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A Control-Theoretic and Spectral Architecture for Multi-Echelon Resilience under Electrified Logistics

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Abstract—
This paper treats multi-echelon resilience under electrified logistics as a closed-loop control problem rather than a scorecard. The plant is an inventory-and-fleet system whose material balances are coupled to usable pack energy, so a shipment is infeasible when every vehicle that could carry it violates an energy floor. The observer is a digital twin augmented by a shift-invariant spectral channel, so periodic bullwhip, delayed sailings, and electrical resonance are visible before fill rate or on-time percentage moves. The actuators are three: a green policy that prices both emissions and spectral health, a discrete solver for packing and disruption re-slotting, and a human override required by a human-centric operating model. Integrity is dual. A ledger attests who committed an event; a spectral watermark tests whether the continuous series still matches what was committed. Sensing may use ordinary conductors on docks and cabinets when radios fail. Urban corridors, charging windows, and zone rules constrain the same loop; they are not decorations around it.
Two operating pictures follow. Under disruption, dwell rises, the spectral channel tests translation versus a new mode, routing and re-packing move, a planner may reject an illegal slot, and a charger harmonic is attributed to infrastructure rather than chemistry. In the quiet case, weekly cycles amplify before service metrics move, differential structure names a buffer that detunes the mode, and the twin tests that prediction instead of waiting for a learning actuator to discover a pole the spectrum already named. An agenda follows directly: exportable twin signals, spectral health reported next to fill rate, override next to automation, thermal margin next to punctuality, irradiance on the same clock as delivery windows, and explicit tests of whether pricing spectral health and pairing watermark with ledger outperform carbon-only cost and ledger-only integrity. Humanitarian and perishable settings will need different weights and labor rules. They should not need a different philosophy of loop closure.
Keywords: closed-loop resilience; FKF observer; digital twin; quantum packing; battery constraint; Industry 5.0

I. INTRODUCTION

Resilience reviews describe absorption, adaptation, and recovery under internal and external complexity. Digital-transformation surveys add sensors, platforms, and visibility programs [10]. What they rarely write down is a plant, an observer, and an actuator. Without those three objects, "resilience" remains a scorecard.

The plant is a multi-echelon inventory-and-fleet system whose vehicles obey energy inequalities from plug-in hybrid sizing and later battery reviews [7], [33]. The observer is a digital twin [29] augmented by an FKF spectral channel so that periodic bullwhip and electrical resonance are visible [13], [14]. The actuators are (i) continuous or mixed-integer AI policies for green routing [30], (ii) a quantum or hybrid discrete solver for unit-load and disruption assignment [5], [8], and (iii) a human override channel required by Industry 5.0 [27]. Measurements are attested on a ledger when integrity matters [31].

Smart mobility work [6] and the IoT–AI–quantum stack [26] define the urban and sensing envelope. Power-line carrier telemetry [32] is kept as a reminder that the measurement channel need not be cellular. The swipe controller [34] is kept as a reminder that actuation includes a finger on a screen. Opportunity framing for quantum logistics [35] locates the discrete solver inside a live planning loop rather than a standalone experiment.

Influence diagram — Section 1

Resilience language [10]		
▼		
Plant: stock + pack energy [7], [33]	**Observer: twin + FKF [29], [14]**	**Actuators: AI / Q / human [30], [5]**
▼	▼	▼
Urban envelope [6], [26]	**Integrity channel [31], [32]**	**Interface [34], [27]**

Figure 1. Influence paths from resilience language to plant, observer, and three actuators.

2. Plant Model with Energy Coupling

2.1 Material balance

Let $q_{k,t}$ be on-hand stock at echelon k and let $o_{k,t}$ be the order placed upstream. A standard balance is written as equation (1). Lead time L_k is not a constant. Shift-invariant FKF analysis of multi-echelon lead times treats $L_k(t)$ as the signal of interest [14]. Demand $d_{k,t}$ may be physical consumption or a shipment onto a vehicle whose energy state we track next. Spectral frameworks for chain dynamics supply the same lead-time object at multiple scales [15].

$$q_{k,t+1} = q_{k,t} + o_{k,t-L_k} - d_{k,t} \quad (1)$$

2.2 Vehicle energy

For a plug-in or solar-assisted vehicle v the usable pack energy evolves as equation). Sizing papers give the integral form of the same balance and the efficiencies that should multiply the charge and discharge terms [33]. Solar-assisted architectures add P_{sol} as a designed source, not an accident [9]. Materials and BMS reviews constrain E and P by temperature, state of health, and chemistry [7]. A shipment scheduled in (1) is infeasible if every vehicle that could carry it violates the floor on E implied by (2). That coupling is the definition of electrified logistics in this paper.

$$E_{v,t+1} = E_{v,t} + \eta_c P_{chg,t}\Delta t + P_{sol,t}\Delta t - \frac{P_{trac,t}\Delta t}{\eta_d}$$

(2)

Contest-era solar-hybrid architecture [28] shows that the right-hand side of (2) is a design variable. Battery reviews change feasible traction power without changing the material balance itself [7]. Formula-style classroom sizing remains the cleanest reduction of (2) when the corridor is known [33].

Influence diagram — Section 2

Material balance (1)	→	**Lead-time signal L_k [14], [15]**
↓		↓
Shipment onto vehicle	→	**Energy balance (2) [33], [9]**
↓		↓
Infeasible if E floor violated	←	**BMS / solar / contest [7], [28]**

Figure 2. Influence of lead-time spectra and pack energy on shipment feasibility.

3. Observer: Twin plus FKF Channel

3.1 Twin estimator

The twin maintains the estimated state as equation (3), as argued in the twin review for adaptive global chains [29]. The measurement y arrives from IoT and, where radios fail, from infrastructure channels such as power-line carrier [32]. Blockchain-attested fields in y reduce the incentive to spoof the innovation $y - h(\hat{x})$ [31]. Convergent IoT–AI–quantum sensing work supplies the envelope in which those measurements are collected [26].

$$\hat{x}_{t+1} = f(\hat{x}_t, u_t) + K_t(y_t - h(\hat{x}_t)) \quad (3)$$

3.2 Spectral channel

The FKF transform of a lead-time or current signal is written as equation (4). This is the working integral of the spectral framework for chain dynamics and resilience [15]. Distributional extension admits stockout impulses [11]. Sequential convergence in the testing-function space tells the implementer when the window is long enough [12].

$$S_{\omega,\tau} = \int_{-\infty}^{+\infty} s(t)\, \kappa(\omega, \tau;\, t)\, dt \quad (4)$$

The time-shift property moves a delayed sailing or a late charge into a structured displacement of (ω, τ) [18]. Exponential modulation supports both growth analysis and integrity watermarks [19]. FKL properties give an alternative inversion route [17]. Differential identities describe how residues move when a buffer changes [16]. Residue extraction is shared with hybrid-vehicle electrical traces [13].

A scalar observer output used later as a constraint is equation (5), with a small ε so that a quiet window does not explode the index. Weight w down-weights known bullwhip and electrical-resonance bands [13], [14]. Duplicate statements of the distributional and sequential results are retained only as cross-checks on inversion practice [20], [21]. The same distributional construction appears again as an independent numbering of the impulse-ready kernel [25].

$$\rho_t = \frac{\int w(\omega,\tau)\,\left|S_{\omega,\tau}\right|^2\, d\omega\, d\tau}{\varepsilon + \int \left|S_{\omega,\tau}\right|^2\, d\omega\, d\tau}$$

(5)

Influence diagram — Section 3

IoT / PLC measurements [32], [26]	**Ledger fields [31]**	
▼	▼	
Digital twin estimator (3) [29]		
▼		
FKF / FKL channel (4) [15], [17]		
▼		
[11], [12] impulses & windows	**[18], [19] shift & watermark**	**[16], [13] residues**
▼		
Scalar health index ρ in (5)		

Figure 3. Influence from attested measurements through the twin and spectral channel to ρ.

4. Actuators

4.1 Green AI policy

Bibliometric work on AI for sustainable logistics organizes methods around routing, demand, and emissions [30]. A representative stage cost is equation (6). The last term is the novelty relative to a pure green-cost review: spectral health is priced. Without it, an AI dispatcher can look green on paper while ringing the lead-time spectrum [15].

$$\ell_t = c_t^{op} + \lambda_c C_t + \lambda_\rho \rho_t \quad (6)$$

4.2 Quantum discrete actuator

When the decision is a packing or a disruption re-slotting, the policy is no longer a smooth u. Quantum annealing encodes equation (7) as in ULD configuration and disruption studies [5]. Opportunity and survey papers locate this actuator inside a hybrid loop, not as a replacement ERP [8], [35]. The twin [29] rebuilds h and J after each major event so that the Hamiltonian matches the live network.

$$H(z) = z^T J\, z + h^T z \qquad (7)$$

4.3 Human actuator

Industry 5.0 treats the planner as a legitimate actuator, not as noise [27]. The convergent IoT–AI–quantum essay already assumes a human still owns exceptions [26]. Interface ancestry includes simple swipe-style controls [34]. Formally we write equation (8), where a_t = 1 means the recommendation is accepted. Override rate is a first-class log, not an embarrassment statistic.

$$u_t = a_t u_t^{rec} + (1 - a_t)\, u_t^{hum}, \;\; a_t \in \{0,1\}$$

(8)

Influence diagram — Section 4

Stage cost ℓ_t with ρ [30], [15]		
▼		
Green AI continuous u [30]	**Quantum assignment (7) [5], [8]**	**Human accept/override (8) [27]**
▼	▼	▼
Twin-refreshed Hamiltonian [29], [35]	**Swipe-style interface [34]**	

Figure 4. Three actuators influenced by spectral cost, live Hamiltonians, and human override.

5. Integrity of the Measurement Channel

AI–blockchain integration is proposed as the integrity layer for traceability and resilience [31]. Exponential modulation of FKF coefficients is proposed as a spectral watermark for digital supply-chain networks [19]. Used together they answer different questions. The ledger answers “who committed this event?” The watermark answers “does this time series still look like the series that was committed?” An adversary who forks neither the ledger nor the kernel still fails if the two disagree.

Physical-layer telemetry remains relevant. Power-line carrier anti-theft work showed that existing conductors can carry a low-rate state [32]. Charging cabinets and powered docks in electrified fleets [6], [9] recreate that geometry. The architecture therefore does not assume ubiquitous 5G at every supplier. Sequential testing-function arguments [12] tell the watermark window when it is long enough to be trusted [21].

Influence diagram — Section 5

Event stream	
Ledger attestation [31]	**FKF watermark [19]**
Agreement test	
PLC / dock side-channel [32], [9]	**Window length [12]**

Figure 5. Dual integrity path: ledger identity and spectral watermark, with physical-layer fallback.

6. Closed-Loop Objective

Collecting stages 2–5, the planning problem on a horizon H is equation (9), subject to (1)–(3), energy floors from (2), spectral floors on (5), assignment feasibility from (7), and the accept/override rule (8). Recovery time T_rec is estimated on disruption ensembles drawn from the twin, which is how resilience reviews asked measurement to be done [10]. Green cost and carbon sit inside ℓ_t via the sustainable-logistics review [30].

$$\min \sum_{t=0}^{H} \ell_t + \gamma T_{rec} \qquad (9)$$

Internal complexity in the weaving-resilience sense is the dimension of $\hat{x}$ plus the number of roles that may set a_t [27]. External complexity is the measure of the ensemble that produces T_rec. Adding sensors without adding (5) often raises internal complexity faster than it lowers T_rec—the failure mode named in digital-transformation reviews [10]. Distributional FKF structure [11] keeps stockout impulses inside the same observer that feeds (9). Time-shift structure [18] keeps delayed sailings from being misread as new modes.

Influence diagram — Section 6

Constraints (1)–(3), (5), (7), (8)	
Horizon objective (9)	
T_rec from twin ensembles [10], [29]	**Green ℓ_t [30]**
Internal complexity [27]	**External ensemble size [10]**

Figure 6. Closed-loop objective influenced by energy, spectrum, assignment, and override constraints.

7. Mobility as a Constrained Subsystem

Smart mobility and ITS surveys list connected corridors, charging, and policy as first-class constraints on urban freight [6]. They are not decorations on (1). A van that cannot enter a zone at 08:00 is a missing actuator, not a late shipment. Solar-assisted design frameworks [9] and contest architectures [28] change the right-hand side of (2) in weather-dependent ways that routing AI [30] must see. Battery reviews [7] change the feasible P_trac.

Residue methods [13] watch whether the electrical plant is ringing while the material plant looks calm. Quantum surveys in transportation already list charger assignment and gate allocation as relatives of ULD packing [8]. The same Hamiltonian family (7) can therefore serve depot slotting and aircraft-container slotting if the twin exports a common assignment interface [5]. That is an engineering standard, not a theorem.

Formula-style sizing [33] remains the cleanest classroom reduction of (2): known track, known P_trac, design E. Logistics replaces the track with a stochastic corridor from ITS data [6] and replaces certainty with chance constraints. The algebra does not change; the measure on P does. Practical quantum-logistics notes [35] keep the annealer inside that same corridor problem.

Influence diagram — Section 7

ITS corridors and policy [6]	
Energy RHS of (2) [9], [28]	**Feasible P_trac [7], [33]**
Routing AI [30]	**Charger / ULD Hamiltonian [8], [5]**
Electrical residues [13]	

Figure 7. Mobility constraints influence energy, routing, and discrete assignment.

8. Worked Narrative

A coastal depot loses a berth. The twin [29] raises dwell in L_k. FKF shift analysis [14], [18] shows the delay is a translation, not a new resonant mode, so ρ dips only mildly. Green AI [30] reroutes inland. Several ULDs must be rebuilt; the annealer returns a configuration [5]. A planner rejects two slots that would break a labor rule [27]. Meanwhile a solar-hybrid tractor [9] reports a current harmonic; residues [13] tag the depot charger, not the pack chemistry [7]. The quality event is committed [31] and watermark-checked [19]. Recovery time estimated on the twin enters (9). No single paper in the list simulates this story end to end; every object in the story is cited.

A second narrative is quieter. No berth is lost. Weekly order cycles amplify at echelon three. Shift-invariant spectra [14] catch the amplification before fill rate moves. Differential FKF properties [16] predict that a modest buffer at echelon two will detune the mode. The twin tests that prediction [29]. AI does not need to "discover" the buffer by reinforcement if the spectrum already named the pole [15]. That is the operational case for keeping a spectral observer rather than only a learning actuator. Sequential window tests [12] decide when the quiet narrative has enough samples. FKL inversion [17] is available if the FKF window is awkward.

Influence diagram — Section 8

Disruption: lost berth	**Quiet: weekly cycle**
Twin raises L_k [29]	**Shift spectra [14], [18]**
Reroute + anneal + override [30], [5]	**Buffer from residues [16], [15]**
Watermark + ledger close the event [19], [31]	

Figure 8. Two narratives: disruption recovery and quiet spectral detuning.

9. What This Architecture Refuses

It refuses a twin without an observer channel that can see oscillations [29], [15]. It refuses green AI that cannot see energy floors [30], [33]. It refuses quantum calls on stale Hamiltonians [5], [8]. It refuses ledgers that never look at the continuous signal [31], [19]. It refuses automation that hides override [27]. It refuses mobility programs that treat the pack as an infinite bus [7], [9]. It refuses resilience dashboards that never appear in a constraint [10].

These refusals are scoped to the cited program. They are not a claim that other transforms, other QPUs, or other chemistries are illegitimate. FKL [17] is already an alternative inversion. New batteries change numbers in (2), not the block diagram [7]. New ITS policies [6] change the feasible set of (8), not the existence of a human actuator. Contest solar work [28] and swipe-style interfaces [34] remain reminders that energy and fingers are both designable. Distributional and sequential companions [11], [12] and their cross-listed counterparts [20], [25] keep the observer honest about impulses and window length.

Influence diagram — Section 9

Refused: twin w/o spectrum [29], [15]	**Refused: green AI w/o energy [30], [33]**
Refused: stale Hamiltonians [5], [8]	**Refused: ledger w/o watermark [31], [19]**
Refused: hidden override [27]	**Refused: infinite bus [7], [9]**
Kept: FKL [17], ITS [6], solar [28], swipe [34]	

Figure 9. Refusals bound the architecture; alternative inversions and interfaces remain admissible.

10. Research and Engineering Agenda

Publish a toy twin with exportable y and L_k so that FKF code [11], [15] and annealer embeddings [5] can be compared. Report ρ next to fill rate. Report override rate next to automation rate [27]. Report pack thermal margin next to on-time percentage [7]. Put solar irradiance on the same clock as delivery windows [9], [6].

Prove, or fail to prove, that pricing ρ in (6) reduces bullwhip amplification relative to carbon-only ℓ [30], [15]. Prove, or fail to prove, that watermark-plus-ledger catches a class of spoofs that either control alone misses [31], [19]. Measure whether power-line side channels [32] still matter on electrified docks. Keep teaching sizing [33] and simple interfaces [34] so that students who will meet (4) and (7) still know a watt and a button.

The systematic agenda in the digital-transformation resilience review remains the outer envelope [10]: measurement, governance, multi-tier visibility. This paper only tightens that envelope into a plant, an observer, and three actuators. Humanitarian and perishable settings flagged in general resilience writing will need different w in (5) and different labor rules in (8). They should not need a different philosophy of loop closure. Time-shift and differential identities [18], [16] are the first instruments those settings should reuse. Quantum opportunity notes [35] and transportation surveys [8] remain the discrete-actuator reading list. Sequential convergence [12] and FKL inversion [17] remain the observer reading list.

Influence diagram — Section 10

Toy twin + exportable y, L_k [29], [14]
Compare FKF [15] vs annealer [5]
Metrics: ρ, override, thermal, irradiance [27], [7]
Tests: ρ vs carbon [30]; watermark vs spoof [31]

Teach watts [33] and buttons [34]

Figure 10. Agenda items influenced by the observer, the discrete actuator, and classroom reductions.

11. Limitations

No new field experiment is reported. Equations (1)–(9) reorganize published constructs; they do not replace stochastic inventory theorems or vehicle type-approval. Quantum sections inherit near-term device limits [8], [35]. Spectral sections inherit the assumptions of the FKF/FKL series [15], [17]. Mobility sections inherit the coverage of battery and solar papers [7], [9]. Early hardware citations [32], [34] are conceptual, not a 2026 bill of materials.

Commensurability remains a risk. A testing-function space [12] and a shop-floor override [27] live in different categories. The architecture claims only that both appear in the same loop, not that they are the same kind of object. Single-author corpus bias is inherited from the reference list. Cross-listed distributional and sequential statements [11], [20] and [21], [25] should be treated as overlapping claims, not independent replications. Contest architecture [28] and classroom sizing [33] are existence proofs for (2), not fleet statistics. Green-AI and twin reviews [30], [29] remain bibliometric and survey-grade evidence.

Influence diagram — Section 11

No new field experiment	
QPU limits [8], [35]	**FKF/FKL assumptions [15], [17]**
Battery/solar coverage [7], [9]	**Hardware as concept [32], [34]**
Category gap: testing space vs override [12], [27]	

Figure 11. Limitations inherited from devices, transforms, mobility evidence, and category mismatch.

12. Conclusion

Multi-echelon resilience under electrified logistics is not a dashboard score and not a single algorithm. It is a closed loop. The plant is on-hand stock coupled to usable pack energy, so a shipment that looks feasible on a material balance can still be infeasible when every candidate vehicle violates an energy floor. The observer is a digital twin plus a spectral channel: the twin carries the estimated state; the spectral channel makes periodic bullwhip, delayed sailings, and electrical resonance visible before fill rate or on-time percentage moves. The actuators are three and not one: a green policy that prices both carbon and spectral health, a discrete solver for packing and disruption re-slotting, and a human who may accept or override. Integrity is dual. A ledger answers who committed an event. A watermark on the continuous series answers whether the series still looks like the series that was committed. Sensing need not assume ubiquitous cellular coverage; ordinary conductors on docks and cabinets can still carry a low-rate state. Cities, corridors, charging windows, and zone rules are constraints on the same loop, not decorations around it.

What the architecture contributes is commutation, not invention. It does not replace inventory theorems, type-approval, a new transform, or a new vehicle. It places those literatures on one block diagram so that a twin without an oscillation channel, a green dispatcher that cannot see energy floors, a discrete solver running on a stale Hamiltonian, a ledger that never looks at the continuous signal, automation that hides override, and mobility programs that treat the pack as an infinite bus are all visible as the same class of mistake: an open loop dressed as resilience.

Two operating pictures follow from that diagram. In disruption, dwell rises, the spectral channel tests whether the delay is a translation or a new mode, routing and re-packing move, a planner may reject a labor-illegal slot, and a charger harmonic is tagged to the dock rather than to chemistry. Recovery time is then an estimated quantity on the twin, not a slogan. In the quiet case, weekly order cycles amplify before service metrics move; differential structure names the buffer that detunes the mode; the twin tests the prediction; reinforcement does not have to discover a pole the spectrum already named. Those two pictures are the operational case for keeping a spectral observer beside a learning actuator.

The research program is correspondingly concrete. Export a toy twin's measurements and lead times so observer code and discrete embeddings can be compared on the same clock. Report spectral health next to fill rate, override rate next to automation rate, pack thermal margin next to on-time percentage, and irradiance next to delivery windows. Test whether pricing spectral health reduces amplification relative to carbon-only cost. Test whether watermark plus ledger catches spoofs that either channel misses alone. Measure whether physical-layer side channels still matter on electrified docks. Keep teaching a watt and a button so the students who will meet the observer integral and the discrete Hamiltonian still know what the plant and the interface are.

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