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Energy-Bounded Freight Recovery through a Green AI–Spectral Control Cycle

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Abstract—
Concurrent pressure from geopolitics, cyber intrusion, climate extremes, and network congestion now lands on freight systems as a single compound event rather than as isolated incidents. Cascading losses then travel through movement, stock, energy, and data layers at the same time. This paper reconstructs a constrained recovery architecture in which digital twins, emission-aware logistics, hash-chain provenance, operator swipe release, two-sided FKF/FKL spectral operators with sequential convergence, selected quantum packing kernels, anti-theft integrity bits, hybrid-electric energy bounds, and intelligent-mobility telemetry are joined inside one forecast–response loop. Heterogeneous field signals are watched continuously, converted into risk-bearing features, and admitted as recovery commands only when energy, transport, security, and integrity predicates are jointly satisfied. Blockchain verification supplies a trusted record of the evidence that licensed the command. Resilience is therefore framed as an ongoing, constraint-checked practice that anticipates shock, screens feasible recoveries, and revises the predictor from residual evidence rather than as a one-shot repair after collapse.

Keywords— digital twins; green logistics; blockchain provenance; swipe release; FKF/FKL operators; quantum packing; anti-theft integrity; hybrid-electric fleets; intelligent mobility; freight networks; sequential convergence; Industry 5.0; constrained resilience

I. INTRODUCTION

Packing and routing combinatorics remain the setting in which quantum logistics can be judged with the least ambiguity. Annealing formulations convert disrupted assignment and unit-load-device configuration into combinatorial models that an AI planner can call as a kernel rather than as a replacement for planning itself [19], [21], [35]. The same literature shows that routing, scheduling, and allocation remain the tasks where conventional heuristics first saturate.

A disruption is treated as a multi-scale series on the freight network, not as a single stamped incident. Distributional extensions of the Fourier–Kontorovich–Lebedev (FKF) transform give a legitimate domain for irregular logistics signals [24], and sequential-convergence theorems allow those operators to act on streaming testing-function spaces [25]. Subsequent FKF studies extract residue resonances, shift-invariant multi-echelon lead times, and spectral resilience signatures [39], and they show how a small lead-time nudge relocates that signature [37], [38], [40].

Delay, scale, and amplitude change can be isolated inside the same operational trace. The companion FKL transform and its documented properties support an alternative spectral chart of supply-chain series [11]. Time-shift identities locate delayed events [12], while exponential modulation marks intensity change on a secured digital channel [13]. Those identities give the predictor a spectral map of lead-time drift, anomalies, and repeating disruption motifs.

Live sensing, twin simulation, provenance hashes, mobility feeds, selective quantum search, and FKF/FKL features can be stacked against a purely reactive control tower. IoT and intelligent-transportation streams supply observations; the swipe controller remains the human-machine release; power-line-carrier anti-theft signalling watches infrastructure integrity; hybrid-electric and solar-assisted fleets bound what a predicted recovery may physically execute [14], [16]–[18], [20], [22], [34], [36]. Interface and integrity notes stay in the stack only as sensing and operator-control antecedents [17], [34]. The reconstruction that follows therefore starts from a coupled kernel and ends with a gated release rather than from a catalogue of shocks.

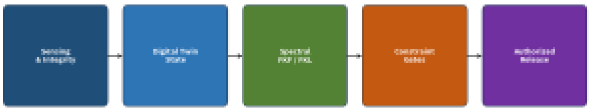

Fig. 1. Sensing–twin–spectral–gate–release pipeline used as the working skeleton of the reconstructed cycle.

II. LITERATURE ANCHOR AND DOMAIN MAPPING

A. Working Definitions of Exposure, Capacity, Forecast, and Response

Any material, informational, or financial deviation large enough to injure service, cost, or continuity is treated as exposure. Capacity is the network's ability to anticipate, absorb, restore, and adapt. Forecast estimates occurrence, magnitude, duration, or propagation before consequences harden. Response then names the dual-sourcing, inventory, mode-switch, contractual, cyber-containment, and re-planning moves that cut that exposure.

Visibility, connectivity, analytics, and automation still dominate digital-transformation surveys of resilience levers [23]. The present synthesis asks how twins, green logistics, hash-chain provenance, and a swipe release can close a live forecast–response loop instead of only cataloguing shocks after they land. Shared vocabulary is therefore a prerequisite for later equations rather than a decorative preface.

B. Scope of the Source Corpus and Reading Protocol

Field-wide systematic reviews typically mine Scopus or Web of Science and sort records by algorithm, use-case, or risk-management stage. The reconstruction adopted here follows a narrower authorial corpus so that couplings, leftover gaps, and operator roles can be named without pretending to a global census.

The twenty-five core sources are therefore read as linked strands. Methods are extracted only when an input–output role can be assigned, and leftover gaps are retained as explicit limits rather than being smoothed away. That reading rule keeps later flow descriptions auditable against the same corpus.

C. Operational Clusters Extracted from the Source Set

The selected corpus is partitioned into six working clusters that later operators reuse. Connected resilience rests on digital twins of adaptive global networks [31], AI–blockchain traceability [33], and digital-transformation capability [23]. Green logistics [32] is paired with Industry 5.0 human-centric automation and the swipe controller as the operator gate [15], [34].

Smart mobility and logistics appear as a layered IoT–AI–quantum stack [14], [20]. Annealing for disrupted unit-load-device configuration [19] is the only combinatorial primitive taken from quantum logistics. FKF/FKL work supplies distributional extensions, sequential convergence, shift and modulation identities, and multi-echelon lead-time spectra [11]–[13], [24], [25], [37]–[40].

Hybrid-electric battery limits [36], plug-in sizing [18], solar-assisted architectures [16], [22], and ITS mobility traces [20] bound what a predicted recovery may physically execute. The swipe controller [34] and the power-line-carrier anti-theft system [17] prefigure operator interfaces and infrastructure watch. Every corpus item is given one operational role so the reconstruction can be checked against the source list rather than against a pictorial maturity plot. The working citations are therefore confined to the linked corpus [11]–[25], [31]–[40].

III. ASSEMBLY OF THE FORECAST–RESPONSE CYCLE

An integrative reading of the defined corpus, rather than a new plant-floor experiment, is the method used here. Twins, green objectives, hash-chain provenance, Industry 5.0 swipe control, selected quantum kernels, FKF/FKL spectral theory, hybrid-electric mobility, anti-theft sensing, and mobility feeds are organized into one forecast–response cycle. The product is a stage-wise function map, not a fitted industrial benchmark.

Four supporting domains seat intelligent recovery. Physical and energy infrastructure—fleets, warehouses, battery systems, charging assets, and solar-assisted architectures—sets the physical limits of action [16], [18], [22], [36]. Anti-theft integrity remains a hard requirement [17]. The swipe controller [34] and Industry 5.0 rules [15] then decide how far automation may travel without a human grant. The intelligence layer mixes learning, twin simulation [31], FKF/FKL analysis with sequential convergence [11]–[13], [24], [25], and selective quantum logistics [19], [21], [35]. Green objectives [32] and digital-transformation capability [23] remain binding context, not optional add-ons.

A. Construction of the Predictive State

Forecasting begins by packing multi-echelon telemetry, mobility traces, swipe events, and anti-theft alarms into one feature space. Twin state, FKF/FKL descriptors, and a provenance digest are concatenated before a learning model estimates disruption probabilities and the twin explores alternative futures. Confidence is a verification predicate on the observation window, not a generic traffic-light score.

The resulting predictive state is therefore a calibrated object that already carries twin discrepancy, spectral texture, and an integrity digest. That object, rather than a raw alarm list, is what the planner later consumes.

B. Licensed Intervention under Binding Predicates

Response begins when the predictive state is handed to a planner that may use rules, mathematical programming, twin scenarios, or a QUBO/Ising kernel for selected packing instances [19]. Proposed actions are then screened by green-logistics and hybrid-electric constraints, auditable hash-chain requirements, anti-theft integrity, and a swipe grant consistent with Industry 5.0 [15], [33], [34].

After execution, residuals update the predictor. Residual feedback may be marked with the FKF exponential-modulation identity before it re-enters learning [13]. No command is treated as complete until that residual has been written back.

C. Operating Rules of the Closed Cycle

Three operating rules keep the cycle technically valid, operationally feasible, and auditable. First, forecasts must remain inside hybrid-electric energy, transport resource, inventory, fleet, and capacity limits so that estimated risk and recommended action stay consistent with the plant. Second, mitigation must rely on hash-traceable data, explicit governance, anti-theft integrity, and a swipe authorization or override. Third, FKF/FKL analysis with sequential convergence should complement rather than replace machine-learning methods by exposing scale and resonance patterns that conventional predictors may miss.

Together the rules create a controlled interaction among forecast, spectral analysis, operational bounds, trusted data, and decision authority. Without common resilience indicators, however, the same cycle cannot be compared across firms, which remains an important gap in digital-transformation research [23].

D. Named Operators and Working Identities

Named technologies enter as operators with explicit inputs and outputs. A digital twin supplies the state estimator [31]; green logistics supplies the emission-weighted objective [32]; blockchain supplies the provenance hash that licenses action [33]; the swipe controller supplies the human release [34]; FKF/FKL analysis with sequential convergence supplies the multi-scale feature map [24], [25], [37]–[40]; hybrid-electric and solar-assisted fleets supply the energy bound [16], [18], [22], [36]; the anti-theft system supplies the integrity bit [17]; smart mobility supplies ITS traces [20]; and quantum logistics is invoked only when the action is a combinatorial packing or routing decision [19], [21], [35].

The identities that follow are the working pipeline of the reconstructed cycle. Each identity is rewritten in equivalent operational form so that later implementation notes can cite a numbered line rather than a narrative claim.

Named technologies can therefore be represented not merely as independent components, but as functional operators within an integrated resilience architecture, where each technology receives a clearly defined input and produces an operational output. This operator-based interpretation establishes a traceable pathway from physical-system observations to validated, energy-aware, human-supervised, and computationally optimized decisions.

The digital twin functions as the principal state-estimation operator. It continuously assimilates equipment conditions, inventory levels, transportation status, demand information, and other real-time observations to maintain a synchronized representation of the physical supply-chain system. Its output is an updated estimate of the current operational state and the associated deviations from expected conditions [31]. Green logistics subsequently transforms operational alternatives into an emission-aware objective by incorporating fuel consumption, energy usage, travel distance, vehicle utilization, and associated environmental impacts. The resulting output is an emission-weighted performance measure that allows resilience decisions to be evaluated jointly against operational and sustainability requirements [32].

The blockchain layer provides a trusted provenance operator. Relevant transactions, sensor observations, approvals, and state changes can be associated with verifiable records and cryptographic hashes, thereby establishing data lineage and supporting the authorization of downstream actions [33]. In this architecture, blockchain does not independently make the operational decision; rather, it provides the integrity and provenance evidence required for a decision to proceed. The swipe controller then introduces an explicit human-release mechanism [34]. Its output is a human authorization signal that prevents an automatically generated recommendation from being executed without appropriate supervisory confirmation.

The FKF/FKL analytical layer operates as a multi-scale feature-extraction operator. Temporal information can be represented through Fourier-domain characteristics, while scale-, distance-, or intensity-dependent behavior can be represented through the Kontorovich–Lebedev component. Sequential convergence provides a mathematical mechanism for progressively combining these representations while maintaining analytical consistency [24], [25], [37]–[40]. The resulting output is a multi-scale spectral feature map capable of characterizing recurring lead-time behavior, disruption signatures, oscillatory patterns, and scale-dependent changes in supply-chain dynamics. These features can subsequently be supplied to predictive or decision-support models.

Energy constraints are introduced through hybrid-electric and solar-assisted fleet technologies, which act as energy-bound operators [16], [18], [22], [36]. Their operational data can provide information on available battery energy, charging requirements, renewable-energy contribution, fuel consumption, vehicle range, and route-dependent energy demand. The resulting output is an admissible energy envelope that restricts transportation decisions to solutions compatible with available energy resources and sustainability objectives.

The anti-theft system contributes an integrity operator by generating an integrity or security-status bit [17]. This signal can indicate whether a shipment, vehicle, container, or monitored asset satisfies predefined security conditions. A failed integrity state can therefore prevent or modify downstream actions even when the corresponding logistical solution is otherwise feasible.

Smart-mobility infrastructure contributes an ITS-trace operator, transforming traffic, vehicle, route, and mobility observations into transportation-state information [20]. These traces can support dynamic travel-time estimation, congestion detection, route adaptation, and real-time logistics monitoring.

Finally, quantum logistics is deliberately treated as a specialized optimization operator rather than as a universal computational layer. It is activated only when the decision contains a sufficiently combinatorial structure, such as unit-load-device packing, vehicle-routing assignment, scheduling, or related discrete optimization problems [19], [21], [35]. The classical resilience architecture therefore determines the relevant state, constraints, features, provenance, energy limits, and human authorization conditions before a quantum or hybrid quantum-classical optimizer is invoked. Its output is a candidate combinatorial solution that must subsequently satisfy the established operational and governance constraints.

Collectively, these operators form a closed-loop decision chain:

physical observations → state estimation → spectral feature extraction → risk evaluation → sustainability and energy constraints → provenance/security validation → optimization → human release → execution → residual-state feedback.

This formulation clarifies the role of each technology and avoids treating digital twin, AI, blockchain, IoT, mobility, energy, and quantum computing as disconnected additions. Each component performs a defined transformation, and its output becomes an input or constraint for the next stage. The architecture consequently supports an auditable progression from heterogeneous sensing to adaptive action while retaining multi-scale analytical information, environmental constraints, data integrity, energy feasibility, combinatorial optimization, and human oversight.

E. Twin Dynamics of the Physical Network

Write the physical multi-echelon freight state, command, and disturbance at epoch t as ξ_t, ν_t and δ_t. The plant and its digital twin [14], [31] then evolve as

$$\xi_{t+1} = \Phi\, \xi_t, \nu_t, \delta_t; \vartheta + \eta_t, \quad \hat{y}_t = H\, \xi_t; \vartheta + \varepsilon_t \quad (1)$$

$$\xi_{t+1} = \Phi\, \xi_t, \nu_t, 0; \vartheta, \quad \tilde{\hat{y}}_t = H\, \xi_t; \vartheta \quad (2)$$

Identifiable twin parameters sit in ϑ, and y_t is the IoT / mobility observation [14], [20]. The twin discrepancy that later enters the risk feature is

$$\rho_t = \| y_t - \tilde{\hat{y}}_t \|_W + \kappa \| \xi_t - \xi_t \|_Q \quad (3)$$

The discrepancy ρ_t is the first quantitative reminder that a recovery plan computed on the twin is admissible only when the plant and the replica remain close in the chosen norms.

F. Emission-Weighted Recovery Objective

Each feasible recovery mode k (lane, hybrid-electric vehicle, or energy architecture) carries an operating cost γ_k and an emission intensity χ_k from green logistics [16], [22], [32]. With binary activation ζ_k and carbon price μ, the green objective used by the planner is

$$J_g(\zeta) = \sum_k (\gamma_k + \mu\chi_k)\zeta_k \quad (4)$$

Assigned flows φ_{ij} also generate network-level CO_2 over distance ℓ_{ij} and mode factor $\psi_{m(i,j)}$.

$$E_{net} = \sum_{i,j} \psi_{m(i,j)} \cdot \ell_{ij} \cdot \varphi_{ij} \quad (5)$$

Equations (4)–(5) keep carbon intensity inside the planner rather than as a report written after dispatch.

G. Hash-Chain Provenance and Licensed Release

Blockchain traceability is a hash chain on the observation that justifies v_t [33], not a dashboard badge. With cryptographic hash ħ and concatenation ∥,

$$H_t = \hbar(H_{t-1} \parallel y_t \parallel meta_t) \quad (6)$$

A mitigation command is released only after verification against the payload window $y_{1:t}$ and a swipe-controller grant.

$$Release\, v_t = 1 \;\Leftrightarrow\; Ver\, H_t, y_{1:t} = 1 \,\wedge\, Swipe_t = 1 \,\wedge\, I_t^{ath} = 1 \quad (7)$$

The predicate in (7) is the governance hinge of the cycle: no spectral score, however sharp, can fire a command without provenance, integrity, and an operator grant.

H. Two-Sided FKF Operator and Companion FKL Transform

Lead-time and disruption signals σ from the freight network pass through the two-sided Fourier–Kontorovich–Lebedev operator of the corpus [24]. With modified Bessel kernel $K_{i\tau}$,

$$F\,\sigma\,(\tau,\omega) = \int_0^\infty \sigma\, r\; r^{-1}\, K_{i\tau}(r)\; exp - i\omega \ln r\; dr \quad (8)$$

Delayed multi-echelon events are handled by the documented time-shift identity [12].

$$F\,\sigma\cdot - \alpha\,(\tau,\omega) = exp - i\omega\alpha\;\, F\,\sigma\,(\tau,\omega) \quad (9)$$

Exponential modulation records both a spectral-intensity change and a mark on residual feedback for a secure digital channel [13].

$$F\, e^{\beta\cdot}\sigma\,(\tau,\omega) = F\,\sigma\,(\tau,\omega + i\beta) \quad (10)$$

The companion FKL operator [11] replaces the Kontorovich kernel by an L-kernel on the same half-line.

$$L\,\sigma\,(\tau) = \int_0^\infty \sigma\, r\;\, L_{i\tau}(r)\; dr \quad (11)$$

Residue-based resonance extraction [37] isolates a scale peak by a contour integral about a neighbourhood Γ_n of a suspected pole.

$$R_n(\sigma) = \frac{1}{2\pi i} \int_{\Gamma_n} F\,\sigma\,(\zeta)\; d\zeta \quad (12)$$

Streaming updates of (8) rest on sequential convergence in the testing-function space [25].

$$\sigma_n \to \sigma \;\; in\; \mathcal{S} \;\;\Rightarrow\;\; F\,\sigma_n \to F\,\sigma \quad (13)$$

Identities (8)–(13) therefore supply delay, intensity, resonance, and streaming licences from one operator family rather than from five disconnected detectors.

I. Calibrated Predictor Coupled to a Packing Kernel

The control tower consumes a calibrated disruption probability built from the twin state, the FKF feature, and the provenance digest.

$$\pi_t = \Psi\; \xi_t, F\,\sigma_t\,, L\,\sigma_t\,, H_t, \rho_t \quad (14)$$

When the chosen action is unit-load-device (re)packing or disruption-aware assignment, quantum logistics solves a QUBO by annealing [19], [21].

$$min_z\;\; z^T Q z \;+\; q^T z, \quad z \in (0,1)^n \quad (15)$$

$$Q\; a, b = \lambda_c\, C\; a, b + \lambda_d\, D\; a, b + \lambda_e\, E\; a, b \quad (16)$$

The same assignment has an Ising form for analog annealers.

$$min_s\;\, - \textstyle\sum_{a<b} J\; a, b\; s_a s_b \;- \sum_a h_a s_a, \quad s_a \in \{-1, +1\} \quad (17)$$

Every non-combinatorial action remains classical. The constrained planner that mixes twin loss, green-logistics cost, hybrid-electric state-of-charge, anti-theft integrity, and swipe/blockchain licence is

$$v_t^* \;\in\; arg\, min_v\; [J_g + \lambda_\rho \rho_t + \lambda_e\, max\; SOC_{min} - SOC\; t\,, 0] \quad (18)$$

$$s.t.\;\; Release\, v = 1, \;\; cap\; v \le cap\; t, \;\; SOC\; t - \Delta\; v \ge SOC_{min} \quad (19)$$

After execution, predictor parameters are rewritten from the residual.

$$\vartheta_{t+1} = \vartheta_t - \eta \nabla_\vartheta\, \ell\; \pi_t, r_{t+1}, \quad r_{t+1} = y_{t+1} - \hat{y}_{t+1|t} \quad (20)$$

Equations (1)–(3) implement the twin; (4)–(5) implement green logistics; (6)–(7) implement provenance; (8)–(13) implement FKF/FKL analysis with sequential convergence; (14) is the predictor; and (15)–(19) implement quantum or classical mitigation under energy, integrity, and swipe governance. Table I and Fig. 2 collect the same operators as a compact checklist.

TABLE I. OPERATORS, INPUTS, AND RELEASE CONDITIONS

Operator	Primary input	Release condition
Digital twin	Telemetry ξ, y	ρ_t below tolerance
FKF / FKL map	Lead-time series σ	F{σ_n} converges
Green objective	Cost γ_k, intensity χ_k	Finite J_g at price μ
Hash chain	Window y_{1:t}	Ver(H_t, y_{1:t})=1
HEV energy gate	SOC_t, charging	SOC_t−Δ(ν)≥SOC_min
Anti-theft bit	PLC integrity watch	I_t^{ath}=1
Swipe grant	Operator panel	Swipe_t=1

QUBO kernel	Packing instance	Heuristics saturate

Fig. 2. Constraint gates that convert the predictive state π_t into a licensed recovery command.

IV. FUNCTIONAL READING OF THE CONTROL STACK

A. From Mixed Streams to Risk Signatures

Identification starts when mixed telemetry, text, swipe events, and operational observations become recognisable risk signatures. Mobility platforms and intelligent transportation systems provide continuous streams [14], [20], while hash-chain provenance can raise the reliability of those observations [33]. The anti-theft system [17] remains the reminder that physical tampering can erase signatures before any model runs.

On the spectral side a disruption is a resonance, a shift, or a multi-scale change rather than an isolated timestamp. Residue extraction detects hidden periodic stress in hybrid-electric and logistics systems [37]. Shift-invariant FKF analysis of lead times seeks to preserve relevant spectral character when delays appear without rewriting the underlying motif [12], [38]. Distributional extensions and sequential-convergence theorems then licence the same operators on irregular and heavy-tailed streams [24], [25].

Green logistics adds an identification axis that cost-and service models often omit. Environmental and regulatory exposure can remain hidden when predictors optimize only delivery and cost [32]. Carbon, fuel, energy efficiency, and ecological impact therefore belong inside the feature space. Risk is defined not only by the detector an organisation trains, but also by the loss, constraints, and measures it actually chooses to optimise.

B. From Signature to Network-Wide Consequence

Assessment converts a detected signature into probability, severity, exposure, and propagation. Digital twins are relevant because they permit alternative disruption scenarios to be simulated without physically exposing the network to failure [31]. The same reviews still report no stable resilience metric across studies, which limits how far any assessed score can be compared [23].

Spectral differentials of the distributional FKF transform ask how a lead-time perturbation moves a resilience signature [24], [40]. Hybrid-electric battery chemistry, management systems, and sizing approaches influence available transport capacity after grid or charging shocks [18], [36]. Solar-assisted hybrid architectures add generation and therefore change the feasible recovery set [16], [22]. If those energy limits are ignored, last-mile recovery will look more feasible than the fleet can deliver.

C. From Assessed Score to Feasible Action

Mitigation is the step that turns a forecast into an operational intervention. Quantum-logistics studies frame several mitigation problems as combinatorial tasks involving configuration, rerouting, scheduling, and unit-load-device packing under disrupted capacity [19], [21], [35]. Those approaches remain largely prospective, whereas conventional twins can already support counterfactual experiments [31]. Mobility therefore senses, AI forecasts, the swipe controller authorizes, and quantum search is reserved for packing and scheduling kernels that exhaust classical heuristics [14], [34].

Whether an automated action may fire is a governance question before it is a control question. Hash-chain provenance can provide an auditable record of decisions and of the data beneath them [33]. Industry 5.0 places the human operator, through the swipe controller, at the centre of exception handling rather than treating human involvement as residual error [15], [34]. Exponential modulation of the FKF transform has been proposed as a marking method for secure digital channels [13], which matters whenever a decision is computed from a signal that an adversary—or a failed anti-theft node—could spoof.

D. Residual Watch and Predictor Rewrite

Monitoring closes the loop by measuring what an implemented action actually changed and by feeding that residual forward. Digital-transformation research emphasizes continuous visibility while identifying weaknesses in standardized resilience metrics [23]. Mobility systems generate extensive post-event data from connected vehicles, charging assets, and traffic management [20]. Green monitors then add emissions, energy use, and circularity to the usual delivery and cost KPIs [32].

Spectral monitors track frequency and scale drift instead of waiting for a KPI threshold to break. Sequential-convergence results [25] become relevant when streaming observations are incorporated as consistent elements of the transform's testing-function framework.

Detection, assessment, swipe-released intervention, and learning then form one cycle rather than four disconnected reports.

Fig. 3. Residual-monitoring loop that rewrites predictor parameters after each licensed recovery.

V. GUIDANCE FOR RESEARCHERS AND PRACTITIONERS

Researchers should therefore view the available literature as an **integrated research programme with distinct but complementary streams**, rather than as a flat collection of references. The choice of citations should correspond directly to the nature of the contribution being developed. Studies on **digital twins, blockchain, Industry 5.0, and digital supply chains** are most appropriate when the emphasis is on managerial architecture, digital integration, governance, traceability, and resilient operational design [15], [23], [31], [33].

When the contribution is primarily **mathematical or spectral**, the FKF/FKL studies and sequential-convergence framework provide the appropriate theoretical foundation and should be cited accordingly [11]–[13], [24], [25], [37]–[40]. In contrast, **quantum-logistics research** should be introduced selectively when the underlying problem has a strongly combinatorial structure—such as packing, routing, or assignment—and conventional heuristic or classical optimization approaches become inadequate [19], [21], [35]. This structured citation strategy preserves the methodological identity of each research stream while demonstrating how the streams collectively support the proposed resilience architecture.

Hybrid-electric sizing, anti-theft, and swipe-controller papers specify constraints or interfaces; they are not evidence that AI predicts freight risk [16]–[18], [22], [34], [36]. Mixing those roles in a single citation block obscures what was actually shown.

Practitioners should assemble the loop from the middle outward rather than from a full technology catalogue. Identification quality and a twin of the two or three lanes that dominate disruption cost provide a practical starting point [31], [33]. The swipe override should be added before autonomy [15], [34]. Hybrid-electric fleet state and anti-theft integrity should be treated as live risk inputs [17], [20], [22]. Quantum kernels and specialised transforms stay on a research track until a controlled bake-off exists.

TABLE II. IMPLEMENTATION SEQUENCE FOR FIELD TEAMS

St.	Minimum viable object	Do not add yet
1	Lane-level twin of cost-dominant corridors	Network-wide multi-firm twin
2	Provenance hash on the observation window	Public tokenised marketplaces
3	Swipe exception panel with an audit log	Fully autonomous dispatch
4	SOC and anti-theft bits as live features	Unconstrained last-mile promises
5	Classical planner with green objective	Annealer kernel without bake-off
6	Residual write-back into the predictor	KPI dashboards without residuals

VI. OPEN QUESTIONS AND MEASUREMENT NEEDS

A short but material set of research gaps still separates the proposed architecture from reliable industrial adoption. Explainable risk scoring is particularly important because managers, operators, and regulators must be able to identify which variables influenced a forecast, how the risk level was derived, and why a particular recovery action was authorized. This transparency is essential for accountability, auditability, and trust in AI-supported decisions.

Multi-tier visibility also needs to move beyond the focal organization toward network-level representations that capture supplier dependencies, transportation connections, information exchanges, capacity constraints, and cascading losses across multiple supply-chain echelons. Such representations would allow disruptions originating at one node to be traced more effectively through interconnected physical and information flows.

In addition, climate, social, environmental, and green-logistics factors remain insufficiently integrated into many predictive risk models. Future measurement frameworks should incorporate climate exposure, carbon emissions, energy consumption, social conditions, resource constraints, and sustainability objectives directly into both risk forecasting and recovery evaluation. Cross-firm digital twins likewise require common data models, interoperability standards, and secure exchange mechanisms before they can provide reliable shared situational awareness.

Finally, agentic AI provides a potential pathway from prediction toward semi-autonomous mitigation, but such autonomy should remain bounded by operational, ethical, safety, anti-theft, provenance, and swipe-controller constraints. Without these safeguards, increasingly autonomous supply chains could progressively remove human oversight, contrary to the Industry 5.0 principle of human-centered operation. The future challenge is therefore not simply to increase automation, but to develop controlled autonomy in which AI proposes and coordinates actions while humans retain meaningful authority over critical decisions.

VII. FUTURE DIRECTIONS

The next research programme should convert the reconstructed cycle from an interpretive architecture into a measurable and experimentally comparable framework. Five complementary strands are proposed. First, an explainability layer should attach feature attributions, confidence measures, and constraint-violation reports to every licensed command, enabling operators to understand, question, and contest a proposed release rather than simply accept an automated score. Second, multi-tier visibility experiments should evaluate whether a shared, privacy-preserving digital-twin schema can transmit lead-time, risk, and integrity features across at least three supply-chain echelons while preventing disclosure of commercially sensitive flows and relationships. These experiments should also assess interoperability, information loss, and decision quality under different levels of network visibility.

Third, climate and green variables should enter the predictive state as first-class coordinates rather than as after-action reports, using the emission terms already written in (4)–(5). Fourth, a bake-off protocol is needed for the QUBO kernel: packing instances of documented size should be solved classically and by annealing under identical energy and integrity gates, with wall-clock, feasibility, and residual-error reported on the same sheet. Fifth, governed agentic prototypes should be allowed to propose but not release actions, so that swipe-controller latency, override rate, and residual improvement can be measured before autonomy is widened.

A common indicator set is the hinge of all five strands. Until recovery time, residual risk, emission intensity, energy slack, integrity uptime, and override rate are reported together, cross-firm comparison will remain rhetorical. The figures and tables in this reconstruction are therefore offered as a measurement agenda rather than as completed industrial proof.

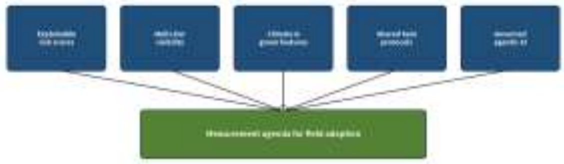

Fig. 4. Priority strands that turn the architecture into a testable research and measurement programme.

TABLE III. PROPOSED MEASUREMENT AGENDA

Strand	Primary metric	Acceptance sketch
Explainable release	Contest rate; attribution	Contest possible before dispatch
Multi-tier twin schema	Cross-firm completeness	Three echelons, no raw-flow leak
Green–climate features	Share of π_t from χ_k	Non-zero weight in licensed plans
QUBO bake-off	Feasibility, time, residual	Use kernel only if it beats heuristics
Governed agents	Override rate; residual gain	Propose-only until swipe latency known
Shared indicators	TTR, residual, energy slack	Same six numbers on every trial

VIII. CONCLUSION

Predictive models, mobility sensing, digital twins, hash-chain provenance, FKF/FKL spectral analysis, sequential convergence, and selected quantum packing kernels are joined here into one constrained recovery architecture for freight networks. Heterogeneous observations of movement, demand, inventory, energy, and system state are converted into dynamic risk estimates and then into adaptive, constraint-aware commands. Continuous residual feedback compares predicted and observed conditions, marks deviations, and rewrites the predictor before the next cycle.

Effective recovery depends not only on model accuracy but also on coordinated management of hybrid-electric energy, transport capacity, anti-theft integrity, cybersecurity, green logistics, and swipe-controller oversight. Twins give a living replica of physical assets; provenance strengthens trust across distributed operations; FKF/FKL analysis exposes temporal and scale-dependent disruption patterns; sequential convergence keeps those operators stable as streams arrive. Together the components support a multidimensional practice that anticipates shock, screens feasible recoveries, reduces residual exposure, and keeps freight performance both secure and energy-feasible.

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