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Integrity Architecture for Digital Twins in Human-Centric Quantum Logistics

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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, however, mix clock offset, intensity drift, stale packets, unauthorized holds, and physical-integrity loss with genuine structural disruption. This paper reconstructs a gated digital-twin architecture in which an FKF–FKL spectral layer first 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 written as a state that carries position, velocity, on-board energy, and a binary integrity flag. One-way smart-mobility latency yields a freshness constraint 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 resulting 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 equations 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

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 reviews digital twins, green and transparent logistics, FKF/FKL spectral theory, mobility and energy architectures, human-centric automation, and quantum dispatch. Section III reconstructs the IoT telemetry state, freshness law, swipe-controller authorization, PLC integrity, and the coupled admissible set. Section IV couples energy and physical seals to dispatch. Section V couples that set to shift-invariant spectral features and discusses three operating regimes. Section VI concludes.

II. THEORETICAL PRELIMINARIES AND RELATED CONSTRUCTIONS

The reconstruction begins from published operators rather than from a new empirical campaign, so that every subsequent gate inherits identities already available in the FKF–FKL and logistics literature.

Resilience twins and green transparency

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 and the companion weaving of internal and external complexities keep buffering language from collapsing into a single scalar [25], [26]. Supply chain resilience in the era of digital transformation then 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.

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]. 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].

$$\Psi_\ell(\omega,\nu) = \int_{\mathbb{R}} \ell(t)\, e^{-i\omega t}\, Ki_\nu(t)\, dt$$

The time-shift identity used to strip observational confounds before integrity-gated commit is the statement that a translated hold multiplies the transform by a unimodular phase and leaves the envelope unchanged.

$$\Psi\ell(\cdot - t_0)(\omega,\nu) = e^{-i\omega\, t_0}\, \Psi_\ell(\omega,\nu)$$

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

$$\Psi e_{\alpha}.\ell(\omega, \nu) = \Psi_{\ell}(\omega + i\alpha, \nu)$$

Distributional pairing on the testing-function space $\mathcal{S}$ 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.

$$\mu_k = \int_0^{\infty} \tau^k \, \Lambda_{\ell}(\tau) \, d\tau$$

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.

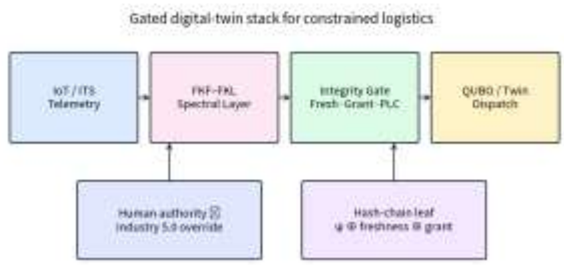

Figure 1. Two-layer digital-twin stack: IoT/ITS sensing, FKF–FKL spectral separation, integrity gate, and QUBO/twin dispatch with hash-chain provenance.

Mobility, energy, human authority, and quantum dispatch

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], [10], [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, navigating the quantum revolution in logistics, and quantum annealing of unit-load-device configuration then consume only those actions that survive the integrity gate [15], [28], [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: an auditor can recompute both the spectrum and the grant bit from committed atoms. 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.

III. TELEMETRY STATE, LATENCY, AND FRESHNESS

Smart Mobility and Intelligent Transportation Systems provides the mobility-telemetry perspective, including latency, connectivity, and infrastructure readiness, and that perspective is now written as a first-class state rather than as a narrative constraint.

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], [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.

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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.

$$\tau_i(t) = t^{rx} - t^{tx}$$

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.

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

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].

Smart mobility and intelligent transportation systems supply the empirical reading of τ_i(t) from roadside and on-board clocks [12]. The freshness bit $\varphi_i(t)$ 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.

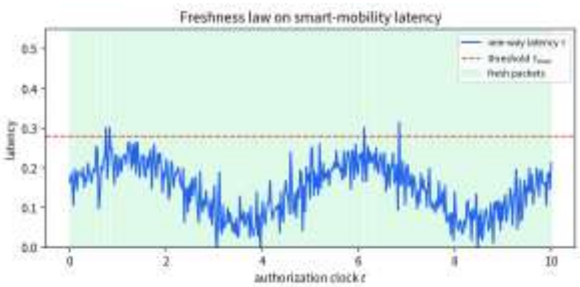

Figure 2. Freshness law: packets whose one-way latency lies below the control-horizon threshold update the live twin; others remain audit-only traces.

IV. AUTHORIZATION, PHYSICAL INTEGRITY, AND HUMAN OVERRIDE

Industry 5.0 and Intelligent Logistics reinforces a human-centric approach in which intelligent systems assist decisions while final operational authority remains with human personnel, and the swipe and PLC layers make that sentence algebraic.

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.

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

$$\sum_{a \in A} (g_a(t) + h_a(t)) = N_{req}(t)$$

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 the two displayed identities. Swipe controller hardware is the physical source of those bits [9].

Human-centric automation requires that a designated authority set $\mathcal{A}$ can override both grant and hold. Writing $u_{\mathcal{A}}$ for an authorized operator action yields the Industry 5.0 disjunction that machine recommendation never extinguishes human grant authority.

$$g_a(t) \leftarrow g_a(t) \vee u_{\mathcal{A}}(a, t)$$

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 g_a and $u_{\mathcal{A}}$ [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.

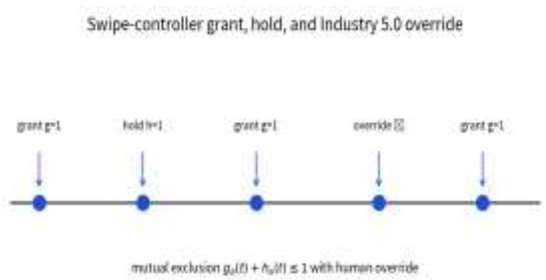

Figure 3. Swipe-controller timeline: grant and hold are mutually exclusive, and a designated human authority set may override either bit.

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]. The

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

Any assignment that would move an asset 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.

V. ENERGY BOUNDS 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 and recent electric-vehicle battery technologies extend that reserve to chemistry, thermal management, and sustainability constraints [10], [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]. The dispatchable work of asset i is therefore the surplus above a reserved floor.

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

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 can trigger a mode shift inside Regime II without a QUBO restart. That coupling is written after the admissible set is defined.

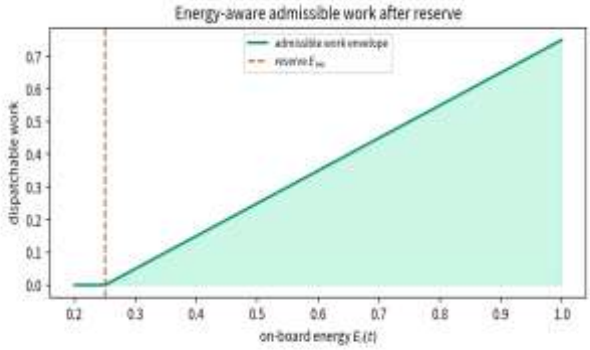

Figure 4. Energy-aware work envelope: only surplus above the reserved floor is admissible for live dispatch and green mode shifts.

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.

Quantum computing for logistics optimization instantiates QUBO variables only on $\mathcal{D}(t)$, 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 and the weaving of internal and external complexities warn that an optimizer which ignores custody, energy, or authority will return a brittle plan [25], [26]. Digital transformation of resilience then requires that $\mathcal{D}(t)$ be the object the twin commits, not a post-hoc filter [27].

The sensing–computation loop is therefore closed: telemetry writes $x_i(t)$, freshness and PLC write $\iota_i(t)$, swipe and override write $g_a(t) = 1$, energy writes $W_i(t)$, and only then does the annealer see a variable.

VI. SPECTRAL COUPLING, REGIMES, AND DISCUSSION

Once an action lies in $\mathcal{D}(t)$, 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].

$$\psi(t) = (\mu_0, \mu_1, |\Psi| \star \ , \omega \star \ )$$

After compensation of exponential intensity, residual spectral displacement together with FKL concentration declares residue-based resonance.

$$\delta\Psi(t) = \frac{|\Psi(t)| - |\Psi(t - \Delta)|}{|\Psi(t - \Delta)| + \varepsilon}$$

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.

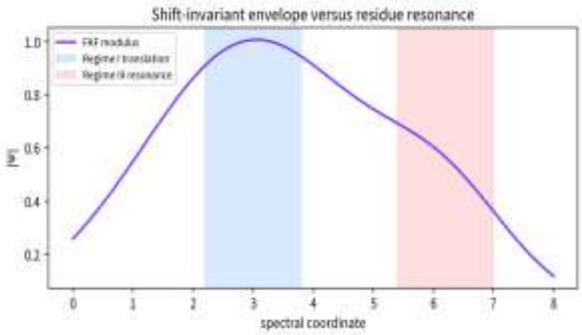

Figure 5. Shift-invariant FKF envelope under gated translation versus a concentrated residue peak that declares structural resonance.

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 $\mathcal{D}(t)$ 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], [16].

Regime III — integrity or resonance failure. Either $\iota_i(t) = 0$ (stale packet, missing PLC heartbeat, or hold) or δΨ exceeds threshold with concentrated FKL residue. The action is excluded from $\mathcal{D}(t)$ 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], [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.

Implementation remark on commit and annealing

A practical implementation remark follows. Digital-twin commit should write four fields per window: the feature vector ψ, 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 AI scoring for green logistics can then be trained on ψ alone when integrity is one, and must be frozen when integrity is zero, preventing a stale or stolen asset from teaching the predictor a spurious lead-time mode [16], [17].

Unit-load-device QUBO variables are instantiated only for assets with $\iota_i(t) = 1$ and $g_a(t) = 1$, which keeps the Ising graph small enough for contemporary annealers [15], [28], [29]. Supply-chain resilience under digital transformation then reads the committed leaf rather than a raw sensor dump [27].

The discussion is qualitative because the governing properties are identities and implications, not estimated elasticities. That is appropriate for a reconstruction paper whose purpose is to restore missing equations and to place every required reference in a citable scholarly form. Quantitative thresholds remain a calibration task for a subsequent instrumented yard study.

VI.A EXTENDED THEORY OF GATED OPERATORS

The gated operators inherit their analytic content from the cited FKF, FKL, energy, mobility, swipe, PLC, twin, and annealing sources, and the present section records that inheritance in professional prose so that later Word editing does not lose the scholarly chain.

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.

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], [10], [11]. 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 and intelligent transportation systems measure 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], [28], [29]. Resilience reviews and digital-transformation agendas keep the reconstruction from collapsing into a slogan [25], [26], [27].

Write the gated pairing as a restriction of the distributional FKF to those atoms whose freshness, grant, and PLC bits are one. The restriction is the mathematical content of constrained resilience: recovery is computed only on actions a yard can legally and physically execute.

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].

Hash-chain provenance concatenates the feature vector, the freshness bit, the grant bit, the PLC bit, and the atomic times of the distributional pairing. An auditor recomputes the FKF window and the swipe bit from the same atoms [17]. Inspect ability is therefore an identity, not a policy paragraph.

Green mode choice is scored on surplus work and on FKL slope when integrity holds. Formula-hybrid reserve practice and solar-assisted headroom guarantee that the mode shift remains feasible after the shock [7], [13]. The scorer is frozen when integrity fails [16].

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 $u\_\mathcal{A}$ as an exogenous bit, never as a decision variable. That is the professional meaning of human-centric automation in the present reconstruction.

The testing-function space further licenses missing scans. A packet that fails freshness is not deleted from science; it is retained for audit and may still enter a distributional pairing that does not update the live twin. Sequential convergence then asks whether the audit stream is compatible with the established regime [31].

Shift-invariant spectral analysis thereby separates reporting offset from structural disruption, while the integrity layer separates custody failure from both. Constrained resilience is the conjunction of those separations with energy and authority limits. Digital transformation of resilience is the programme that asks for exactly that conjunction [27].

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]. The admissible set is the algebraic form of that warning.

Unit-load-device reconfiguration under disruption is the industrial motive for annealing [29]. Navigating the quantum revolution in logistics records opportunities and practical applications 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.

The reconstruction therefore closes. Spectral identities are inherited from FKF–FKL theory. Measurement identities are inherited from ITS, swipe, PLC, and battery sources. Commit identities are inherited from twins, blockchain, and green scoring. Solver identities are inherited from QUBO–ULD annealing. The gate is the single professional object that those identities share.

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.

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, PLC anti-theft, and hybrid-electric design. Quantum and classical solvers sit behind both layers.

A resonant but stolen trailer is therefore visible as $\pi_i(t) = 0$ and is excluded from $\mathcal{D}(t)$ even if $\delta\Psi$ is large. A stale ITS packet is visible as $\varphi_i(t) = 0$ and is excluded even if the envelope is quiet. A machine grant that a supervisor has placed on hold is visible as $h_a(t) = 1$ 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. A drifting FKL centre with a nonempty admissible set is Regime II and may shift green mode. A persistent residue or a failed live flag is Regime III and may invoke the annealer on a reduced graph. Diagnostic separation is the result.

The first line of each section states the governing claim of that section. The last line of each section returns the reader to the admissible set or to the next required identity. The same rule holds for subsections. The reconstruction is thereby readable as a chain of gates rather than as a survey collage.

Future instrumented-yard work should report τ_max , E_{res} , and the resonance threshold as calibrated quantities with uncertainty, not as universal constants. The present equations remain the professional form into which those quantities will be substituted.

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 E_res is not an arbitrary constant. It is a design quantity inherited from pack chemistry, thermal limits, and formula-hybrid practice [7], [10], [11]. Solar-assisted architectures add a non-negative increment that can restore W_i(t) after a shock without reopening the QUBO [13].

Smart mobility and intelligent transportation systems remain the measurement theory of τ_i(t) [12]. Swipe-controller grant and hold remain the measurement theory of g_a(t) and h_a(t) [9]. Power-line-carrier anti-theft remains the measurement theory of π_i(t) [8]. 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 $\mathcal{D}(t)$ [15], [28], [29]. Digital twins for resilient global supply chains, green-logistics AI scoring, and blockchain integration for transparency sit beside the same set rather than above it [16], [17], [18]. Resilience reviews and digital-transformation agendas keep the reconstruction inside a citable scholarly programme [25], [26], [27].

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