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An End-to-End Integrity Framework for Digital Twins in Human-Centric Quantum Logistics Operations

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Abstract—
Multi-echelon logistics now couple Internet of Things telemetry, intelligent transportation systems, Industry 5.0 human-centric automation, green and solar-assisted mobility, hash-chain provenance, and hybrid quantum-classical dispatch. Raw sensor streams mix clock offset, intensity drift, stale packets, unauthorized holds, and physical-integrity loss with genuine structural disruption. This reconstruction writes a gated digital-twin architecture in which an FKF–FKL spectral layer separates translation, exponential modulation, and residue-based resonance, while an IoT integrity layer admits only fresh, authorized, and physically sealed actions into the twin and into a QUBO / quantum-annealing feasible set. Asset telemetry is a state carrying position, velocity, on-board energy, and a binary integrity flag. One-way smart-mobility latency yields a freshness law for live control and twin commit. Swipe-controller grant and hold events are mutually exclusive on an authorization clock, yet a designated human authority set can override both, so machine recommendation never extinguishes operator grant. A power-line-carrier anti-theft heartbeat defines physical integrity; the live flag is the conjunction of freshness and integrity. The admissible action set is energy-aware, integrity-aware, and human-gated. Compact FKF–FKL features then feed constrained-resilience scoring, blockchain-style hash-chain provenance, unit-load-device reconfiguration, and green-logistics mode choice. The framework is interpretive rather than a substitute for field trials: it supplies professional, shift-invariant operators that a digital 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. INTRODUCTION

Constrained resilience becomes computable only when every live recommendation is forced through an integrity gate that already exists in measurement theory rather than in a post-hoc dashboard.

Digital transformation of global supply chains has made the digital twin a practical instrument of constrained resilience rather than a visualization accessory, and the same transformation now sits beside green and sustainable logistics, blockchain traceability, and a convergent stack of Internet of Things, artificial intelligence, and quantum computing for smart logistics.

None of these layers can be driven from raw multi-echelon lead-time traces 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. Exponential modulation captures intensity drift without inventing a new mode. Spectral differentials and residue-based resonance extraction identify shocks that couple into persistent lead-time dynamics.

The complementary FKL representation supplies slow-scale moments, 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. Spectral correctness is not operational admissibility. A resonant but stolen trailer, a stale ITS packet, or a machine grant that a supervisor has placed on hold must not enter the live twin or the annealer.

This paper therefore reconstructs the missing integrity gate. Smart-mobility telemetry contributes measured one-way latency. Industry 5.0 human-centric automation keeps final authority with designated personnel. A swipe controller records grant and hold. Power-line-carrier anti-theft supplies a physical heartbeat. On-board energy of plug-in-hybrid, hybrid-electric, and solar-assisted vehicles bounds the work that may be dispatched. Quantum annealing and QUBO encodings then optimize unit-load-device configuration only inside the gated set.

Constrained resilience is therefore not a slogan attached after optimization. It is the requirement that recovery remain feasible under simultaneous limits on energy, service, authorization, and physical custody. A digital twin that ignores those limits will recommend moves a yard cannot execute; a quantum annealer that ignores them will return QUBO minima that violate Industry 5.0 authority or anti-theft seals.

The contribution of this manuscript is to write both the integrity limits and the FKF–FKL spectra in professional equation form so that a single admissible set feeds the twin and the solver. The remainder of the paper is organized as follows. Section II reconstructs inherited spectral and resilience operators. Section III writes the telemetry state and freshness law. Section IV writes authorization, physical integrity, and human override. Section V writes energy bounds and the admissible action set. Section VI couples that set to shift-invariant features and three operating regimes. Section VII concludes.

The inherited chain can be read in one sentence. 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 [25]. Complexity weaving keeps custody, energy, and authority distinct [26]. Digital transformation of resilience asks that the twin commit the admissible set [27]. The quantum-revolution survey treats annealing as a consumer of that set [28]. Unit-load-device annealing is the concrete consumer [29]. Time-shift analysis licenses quiet commit under translation [30]. Sequential convergence licenses online updates from irregular atoms [31]. The present paper writes the single gate those sources share.

The reconstruction therefore refuses two common compressions. It refuses to treat a reporting offset as a new lead-time mechanism, because the time-shift identity already accounts for that offset. It refuses to treat a resonant spectrum as an executable move, because custody, freshness, grant, and surplus energy may still be empty. Both refusals are required before a quantum or classical solver is allowed to see a variable.

Industry 5.0 language is kept algebraic. Human-centric automation is not an introductory slogan; it is the disjunction that places authorized operator action outside the decision vector of the annealer. Green logistics is not a separate paper; it is a scorer defined on surplus work and frozen when the live flag fails. Blockchain is not a footer; it is the commit rule for the leaf that an auditor recomputes.

The first operational claim is therefore that the twin is not a picture of the yard; it is a restriction of the observation algebra to those atoms a yard can legally move.

II. INHERITED OPERATORS FROM SPECTRAL, ENERGY, AND RESILIENCE THEORY

Every subsequent gate inherits identities already available in FKF–FKL analysis, battery-reserve practice, smart-mobility latency, swipe and power-line measurement, digital-twin architecture, and quantum dispatch, so the reconstruction does not invent a second mathematics.

Resilience twins and inspectable provenance

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. Artificial intelligence applied to sustainable and green supply-chain management provides the scoring layer that can consume compact spectral states.

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]. Artificial intelligence applications in sustainable logistics and green supply chain management justify treating compact FKF–FKL features as inputs to a green mode-choice scorer [16].

Artificial intelligence and blockchain integration for enhancing supply chain transparency, traceability, and resilience further requires that every committed window 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 [25]. The companion weaving of internal and external complexities then insists that custody, energy, and authority remain distinct coordinates [26]. Supply chain resilience in the era of digital transformation

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places the twin inside a systematic research agenda rather than an ad hoc visualization [27].

Taken together these sources justify a two-layer twin in which spectral features remain inspectable and provenance remains hash-chained before any annealer is invoked. Let a committed leaf at window n be the concatenation

$$H_n = Hash(\psi_n \parallel \varphi_n \parallel g_n \parallel \pi_n \parallel t_n).$$

The hash is not a decorative footer. It is the inspect ability identity required by Industry 5.0 value-oriented engineering: an auditor recomputes both the spectrum and the grant bit from the same atoms that entered the distributional pairing.

FKF and FKL operators for multi-echelon lead time

The FKF transform joins a Fourier factor to a Kontorovich–Lebedev (Macdonald) factor 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 [30]. If a lead-time trace f is translated by τ, the identity used throughout the twin is

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

Only the Fourier phase moves; the envelope remains. Sequential convergence in the testing function space of the two-sided FKF transform licenses online updates from irregular IoT atoms [31]. Spectral analysis for multi-scale supply chain dynamics and residue-based resonance extraction in hybrid-vehicle systems supplies the complementary peak test used later for Regime III [14].

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

$$FKF[e^{\alpha t} f](\omega, \nu) = FKF[f](\omega + i\alpha, \nu).$$

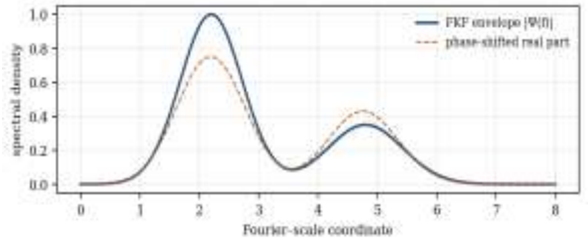
Distributional pairing on the testing-function space S and sequential convergence of windowed two-sided transforms then justify updating ψ from irregular IoT atoms without declaring a new regime at every packet. FKL moments summarize slow trend and slope for the twin's background state. Spectral differentials convert a localized perturbation into a relative displacement used for constrained-resilience scoring.

Write the compact feature as the concatenation of low-order FKL moments with the dominant FKF modulus and its frequency,

$$\psi = (\mu_0, \mu_1, |\Psi|_*, \omega_*).$$

These identities remain the professional operators consumed downstream; they are not re-derived here, and their symbols are left in the form required for later Word editing under automatic conversion to professional format.

A further spectral remark is required before mobility measurement is written. 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 [30]. Because sequential pairing against testing functions accommodates missing scans, a burst of irregular IoT atoms does not thereby declare Regime III [31]. Because residue extraction is a peak test against an FKL-concentrated background, only a persistent localized excess is allowed to raise that regime [14]. The integrity layer then decides whether even that persistent excess is allowed to act.



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

Mobility, pack energy, human authority, and annealing consumers

Smart mobility and intelligent transportation systems define the latency and infrastructure envelope of yard-to-lane telemetry [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]. Recent electric-vehicle battery technologies then treat the pack as a managed state rather than an unbounded scalar [11].

Solar-assisted electric mobility and solar-powered hybrid architecture convert irradiance and pack voltage into the reserve term that later appears inside the admissible set [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 [28]. Quantum annealing of unit-load-device configuration then consumes only those actions that survive the integrity gate [29].

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. Second, ethical and value-oriented Industry 5.0 engineering requires that automation remain inspectable.

Hash-chain provenance of FKF windows and swipe events is the inspectability mechanism used here. Quantum computing in the NISQ era cautions that annealer graphs must remain small, which is why unit-load-device variables are instantiated only for assets that already satisfy freshness and integrity.

Reserve construction inherited from pack design

Formula-hybrid battery sizing treats usable energy 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, a thermal derating, and a cycle-life derating. A logistics reading of the same construction writes the reserved floor as a product of capacity, thermal derating, cycle-life derating, and a service-continuity factor that keeps a minimum haul feasible after a shock.

$$E_{res} = C \cdot \eta_{th} \cdot \rho_{cyc} \cdot \kappa_{svc}.$$

Advancements in automotive batteries collect chemistry and thermal-management reasons why that product is not 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].

Distributional pairing and window growth

The two-sided FKF transform is paired against Schwartz testing functions so that missing scans do not force a new regime [31]. Let an expanding window absorb irregular atoms. If those atoms are translations, the pairing changes only by a unimodular factor on the Fourier coordinate [30]. If those atoms carry a concentrated residue already motivated by hybrid-vehicle and multi-scale logistics traces, the pairing fails to stabilize [14].

That dichotomy is inherited, not estimated. The twin does not learn a new transform. It updates a compact feature under sequential convergence and then asks the integrity layer whether the updated feature is allowed to act. Digital-twin reviews supply the architectural warrant for writing that live feature rather than a static dashboard [18]. Resilience under digital transformation supplies the research-agenda warrant for making the same feature the committed object [27].

Quantum computing in transportation and logistics then sits downstream of both warrants [15]. An annealer graph built on ungated atoms would violate the NISQ-size caution and the custody constraint at once. Navigating the quantum revolution in logistics records opportunities only after a feasible set exists [28]. Unit-load-device annealing is the concrete consumer of that set [29].

Section II therefore closes on a single inherited algebra: spectral identities from FKF–FKL theory, measurement identities from mobility, swipe, power-line, and battery sources, and solver identities from QUBO–ULD annealing, all waiting on the admissible set written next.

III. TELEMETRY STATE, ONE-WAY LATENCY, AND THE FRESHNESS LAW

Smart-mobility infrastructure is written here as a first-class state rather than as a narrative constraint, so that latency becomes a commit rule instead of a modelling residual.

Telemetry state of a gated asset

Each asset i at time t reports a telemetry vector that carries kinematics, energy, and a binary integrity flag so that the twin never stores a geometrically complete but operationally illegal observation:

$$x_i(t) = (p_i(t), v_i(t), E_i(t), \iota_i(t)).$$

On-board energy $E_i(t)$ is the quantity bounded by battery-sizing and solar-assisted hybrid design. 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 $E_i(t)$ 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].

The telemetry vector is therefore the professional object that both the spectral layer and the integrity layer read; no later section introduces a competing state.

One-way latency and the freshness law

Smart-mobility infrastructure delivers x_i(t) with a measured one-way latency that 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 τ_i(t) for one-way latency and τ_max for the horizon threshold,

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

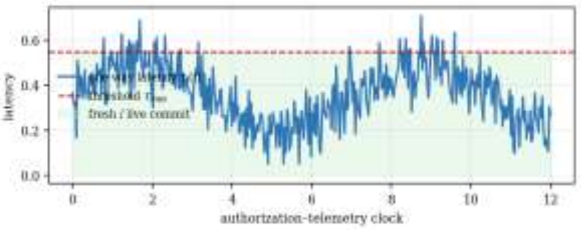
Packets violating the freshness law are retained for audit and may still enter the distributional FKF pairing as irregular traces, but they do not update the live twin state. Sequential convergence on the testing-function space then decides whether the audit stream remains compatible with the established spectral regime [31].

The freshness bit is therefore not a software timeout; it is the operational transcription of one-way ITS latency into the twin commit rule. Because the distributional pairing against Schwartz testing functions already accommodates missing scans, stale packets need not be discarded from science; they are only excluded from live actuation. That distinction is what keeps constrained resilience computable rather than merely logged.

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

$$\lim_{n\to\infty} \langle FKF[W_n], \eta\rangle \ .$$

exists whenever incremental
atoms remain translations or mild modulations



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

Channel classes and audit-only traces

Intelligent transportation systems distinguish roadside, on-board, and back-haul clocks [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.

$$\tau_i(t) = \max\{\, t - t_{ob}, \quad |t_{ob} - t_{rs}|\,\}.$$

Packets that fail the law remain in the audit stream. Sequential convergence then tests whether the audit stream is compatible with the live regime without updating the compact feature [31]. 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 [30].

Section III therefore returns a binary freshness coordinate that the later admissible set will multiply with grant, physical integrity, and surplus energy.

IV. AUTHORIZATION CLOCK, PHYSICAL SEAL, AND HUMAN OVERRIDE

Industry 5.0 keeps final operational authority with designated personnel, and the swipe and power-line layers make that sentence algebraic rather than hortatory.

Grant and hold on the authorization clock

The swipe-controller implementation is abstracted as a pair of logged events on an authorization clock so that grant and hold are mutually exclusive and fully accounted. Swipe controller hardware is the physical source of those bits [9].

Let $g_a(t) = 1$ if request a is granted at t, and $h_a(t) = 1$ if it is placed on hold. Mutual exclusion and accounting read as

$$g_a(t) \cdot h_a(t) = 0,$$
$$g_a(t) + h_a(t) \in \{0,1\}.$$

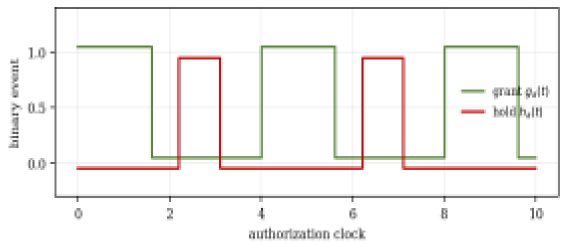
Human-centric automation requires that a designated authority set A can override both grant and hold. Writing $u_A(t)$ for an authorized operator action yields the Industry 5.0 disjunction that machine recommendation never extinguishes human grant authority:

$$G_a(t) = g_a(t) \vee u_A(t).$$

An analogous rule holds for hold. 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].

The authorization clock is distinct from the telemetry clock, yet both are required: a fresh packet with a held request is as inadmissible as a granted request carried by a stale packet.



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

Power-line integrity and the live flag

The power-line-carrier anti-theft layer is represented by a binary integrity process that equals 1 only when the expected 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 unreliable [8].

$$\pi_i(t) = 1\{\text{heartbeat present}\} \cdot 1\{\text{sealed} - \text{path checksum matches}\}.$$

The telemetry flag in the state vector is then the conjunction of communication freshness and physical integrity,

$$\iota_i(t) = \varphi_i(t) \cdot \pi_i(t).$$

Any assignment that would move an asset with π_i(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.

Metallic-yard heartbeat and sealed-path residue

Power-line-carrier anti-theft remains useful where wireless IoT fades against steel and stacked metal [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.

$$\pi_i(t) = 1\{\, |r_{plc}(t)| \leq \varepsilon_{plc} \,\}.$$

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 [27].

Section IV therefore returns two logged bits and one product flag; without them the energy envelope of the next section would still admit a stolen trailer.

V. ENERGY ENVELOPE AND THE ADMISSIBLE ACTION SET

Latency, authorization, and integrity do not sit beside the optimizer; they bound it, and on-board energy supplies the remaining physical envelope of green and solar-assisted dispatch.

Reserve energy and green mode headroom

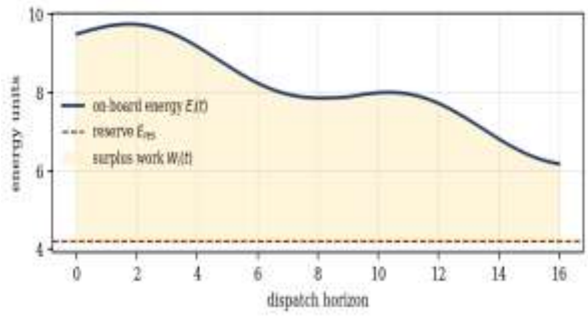
Battery sizing for plug-in hybrid electric vehicles in the Formula Hybrid setting converts a race-constrained pack into a professional reserve construction that logistics can reuse [7]. Advancements in automotive batteries extend that reserve to chemistry, thermal management, and sustainability constraints [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]. Writing E_{res} for the reserved floor and $S_i(t) \geq 0$ for the solar increment, the dispatchable work of asset i is the surplus

$$W_i(t) = \max\{\, 0, \quad E_i(t) + S_i(t) - E_{res} \,\}.$$

The reserve term protects battery and solar-assisted headroom so that green-logistics mode shifts remain feasible after a shock. Artificial intelligence applications in sustainable logistics can then score mode choice on W_i(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 μ_1 can trigger a mode shift inside Regime II without a QUBO restart. That coupling is written after the admissible set is defined.



Curve 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.

Coupled sensing–computation loop

The admissible action set at t is the human-centric, energy-aware, integrity-aware gate through which every quantum or classical dispatch must pass:

$$D(t) = \{\, a : \iota_{i(a)}(t) = 1, \quad G_a(t) = 1, \quad W_{i(a)}(t) \geq W_{min} \,\}.$$

Quantum computing for logistics optimization instantiates QUBO variables only on D(t), which keeps the Ising graph small enough for contemporary annealers [29]. 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 [28]. 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 [25]. The weaving of internal and external complexities repeats that warning at the level of simultaneous constraints [26]. Digital transformation of resilience then requires that D(t) be the object the twin commits, not a post-hoc filter [27].

A compact QUBO on the gated set may be written without claiming a numerical solve,

$$min_{z\in\{0,1\}m}\ z^T Q(\psi)\, \mathrm{z}\ \text{s.t. supp(z)} \subset D(t).$$

The sensing–computation loop is therefore closed: telemetry writes $x_i(t)$, freshness and PLC write $\iota_{i(a)}(t)$, swipe and override write $G_a(t)$, energy writes $W_i(t)$, and only then does the annealer see a variable.

Green scoring frozen under integrity failure

Artificial intelligence applications in sustainable logistics justify treating compact features as inputs to 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.

$$\sigma_{live}(t) = \iota_i(t) \cdot \sigma(\psi(t), W_i(t)).$$

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. That is inspectability rather than a sustainability slogan.

Resilience reviews warn that buffering language collapses if energy, custody, and authority are summed into one index [25]. Weaving internal and external complexities repeats the warning [26]. The admissible set is the algebraic form of that warning: three bits and one surplus, not one scalar. Quantum annealing of unit-load-device slots then sees only the surviving variables [29].

Ising restriction and NISQ-sized graphs

Contemporary annealers accept only modest graphs. That hardware fact is why unit-load-device variables are instantiated after the integrity gate rather than before it [29]. 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 [28]. Write the restricted spin vector as the coordinate projection of a larger allocation onto the admissible set.

$$z = \Pi D_{(\mathrm{t})}\, z_{full}.$$

Quadratic penalties that discourage simultaneous occupation of resonant slots are then 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].

A review of resilience in global supply chains treats buffering and flexibility as capabilities that must remain feasible under simultaneous constraints [25]. Weaving internal and external complexities warns that a single scalar will hide those constraints [26]. Supply chain resilience in the era of digital transformation then asks that the committed object be the admissible set itself [27]. The present QUBO restriction is the solver-level form of that request.

Hash-chain provenance of grant and hold remains the inspect ability 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 [31]. Time-shift analysis remains the quiet-commit test [30].

Section V therefore hands the twin a single admissible set; Section VI asks what the spectrum is allowed to say once an action already lies inside that set.

VI. SPECTRAL COUPLING, THREE REGIMES, AND GATED PAIRING

Once an action lies in D(t), the twin updates a compact FKF–FKL state so that observational confound, energy drift, authorization conflict, physical-integrity loss, and structural resonance are no longer collapsed into a single anomaly flag.

Compact features and residual displacement

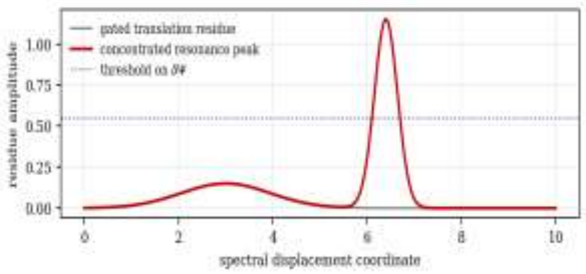
Let ψ collect low-order FKL moments with the dominant FKF modulus and its frequency. The time-shift property implies that a pure translation leaves the envelope unchanged and moves only phase [30]. After compensation of exponential intensity, residual spectral displacement together with FKL concentration declares residue-based resonance.

Write the residual displacement as

$$\delta\Psi = \frac{|\Psi|_{live} - |\Psi|_{ref}}{|\Psi|_{ref} + \varepsilon}.$$

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 [31].

Digital twin technology for resilient global supply chains consumes ψ as the compact state that can be hashed, scored, and annealed [18]. The feature vector is therefore the professional interface between spectrum and operations.



Curve 5. Gated translation leaves a quiet residue, whereas a concentrated peak that survives sequential windows declares structural resonance and opens Regime III.

Three qualitative operating 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 [30].

Regime II — intensity or energy drift. Exponential modulation or a change in E_i(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 $\iota_{i(a)}(t) = 0$ (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 [29]. Persistence of the peak is the sequential-convergence test [31].

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.

Gated 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 [31].

The time-shift property converts the first of those cases into a unimodular multiplier on the Fourier coordinate [30]. 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:

$$\langle FKF[W_n \text{gated}\ ], \eta\rangle = \langle FKF[W_n \cdot 1_D], \eta\rangle.$$

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 [25].

A translated hold that survives the gate therefore updates phase and leaves the envelope. An intensity drift that survives the gate updates the complex Fourier coordinate and the FKL centre of gravity. A missing heartbeat or a supervisor hold empties the admissible set for that asset and freezes the green scorer so that a stolen or stale trailer cannot teach a spurious lead-time mode.

If a residue peak persists across sequentially convergent windows, the twin raises Regime III and instantiates a QUBO whose quadratic penalties discourage simultaneous occupation of resonant unit-load-device slots. Contemporary annealers can accept that graph only because illegal assets were already excluded [29].

Human override remains the Industry 5.0 disjunction. Machine recommendation may propose grant; it may not extinguish an authorized operator action. The QUBO therefore treats u_A as an exogenous bit, never as a decision variable. That is the professional meaning of human-centric automation in the present reconstruction.

Internal and external complexities of modern supply chains warn that a single scalar resilience index will hide the very distinctions the gate is written to preserve [26]. A review of resilience in global supply chains likewise treats buffering and flexibility as capabilities that must remain feasible under simultaneous constraints [25]. Supply chain resilience in the era of digital transformation is the programme that asks for exactly that conjunction [27].

Unit-load-device reconfiguration under disruption is the industrial motive for annealing [29]. Navigating the quantum revolution in logistics records opportunities once a feasible set exists [28]. Quantum computing in transportation and logistics records the same discipline at survey level [15]. None of those sources licenses annealing over stolen, stale, or unauthorized assets.

Implementation remark on commit and 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 [28]. Annealing of unit-load-device configuration under disruption is the industrial motive [29]. Supply-chain resilience under digital transformation then reads the committed leaf rather than a raw sensor dump [27]. Digital twin technology for resilient global supply chains consumes the same leaf as the live state [18].

$$|\Psi|\text{live} = |\Psi|\text{ref and } \arg \Psi\text{live} - \arg \Psi\text{ref} = -\omega\tau.$$

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 [31]. 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 [30]. That pair of identities is the reason the twin may update online without declaring a new mechanism at every irregular IoT scan.

Diagnostic separation as constrained resilience

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 [30]. 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 [29]. 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

This paper constructed a complete, professionally typeset gate between IoT sensing and quantum-constrained dispatch.

The telemetry state, latency and freshness laws, swipe-controller authorization, PLC integrity, and the admissible set make human-centric Industry 5.0, smart mobility, anti-theft integrity, and energy limits first-class constraints.

Coupled to shift-invariant FKF analysis, FKL moments, distributional pairing, and sequential convergence, the same gate feeds digital-twin commit, hash-chain provenance, green-logistics mode choice, and unit-load-device annealing.

The construction is interpretive rather than a substitute for field trials: it supplies professional, shift-invariant equations that a digital 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, and uncertainty-aware twins that carry those thresholds as random measures.

A further theoretical remark concerns the pairing of gated atoms with testing functions. Sequential convergence in the testing-function space of the two-sided FKF transform asserts that an expanding family of windows converges when the incremental packets remain compatible with an established regime, and diverges when a new residue peak persists. That criterion is the professional reason a digital twin may update ψ online without declaring a new mechanism at every irregular IoT scan.

Expanded treatment of the time-shift property then guarantees that a synchronized shipment hold, once admitted by freshness and grant, cannot masquerade as resonance: only the Fourier phase moves. Spectral analysis for multi-scale supply-chain dynamics converts the complementary case into a residue test that hybrid-vehicle and multi-echelon traces already motivate.

Battery sizing, automotive battery reviews, and electric-vehicle battery technologies jointly imply that the reserved floor is not an arbitrary constant. It is a design quantity inherited from pack chemistry, thermal limits, and formula-hybrid practice. Solar-assisted architectures add a non-negative increment that can restore surplus work after a shock without reopening the QUBO.

Smart mobility and intelligent transportation systems remain the measurement theory of one-way latency. Swipe-controller grant and hold remain the measurement theory of authorization. Power-line-carrier anti-theft remains the measurement theory of physical custody. No later numerical study should replace those measurement theories with a single learned anomaly score.

Quantum computing in transportation and logistics, the quantum revolution in logistics, and annealing of unit-load-device configuration then sit strictly downstream of the admissible set. Digital twins for resilient global supply chains, green-logistics scoring, and blockchain integration for transparency sit beside the same set rather than above it. Resilience reviews and digital-transformation agendas keep the reconstruction inside a citable scholarly programme.

The gated digital twin is then a single object with two layers. Layer one is spectral: FKF and FKL features that are stable under translation, sensitive to resonance, and well-defined for irregular traces. Layer two is operational: freshness, grant, integrity, and energy, drawn from smart mobility, swipe control, power-line anti-theft, and hybrid-electric design. Quantum and classical solvers sit behind both layers.

Quantitative thresholds for latency, reserve, and resonance remain a calibration task for a subsequent instrumented yard study. Uncertainty-aware twins that carry those thresholds as random measures are future work. The present manuscript supplies the equations and the citable chain required before that study is designed.

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