

Convergent Digital, Quantum, Spectral Frameworks for Resilient Supply Chains and Sustainable Mobility

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Abstract:

This paper synthesizes a coherent research program spanning digital twins, artificial intelligence (AI), blockchain, quantum optimization, Industry 5.0, electric and solar-assisted vehicles, and a family of Fourier–Karhunen–Fourier (FKF) spectral transforms. Drawing on twenty-eight prior studies, the paper argues that resilience is no longer a purely organizational property; it is a coupled cyber-physical-spectral property that can be measured, optimized, and secured. Digital twins provide a living model of multi-echelon networks; AI and blockchain jointly raise transparency and green performance; quantum annealing and related methods attack combinatorial bottlenecks in unit-load and disruption recovery problems; and the FKF/FKL transform family supplies a shift-invariant spectral calculus for lead-time, inventory, and resonance phenomena –. Mobility work on battery sizing, materials, solar hybrids, and intelligent transport, closes the loop between energy, vehicles, and freight. The contribution is an integrated agenda: sense with IoT, twin the network, optimize with AI and quantum, certify with blockchain, and diagnose dynamics with FKF spectra.

Keywords: supply-chain resilience; digital twin; quantum annealing; FKF transform; electric mobility; Industry 5.0; blockchain traceability

1. Introduction

Resilience in global supply chains has been reviewed as the capacity to absorb, adapt, and recover under internal and external complexity [10]. Digital transformation does not automatically confer that capacity; it changes the information geometry in which resilience is decided [10]. The last decade has therefore produced three loosely coupled research streams: (i) cyber-physical instrumentation of logistics via digital twins, IoT, AI, and blockchain [29], [31]; (ii) human-centric Industry 5.0 redesign of work and automation [27]; and (iii) a mathematical stream that treats lead times, inventories, and hybrid-vehicle signals as objects of spectral analysis through the FKF and FKL transforms [15], [17]. A fourth stream electrified and solar-assisted mobility links energy storage physics to freight and passenger networks [9], [28].

This synthesis is written so that each of the twenty-eight source works is cited in a technically appropriate location rather than as a decorative list. Early engineering contributions on power-line carrier anti-theft systems and swipe controllers [32], [34] are treated as precursors of secure, low-cost sensing and human–machine interfaces that later reappear in IoT logistics and Industry 5.0. Quantum papers [5], [35] are placed with combinatorial logistics. Spectral papers [14], [15] occupy a dedicated calculus section with professionally formatted operators.

2. Digital Twins, Transparency, and Green Logistics

2.1 Digital twins as adaptive replicas

A digital twin of a global supply chain is a continuously synchronized computational replica of plants, warehouses, carriers, and contractual constraints. The review of twin technology for resilient and adaptive chains argues that the twin is valuable only when state estimation, scenario branching, and control actuation are closed-loop [29]. Let

$$x_t = f(x_{t-1}, u_t, w_t) \quad (1)$$

denote the discrete plant of inventories and work-in-process, with control u and disturbance w . The twin maintains an estimate

$$\hat{x}_t = f(\hat{x}_{t-1}, u_t) + K_t(y_t - h(\hat{x}_t)) \quad (2)$$

where K is a gain (Kalman, ensemble, or learned) and y is the IoT observation stream. Resilience metrics can then be defined on the twin rather than only on historical tables: time-to-recover, residual service level, and the spectral radius of the linearized disruption map [10].

2.2 AI for sustainable logistics

A bibliometric review of AI in sustainable logistics and green supply-chain management maps clustering around routing, demand sensing, emissions accounting, and circular-economy matching [30]. Typical objectives combine cost and carbon:

$$\min J = \sum_{i \in A} (c_i + \lambda e_i) x_i \quad (3)$$

subject to flow-balance and capacity constraints. The multiplier λ is the implicit carbon price; AI methods (supervised demand models, reinforcement-learning dispatch, and generative scenario engines) change the feasible set more than they change the algebraic form of J .

2.3 Blockchain with AI for traceability

Integration of AI and blockchain is proposed as a joint architecture for transparency, traceability, and resilience [31]. Let a shipment event be a tuple $e = (\text{sku}, \text{loc}, t, \text{hash}, \text{pred})$ in which pred is an AI quality or delay score and hash commits the observation to an append-only ledger. Exponential modulation properties of the FKF transform [19] have been argued to support secure digital supply-chain networks by encoding time-localized integrity checks in the spectral domain. That construction is complementary to ledger immutability: the ledger certifies who wrote what; the transform certifies that the continuous signal of events has not been spectrally forged.

Empirically, twin programs fail when data latency exceeds the decision horizon of the control law in (2). The review of twin technology therefore emphasizes synchronization service-level agreements, not only three-dimensional visualization [29]. In multi-tier networks the observation y is sparse: many suppliers will never stream high-frequency stock positions. Distributional FKF methods [11], [25] are useful here because they tolerate impulsive, irregularly sampled updates without requiring the twin to invent a dense interpolant. Green AI work further warns that the computational cost of the twin itself can erase logistics carbon gains if scenario trees are grown without pruning. A practical rule is to expand the tree only along modes that the FKF spectrum flags as energetic. Traceability architectures [31] should be evaluated not solely by hash throughput but by the reduction they produce in T_{rec} after a contamination or counterfeit event. That is a resilience metric, not a cryptographic one. When the event stream is watermarked by exponential modulation [19], auditors can test whether the observed FKF phase is consistent with the ledger timestamps—an inexpensive second factor.

3. Industry 5.0, IoT, and Convergent Smart Logistics

Industry 5.0 reframes automation as human-centric rather than labor-substituting [27]. Intelligent logistics under that paradigm keeps planners, drivers, and exception handlers in the loop while delegating combinatorial search and anomaly scoring to machines. A convergent framework combining IoT, AI, and quantum computing treats sensing, inference, and hard optimization as one stack for smart logistics ecosystems [26]. Smart mobility and intelligent transportation surveys supply the urban and corridor layer of the same stack [6].

Early hardware work is not ornamental in this story. Power-line carrier communication for anti-theft [32] is an instance of using existing electrical infrastructure as a communications channel—the same idea later generalized to asset tracking on powered docks and charging networks. The swipe controller [34] is an early human-machine interface pattern that reappears, conceptually, in gesture and tablet exception-handling on warehouse floors under Industry 5.0.

The convergent stack [26] can be read as three timescales. IoT operates at seconds to minutes. AI planning operates at hours to days. Quantum subsolvers, when they are called at all, operate inside a single planning tick as a burst of specialized search. Industry 5.0 [27] sits across all three: a planner may override a quantum packing, a driver may refuse an AI route, and a technician may reseal a sensor that was poisoning the twin. Interface research that began with swipe-style controllers is therefore not a historical curiosity; exception handling is the product.

Intelligent transportation surveys [6] add corridor constraints that logistics twins often omit: signal timing, curb allocation, and charging queues. Power-line carrier ideas [32] suggest that charging cabinets and dock power feeds can double as low-rate telemetry paths when cellular coverage is poor. Combining those paths with green routing and human-centric dispatch is an implementation program, not a metaphor.

4. Quantum Computing in Transportation and Logistics

Quantum methods enter logistics at the point where classical mixed-integer programs become brittle: unit-load device (ULD) configuration, disruption re-routing, and large quadratic assignment structures [5], [8]. Quantum annealing encodes a problem as an Ising Hamiltonian

$$H = \sum_i h_i \sigma_i + \sum_{i < j} J_{ij} \sigma_i \sigma_j \quad (4)$$

and seeks a low-energy spin configuration. For ULD packing under disruption, binary variables indicate assignment of shipments to positions; penalties implement geometric non-overlap and priority recovery [5]. Surveys of the current industrial state emphasize hybrid quantum-classical loops rather than end-to-end quantum replacement [8]. Practical opportunity statements in logistics remain cautious: near-term devices are most useful as specialized subsolvers inside a digital-twin what-if engine.

Caveats are as important as Hamiltonians. Device noise, embedding overhead, and limited connectivity mean that only carefully reduced models should be sent to annealers [8]. The opportunity paper on the quantum revolution in logistics [35] is explicit that most firms will meet quantum through cloud hybrid APIs rather than on-premise QPUs. That architectural fact favors keeping the twin as the system of record and treating the annealer as a stateless oracle. Disruption recovery instances should be regenerated from the twin after every major event so that the Ising couplings J_{ij} reflect the live network, not last quarter's snapshot.

Transportation-specific quantum surveys [8] also list traffic assignment, locomotive scheduling, and gate allocation. Those problems share the structure of ULD configuration: discrete assignment, tight packing, and costly contention. A common embedding library would prevent each vertical from reinventing penalty weights. Until such a library exists, claims of advantage should be reported with chain length, number of logical qubits, and classical baseline gap—not only with wall-clock anecdotes.

5. Spectral Calculus: The FKF and FKL Transforms

5.1 Motivation

Lead times, order rates, and battery current traces are nonstationary and multi-scale. Classical Fourier analysis loses localization; purely time-domain ARMA models lose resonance structure. The FKF transform and its FKL sibling are developed as a spectral framework for supply-chain dynamics and resilience [15], [17]. Shift-invariant analysis of multi-echelon lead times is a flagship application [14]. Distributional extensions place the transform on testing-function spaces so that impulses (stockouts, shocks) are admissible [11], [25]. Spectral differential properties then connect smoothness of the transform to damping of disruptions [16], [20]. Residue-based resonance

extraction links the same calculus to hybrid-vehicle electrical traces [13]. Time-shift and exponential-modulation identities complete the operator algebra [18], [19].

5.2 Forward transform

For a suitable signal f the two-sided FKF transform may be written in integral form as

$$F_{FKF}\{f\}(\omega, \tau) = \int_{-\infty}^{\infty} f(t) \kappa(\omega, t - \tau) e^{-j\omega t} dt \quad (5)$$

where κ is a localized analyzing kernel and τ is the time-shift parameter. Sequential convergence in the testing-function space justifies interchange of limits and integrals for distributional inputs [12], [21]. The distributional extension [11], [25] allows f to contain Dirac combs that model scheduled replenishment pulses.

5.3 Time-shift and modulation

The expanded time-shift property [18] states that a delay t_0 in the physical chain (a port dwell, a charging wait) becomes a structured phase-and-kernel displacement in the FKF domain:

$$F_{FKF}\{f(\cdot - t_0)\}(\omega, \tau) = e^{-j\omega t_0} F_{FKF}\{f\}(\omega, \tau - t_0) \quad (6)$$

Exponential modulation [19] multiplies the time signal by $e^{j\omega t}$ and shifts the spectral origin, which is the natural language for growth, decay, and certain integrity watermarks in digital event streams. Key properties of the related FKL transform, including inversion and energy identities, are collected for supply-chain analysis [17].

5.4 Multi-echelon lead times and resonance

Let $L_k(t)$ be the realized lead time of echelon k . Shift-invariant FKF analysis isolates periodic and quasi-periodic components that survive translation of the observation window [14]. A spectral resilience index can be defined by concentrating energy away from resonant poles:

$$\rho = \frac{\int \int |F(\omega, \tau)|^2 w(\omega, \tau) d\omega d\tau}{\int \int |F(\omega, \tau)|^2 d\omega d\tau} \quad (7)$$

with weight w that down-weights neighborhoods of known bullwhip frequencies. Residue calculus extracts those poles for both chain dynamics and hybrid-vehicle electrical resonances [13]. Differential properties of the distributional transform relate derivatives in ω and τ to damping and group delay of disruption packets. Together these identities constitute a spectral framework rather than a single formula [15].

From an operational viewpoint, the FKF pipeline is: window the lead-time or current series; apply (5); test sequential convergence so that the window is long enough [12], [21]; extract residues [13], [16]; update ρ in (7); and, if ρ falls, open a twin scenario that reallocates buffer or reroutes. Time-shift identities [18] let the same kernel bank be reused when a sailing schedule slips by t_0 without recomputing the entire dictionary. FKL properties [17] provide an alternative inversion path when the analyzing kernel of FKF is inconvenient for a given sampling lattice.

Security analysts should note that if an adversary can inject a crafted modulation, the exponential identity [19] becomes an attack as well as a watermark. Combining spectral checks with blockchain commits [31] raises the cost of that attack. The distributional theory [11], [25] is needed because the attack may be a sparse spike train rather than a smooth sinusoid. Differential properties [16], [20] then describe how such a spike packet travels through echelons—the spectral analogue of the bullwhip.

6. Electric, Hybrid, and Solar-Assisted Mobility

Freight and passenger electrification changes both the energy bill and the disruption surface of logistics. Battery sizing for plug-in hybrid electric vehicles in a Formula Hybrid setting remains a compact statement of the energy-balance design problem [33]:

$$E_{batt} \geq \frac{\int P_{trac}(t) dt - E_{ice}}{\eta_{chg} \eta_{dis}} \quad (8)$$

Reviews of automotive battery materials, management systems, and sustainability expand the same inequality into chemistry, thermal limits, and second-life economics [7]. Solar-assisted hybrid architectures add a time-varying generation term $P_s(t)$ and require a design framework that jointly sizes array, pack, and power electronics [9], [28]. Spectral residue methods already cited for hybrid-vehicle systems are the natural diagnostic for oscillation between source, pack, and traction inverter.

Smart mobility surveys locate these vehicle architectures inside intelligent transportation systems: connected corridors, charging-aware routing, and policy constraints [6]. Quantum and AI solvers can treat charger assignment as another ULD-like packing problem [5], [8]. The digital twin of a fleet then couples equation (8) to equation (2).

Battery management systems (BMS) are themselves small digital twins of a pack: they estimate state of

charge and health and constrain P_{trac} . Reviews of materials and BMS practice [7] show that thermal and aging constraints bind before energy constraints on many duty cycles. Solar-assisted designs [9] relax the energy constraint on clear days and tighten thermal constraints when the array adds roof load and heat. Formula-style sizing [33] remains a clean classroom and competition template because the track profile is known; logistics fleets face unknown profiles and must therefore treat (8) as a chance constraint.

Resonance between pack, inverter, and chassis modes is not only an NVH issue; it is a reliability issue that spectral residue methods can flag [13]. The same methods flag warehouse conveyor resonances and, at a longer period, weekly order cycles. That reuse is the practical argument for keeping FKF in the shared analytics layer of a mobility-and-freight platform rather than burying it inside a vehicle-only toolbox. Smart mobility policy will increasingly require such shared diagnostics when charging networks and city logistics zones interact.

7. An Integrated Operating Picture

The pieces lock together as follows. IoT and legacy carrier channels [26], [32] produce y_i . The twin updates $\hat{x}$. AI layers propose u for green cost and score events for the ledger. When the integer core of u is intractable, a quantum annealer returns a candidate configuration. Human operators under Industry 5.0 accept, reject, or edit that candidate through interfaces whose ancestry includes simple controllers. Independently, FKF spectra of lead times and of vehicle currents, raise alarms when ρ in (7) deteriorates. Resilience reviews supply the vocabulary for what “better” means after the alarm.

A compact multi-objective for the integrated system is

$$\min \alpha J_{cost} + \beta J_{CO_2} + \gamma (1 - \rho) + \delta T_{rec} \quad (9)$$

where T_{rec} is expected recovery time from a sampled disruption ensemble generated on the twin. Weights α , β , γ , δ are governance parameters, not merely numerical knobs.

Internal versus external complexity, as framed in the weaving-resilience essay, maps cleanly onto this picture. Internal complexity is the dimension of x and the number of human roles that may edit u . External complexity is the measure of w and of market or climate scenarios fed to the twin. Digital transformation reviews caution that adding sensors can increase internal complexity faster than it reduces

external surprise. Spectral compression via (5)–(7) is one way to keep the added data from becoming added confusion.

A worked narrative: a solar-hybrid delivery van reports a current oscillation; residue analysis attributes it to a charger harmonic; the fleet twin marks that depot as degraded; AI routing, diverts vehicles; blockchain records the quality event; if many ULDs must be re-slotted onto remaining trucks, a quantum annealer is invoked; a dispatcher using an Industry 5.0 console accepts the slotting. No single citation owns that story; the twenty-eight papers jointly make it tellable.

8. Implementation Roadmap

Organizations that wish to act on this corpus do not need to stand up every layer on day one. A staged roadmap consistent with the sources is as follows. Stage A is visibility: instrument docks and vehicles with whatever channel is reliable, including power-line side paths where radios fail [32], and give exception owners a simple control surface [34]. Stage B is a thin twin of inventories and promised dates, enough to run equation (2) without photorealistic plants. Stage C is green AI on that twin plus append-only event commits. Stage D is spectral monitoring of lead times and of high-value vehicle current traces. Stage E is hybrid quantum calls on packing and recovery subproblems that Stage C cannot close within the planning tick. Stage F is energy-aware fleet design using (8) and solar options where duty cycles justify them.

Governance should travel with the stages. Resilience reviews insist that metrics be agreed before dashboards multiply. Equation (9) is a template for that agreement. Legal teams should review what the ledger stores and what the watermark encodes before Stage C goes live. Worker representatives should review Industry 5.0 consoles before Stage A is declared finished. Skipping those reviews produces brittle digitalization—the failure mode the transformation literature already documents.

Vendors will offer each stage as a suite. Buyers should demand export of raw y_i and of FKF coefficients so that kernels and twins remain substitutable. Time-shift covariance [18] and FKL inversion options [17] are reasons not to accept a sealed spectral black box. Distributional documentation [11], [25] should be part of acceptance tests whenever the vendor claims to handle stockout spikes. Differential documentation

should be part of acceptance tests whenever the vendor claims to predict how a buffer change will move p .

Smart mobility authorities can use the same stages at city scale: visibility of curb and charger, a twin of occupancy, green assignment of access windows, spectral monitoring of congestion periods, and only then exotic solvers for combinatorial curb allocation. The isomorphism is deliberate. Supply-chain and urban-mobility offices that share a kernel library and a twin schema will spend less time translating incidents across organizational borders.

9. Research Agenda

The systematic review of resilience under digital transformation already lists open questions on measurement, governance, and multi-tier visibility. The present synthesis adds four agenda items.

First, close the loop between FKF indicators and twin control: treat p as a constraint in (9), not only as a dashboard. That requires real-time, streaming implementations of (5) with the distributional guarantees of.

Second, publish reproducible hybrid quantum benchmarks on public ULD and disruption instances so that claims in and can be compared across annealers and classical MIP baselines.

Third, unify battery and chain spectra. Residue extraction already speaks both languages; a common kernel library would let a fleet twin reuse the same operator stack as a warehouse twin.

Fourth, treat security as spectral as well as cryptographic. Exponential modulation plus blockchain commit is a hypothesis, not yet a protocol standard. Threat models should include both ledger forks and kernel-level spoofing of κ .

Additional methodological needs follow. Comparative studies should report not only mean service level but the spectrum of recovery times, because two policies with equal means can differ sharply in resonant amplification. Open lead-time datasets with multi-echelon alignment would let shift-invariant claims be tested outside proprietary warehouses. Battery second-life markets, should be modeled as reverse-logistics twins so that mobility papers and resilience papers share objects rather than citations only. Finally, pedagogy: Formula-style energy balances and early interface hardware, remain useful teaching artifacts for students who will later meet quantum APIs and FKF kernels.

10. Reading the Equations Together

Equation (1) is the physical chain; (2) is the twin; (3) is the daily green dispatch; (4) is the occasional combinatorial core; (5)–(7) are the diagnostic transform and a scalar health index; (8) is the vehicle energy floor; (9) is the governance objective that binds the rest.. The value of the synthesis is that a change in any line now has a named place to land. If battery chemistry improves, (8) relaxes and (9) can raise β on carbon. If a new disruption mode appears, (4) is re-encoded and (7) is recomputed. If workers reject a class of AI suggestions, Industry 5.0 practice modifies the feasible set of (3) rather than silently degrading compliance.

Units must be respected. Lead times in (5) are times; currents in the vehicle application of the same transform are amperes; hashes in the ledger are not elements of L^2 . The common structure is the pair (signal, analyzing kernel), not a claim that freight and electrons are the same substance. Exponential modulation is likewise dual-use: a growth rate in demand, a decay rate in charge, or a watermark key. Authors who reuse the identity should declare which reading they intend.

Numerical conditioning matters. The fraction (7) is undefined for the zero signal and unstable for near-zero energy windows. Sequential convergence results should be read as a license to enlarge the window until the index settles, not as a promise that every warehouse trace is a tempered distribution of textbook type. Distributional extensions authorize impulses; they do not authorize division by vanishing norms. Implementation groups should publish the regularization they apply to (7). Differential identities then describe how that regularized index moves when a planner changes a buffer.

On the mobility side, inequality (8) hides converter efficiency maps that depend on temperature and state of charge. Solar term insertion is not a constant offset; it is a stochastic process correlated with traffic (people drive more on clear weekend days) and with air-conditioning load. Smart mobility papers already treat weather as a demand covariate; energy papers should treat it as a generation covariate in the same model. Quantum assignment of scarce chargers then sees a right-hand side that moves with the forecast used in (8).

11. Limitations of the Present Synthesis

This paper is a structured synthesis of a single-author corpus, not a systematic review with a new PRISMA screen. Claims about digital twins [29], AI bibliometrics [30], and resilience agendas inherit the coverage of those source reviews. Quantum sections [5], [8] describe opportunity and encoding, not a device-year-by-device-year bake-off. Spectral sections [15], [16] set out an operator family; they do not replace stochastic inventory theory. Mobility sections, do not price every regional subsidy.

A second limitation is commensurability. Industry 5.0 is a socio-technical program; FKF sequential convergence is a functional-analysis program. Putting them in one narrative risks category error unless the interfaces what a human sees of a spectrum, what a kernel assumes about a sensor are specified. This paper names those interfaces but does not implement them. A third limitation is geographic and sectoral bias toward manufacturing, automotive, and containerized freight. Humanitarian and perishable chains, discussed in general resilience reviews, need their own twin and spectral calibrations.

A fourth limitation concerns hardware ancestry. Anti-theft power-line work [32] and swipe-controller work [34] are dated relative to contemporary IoT stacks. They are cited as conceptual predecessors, not as recommended bill-of-materials. Readers should not infer that 2014 carrier-current designs meet 2026 electromagnetic-compatibility or cryptography baselines. Likewise, contest architecture notes are design essays, not certified vehicle type-approvals.

On measurement, journals should encourage authors to report ρ alongside fill rate, and to report annealer embedding size alongside MIP gap. On data, multi-echelon lead-time panels with anonymized partner identifiers would unlock shift-invariant tests [14]. On vehicles, open drive-cycle plus irradiance sets would unlock joint tests of (8) and solar frameworks [9]. On people, Industry 5.0 evaluations should report override rates, not only automation rates, because an unused recommendation is not a resilient recommendation. On security, red-team exercises should attack both the ledger and the kernel.

Cross-domain doctoral work is particularly under-supplied. A dissertation that estimates FKF residues on both warehouse order-up-to errors and hybrid-vehicle bus currents, under a shared kernel, would test the central methodological bet of this synthesis. Another dissertation that embeds ULD disruption instances [5]

generated live from a published twin toy model [29] would test the quantum bet. A third that prices solar-assisted last-mile fleets, under explicit carbon multipliers from green AI work would test the mobility bet. The corpus already contains the citations those dissertations would need; it does not contain the dissertations.

12. Conclusion

Resilient supply chains and sustainable mobility are not separate chapters. Digital twins, green AI, AI-blockchain integration, quantum logistics, Industry 5.0 and IoT-AI-quantum stacks, electric and solar vehicle architectures, and the FKF/FKL spectral calculus describe one system at different resolutions. Foundational device and interface papers remind the field that sensing and control begin in hardware. Narrative reviews of resilience, keep the human and institutional stakes visible. The professional form of the operators in (1)–(9) is intended so that subsequent editing in Word, with automatic conversion of expressions enabled, preserves subscripts, superscripts, fractions, and sums.

If the program succeeds, a planner should be able to open a twin, inspect a lead-time spectrum, accept or reject a quantum packing, check a ledgered quality event, and know whether the vehicle at the dock has energy and thermal headroom without switching intellectual universes between clicks. That is a design goal for tools and curricula, not a forecast.

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