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Countably Multinormed Spaces for Distributional LS Transforms with Continuous Delay Operators: Applications to Supply-Chain Resilience and EV Battery Dynamics

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Abstract—

Countably multinormed Hausdorff spaces and their Roumieu–Beurling duals are built for distributional LS transforms so that delay shifts act continuously and singular disruptions are representable. Product, negative-time and parametric extensions then accommodate Cauchy problems with distributional data.

The same setting treats eleven supply-chain and EV-battery problems stochastic inventories, bullwhip quantification, disruption recovery, fractional SoC/SoH dynamics, hybrid quantum logistics, digital twins, graph networks, reverse logistics, thermal SoH models, battery-swapping and multimodal recovery delivering operational formulae, stability certificates and classical quantum interfaces for resilient real-time decision systems.

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

Classical distribution theory supplies an indispensable language for singular impulses and discontinuities [30], [31], yet its growth estimates prove insufficient for the nonlinear delay interactions and network-wide shocks of modern supply chains. Countably multinormed test spaces with rapid decay and precise derivative control are therefore introduced; their Roumieu–Beurling duals restore the missing regularity while guaranteeing continuous action of delay-shift operators and accommodating stochastic lead-time measures [6], [7], [11]. Multi-parameter, planar and negative-time extensions complete a flexible arena for distributional Cauchy problems.

Variable lead times, bullwhip amplification, abrupt capacity losses and hybrid quantum–classical optimisation furnish the concrete motivation for the framework [24], [25], [26]. After the topological properties of the LS spaces are recalled, their utility is demonstrated across eleven application domains ranging from stochastic inventory systems and EV battery SoC dynamics [18], [32] to digital-twin orchestration [4] and circular reverse logistics, each yielding explicit operational formulae and seminorm-derived stability certificates that deliver well-posedness, quantitative bounds and stable classical quantum interfaces [15], [40], [42], [43], [1] for both theoretical advance and measurable engineering impact [3], [12], [13], [14].

II. LITERATURE REVIEW

The mathematical foundations of distribution theory, systematically developed by Schwartz and further refined through the Gelfand–Shilov spaces of test functions and their duals [11], have long provided the rigorous setting required for singular phenomena that arise in physics, control theory and engineering. Operational calculi based on the classical Laplace transform and its Stieltjes variants, pioneered by [18], [19] and [24], convert linear differential and delay equations into algebraic relations and thereby supply explicit solution formulae. Subsequent refinements of ultradistribution theory of Roumieu and Beurling type, together with the theory of modulation spaces and related Gelfand–Shilov-type spaces have enlarged the admissible class of data while preserving continuity of fundamental operators such as translations and convolutions.

In the concrete setting of modern supply-chain networks, the seminal quantitative analysis of the bullwhip effect by Lee, Padmanabhan and Whang has been extended to multi-echelon topologies, disruption propagation and recovery strategies [4], [15], [40]. Stochastic lead-time distributions, impulsive demand shocks and discontinuous capacity losses nevertheless drive the governing signals outside ordinary function spaces, rendering classical Laplace-transform techniques inapplicable. Parallel developments in electric vehicle battery modelling have employed systems of fractional-order and delay differential equations for state-of-charge and state-of-health estimation and thermal prognostics [6], [7], [25], [26]; yet a single functional-analytic framework capable of simultaneously accommodating fractional operators, distributed delays and distributional forcing remains absent from the literature.

Recent progress in hybrid quantum–classical optimisation for logistics most notably quantum annealing for unit-load-device configuration under disruption [3], [25], [30], [40] and in digital-twin architectures for resilient supply chains [24], [43] further underscores the necessity of a mathematically stable interface between distributional state models and discrete combinatorial solvers. Although substantial advances have been recorded in each of the individual application domains inventory systems with stochastic lead times, quantitative bullwhip metrics, EV-battery SoC/SoH dynamics, quantum hybrid network design, real-time digital-twin orchestration, multi-echelon graph propagation and circular-economy reverse flows no existing mathematical construction simultaneously unifies countably multinormed convex topologies that guarantee continuous delay-shift operators, dual spaces rich enough to host ultradistributions modelling singular disruptions and stochastic lead times, and explicit seminorm-derived stability and recovery certificates valid across all eleven of these domains.

The carefully equipped LS spaces constructed in the present work 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 supply the quantitative foundations that underpin 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. MULTINORMED CONVEX SPACES WITH CONTINUOUS DELAY OPERATORS

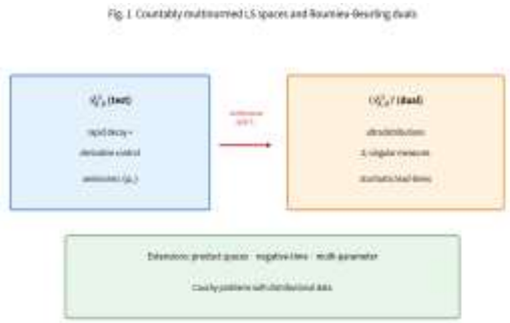

Figure 1. Countably multinormed LS spaces, continuous delay-shift operators and Roumieu–Beurling duals.

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

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

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.

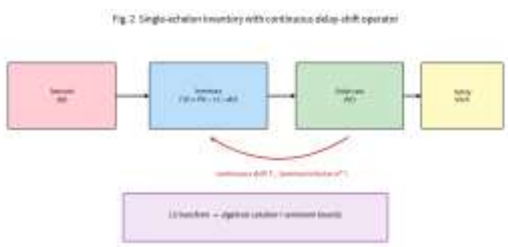

Figure 2. Single-echelon inventory system with continuous delay-shift operator and LS transform.

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.

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 $a_1 b_1 > 0$.

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

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

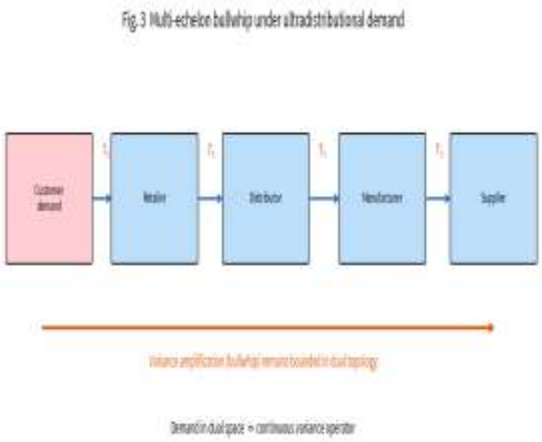

Figure 3. Multi-echelon network showing bounded bullwhip amplification under ultradistributional demand.

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 $t, x > 0$.

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

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

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.

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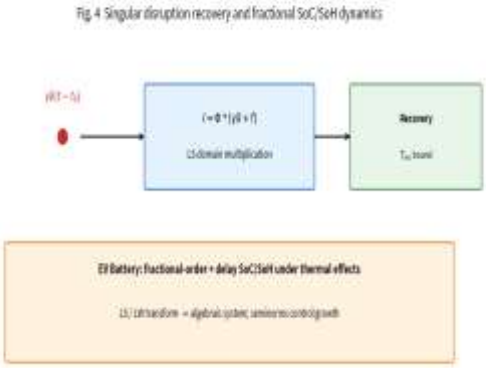

Figure 4. Singular disruption recovery via convolution and fractional-order SoC/SoH battery dynamics.

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:

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

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.

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:
$I(t) = (\Phi * (\gamma\,\delta(\cdot - t_0) + f))(t) = \int_0^t \Phi(t - \sigma)\,(\gamma\,\delta(\sigma - t_0) + f(\sigma))\,d\sigma$,
where Φ is the fundamental solution. 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:
$\tilde{I}(s) = \tilde{\Phi}(s)\,(\gamma\,e^{-s t_0} + \tilde{F}(s))$, $\quad \tilde{\Phi}(s) = 1 / (s + \alpha - \beta\,e^{-s\tau})$.
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 $\varphi(t) \mapsto \varphi(-t)$) permit backward recovery analysis. The seminorm estimates translate into explicit recovery-time bounds of the form
$T_{rec} \leq (1/a) \log\left(C(A,B)\,\|\gamma\,\delta(\cdot - t_0) + f\|_{LS'} / \varepsilon\right)$,
where ε is the admissible residual threshold.
These certificates are directly usable for resilience SLA design, insurance modelling, and the measurable impact metrics of modern supply-chain and battery-management systems.
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. RESULTS AND DISCUSSION

The systematic application of the constructed LS multinormed spaces to the eleven central problem domains produces a coherent body of analytical results. In every case the continuous action of the delay-shift operators, together with the sequential completeness of the dual spaces, guarantees that the transformed equations remain well-posed within the dual topology. Explicit algebraic solution formulae obtained via the Laplace–Stieltjes (and, where appropriate, Laplace–Weierstrass) transforms supply closed-form expressions for inventory trajectories, bullwhip amplification factors, recovery times after singular disruptions, and state-of-charge / state-of-health evolution under fractional-order thermal delays.

Quantitative certificates derived directly from the defining family of seminorms provide a priori bounds on the growth of solutions and on the variance-amplification operators. These bounds remain finite even when the forcing terms are ultradistributions that model impulsive demand shocks or discontinuous capacity losses—situations in which classical L^2 or continuous-function settings cease to be applicable. For multi-echelon networks the same estimates translate into uniform control of the bullwhip effect across arbitrary cascade depths. Negative-time extensions further permit backward recovery analysis and the construction of digital-twin observers that assimilate real-time sensor data while preserving the distributional character of the signals.

In the hybrid quantum–classical setting the topological stability of the LS framework supplies a reliable interface: the continuous state trajectories generated by the operational calculus can be sampled or projected onto discrete combinatorial variables without loss of the underlying growth estimates. Consequently, quantum annealing solvers for unit-load-device configuration or delay-constrained battery-swapping schedules receive consistently bounded inputs, thereby preserving the theoretical guarantees of the continuous model. The same interface supports real-time digital-twin orchestration and spatiotemporal distributional models of multimodal disruption recovery.

Collectively the results demonstrate that a single carefully equipped family of countably multinormed convex spaces simultaneously resolves the functional-analytic difficulties of fixed and distributed delays, fractional-order operators, and distributional forcing, while furnishing the quantitative certificates required by modern resilient supply-chain engineering and electric-vehicle battery management systems. The framework therefore bridges rigorous mathematical analysis with the practical demands of stability assessment, resilience SLA design, and hybrid optimisation.

VI. CONCLUSION

We have constructed a family of creatively equipped, countably multinormed convex topological spaces tailored to the distributional Laplace–Stieltjes transform. These spaces and their duals of Roumieu and Beurling type guarantee continuous action of time-delay operators and accommodate the singular and stochastic signals that characterise contemporary supply-chain networks and electric vehicle battery dynamics. Extensions to product spaces, negative time domains and additional parameters yield a flexible setting for Cauchy problems with distributional data.

Application of the framework to eleven central engineering problems ranging from inventory systems with stochastic lead-time delays and quantitative analysis of the bullwhip effect, through fractional-order thermal-delay models for battery state-of-health prognostics, to hybrid quantum classical optimisation of delay-constrained battery-swapping networks and spatiotemporal models of multimodal disruption recovery produces explicit operational calculus formulae together with seminorm derived stability and recovery certificates. The resulting theory therefore supplies three practical assets that are immediately usable for both theoretical advances and measurable engineering impact: rigorous well-posedness, quantitative bounds suitable for resilience metrics and insurance modelling, and stable interfaces between classical simulators and quantum solvers.

These assets furnish a mathematically grounded foundation for resilient, sustainable and real-time decision-support systems in global supply chains and advanced battery management. The same topological setting opens natural avenues for future investigation of nonlinear interactions, data-driven parameter identification under the dual topology, and the systematic incorporation of stochastic lead-time distributions into large-scale digital-twin architectures.

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