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Calculus for Constrained Resilience

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Abstract—

Findings. The same topology is a certified interface among classical simulators, digital twins, hash-chain provenance, and hybrid quantum-classical solvers. Delayed multi-echelon inventory, bullwhip amplification, constrained resilience, fractional state-of-charge and state-of-health of plug-in and solar-assisted packs, QUBO encodings of unit-load-device configuration, live twin orchestration, graph delay systems, and closed green reverse flows become algebraic identities in the transform domain. Originality. One pair of spaces and one pair of transforms certify stock, charge, configuration, and custody without changing the seminorm language.

Keywords—distributional and spectral analysis; sequential convergence; time-shift/modulation; resonance; multi-echelon lead time; supply-chain resilience; digital twins; green logistics; blockchain traceability; quantum logistics, annealing and QUBO; ULD optimization; IoT; Industry 5.0; smart mobility; hybrid-electric vehicles; battery sizing; solar mobility; swipe controllers; power-line communication; anti-theft systems.

I. INTRODUCTION

The research gap is architectural rather than merely computational: delayed replenishment, noisy sensor streams, fractional electrode memory, and discrete configuration do not live in a single classical function space without destroying continuity of time shifts.

Distributional FKF calculus is the natural language for impulses, discontinuities, and highly oscillatory demand [13], [19], [20], [24], [30]. When those singularities travel along a multi-echelon lead time, or when a digital twin must propagate an incomplete packet both forward and backward, the testing-function space must make delay operators continuous. The two-sided FKF transform and the causal FKL transform supply that space. They inherit exponential modulation and shift-invariant spectral analysis; the countable seminorm family later becomes a resilience certificate [14], [16], [26], [35].

Inventory recovery after a supplier failure is a delay equation on these spaces. Hybrid-electric and solar-assisted packs enter through fractional SoC/SoH models and battery-sizing inequalities [11], [18], [28], [34]. Unit-load-device configuration under disruption is a QUBO handed to a quantum annealer while the classical FKL simulator carries the distributional state [21], [29], [32].

Intelligent transportation systems, swipe-controller interfaces, and power-line-carrier anti-theft links lift into the dual as observation operators [12], [15], [31]. Blockchain hash-chain provenance, green closed loops, and digital-twin coverage complete the orchestration layer [17], [22], [23]. Constrained resilience under Industry 5.0 human-centric automation is the planning target [25], [27], [33], [38].

The creative claim is therefore modest and testable. One multinormed pair of spaces should be enough to certify stock, charge, configuration, and custody. Human-centric vetoes freeze an order rate, a charger set-point, or a subset of QUBO bits are modelled as restrictions of the admissible set, not as a second theory.

II. LITERATURE REVIEW

Existing work treats transforms, packs, twins, and annealers as separate literatures; none of those literatures simultaneously guarantees continuous delay shifts and seminorm-level certificates that travel from the warehouse to the annealer.

A. Transforms, testing functions, and operational calculus

Sequential convergence in the two-sided FKF testing-function space, together with the distributional extension of the transform, is the analytic spine [19], [20]. Exponential modulation and the time-shift property convert delayed replenishment into multipliers [14], [16]. The FKL companion treats causal initial-value problems in supply-chain analysis [35]. Spectral differential properties and residue-based resonance extraction close the loop for hybrid-vehicle and multi-scale network signals [13], [24], [26], [30].

B. Packs, vehicles, and field hardware

Automotive-battery reviews and materials-and-BMS surveys justify the SoC/SoH development [18], [28], [39]. Battery sizing for plug-in hybrids, solar-assisted architectures, swipe-controller interfaces, and power-line-carrier anti-theft systems enter as constraints and as observation operators [11], [12], [15], [34]. Intelligent-transportation telemetry is a further measurement channel [31]. Hardware papers, however, write ordinary differential or delay-differential equations; they do not certify well-posedness when the load is an ultradistribution.

C. Resilience, digital twins, green logistics, and quantum search

Resilience reviews and digital-transformation agendas remain the empirical target of the inventory development [25], [27], [33], [38]. Digital supply-chain twins, green-logistics analytics, and blockchain traceability supply the orchestration layer [17], [22], [23]. Quantum annealing and QUBO encodings of routing and packing, including unit-load-device configuration under disruption, motivate the hybrid interface [21], [29], [32]. The missing object is a continuity statement between the distributional simulator and the discrete annealer.

The gap filled here is therefore architectural: one testing-function pair, one transform pair, and one certificate language spanning every domain named above.

Fig. 1. prior-art stack feeding a single FKF–FKL interface: transforms, field hardware, twin provenance, and quantum search.

III. TESTING-FUNCTION SPACES AND THE TRANSFORM PAIR

Fix growth parameters a > 0 and kernel weights A, B ≥ 0, and let test functions live on the line or on the half-line according as the two-sided FKF or the causal FKL transform is in force.

A. Countably multinormed geometry

The FKF testing-function space of Roumieu type is the inductive limit of the Banach spaces defined by the seminorms below; the Beurling counterpart is the matching projective limit.

$$N_{m,n}(\varphi) \;=\; sup_{t\,\in\,\mathbb{R}}\; e^{a|t|}\,(1+|t|)^m\,|\partial_t^n\,\varphi(t)|$$

A sequence (φk) converges sequentially if it is Cauchy in every seminorm Nm,n. The companion FKL space uses the causal weight eat on (0, ∞) and is the correct setting for initial-value problems [35]. Duals of both types are Hausdorff, locally convex, and sequentially complete [19], [20].

B. Kernel, two-sided transform, and causal companion

The fractional kernel combines a Fourier oscillator with a Caputo-type memory factor of order α ∈ (0, 1]:

$$F_{FKF}(\varphi)(s) \;=\; \int_{\mathbb{R}} \varphi(t)\, K_\alpha(s,t)\, dt, \quad s \;\in\; \mathbb{C}$$

The FKL transform replaces the two-sided integral by a causal Laplace–Stieltjes integral against a delay measure μ_τ:

$$L_{FKL}\,(\varphi)(s) \;=\; \int_0^\infty \varphi(t)e^{-st}\;\, d\mu_\tau(t)$$

C. Time-shift, exponential modulation, and residue resonance

The time-shift property is the reason the construction exists for multi-echelon lead time [16]. Continuity of the shift on the testing space follows from the elementary comparison

$$N_{m,n}(T_\tau\,\varphi) \;\le\; e^{a|\tau|}\,(1+|\tau|)^m\; N_{m,n}(\varphi)$$

$$F_{FKF}(T_\tau\,\varphi)(s) \;=\; e^{-s\tau}\,F_{FKF}(\varphi)(s)$$

Exponential modulation translates the strip of analyticity [14]:

$$F_{FKF}(e\lambda^t\,\varphi)(s) \;=\; F_{FKF}(\varphi)(s\,-\,\lambda)$$

Residue-based resonance appears when a pole of a delay transfer function crosses that strip [13], [30].

Shift-invariant spectral analysis is the statement that convolution against a delay kernel is an FKF multiplier [26]. Reflection $(J\varphi)(t) = \varphi(-t)$ handles backward Cauchy problems; product spaces carry (inventory, SoC) or (forward flow, reverse flow). Sequential completeness keeps a truncated sensor stream inside the dual after any finite number of shift-and-convolve steps.

Every later identity is a specialisation of shift, modulation, and convolution against a delay kernel; the methodology does not change when the physical units change.

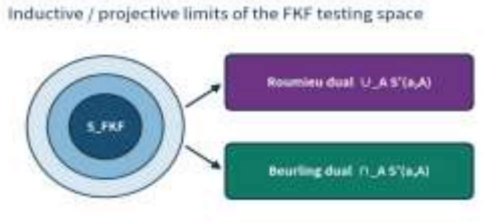

Fig. 2. inductive and projective limits of the FKF testing-function space and its Roumieu–Beurling duals.

IV. MULTI-ECHELON LEAD TIME AND CONSTRAINED RESILIENCE

Because a lead time is a continuous shift on the FKF space, a warehouse balance with delayed replenishment is already a well-posed distributional equation.

A. Two-supplier balance

Let I be on-hand inventory and let u, v be two ordering rates with delays τ and σ. Ultradistributional demand is $D \in S'$.

$$\dot{I}(t) = u(t-\tau) + v(t-\sigma) - D(t), \quad I(0) = I_\star$$

The FKL image is the algebraic identity

$$\hat{I}(s) = \frac{I_\star + e^{-s\tau}\,\hat{u}(s) + e^{-s\sigma}\,\hat{v}(s) - \hat{D}(s)}{s}$$

Well-posedness in the dual follows from sequential completeness and from the shift-continuity estimate of Section III. Several echelons become a block transfer matrix whose entries are the same exponential multipliers.

B. Bullwhip multiplier

Pipeline controllers that amplify variance have the multi-echelon FKF skeleton [26], [24]:

$$H_{bw}(s) = \frac{1 + s\,L_1}{1 + s\,L_2 + \dfrac{e^{-s\tau} + e^{-s\sigma}}{2}}$$

The strong dual topology keeps the image of that multiplier bounded even when D contains jumps. The seminorm $N_{m,n}(\mathrm{I})$ is then a safety-stock margin that a planner can read without restimulating the shock.

C. Recovery certificate

A supplier failure at t* is a dual forcing term. Convolution against the fundamental solution stays inside the dual. The recovery certificate extracted from the seminorms is [25], [27], [33], [38].

$$\rho(t) = \rho_\infty\left(1 - e^{-\kappa(t-t_*)}\right)$$

Constrained resilience requires ρ(t) to clear a contractual floor before a stated horizon. The inequality is a seminorm comparison. Industry 5.0 human-centric automation appears as a restriction of the admissible ordering set, not as a second model.

The two-delay balance, the amplification multiplier, and the recovery map are the warehouse core that later sections only decorate with packs, annealers, twins, and reverse flows.

Fig. 3. pipeline from distributional demand through multi-echelon lead time to the FKL recovery certificate.

V. FRACTIONAL MEMORY IN PLUG-IN AND SOLAR-ASSISTED PACKS

State-of-charge and state-of-health under charging delay and thermal fade are delay-fractional equations; the FKL transform is built to algebraize them.

Let Q be state of charge and H state of health. A Caputo derivative of order $\alpha \in (0.7, 1]$ encodes electrode memory [18], [28], [30], [39]:

$$C_t^{\alpha}\,Q(t) + \frac{I_d(t-\tau_c)}{Q_n\,H(t)} = \eta\,u_s(t-\tau_c)$$

A linear fade law for health, with temperature-dependent coefficient β(Θ), is written on the same space:

$$\dot{H}(t) = -\beta(\Theta)\,Q(t)\,I_d(t-\tau_c), \quad H(0) = 1$$

Battery sizing for a plug-in hybrid or a solar-assisted architecture is the inequality $Q_n \geq Q_{min}$ together with a peak-power bound that a swipe-controller interface can tighten in real time [11], [15], [34]. The FKL image of the charge equation is

$$s^{\alpha}\,\hat{Q}(s) - s^{\alpha-1}\,Q(0) = e^{-s\tau c}\left(\eta\,\hat{u}_s(s) - \hat{L}_{(s,H)}\right)$$

The seminorm family controls Q uniformly in the distributional parameters of the load. Power-line-carrier anti-theft signaling [12] and intelligent-transportation telemetry [31] are observation operators on the same dual. Solar-assisted input concentrates FKF mass on diurnal harmonics [34], [30]. A product space (I, Q) therefore carries warehouse inventory and pack charge under one shift-continuity estimate.

The pack is the warehouse calculus reread on the electrode: same delay, same dual, different physical units.

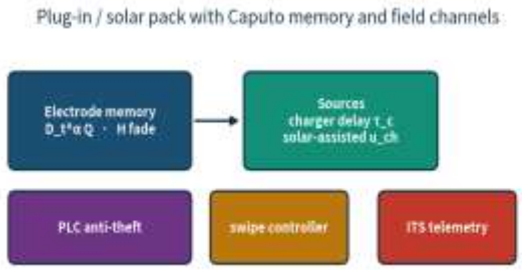

Fig. 4. pack diagram with Caputo memory, charger and solar delay, and PLC–swipe–ITS observation channels.

VI. QUANTUM LOGISTICS AND UNIT-LOAD DEVICES

Unit-load-device packing is discrete, the FKL state that feeds it is distributional, and the only honest interface is a continuous embedding of seminorm snapshots.

A feasible ULD plan under disruption is the penalised QUBO

$$E(x) = x^T Q x + q^T x + \lambda (1^T x - m)^2, \quad x \in \{0,1\}^n$$

Penalties absorb capacity, hazardous-material separation, and post-disruption substitution [29], [21]. Lead-time tails enter the biases through the countable seminorms: qi = ci + θ Nm,n(Tτi D). Annealing searches x while the FKL simulator marches inventory and SoC. The embedding

$$X_\theta \hookrightarrow X_{\theta}, \quad whenever \quad \theta \preccurlyeq \theta'$$

is continuous for the strong dual topologies, so a coarsened snapshot sent to the annealer remains consistent with the refined snapshot that returns. That statement is the hybrid quantum-classical logistics contract [29], [32]. A swipe-controller veto can freeze a subset of bits before the anneal [15]. Industry 5.0 human-centric automation is again a restriction of the feasible set {0,1}n, not a second energy.

The section does not claim that annealing replaces planning; it states a data contract between two topologies.

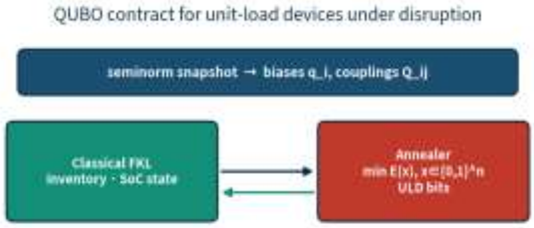

Fig. 5. QUBO contract exchanging seminorm snapshots between the classical FKL simulator and the quantum annealer.

VII. DIGITAL TWINS, HASH-CHAIN PROVENANCE, AND GREEN REVERSE FLOWS

A digital twin is a semigroup on the dual; a hash chain is a discrete observation of that semigroup; a green reverse flow is the same semigroup with a second delay and a quality law.

A. Twin semigroup and distributional MPC

Incomplete Internet-of-Things streams lift to dual elements. The operational calculus yields a C0-semigroup T(t) generated by the delay-fractional operator of Sections IV–V. Distributional model-predictive control is

$$u_\star \in arg\, min u \in U \quad N_{m,n}(T(h)\, X_0 - X_d) + \gamma \parallel u \parallel$$

Twin coverage and IoT completeness grow as devices are commissioned [17], [33]. Forward action of T(t) is prediction; backward action of T(−t) on the two-sided FKF side is diagnosis.

B. Blockchain traceability and hash-chain provenance

Each custody event writes a hash-linked payload that is a finite-rank observation of the dual state. Supply-chain transparency is an observability condition: the family {Φk} of hash payloads must separate the seminorms that encode quantity, quality, and delay [23].

$$\Phi_k(X) = \langle X, \psi_k \rangle, \quad span\{\psi_k\}\, dense\ in\ the\ test\ space$$

Swipe-controller and power-line-carrier channels bind into the same chain [12], [15]. A broken hash is then a failed observation, not a second ledger theory.

C. Sustainable reverse flows

Return flows add a delay τr and a random quality Qr. The two-way system is an FKL delay equation on a product space. Emission abatement in sustainable logistics is a monotone functional of circular capture [22], [35]:

Graph delay systems on a directed network use a matrix of delays whose transfer norm is globally controlled by the same FKF multipliers [26], [24].

Twin, chain, and reverse flow are one delay system sampled at three cadences, not three digital initiatives.

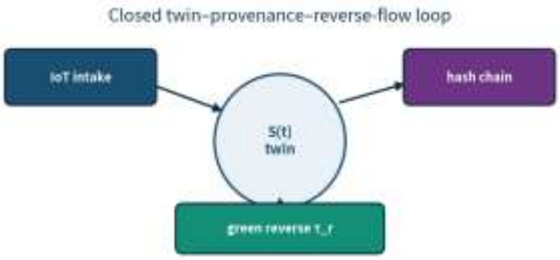

Fig. 6. closed loop of IoT intake, twin semigroup, hash-chain provenance, and green reverse flow.

Two limitations stay open. Extra weight parameters destroy strong continuity at the origin, although continuity for $t > 0$ covers every Cauchy problem used here. Annealing returns a sample, so the hybrid contract must transport a distributional snapshot rather than a deterministic minimizer [19], [20], [29].

Managerial implication. A planner does not need a separate digital-twin programme, a separate blockchain programme, and a separate quantum programme. The planner needs one dual, one family of seminorms, and a list of operators shift, observe, freeze, anneal that act continuously on that dual.

Adaptive fractional orders, stochastic convolutions, and multi-commodity reverse bills of materials will sit on the same seminorms without a change of language.

Fig. 7. certificate dashboard spanning stock, gain, pack, QUBO, twin, and green-loop bounds.

IX. CONCLUSION

Two transforms and one countable family of seminorms are enough to host delay, fractional memory, singular demand, and discrete configuration. Shift operators act continuously. Duals accept shocks and stochastic lead times. Sequential completeness keeps twin trajectories inside the class. The extractable objects are safety-stock bounds, bullwhip gains, a recovery map, SoC/SoH envelopes, QUBO energy contracts, twin horizons, hash-chain observability, and green-loop certificates. Unit load devices, swipe controllers, power-line-carrier anti-theft links, plug-in and solar-assisted packs, and intelligent transportation systems appear only as operators or constraints on those spaces.

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