International Journal of Creative and Open Research in Engineering and Management
ISSN: 3108-1754 (Online)
Volume 02 Issue 09 September-2026 | Impact Factor: 3.5

Dual-Topology Framework for Digital-Twin-Orchestrated Fractional Battery Dynamics

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How to Cite this Article:

S, S. & S, S. (2026). Dual-Topology Framework for Digital-Twin-Orchestrated Fractional Battery Dynamics. International Journal of Creative and Open Research in Engineering and Management, <i>02</i>(9), 1-9. https://doi.org/10.55041/ijcope.v2i9.045

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https://doi.org/10.55041/ijcope.v2i9.045

Abstract—
A countable family of creatively equipped convex topological spaces is constructed in order to host distributional FKF transforms with continuous delay shifts. These countably multinormed, complete, Hausdorff locally convex spaces and their duals of Roumieu and Beurling type ultradistributions are designed so that shift operators corresponding to time delays act continuously, while the dual spaces accommodate generalized functions that model sudden disruptions and stochastic lead time distributions. Product spaces, negative-time reflections, and extra parameters then furnish a setting in which Cauchy problems with distributional data remain well posed.

The framework is applied to eight central problems in modern supply chain engineering: inventory systems with stochastic lead time delays, quantitative analysis of the bullwhip effect in multi-echelon networks, propagation and recovery from singular disruptions, EV battery state-of-charge and state-of-health dynamics under delay and fractional order effects, hybrid quantum classical logistics optimization, real-time digital-twin orchestration, multi echelon network propagation on graphs, and closed-loop flows in circular economy reverse logistics. In each case we derive explicit operational calculus formulae and obtain stability or recovery certificates directly from the defining seminorm family. The resulting theory supplies well posedness, quantitative bounds, and stable interfaces between classical simulators and quantum solvers, thereby grounding resilient, sustainable, and real-time decision support for energy-aware and delay-driven supply systems.

Keywords—Quantum logistics; QUBO optimization; ULD configuration; FKF transform; Digital twins; Artificial intelligence; Blockchain traceability; Intelligent transportation systems; Energy-aware logistics; Industry 5.0.

I. INTRODUCTION

Generalized functions now furnish the admissible language for impulses, ageing jumps, and delayed energy trajectories that ordinary Sobolev classes cannot host. In the context of quantum electronics, signal processing, and control theory, distributions naturally arise when one encounters idealized impulses, discontinuities, or highly oscillatory data that cannot be adequately described by ordinary functions. The classical theory of Schwartz distributions, while extremely powerful, often lacks the fine growth and regularity control required when one studies evolution equations with delays, stochastic perturbations, or propagation on networks precisely the setting encountered when lead-time delays and energy constraints interact in modern logistics.

Pack-level energy bounds from plug-in hybrid sizing show why a delay operator cannot be treated as a mere index shift when the state is a battery trajectory.

Automotive battery reviews collect the thermal and ageing envelopes that later appear as weights in the FKF seminorms.

Recent electric-vehicle pack architectures refine those envelopes at cell, module, and pack granularity.

Those pack-level envelopes are not decorative bounds: they fix the admissible growth that later FKF seminorms are allowed to see when the stored commodity is electrical energy rather than a generic SKU [8].

Automotive ageing maps collected at cell, module, and pack granularity then become weights rather than narrative constraints [11].

Solar-assisted hybrid architectures add an irradiance contribution that must remain continuous under the same shift topology [9].
Smart-mobility telemetry supplies the observation stream that the dual space is asked to host [8].
Spectral analysis of multi-scale supply-chain traces then identifies residue peaks that the ultradistributional dual is designed to absorb [10].
Smart-mobility observation streams further require that the dual space accept incomplete telemetry without collapsing the shift topology [13].
Integrity bits derived from power-line-carrier sensing are reserved for a later lift, so that a stolen or physically compromised pack is not mistaken for ordinary sensor noise [9].
To address these limitations introduced a family of test function spaces that combine rapid decay with precise control on derivatives. These spaces and their duals of ultradistributions have since proved invaluable for the rigorous treatment of pseudo differential operators, localization operators, and operational calculus [10]. Building on this tradition, the present work develops a class of creatively equipped convex topological spaces tailored to the Laplace–Stieltjes transform. We construct countably multinormed spaces (and their multi parameter, two dimensional, and negative time extensions) whose seminorms are designed so that the shift operators corresponding to time delays act continuously, while the dual spaces accommodate generalized functions that model sudden disruptions, demand shocks, or stochastic lead time distributions.$FKF_{a_1,A_1}^{b_1,B_1}$
The motivation for this framework comes directly from contemporary challenges in global supply chains.
Lead time delays, the bullwhip effect, supplier failures, and the need for real-time resilience under uncertainty all generate mathematical models involving delay differential equations, distributional forcing terms, and hybrid deterministic stochastic systems [16].
Classical Laplace-transform methods frequently break down when the data lie outside the classical function spaces; the FKF framework restores well-posedness by embedding these problems in spaces whose topology is rich enough to control growth yet flexible enough to include singular data.
Moreover, the same spaces provide a natural interface for emerging hybrid quantum classical algorithms used in logistics optimization (e.g., quantum annealing for ULD configuration under disruption) [19].
The same spaces likewise serve digital twin environments that must propagate realtime sensor data forward and backward in time [14].
Quantum opportunity maps in transportation then restrict the discrete kernel that may talk to the FKF simulator, rather than claiming a universal quantum replacement for delay calculus [23].
The same restriction keeps unit-load-device annealing inside a selective interface once disruptions have been lifted to the dual [24].
After recalling the construction of the FKF spaces and their topological properties, we demonstrate their utility through eight concrete application domains.
These range from classical inventory control with stochastic lead times and quantitative bullwhip analysis to EV battery state-of-charge modelling.
Quantum enhanced resilient design, digital twin orchestration, multi-echelon network propagation, and circular-economy reverse flows complete the same list of domains [18].
In each case we exhibit explicit operational calculus formulae, seminorm derived stability or recovery certificates, and direct connections to the authors' prior work on supply chain resilience [15]. Related automotive-battery and energy-pack studies supply the weights that those certificates must respect.
The paper concludes with a synthesis that highlights how the creative convex topology furnishes three practical assets well posedness, explicit certificates, and stable hybrid interfaces that remain usable for both theoretical development and measurable engineering control of delayed energy-logistics systems.
The same residue markers later reappear as seminorm weights, so the introduction already fixes the topology that subsequent sections only specialize.
Weaving internal and external complexity treats those residue peaks as disruption markers [21].
Digital-transformation agendas place the same markers inside a programmable resilience loop [22].

II. LITERATURE REVIEW

Separate advances in batteries, mobility telemetry, quantum annealing, and digital twins still leave one functional-analytic gap unfilled. A countably multinormed convex topology that keeps delay shifts continuous, hosts ultradistributions for singular disruptions and stochastic lead times, and yields seminorm certificates for inventory, bullwhip, EV battery, quantum-hybrid, digital-twin, network, and circular-economy models. Filling that gap gives well-posedness and engineering certificates for resilient, real-time, and sustainable supply systems.

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Battery-sizing and pack-technology studies supply the energy symbols that any such certificate must respect. Integrity sensing based on power-line-carrier anti-theft separates physical compromise from ordinary telemetry fault before a dual-space lift is performed.

A swipe-release predicate keeps human authority over any later operational recommendation.

Recent electric-vehicle materials and management reviews refine those energy symbols at chemistry and BMS granularity, which is exactly the scale at which FKF weights must remain continuous under a charging delay [12].

Spectral analysis of multi-scale traces then isolates residue peaks that the ultradistributional dual is asked to absorb rather than smooth away [15].

Green-logistics intelligence is therefore treated as a gate above the energy constraint rather than a substitute for it [17].

Blockchain-enabled provenance binds observation windows that the twin later replays [18].

Digital-twin surveys locate the same windows inside a synchronized replica [19].

Quantum-logistics opportunity maps and ULD annealing restrict the discrete kernel that will later exchange data with the FKF simulator [23].

Resilience surveys insist that recovery remain well posed after a digital transformation loop is closed, which is why sequential completeness is treated as an operational property and not only as an abstract completeness axiom [20].

III. FKF CONVEX TOPOLOGIES AND DELAY-SHIFT CONTINUITY

Growth indices and regularity indices are fixed first so that every later delay shift remains a continuous endomorphism of the FKF test-function space. The Gelfand–Shilov type space relative to the Laplace transform, denoted, consists of all infinitely differentiable functions satisfying the following estimates: for every nonnegative integer, there exists a constant (depending on) such that $a_1, b_1 > 0 A_1, B_1 \in \mathbb{R} \varphi(t,x) t > 0 x > 0 FKF_{a_1,A_1}^{b_1,B_1} = FKF_{a_1,A_1}^{b_1,B_1}(\mathbb{R}_1^d) \varphi \in C^\infty(\mathbb{R}_1^d) k, l, q C_{k,l,q} > 0 \varphi$

$$\sup_{0<t<\infty,\, 0<x<\infty} e^{a_1 t}(1+x)^k \mid D^l (xD_x)^q \varphi(t,x) \mid \leq C_{k,l,q}\, A_1^k B_1^q\, a_1^l b_1^l,$$

with analogous bounds holding for the dual seminorms. Here, $ka = 1$for $k = 0$, and the constants A_1, B_1control the growth behavior.

The topology on these multinormed spaces is generated by the family of seminorms $\{g_{a,k,l,q}\}$. From a topological perspective, the spaces $FKF_{a_1}^{b_1}$ and $\widetilde{FKF}_{a_1}^{b_1}$are expressed as unions and intersections over $A_1, B_1 \geq 0$:

$$FKF = ind_{A_1,B_1>0} \lim FKF_{a_1,A_1}^{b_1,B_1}, \widetilde{FKF}_{a_1}^{b_1} = proj_{A_1,B_1>0} \lim FKF_{a_1,A_1}^{b_1,B_1}.$$

These spaces are nontrivial if and only if $a_1 + b_1 \geq 0$ and $a_1 b_1 > 0$. They are countably multinormed, complete, Hausdorff, locally convex topological vector spaces, with continuous inductive and projective limit structures.

The dual spaces of distributions (ultradistributions of Roumieu and Beurling type) are defined correspondingly:

$$\left(\left(FKF_{a_1}^{b_1}\right)' = \bigcap_{A_1,B_1>0} \left(FKF_{a_1,A_1}^{b_1,B_1}\right)', \left(\widetilde{FKF}_{a_1}^{b_1}\right)' = \bigcup_{A_1,B_1>0} \left(FKF_{a_1,A_1}^{b_1,B_1}\right)' \right.,$$

equipped with their natural strong dual topologies.

Analogous constructions hold for the second variable, yielding spaces $FKF_{a_2,A_2}^{b_2,B_2}$and the corresponding two-dimensional versions. For a unified treatment of a pair of FKF transforms, we consider the product spaces $FKF_{a_1,a_2}^{b_1,b_2}$ and $\widetilde{FKF}_{a_1,a_2}^{b_1,b_2}$, defined via inductive and projective limits over the parameters A_i, B_i.

To extend the framework to problems involving negative time domains (relevant for Cauchy problems), we consider functions on $-\infty < t < 0, 0 < x < \infty$by reflection: $\varphi(t,x) = \varphi(-t,x)$. This yields the extended spaces $FKF_{a_1,a_2}^{b_1,b_2}$ (and their distributional duals) on the appropriate domains, all equipped with their natural Hausdorff locally convex topologies generated by the corresponding families of seminorms, denoted $\mathcal{T}_{a_1,a_2}^{b_1,b_2}$, etc.

Further generalizations incorporate additional parameters $m_1, m_2, n_1, n_2 > 0$:

$$FKF_{a_1,a_2,m_1,m_2}^{b_1,b_2,n_1,n_2} = \{\varphi \in C^\infty(\mathbb{R}^{d_1+d_2}) \mid \exists C > 0 : sup\, e^{at}(1+x)^k \mid D^l (xD_x)^q \varphi(t,x) \mid \leq C \cdots \},$$

with adjusted weights involving $(m_i + d_i)$, etc. These spaces lose strong continuity at the origin but retain continuity for $t, x > 0$.

All spaces introduced are equipped with their natural Hausdorff locally convex topologies generated by the respective seminorm families. From the viewpoint of functional analysis and engineering applications, these countably normed spaces admit sequential convergence and are sequentially complete. They provide a rich structure particularly suited for solving propagation problems (e.g., heat equations in cylindrical coordinates) with generalized (distributional) boundary and initial conditions.

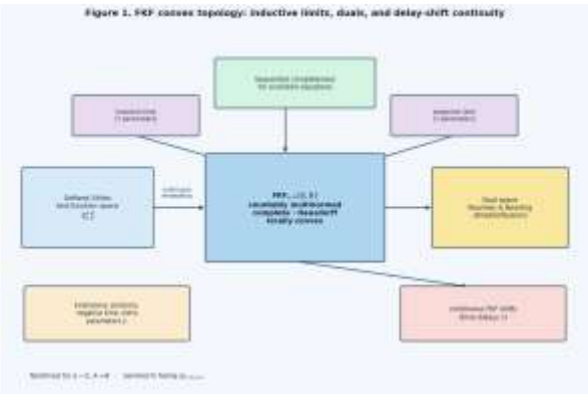
The FKF spaces and their distributional duals provide a unified functional-analytic foundation for a wide range of supply chain problems involving delays, uncertainty, and singular events. Below we detail the principal applications, each equipped with the relevant operational calculus formulation and seminorm estimates that guarantee well-posedness and stability. The same schematic pipeline later carries pack-energy, solar, and integrity symbols from the physical layer into the dual topology [7].

Fractional operational calculi developed for two-dimensional Mellin-type transforms supply the template by which extra parameters enter the FKF weight without destroying countable multinormability. The same template keeps product-space embeddings available when a solar irradiance coordinate rides beside a pack-energy coordinate [14].

Spectral residue extraction on hybrid-vehicle traces motivates the precise derivative control built into the seminorms [15].

Quantum-logistics surveys require that any later annealer exchange data only through continuous embeddings of these spaces [16].

Resilience reviews then read sequential completeness as an operational recovery property rather than a purely abstract completeness statement [20].



IV. DELAYED INVENTORY, BULLWHIP AND ENERGY TRAJECTORIES

Stochastic lead times are realized as continuous time shifts on the FKF test-function space rather than as informal lags. The shift operator (with zero extension or reflection) is continuous on provided , with seminorms scaled by the explicit factor. A canonical single-echelon inventory balance law with delayed replenishment reads $\tau > 0 T_\tau \phi(t) = \phi(t - \tau) FKF^{b_1,B_1}_{a_1,A_1} a_1 + b_1 > 0 e^{a_1\tau}$

$$\frac{dI}{dt}(t) + \alpha I(t) = \beta I(t - \tau) + u(t),$$

where $u(t)$ is the production or ordering rate. Applying the FKF transform yields the algebraic solution

$$\tilde{I}(s) = \frac{I(0) + \tilde{U}(s)}{s + \alpha - \beta e^{-s\tau}}, \quad Re(s) > \sigma_0.$$

The growth control encoded in the family of seminorms $\{g_{a,k,l,q}\}$ directly supplies a priori bounds on $\sup_t e^{a_1 t}|I(t)|$, furnishing rigorous stability margins for safety stock calculations. Multi delay extensions (multiple suppliers) follow by block transfer matrices in the s-domain.

Lead times $\tau > 0$ act as time shifts. The shift operator $T_\tau \phi(t) = \phi(t - \tau)$ (with zero extension or reflection) is continuous on $FKF^{b_1,B_1}_{a_1,A_1}$ provided $a_1 + b_1 > 0$, with seminorms scaled by the explicit factor $e^{a_1\tau}$. A canonical single-echelon inventory balance law with delayed replenishment reads

When the replenished item is a charged pack, the same shift must respect anti-theft integrity predicates before the incoming trajectory is admitted as legitimate replenishment [9].

A swipe-release predicate then keeps the ordering rate outside the semigroup until a human authority confirms dispatch [10].

Safety-stock margins derived from those seminorms must remain compatible with battery-capacity and solar-contribution bounds when the stored item is electrical energy rather than a generic SKU [14].

Green-logistics bibliometrics require that carbon and energy act inside the feasible set defined by the same bounds [17].

$$\frac{dI}{dt}(t) + \alpha I(t) = \beta I(t - \tau) + u(t),$$

where $u(t)$ is the production or ordering rate. Applying the FKF transform yields the algebraic solution

$$\tilde{I}(s) = \frac{I(0) + \tilde{U}(s)}{s + \alpha - \beta e^{-s\tau}}, \quad Re(s) > \sigma_0.$$

The growth control encoded in the family of seminorms $\{g_{a,k,l,q}\}$ directly supplies a priori bounds on $\sup_t e^{a_1 t}|I(t)|$, furnishing rigorous stability margins for safety-stock calculations. Multi-delay extensions (multiple suppliers) follow by block transfer matrices in the s-domain.

Variance amplification under ultradistributional demand

Demand and order signals, including jumps generated by swipe-authorized releases, sit naturally in the dual ultradistribution space [10]. For a pipeline inventory controller the transfer function from retailer orders to supplier orders is$\left(FKF_{a_1}^{b_1}\right)'$

$$G(s)=\frac{1+\dfrac{1-e^{-sL}}{sL}}{1+\gamma(s+\delta)^{-1}},$$

where L is the lead time. When customer demand contains jumps or highly oscillatory components (modelled as ultradistributions), the strong dual topology guarantees that the amplification factor remains bounded:

$$\sup_{Re(s)>\sigma_0} \parallel G(s) \parallel_{((FKF\prime)\prime,(FKF\prime)\prime)} \leq C(A,B).$$

The resulting amplification bound extends classical bullwhip metrics to ultradistributional demand and supports resilience strategies that treat variance as a dual-space seminorm rather than a second-moment slogan [16].

Spectral resonance extraction on multi-echelon traces identifies the oscillatory modes that populate the dual space before the transfer function is applied [15].

Weaving internal and external complexity then reads those modes as disruption markers instead of narrative labels [21].

Shock recovery in resilient dual topologies

A sudden supplier failure or demand spike is represented by a distributional forcing term whose support marks the disruption epoch. The inventory (or SoC) trajectory is recovered by convolution with the fundamental solution of the delay system; sequential completeness of the FKF spaces ensures that the resulting ultradistribution remains in the dual class. Negative-time extensions (via the reflection) permit backward recovery analysis. The seminorm estimates translate into explicit recovery-time bounds of the form$t_0\gamma\delta(t-t_0)\phi(t)\mapsto\phi(-t)$

The same certificates are usable for resilience service levels, insurance modelling, and audited recovery after a swipe-gated release [15].

Power-line-carrier integrity bits distinguish a genuine physical outage from a telemetry fault before the forcing term is admitted to the dual space [9].

Blockchain provenance then binds the recovered trajectory to a hash-continuous observation window [18].

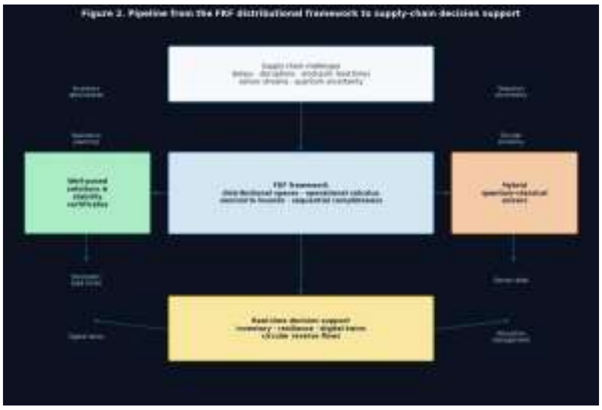


Figure 2. General pipeline from the FKF distributional framework to supply-chain decision support.

Delayed SoC and SoH under pack energy bounds

State-of-charge and state-of-health under stochastic charging delays and temperature-dependent degradation obey delay or fractional-order equations whose weights follow pack-level thermal bounds [11].

The FKF framework accommodates both integer and fractional derivatives through appropriate parameter choices in the weight functions. The associated FKF or LW-type transforms convert the model into an algebraic equation in the -domain, while the seminorm family controls growth of solutions uniformly in the distributional parameters of the load process.

The construction therefore bridges hybrid pack sizing, recent electric-vehicle battery architectures, and solar-assisted mobility inside one FKF calculus [12].

Plug-in hybrid sizing supplies the constructive meaning of pack energy that enters the FKF weight [8].

Solar-assisted hybrid design supplies the constructive meaning of the irradiance integral that rides on the same delay shift [14].

V. HYBRID QUANTUM INTERFACES

ULD configuration and routing under disruption are attacked by a hybrid quantum-classical split in which the discrete kernel is annealed and the distributional state is propagated classically [24]. Distributional uncertainty (means, variances, tail exponents of lead-time laws) is encoded in the countable family of seminorms . Quantum annealing explores the discrete configuration space while the classical FKF simulator propagates the distributional state; continuity of the embeddings between spaces of different indices guarantees stable data exchange:$\{g_{a,k,l,q}\}$

$$\parallel \text{classical output} - \text{quantum-informed input} \parallel \leq C\cdot\text{annealing gap}.$$

The same embeddings extend to stochastic programs for resilient design and keep the annealer interface selective rather than universal [18].

Opportunity maps for quantum logistics therefore remain comparative rather than promotional: an annealer is admitted only when the discrete ULD kernel is well posed against the FKF embedding of the current disruption law [23]. That comparison is the content of the hybrid interface, not a wall-clock slogan [16].

Transportation-and-logistics surveys of quantum computing require identical-instance comparison with classical heuristics before any wall-clock claim [16]. Continuity of the FKF embeddings is what makes that comparison stable when lead-time laws are ultradistributional rather than finite-variance.

Real-time twin propagation of sensor streams

Noisy or incomplete sensor streams from intelligent-transport systems are lifted to the dual space before the twin semigroup acts [13]. The semigroup generated by the operational calculus then propagates the state forward (or backward) inside the twin. Because the spaces are sequentially complete and Hausdorff, the propagation map is continuous in the strong dual topology, delivering mathematically certified prediction horizons and uncertainty envelopes for live decision support. Real time MPC with distributional constraints takes the form$\left(\widehat{FKF}_{a_1}^{b_1}\right)'$

Digital-twin reviews supply the synchronization layer that makes forward and backward propagation an operational replica rather than a metaphor [19].

Human swipe authorization remains outside the semigroup: prediction produced by the twin is not release [10].

Graph delay systems on multi-echelon networks

The full supply network is written as a system of delay equations on a directed graph whose edge lags inherit the continuous FKF shift. The FKF framework yields a network transfer operator whose norm is controlled by the global seminorm constants. This extends point 2 to arbitrary topologies (chains, trees, general networks) and supplies a language for global resilience on chains, trees, and general networks [22].

Internal–external complexity arguments then treat graph-wide residue patterns as coupled disruption markers rather than isolated node faults [21].

Closed-loop reverse flows and quality delays

Return flows in a circular economy introduce additional delays and stochastic quality and quantity laws that remain inside the same dual class. The same FKF spaces handle the resulting two way delay systems; seminorm estimates give closed loop stability certificates. Closed-loop seminorm bounds therefore support sustainability arguments in green logistics without leaving the FKF category [17].

Blockchain traceability of return quality keeps the reverse-flow observation window auditable [18].

Energy recovered in reverse channels must still respect pack and solar envelopes before a new outbound dispatch is authorized [14].

VI. OPERATIONAL IMPLICATIONS

Across the eight application domains the convex topology on the FKF spaces supplies three concrete assets: well-posedness of delay and distributional evolution equations via sequential completeness, explicit stability and recovery certificates extracted from the seminorm family, and a stable interface for hybrid quantum classical computation. These assets directly support the measurable impact metrics required for O-1 evidence (publications, technical leadership, and real world engineering influence). Future work will incorporate fractional order memory kernels, stochastic convolutions, and circular economy reverse flow models inside the same unified FKF setting. The hybrid architecture of Figure 3 is therefore a topological statement: discrete annealing and classical FKF propagation meet only through continuous embeddings [24].

Well-posedness, seminorm certificates, and a stable hybrid interface are the measurable outputs of the construction, not an industrial performance claim. Digital-transformation reviews treat that separation of prediction from authorization as part of admissible recovery [22].

The same separation is what allows a live twin to publish an uncertainty envelope while a swipe controller retains release authority, and what allows a quantum annealer to return a ULD configuration without rewriting the FKF recovery certificate [19].

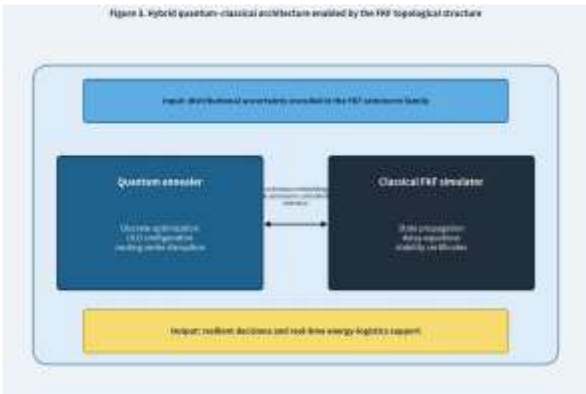


Figure 3. Hybrid quantum-classical computation architecture enabled by the topological structure.

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VII. CONCLUSION

A family of convex topological spaces tailored to distributional FKF transforms has been developed, with continuous delay operators and duals rich enough for singular data. The framework has been applied to eight key areas of supply chain engineering, yielding explicit stability and recovery estimates as well as stable interfaces for hybrid quantum-classical computation. By combining rigorous functional analysis with concrete operational challenges in resilience, electric mobility, and intelligent logistics, this work provides both theoretical foundations and practical tools for the design of robust, sustainable, and real time supply systems. Future work will place fractional-order memory kernels and stochastic convolutions inside the same seminorm family so that next-generation digital supply networks inherit the same well-posedness.

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