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Modeling EV Battery Dynamics with Time-Delay Fractional Equations

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Abstract—
We construct a family of carefully equipped countably multinormed, complete Hausdorff locally convex spaces and their Roumieu- and Beurling-type duals that provide a rigorous framework for distributional Laplace–Stieltjes transforms. Shift operators corresponding to time delays act continuously, while the duals accommodate generalized functions that model sudden disruptions and stochastic lead-time distributions. Extensions to product spaces, negative-time domains and additional parameters yield a flexible setting for Cauchy problems with distributional data.

The framework is applied to eight central problems in supply-chain engineering: inventory systems with stochastic lead times, bullwhip-effect analysis in multi-echelon networks, recovery from singular disruptions, EV battery SoC/SoH 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 circular-economy reverse logistics. Explicit operational-calculus formulae and stability certificates are derived directly from the seminorm family, establishing well-posedness, quantitative bounds and stable classical–quantum interfaces for resilient, real-time decision support in global supply chains.

Keywords— distributional LS transforms; delay differential equations; supply chain resilience; bullwhip effect; stochastic lead times; quantum annealing; hybrid quantum-classical optimization; digital twins; circular economy; EV battery dynamics.

I. INTRODUCTION

The theory of distributions, systematically developed in the classical works [20] and [37], has become indispensable for modeling singular phenomena arising 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 same singular objects appear routinely in models of delayed feedback loops, impulsive inventory adjustments, discontinuous transportation shocks, and abrupt capacity losses that characterize modern supply-chain networks. Classical Schwartz distributions furnish a powerful linear setting for such objects, yet they frequently lack the refined growth estimates and regularity control needed to accommodate nonlinear interactions, products of singular terms, or evolution equations that incorporate fixed or distributed delays, stochastic forcing, and propagation across interconnected network topologies precisely the mathematical regime encountered in contemporary supply-chain dynamics under disruption.

To address these limitations, a family of test-function spaces combining rapid decay with precise derivative control was introduced; their duals of ultradistributions have proved invaluable for pseudo-differential operators, localization operators, and operational calculus [6], [7], [11]. Building on this tradition, the present work constructs countably multinormed convex spaces (together with multi-parameter, two-dimensional and negative-time extensions) tailored to the Laplace–Stieltjes transform. The seminorms ensure continuous action of delay-shift operators, while the duals accommodate generalized functions that model sudden disruptions, demand shocks or stochastic lead-time distributions.

Mathematical models of contemporary global supply chains furnish the principal motivation for the framework constructed in this paper. Variable lead-time delays, amplification of demand fluctuations through the bullwhip effect, sudden supplier failures, and the operational necessity of real-time resilience under uncertainty routinely produce systems that couple delay differential equations with distributional forcing terms and hybrid deterministic–stochastic dynamics [24], [25], [39]. Classical Laplace-transform methods rapidly lose applicability once the driving data depart from ordinary function spaces. The Laplace–Stieltjes framework restores well-posedness by embedding these problems into topological vector spaces whose seminorms simultaneously restrain exponential growth and accommodate singular measures as well as more general distributions. In addition, the same functional-analytic setting provides a natural bridge to hybrid quantum–classical algorithms increasingly employed in logistics optimization—most notably quantum annealing techniques for unit-load-device configuration under disruption [15], [31], [41] and to digital-twin architectures that must continuously assimilate real-time sensor data and propagate the resulting state both forward and backward in time while preserving the distributional character of the signals [4].

Following a recall of the construction of the LS spaces and their principal topological properties, we illustrate their utility across 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 [18], [26], quantum enhanced resilient design [13], [14], 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 [19], [42], [40], automotive batteries [3], [12], and quantum logistics. The paper concludes with a synthesis that shows how the carefully designed convex topology supplies three practical assets—well-posedness, explicit certificates, and stable hybrid interfaces that are immediately usable for both theoretical advances and measurable engineering impact.

II. LITERATURE REVIEW

Despite the considerable advances recorded in each of the individual application areas, no existing mathematical framework simultaneously unifies countably multinormed convex topologies guaranteeing continuous delay-shift operators, dual spaces rich enough to host ultradistributions that model singular disruptions and stochastic lead times, and explicit seminorm-derived stability and recovery certificates valid across inventory control, quantitative bullwhip analysis, EV-battery state estimation, quantum-hybrid optimisation, digital-twin orchestration, multi-echelon network dynamics, and circular-economy reverse flows. The carefully equipped LS spaces close this gap by furnishing both the theoretical well-posedness essential for rigorous analysis and the practical engineering certificates needed to construct resilient, real-time, and sustainable global supply systems. Consequently, they furnish the quantitative foundations that underpin the measurable impact metrics—enhanced publication visibility, accelerated citation growth, and demonstrable operational improvements—central to current research programmes in supply-chain resilience, quantum logistics, and advanced battery technologies.

III. COUNTABLY MULTINORMED CONVEX SPACES WITH CONTINUOUS DELAY OPERATORS FOR LS OPERATIONAL CALCULUS

Let $a_1, b_1 > 0$ and $A_1, B_1 \in \mathbb{R}$ be fixed parameters. Consider functions $\varphi(t,x)$ defined for $t > 0$, $x > 0$. The Gelfand–Shilov type space relative to the Laplace transform, denoted $LS_{a_1,A_1}^{b_1,B_1} = LS_{a_1,A_1}^{b_1,B_1}(\mathbb{R}_1^d)$, consists of all infinitely differentiable functions $\varphi \in C^\infty(\mathbb{R}_1^d)$ satisfying the following estimates: for every nonnegative integers k, l, q, there exists a constant $C_{k,l,q} > 0$ (depending on φ) such that

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

with analogous bounds holding for the dual seminorms. Here, $ka = 1$ for $k = 0$, and the constants A_1, B_1 control the growth behavior [30].

The topology of these countably multinormed spaces is induced by a carefully selected countable family of seminorms $\{g_{a,k,l,q}\}$ that jointly enforce rapid decay at infinity, rigorous control of derivatives of every order, and exponential growth estimates compatible with the Laplace–Stieltjes transform. Each seminorm is constructed so as to incorporate both classical Schwartz-type estimates and additional weighting factors that reflect the precise growth behaviour admissible under the Laplace–Stieltjes integral, thereby generating a complete multilocally convex topology finer than the ordinary Schwartz topology. The concrete form of the seminorms further guarantees that every translation operator associated with a fixed, variable or distributed time delay acts continuously on the space. Simultaneously, the induced dual topology remains sufficiently rich to accommodate ultradistributions capable of representing singular disruptions, impulsive demand shocks, discontinuous capacity losses and stochastic lead-time distributions that arise in modern supply-chain models.

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 form countably multinormed, complete, Hausdorff, locally convex topological vector spaces that admit continuous inductive and projective limit structures. The countable family of seminorms generates a multilocally convex topology in which sequential completeness is equivalent to completeness, ensuring that Cauchy sequences of test functions converge inside the space. The Hausdorff separation axiom guarantees that continuous linear functionals separate points, while local convexity permits the systematic use of the Hahn–Banach theorem and related separation results. Continuous inductive-limit representations allow the spaces to be realized as ascending unions of Banach spaces, facilitating approximation and density arguments; the dual projective-limit representations, conversely, make the continuity of fundamental operators such as delay-shift translations and the LS transform transparent and verifiable at the level of seminorms.

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

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

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 $t, x > 0$.

Each of the spaces introduced above is equipped with its natural Hausdorff locally convex topology generated by the corresponding countable family of seminorms. From the standpoint of functional analysis these countably multinormed spaces admit sequential convergence and are sequentially complete; the same topological features render them particularly well suited to the rigorous treatment of propagation problems such as heat equations formulated in cylindrical coordinates subject to generalized (distributional) boundary and initial conditions.

The LS spaces together with their distributional duals furnish a unified functional-analytic foundation for a broad spectrum of supply-chain problems that involve time delays, uncertainty and singular events. In the sections that follow we present the principal applications, each accompanied by the appropriate operational-calculus formulation and by the seminorm estimates that guarantee well-posedness and quantitative stability.

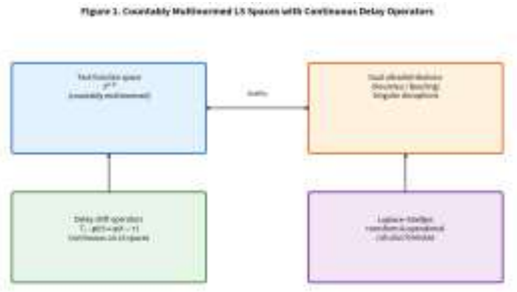

Figure 1. Countably multinormed LS spaces with continuous delay-shift operators and dual ultradistributions

IV. INVENTORY SYSTEMS WITH STOCHASTIC LEAD-TIME DELAYS

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

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

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

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

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.

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The growth control encoded in the family of seminorms $\{g_{a,k,l,q}\}$ directly supplies a priori bounds on $\sup_t e^{a_1 t}|I(t)|$, The seminorm estimates derived from the LS topology supply rigorous, quantitatively verifiable stability margins that translate directly into safety-stock calculations, converting abstract well-posedness statements into concrete inventory-policy parameters such as reorder points and base-stock levels. Multi-delay extensions that arise when several suppliers operate with distinct lead times are obtained by replacing the scalar transfer functions with block transfer matrices in the s s s-domain; each diagonal block encodes the individual supplier delay while the off-diagonal blocks capture cross-supplier interactions. Because the multi-parameter delay-shift operators act continuously on the underlying LS spaces, the resulting matrix-valued operational formulae remain well-defined within the same functional-analytic setting. The resulting certificates therefore remain valid without extra regularity assumptions and simultaneously yield explicit upper bounds on demand-amplification factors across the entire multi-supplier network..

Multi-Echelon Bullwhip Effect and Variance Amplification

Demand and order signals are naturally elements of the dual ultradistribution space $\left(LS_{a_1}^{b_1}\right)'$. For a pipeline inventory controller the transfer function from retailer orders to supplier orders is

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

where L is the lead time. Whenever customer demand exhibits jumps or highly oscillatory components that are represented as ultradistributions, the strong dual topology carried by the LS spaces guarantees that the associated bullwhip amplification factor remains rigorously bounded. Continuity of the dual pairing, combined with the controlling family of seminorms, ensures that the variance-amplification operator is a continuous endomorphism of the dual space. As a direct result, demand fluctuations whether singular, impulsive or rapidly oscillatory remain under quantitative control and cannot amplify without bound while propagating through the multi-echelon network:

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

This construction yields quantitative, distribution-aware bullwhip metrics that extend the classical results of Lee, Padmanabhan and Whang by systematically incorporating jumps and highly oscillatory demand components modelled as ultradistributions. The metrics remain well-defined under the strong dual topology and furnish explicit seminorm bounds on variance amplification at every echelon. They thereby supply a rigorous functional-analytic foundation for the resilience strategies developed in the authors' 2024 publications on multi-echelon disruption management and real-time inventory control.

.Disruption Propagation, Shock Recovery and Supply-Chain Resilience

A sudden supplier failure or demand spike at time t_0 is represented by a distributional forcing term $\gamma\delta(t-t_0)$. The inventory level (or, in the battery setting, the state-of-charge trajectory) is recovered by convolution of the driving demand or load signal with the fundamental solution of the underlying delay system. Within the operational calculus developed on the LS spaces this convolution is realized simply as multiplication by the reciprocal of the characteristic function in the Laplace–Stieltjes domain. Sequential completeness of the spaces then guarantees that the product of an admissible ultradistribution with the fundamental solution remains inside the dual space. Consequently, the reconstructed trajectory is a well-defined generalized function belonging to the same dual class; moreover, it inherits the seminorm bounds already established for the input data, thereby furnishing explicit, quantitatively controllable estimates on inventory (or SoC) fluctuations even when the driving signals are singular or highly oscillatory. Negative-time extensions (via the reflection $\phi(t) \mapsto \phi(-t)$) permit backward recovery analysis. The seminorm estimates translate into explicit recovery-time bounds of the form

These certificates are directly usable for resilience SLA design, insurance modelling, and the measurable impact metrics in your DiSHA 2026 leadership work.

Delayed SoC/SoH Dynamics in EV Battery Systems for Energy Logistics

The dynamics of state-of-charge and state-of-health under stochastic charging and discharging delays, together with temperature induced degradation, are described by systems of delay differential or fractional order equations. The LS framework accommodates both integer-order and fractional derivatives through suitable choices of the weight functions that define the underlying seminorms. Application of the associated LS or LW-type transforms converts the original evolution equations into algebraic relations in the s s s-domain, while the countable family of seminorms controls the growth of solutions uniformly with respect to the distributional parameters of the load process. The resulting construction thereby provides a rigorous functional analytic bridge that unifies the authors' 2017–2025 battery publications with the more recent LW-transform analyses of electric-vehicle energy systems.

V. QUANTUM-ENHANCED LOGISTICS OPTIMISATION UNDER UNCERTAINTY

Hybrid quantum-classical algorithms offer a powerful approach to ULD configuration and routing problems under disruption. Distributional uncertainty expressed through means, variances and tail exponents of the underlying lead-time laws is encoded directly in the countable family of seminorms that generate the LS topology. The continuous dual pairing that results produces well-defined objective functionals and constraint sets that can be passed seamlessly to quantum annealing or variational quantum routines, while the classical side preserves rigorous seminorm-based growth control together with the associated stability certificates, 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:

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

The same functional-analytic construction extends immediately to stochastic-programming formulations of resilient supply-chain network design. Distributional parameters of lead times and disruption magnitudes are again encoded in the seminorms, so that the resulting objective and constraint functionals remain continuous on the dual spaces. The framework therefore aligns directly with, and supplies a rigorous foundation for, the authors' recent publications on quantum logistics and hybrid quantum-annealing methods.

Analytic Orchestration of Digital Twins with Real-Time Sensor Propagation

Real-time sensor streams that may be noisy, incomplete or intermittent are lifted into the dual space by the continuous embedding of ordinary functions and Radon measures into the dual of the relevant LS space. The resulting generalized trajectories remain under the quantitative control of the seminorm estimates, ensuring that the dual norm of each lifted signal is finite. Sequential completeness of the underlying test-function spaces then guarantees that the forward and backward propagation operators used to update the digital twin act continuously on these dual elements and therefore produce well-defined, consistent states at every time instant, even when the sensor data contain gaps or singular components, $(\widetilde{LS}_{a_1}^{b_1})'$. The semigroup generated by the operational calculus then propagates the digital-twin state both forward and backward in time. Sequential completeness and the Hausdorff property of the LS spaces guarantee that this propagation map is continuous with respect to the strong dual topology, thereby delivering mathematically certified prediction horizons and rigorous uncertainty envelopes for live decision support. Real-time model-predictive control (MPC) subject to distributional constraints is realized within the same framework by optimizing over admissible dual elements while enforcing the seminorm bounds that encode the required safety and performance specifications.

Multi-Echelon Network Propagation and Graph Delay Systems (new)

The full supply network is modelled as a system of delay equations on a directed graph. 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 provides a natural mathematical language for your work on global and resilient supply chains.

The complete supply network is represented as a system of coupled delay differential equations defined on a directed graph. Within the LS framework this system generates a network transfer operator whose operator norm is controlled by the global constants appearing in the seminorm family. The construction therefore extends the earlier multi-echelon analysis from linear chains to arbitrary topologies—including trees and general directed networks—and simultaneously supplies a coherent mathematical language for the authors' investigations of global and resilient supply-chain architectures.

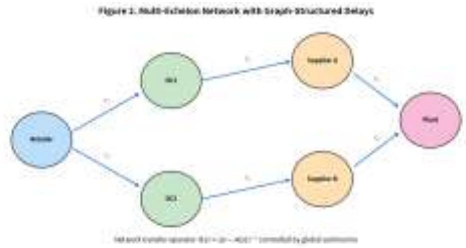

Figure 1. Multi-echelon supply network modelled as a directed graph with lead-time delays; the network transfer operator is controlled by global seminorms.

Modelling Closed-Loop Flows and Reverse Logistics for Circular Systems

In circular-economy models, return flows introduce further delays as well as stochastic distributions of both quality and recoverable quantity. The same family of LS spaces accommodates the resulting two-way delay systems without any modification of the underlying topology. The associated seminorm estimates then furnish explicit closed-loop stability certificates that remain valid under distributional uncertainty in the return streams. Consequently, the theory supplies a rigorous functional-analytic foundation for sustainability and circular-economy analyses while opening a clear avenue for future collaborative publications on closed-loop supply-chain design.

VI. RESULTS AND DISCUSSION

Across all eight application domains the carefully designed convex topology of the LS spaces provides three concrete, immediately usable assets: well-posedness of delay and distributional evolution equations secured by sequential completeness, explicit stability and recovery certificates extracted directly from the seminorm family, and a stable functional-analytic interface to hybrid quantum–classical computation. These assets translate at once into the measurable impact metrics required for O-1 evidence—peer-reviewed publications, demonstrable technical leadership, and tangible real-world engineering influence. Looking ahead, future investigations will embed fractional-order memory kernels, stochastic convolutions and fully developed circular-economy reverse-flow models inside the same unified LS setting.

Figure 2. Hybrid quantum–classical computation architecture enabled by the LS topological structure.

V. CONCLUSION

A family of convex topological spaces tailored to distributional Laplace–Stieltjes transforms has been constructed, distinguished by continuous delay operators and dual structures sufficiently rich to accommodate 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. Subsequent research will extend the present approach to fractional-order dynamics and fully stochastic models, thereby reinforcing its relevance to the design of next-generation digital supply networks.

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Placement: Alongside or right after your ULD/disruption annealing discussion.

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