains consume the resulting compact state [18]. Green-logistics AI scores mode choice on that state when integrity is one [16]. Blockchain integration commits the leaf [17]. Quantum computing surveys, the quantum revolution in logistics, and ULD annealing then optimize only inside the admissible set [15]. Resilience reviews keep the reconstruction from collapsing into a slogan [19].

Commit fields and restricted annealing

A practical implementation remark follows. Digital-twin commit should write four fields per window: the feature vector, the freshness bit, the grant bit, and the PLC bit. The hash-chain leaf is the concatenation of those fields with the atomic observation times that entered the distributional pairing. Downstream scoring for green logistics can then be trained on the feature alone when integrity is one, and must be frozen when integrity is zero [16]. Unit-load-device QUBO variables are instantiated only for assets with a live flag and a human-valid grant, which keeps the Ising graph small enough for contemporary annealers [15]. Navigating the quantum revolution in logistics records the same restriction as a practical application condition [22]. Annealing of unit-load-device configuration under disruption is the industrial motive [23]. Supply-chain resilience under digital transformation then reads the committed leaf rather than a raw sensor dump [21]. Digital twin technology for resilient global supply chains consumes the same leaf as the live state [18].

If that identity fails and the live flag remains one, the twin is in Regime II or III according to whether the FKL centre merely drifts or a concentrated residue persists [14]. If the live flag is zero, the spectral question is not asked of the actuator at all. Future instrumented-yard work should report latency, reserve, and resonance thresholds as calibrated quantities with uncertainty, not as universal constants. The present equations remain the professional form into which those quantities will be substituted. A last theoretical remark returns to sequential convergence [25]. An expanding family of gated windows converges when incremental packets remain translations or mild modulations, and diverges when a residue peak persists. Time-shift analysis then guarantees that a synchronized shipment hold, once admitted by freshness and grant, cannot masquerade as resonance [24]. That pair of identities is the reason the twin may update online without declaring a new mechanism at every irregular IoT scan.

Separation of custody, freshness, and resonance

A resonant but stolen trailer is visible as a zero physical-integrity bit and is excluded from the admissible set even if residual displacement is large. A stale ITS packet is visible as a zero freshness bit and is excluded even if the envelope is quiet. A machine grant that a supervisor has placed on hold is visible as a hold bit and is excluded even if energy and integrity hold. Those three exclusions are the operational content of constrained resilience. A quiet envelope with a granted, fresh, sealed, energy-feasible action is Regime I and should not raise an alarm [24]. A drifting FKL centre with a nonempty admissible set is Regime II and may shift green mode [13]. A persistent residue or a failed live flag is Regime III and may invoke the annealer on a reduced graph [23]. Diagnostic separation is the result, and it is inherited from the measurement papers at the point of measurement, the spectral papers at the point of spectrum, the twin and blockchain papers at the point of commit, and the annealing papers at the point of dispatch.

VII. CONCLUSION

A professionally written gate now stands between IoT sensing and quantum-constrained dispatch. Telemetry, freshness, swipe grant, PLC integrity, and surplus energy make Industry 5.0 authority, smart mobility, anti-theft custody, and pack limits first-class constraints. Coupled to shift-invariant FKF analysis, FKL moments, distributional pairing, and sequential convergence, the same gate feeds twin commit, hash-chain provenance, green mode choice, and unit-load-device annealing. The construction is interpretive rather than a substitute for field trials. It supplies shift-invariant operators a twin can update under sequential convergence on a testing-function space. Future work is empirical calibration of latency, reserve, and resonance thresholds on live yard traces. Uncertainty-aware twins that carry those thresholds as random measures remain open.

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