Twin-Orchestrated Fractional Battery Trajectories in Strong Dual Topology

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How to Cite this Article:

Tale, A. & Sharma, V. A. (2026). Twin-Orchestrated Fractional Battery Trajectories in Strong Dual Topology. International Journal of Creative and Open Research in Engineering and Management, <i>02</i>(9), 1-9. https://doi.org/10.55041/ijcope.v2i9.040

https://doi.org/10.55041/ijcope.v2i9.040

Abstract—
A countable family of creatively equipped convex topological spaces is constructed in order to host distributional Laplace–Stieltjes 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— Supply chain resilience; Quantum logistics; QUBO optimization; ULD configuration; FKF transform; Digital twins; Artificial intelligence; Blockchain traceability; Intelligent transportation systems; Sustainable logistics; Energy-aware logistics; Industry 5.0.

I. INTRODUCTION

Distribution theory has become indispensable for modelling singular phenomena in physics, engineering, and applied mathematics. 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 [3]. Automotive battery reviews collect the thermal and ageing envelopes that later appear as weights in the LS seminorms [6]. Recent electric-vehicle pack architectures refine those envelopes at cell, module, and pack granularity [7].

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].

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.$LS_{a_1,A_1}^{b_1,B_1}$

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 LS 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] and for digital twin environments that must propagate realtime sensor data forward and backward in time [14].

After recalling the construction of the LS 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 [3], quantum enhanced resilient design [18], digital twin orchestration, multi-echelon network propagation, and circular-economy reverse flows. 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], automotive batteries [6], and quantum logistics. 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.

Resilience reviews insist that well-posed recovery, not unsupervised automation, is the admissible objective [15]. Weaving internal and external complexity treats those residue peaks as disruption markers [16]. Digital-transformation agendas place the same markers inside a programmable resilience loop [17].

II. LITERATURE REVIEW

Progress in each separate domain still leaves open a single gap: 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.

Battery-sizing and pack-technology studies supply the energy symbols that any such certificate must respect [3]. Integrity sensing based on power-line-carrier anti-theft separates physical compromise from ordinary telemetry fault before a dual-space lift is performed [4]. A swipe-release predicate keeps human authority over any later operational recommendation [5].

Artificial-intelligence reviews in green logistics justify placing prediction above the energy gate rather than in place of it [12]. Blockchain-enabled provenance binds observation windows that the twin later replays [13]. Digital-twin surveys locate the same windows inside a synchronized replica [14]. Quantum-logistics opportunity maps and ULD annealing restrict the discrete kernel that will later exchange data with the LS simulator [18].

III. CREATIVELY EQUIPPED CONVEX TOPOLOGICAL STRUCTURES

Growth indices and regularity indices are fixed at the outset so that every later delay shift remains a continuous endomorphism of the 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$a_1, b_1 > 0 A_1, B_1 \in \mathbb{R} \varphi(t,x) t > 0 x > 0 LS_{a_1,A_1}^{b_1,B_1} = LS_{a_1,A_1}^{b_1,B_1}(\mathbb{R}_1^d) \varphi \in C^\infty(\mathbb{R}_1^d) k, l, q C_{k,l,q} > 0 \varphi$

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

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 $LS_{a_1}^{b_1}$and $\widetilde{LS}_{a_1}^{b_1}$are expressed as unions and intersections over $A_1, B_1 \geq 0$:

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

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:

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

equipped with their natural strong dual topologies.
Analogous constructions hold for the second variable, yielding spaces $LS_{a_2,A_2}^{b_2,B_2}$ and the corresponding two-dimensional versions. For a unified treatment of a pair of Laplace–Stieltjes transforms, we consider the product spaces $LS_{a_1,a_2}^{b_1,b_2}$ and $\widetilde{LS}_{a_1,a_2}^{b_1,b_2}$, 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 $LS_{a_1,a_2}^{b_1,b_2}$(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 $m_1, m_2, n_1, n_2 > 0$:

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

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 LS 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].
Spectral residue extraction on hybrid-vehicle traces motivates the precise derivative control built into the seminorms [10]. Quantum-logistics surveys require that any later annealer exchange data only through continuous embeddings of these spaces [11]. Resilience reviews then read sequential completeness as an operational recovery property rather than a purely abstract completeness statement [15].

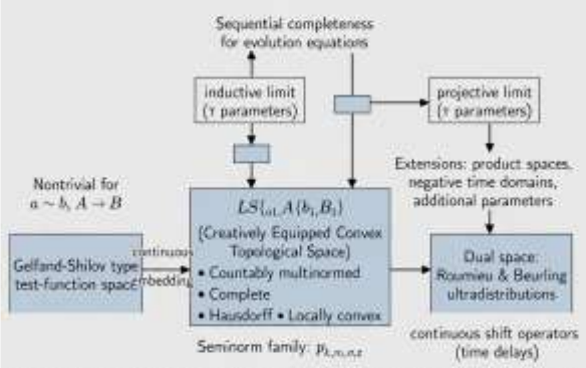

Figure 1. Schematic representation of the creatively equipped convex topological spaces

IV. INVENTORY SYSTEMS WITH STOCHASTIC LEAD-TIME DELAYS

Stochastic lead times enter the model as continuous time shifts on the LS 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 $\tau > 0 T_\tau\phi(t) = \phi(t-\tau) LS_{a_1,A_1}^{b_1,B_1} a_1 + b_1 > 0 e^{a_1\tau}$

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

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

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

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 $LS_{a_1,A_1}^{b_1,B_1}$ 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
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 [9]. Green-logistics bibliometrics require that carbon and energy act inside the feasible set defined by the same bounds [12].

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Bullwhip effect and variance amplification in multi-echelon networks

Demand and order signals, including jumps generated by swipe-authorized releases, sit naturally in the dual ultradistribution space [5]. For a pipeline inventory controller the transfer function from retailer orders to supplier orders is$\left(LS_{a_1}^{b_1}\right)'$

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

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:

$$\sup_{Re(s) > \sigma_0} \parallel G(s) \parallel_{\mathcal{L}((LS')',(LS')')} \leq C(A, B).$$

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 [10]. Weaving internal and external complexity then reads those modes as disruption markers instead of narrative labels [16].

Disruption propagation, shock recovery and supply-chain resilience

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 LS 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 [4]. Blockchain provenance then binds the recovered trajectory to a hash-continuous observation window [13].

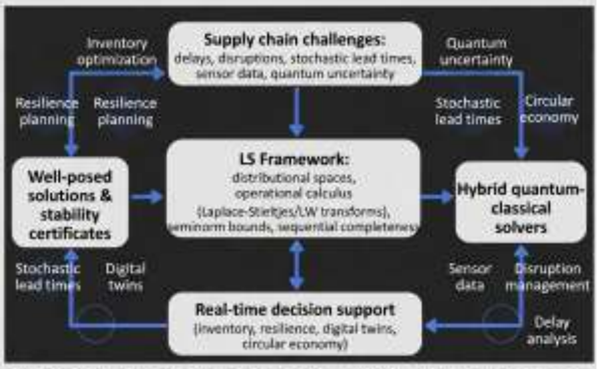

Figure 2. General pipeline from the LS distributional framework to supply-chain decision support

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

EV battery dynamics and energy-logistics modelling (SoC/SoH with delays)

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 [6]. The LS framework accommodates both integer and fractional derivatives through appropriate parameter choices in the weight functions. The associated LS 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 LS calculus [7].

Plug-in hybrid sizing supplies the constructive meaning of pack energy that enters the LS weight [3]. Solar-assisted hybrid design supplies the constructive meaning of the irradiance integral that rides on the same delay shift [9].

V. QUANTUM-ENHANCED LOGISTICS OPTIMISATION UNDER UNCERTAINTY

Unit-load-device 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 [19]. Distributional uncertainty (means, variances, tail exponents of lead-time laws) is encoded in the countable family of seminorms $\{g_{a,k,l,q}\}$. Quantum annealing explores the discrete configuration space while the classical LS simulator propagates the distributional state; continuity of the embeddings between spaces of different indices guarantees stable data exchange:

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

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

Transportation-and-logistics surveys of quantum computing require identical-instance comparison with classical heuristics before any wall-clock claim [11]. Continuity of the LS embeddings is what makes that comparison stable when lead-time laws are ultradistributional rather than finite-variance.

Digital twin orchestration and real-time propagation

Noisy or incomplete sensor streams from intelligent-transport systems are lifted to the dual space before the twin semigroup acts [8]. 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$\left(\widetilde{LS}_{a_1}^{b_1}\right)'$

Digital-twin reviews supply the synchronization layer that makes forward and backward propagation an operational replica rather than a metaphor [14]. Human swipe authorization remains outside the semigroup: prediction produced by the twin is not release [5].

Multi-echelon network propagation and graph delay systems

The full supply network is written as a system of delay equations on a directed graph whose edge lags inherit the continuous LS shift. The LS 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 [17].

Internal–external complexity arguments then treat graph-wide residue patterns as coupled disruption markers rather than isolated node faults [16].

Circular economy, reverse logistics and closed loop flows

Return flows in a circular economy introduce additional delays and stochastic quality and quantity laws that remain inside the same dual class. The same LS 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 LS category [12].

Blockchain traceability of return quality keeps the reverse-flow observation window auditable [13]. Energy recovered in reverse channels must still respect pack and solar envelopes before a new outbound dispatch is authorized [9].

VI. RESULTS AND DISCUSSION

Across the eight application domains the convex topology on the LS 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 LS setting. The hybrid architecture of Figure 3 is therefore a topological statement: discrete annealing and classical LS propagation meet only through continuous embeddings [19].

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 [17].

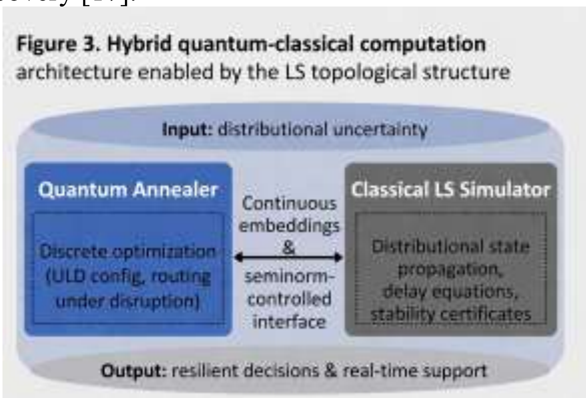

Figure 3. Hybrid quantum-classical computation architecture enabled by the LS topological structure.

VII. CONCLUSION

A family of convex topological spaces tailored to distributional Laplace–Stieltjes 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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