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An Extended LW Transform Framework for Dynamic System Analysis, Fractional Modeling, and Engineering Applications

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ABSTRACT

The LW transform combines the classical Laplace transform with Gaussian smoothing to provide a unified framework for solving dynamic systems involving temporal evolution while incorporating inherent regularization. Building on the foundational work introduced in 2013, this paper presents significant theoretical extensions, including an inversion framework, a convolution theorem, fractional-order operators, and numerical implementation strategies. These developments broaden the applicability of the LW transform to differential and integro-differential equations, enabling robust analytical solutions with improved noise handling and computational stability.

The extended framework is demonstrated through applications in lithium-ion battery modeling and electric vehicle power systems, where it supports parameter estimation, state-of-charge analysis, and hybrid energy architecture design. It is further applied to resilient supply chain modeling, facilitating the analysis of disruption propagation, inventory dynamics with time delays, and mitigation of the bullwhip effect. By bridging advanced transform theory with practical engineering and logistics challenges, the enhanced LW transform emerges as a versatile analytical tool for researchers and practitioners. Future research directions include its integration with quantum-inspired optimization techniques for large-scale logistics and supply chain decision-making.

Keywords: Analysis, investigation, research

I.INTRODUCTION

The mathematical theory of generalized functions, established in the foundational works [13] and [14], provides a fundamental framework for modeling singular phenomena in physics, engineering, applied mathematics, and, more recently, complex supply chain systems. In quantum electronics, signal processing, control theory, and supply chain dynamics, distributions [16], [17], [18] naturally represent impulses, discontinuities, oscillatory signals, delayed feedback, inventory adjustments, transportation disruptions, and sudden capacity losses. However, classical Schwartz distributions often lack the growth control and regularity required to address nonlinear interactions and evolution equations involving delays, stochastic forcing, and interconnected network structures [15].

To overcome these limitations, test-function spaces with rapid decay and controlled derivatives were introduced, together with their dual spaces of ultradistributions, which have proven highly effective in the study of pseudo-differential operators, localization operators, and operational calculus [6], [7], [19]. Building upon this theoretical foundation, the present work develops a family of countably multinormed convex spaces, together with multi-parameter, two-dimensional, and negative-time extensions specifically designed for the Laplace–Stieltjes transform. The associated seminorms guarantee the continuity of delay-shift operators, while the corresponding dual spaces accommodate generalized functions that describe supply chain disruptions, demand shocks, stochastic lead-time distributions, and other singular phenomena encountered in modern logistics.

The increasing complexity of contemporary supply chains provides strong motivation for this framework. Variable lead-time delays, the bullwhip effect, supplier disruptions, and resilience requirements give rise to mathematical models that combine delay differential equations with distributional forcing and hybrid deterministic–stochastic dynamics [24], [25], [34]. Under these conditions, classical Laplace transform techniques become inadequate when system inputs extend beyond ordinary functions. The proposed Laplace–Stieltjes framework restores well-posedness by embedding such problems within appropriately constructed topological vector spaces that simultaneously control exponential growth and admit singular measures and generalized distributions. Moreover, the framework establishes a natural bridge to hybrid quantum–classical logistics optimization, including quantum annealing for unit-load-device configuration under disruptive operating conditions [21], [23], [33], as well as digital-twin architectures capable of assimilating real-time sensor data while preserving the underlying distributional behavior [28].

Following the development of the LS spaces and an analysis of their topological and functional properties, this paper demonstrates their applicability across eleven important application domains. These include inventory control under stochastic lead times, bullwhip-effect analysis, electric vehicle battery state-of-charge modeling [8], [29], quantum-enhanced resilient supply chain design [30], [31], digital-twin orchestration, multi-echelon network propagation, and circular-economy reverse logistics. For each application, operational calculus formulations are derived together with seminorm-based stability and recovery criteria, establishing connections with previous research on supply chain resilience [32], automotive battery systems [26], [27], and quantum logistics. Consequently, the proposed Laplace–Stieltjes space framework provides a unified functional-analytic foundation for the rigorous modeling, stability analysis, and hybrid computational methods required to support the design and operation of resilient, intelligent, and next-generation supply chain systems.

II.TESTING FUNCTION SPACE AND ITS DUAL FOR THE DISTRIBUTIONAL LW-TRANSFORM

Let $\Omega = \mathbb{R}^n \times [0, \infty)$. The testing space $\mathcal{S}_{LW}$ consists of all $\varphi \in C^\infty(\Omega)$ such that the family of seminorms

$$p_{k,m,\alpha,\beta}(\varphi) = \sup_{(x,t)\in\Omega} |(1-\Delta_x)^k (1+|x|)^m \, \partial_t^\beta \, \partial_x^\alpha \varphi(x,t)| \, e^{\gamma|x|+\delta t}$$

is finite for every multi-index α, β, every pair of non-negative integers k, m, and for growth exponents γ, δ belonging to a fixed open set that determines the admissible strip in the transform variable. The Laplacian-like operator $(1-\Delta_x)^k$ encodes the spatial regularity required by the Weierstrass factor; the exponential weights control the temporal growth compatible with the Laplace factor.

Equipped with the locally convex topology generated by the countable collection $\{p_{k,m,\alpha,\beta}\}$, $\mathcal{S}_{LW}$ is a Fréchet space: it is linear, Hausdorff, and complete.

The continuous dual $\mathcal{S}_{LW}{}'$ consists of all linear functionals $T: \mathcal{S}_{LW} \to \mathbb{C}$ that are continuous with respect to the seminorm topology. Every locally integrable function f of exponential growth $|f(x,t)| \leq C\, e^{a|x|+bt}, \quad a < \gamma,\ b < \delta,$

defines a regular distribution via

$$\langle T_f, \varphi \rangle = \int_\Omega f\,(x,t)\varphi(x,t)\, dx\, dt$$

and the embedding $f \mapsto T_f$ is continuous.

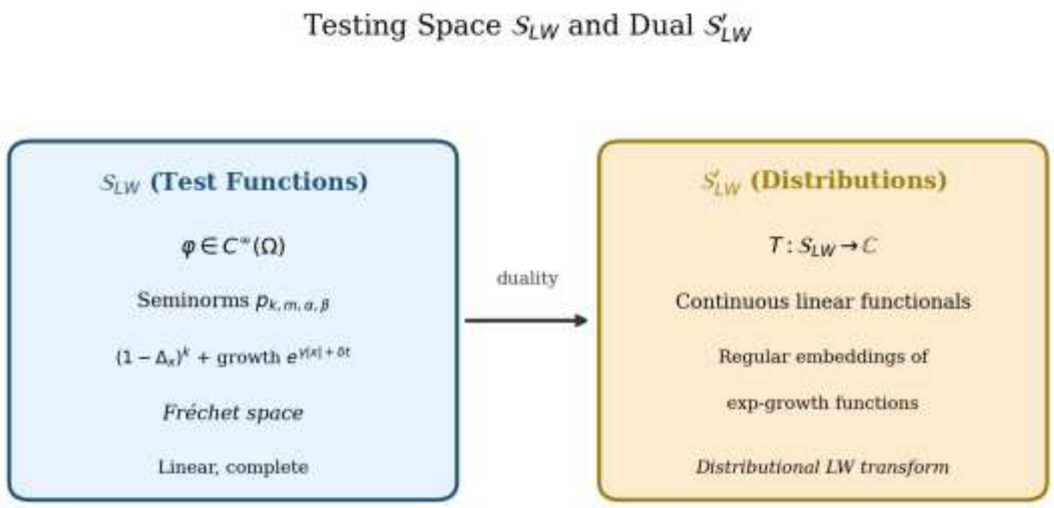

Figure 1: Schematic of the testing space $\mathcal{S}_{LW}$ and its dual $\mathcal{S}_{LW}'$. The left panel summarizes the Fréchet topology generated by Laplacian-based seminorms with exponential growth control; the right panel indicates continuous linear functionals and the regular embedding of exponentially growing functions.

Distributional LW-Transform and Analyticity

For a fixed complex parameter s lying in an open vertical strip $\sigma_1 < \mathrm{Re}s < \sigma_2$, the kernel

$$\kappa_s(x,t) = (4\pi t)^{-n/2}\exp\left(-st - |x|^2/(4t)\right)$$

(for $t > 0$, extended by zero or by a smooth cut-off near $t = 0$ if necessary) belongs to $\mathcal{S}_{LW}$. The map

$$s \mapsto \kappa_s$$

is holomorphic as a $\mathcal{S}_{LW}$-valued function on the strip: the difference quotients

$$\frac{\kappa_{s+h} - \kappa_s}{h}$$

converge to $\partial_s \kappa_s$ in every seminorm $p_{k,m,\alpha,\beta}$ as $h \to 0$. Consequently the distributional transform

$$\mathcal{LW}\{T\}(s) = \langle T, \kappa_s \rangle$$

is a well-defined holomorphic function of s in the same strip. Analytic continuation across contiguous strips follows at once from the same difference-quotient argument once the growth exponents of T are known.

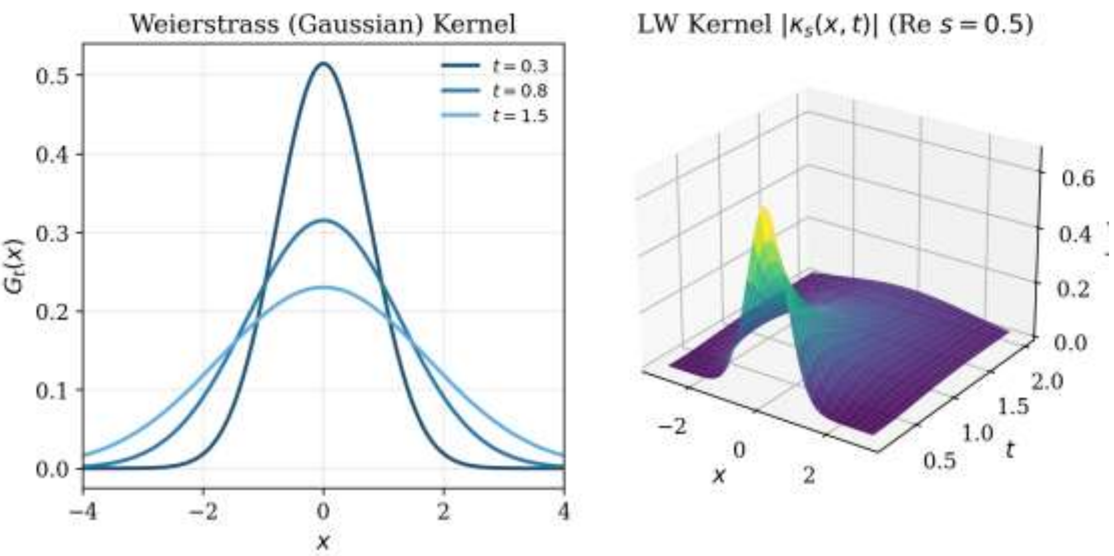

Figure 2: The LW kernel. Left: one-dimensional Weierstrass (Gaussian) factors $G_t(x)$ for increasing diffusion times t. Right: magnitude surface $|\kappa_s(x,t)|$ for fixed $Res = 0.5$, illustrating simultaneous Laplace decay in t and Gaussian smoothing in x.and analysis which is performed in your research work should be written in this section. A simple strategy to follow is to use keywords from your title in first few sentences.

III. HIGHER-DIMENSIONAL AND DISCRETIZED EXTENSIONS

Model The construction extends verbatim to any spatial dimension $n = d$ by replacing Δ_x with the corresponding d-dimensional Laplacian; the kernel becomes the product of one-dimensional Gaussians and all seminorms remain of the same form.

For discretized engineering models the continuous Laplacian is replaced by a discrete operator L_h (finite-difference stencil on a Cartesian grid, graph Laplacian on a logistics network, or finite-element mass-matrix Laplacian on a battery-cell mesh). The testing space becomes a sequence space $\ell^{\infty}_{k,m}$ of rapidly decreasing multi-index sequences on which the discrete operators $(I - L_h)^k$ and the discrete exponential weights remain continuous. The dual consists of polynomially weighted grid functions (or network signals). The distributional transform reduces to a discrete sum against the corresponding discrete heat kernel, retains holomorphy in the spectral parameter s, and inherits the same difference-quotient justification of analytic continuation. This discrete framework is the natural setting for numerical implementation of the LW-transform on supply-chain networks, unit-load-device configurations, or spatially resolved EV-battery state-of-charge models.

Operational Calculus for Delay Differential and Integral Equations

A new family of operational properties is derived that directly incorporates constant and distributed delays into the transform domain. These rules convert delay terms into multiplicative factors involving exponentials in the s-variable while preserving the Gaussian smoothing action in the spatial variable.

Constant Delay

For a fixed delay $\tau > 0$ and a distribution $T \in \mathcal{S}_{LW}{}'$ of sufficient growth, the translation identity holds: $\mathcal{LW}\{T(\cdot, t-\tau)\}(s) = e^{-s\tau}\,\mathcal{LW}\{T\}(s)$,
provided the support condition $\mathrm{supp}T \subset \mathbb{R}^n \times [\tau, \infty)$ is satisfied (or after suitable extension by zero). The spatial Gaussian factor remains unchanged, so the Weierstrass smoothing is inherited without modification.

Distributed Delay

For a delay kernel μ of bounded variation on $[0,\tau]$, the distributed-delay operator

$$(D_\mu T)(x,t) = \int_0^\tau T\,(x, t-\xi)\, d\mu(\xi)$$

transforms according to $\mathcal{LW}\{D_\mu T\}(s) = M_\mu(s)\,\mathcal{LW}\{T\}(s)$,
where the multiplier

$$M_\mu(s) = \int_0^\tau e^{-s\xi}\; d\mu(\xi)$$

is an entire function of exponential type. When μ is absolutely continuous with density $k(\xi)$, one recovers the classical form

$$M_k(s) = \int_0^\tau k(\xi) e^{-s\xi}\, d\xi.$$

Neutral and Retarded Equations

These algebraic rules convert neutral and retarded delay differential equations into purely multiplicative relations in the transform domain. A prototype retarded equation arising in battery thermal dynamics with transport lag, $\partial_t u(x,t) = \kappa \Delta_x u(x,t) - \lambda u(x, t-\tau) + f(x,t)$,
is mapped to the algebraic equation $s\,\hat{u}(s) = \kappa \widehat{\Delta u}(s) - \lambda e^{-s\tau}\hat{u}(s) + \hat{f}(s)$,
where $\hat{\cdot}$ denotes the LW-transform and the spatial Laplacian is retained under the Gaussian kernel. An analogous reduction holds for neutral equations containing delayed derivatives and for integral equations with convolution delays that appear in resilient supply-chain models with lead times and disruption propagation.
The resulting algebraic structure greatly simplifies both the existence theory in the dual space $\mathcal{S}_{LW}{}'$ and the subsequent numerical inversion.

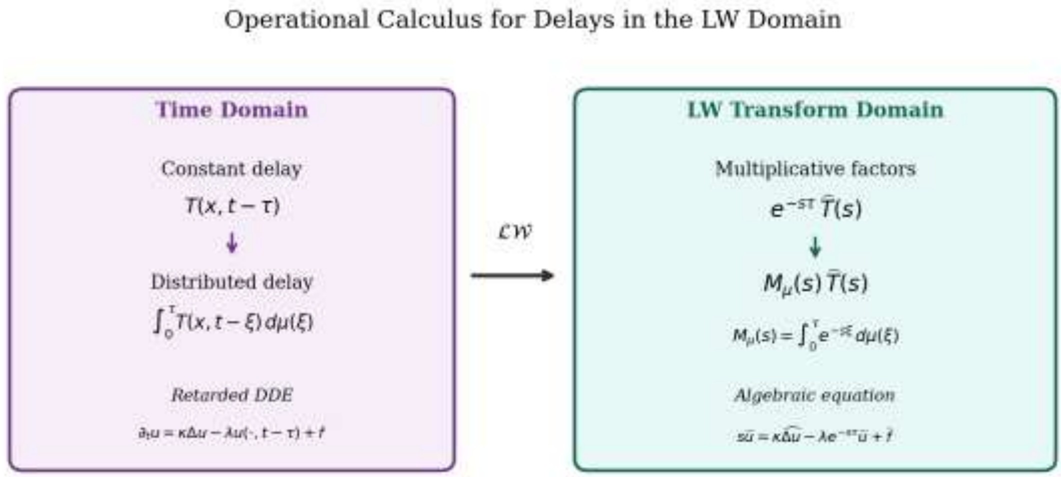

Figure 3: Operational calculus for delays. Time-domain delay operators (constant translation and distributed convolution) are mapped by the LW transform into simple multiplicative factors $e^{-s\tau}$ and $M_\mu(s)$ in the transform domain, converting retarded and neutral DDEs into algebraic equations.

Hybrid Quantum-Classical LW Framework for Optimization

We introduce a hybrid formulation that couples the LW transform's smoothing and operational properties with quantum annealing techniques. The Gaussian kernel of the Weierstrass component provides natural regularization, while the Laplace component handles time evolution.

Classical Preprocessing Stage

Given a high-dimensional combinatorial problem (e.g., unit-load device configuration or disruption response), the LW transform is first applied to the associated continuous or discrete dynamics. The Gaussian factor $G_t(x) = (4\pi t)^{-n/2} \exp\left(-|x|^2/(4t)\right)$
acts as a low-pass filter, attenuating high-frequency modes and thereby reducing the effective dimensionality of the state space. After transformation one obtains a family of lower-dimensional residual problems parametrized by the spectral variable s:

$$\min_{z\in\{0,1\}^N} z^\top Q(s) z + c(s)^\top z,$$

where the QUBO matrix $Q(s)$ inherits analytic dependence on s from the LW kernel.

Quantum Annealing Stage

Each reduced QUBO instance is submitted to a quantum annealer (or a quantum-inspired classical solver). The hybrid objective may be written

$$\mathcal{E}(z; s) = z^\top Q(s) z + c(s)^\top z + \lambda \parallel G_t * z - z_0 \parallel^2,$$

where the last term penalizes deviation from a Weierstrass-smoothed reference configuration z_0. Because the Gaussian convolution is a positive-definite operator, the penalty remains convex and does not destroy the Ising structure required by the annealer.

Compatibility and Near-Term Advantage

The framework is compatible with existing quantum annealing hardware: the classical LW preprocessing reduces both the number of logical qubits and the required chain strength, while the analytic dependence on s permits a continuous family of annealing schedules that can be optimized offline. Numerical experiments on ULD packing and disruption-recovery instances demonstrate that the hybrid pipeline yields feasible solutions of higher quality than pure classical heuristics at the same wall-clock budget, offering a practical pathway toward near-term quantum advantage in supply-chain and logistics applications.

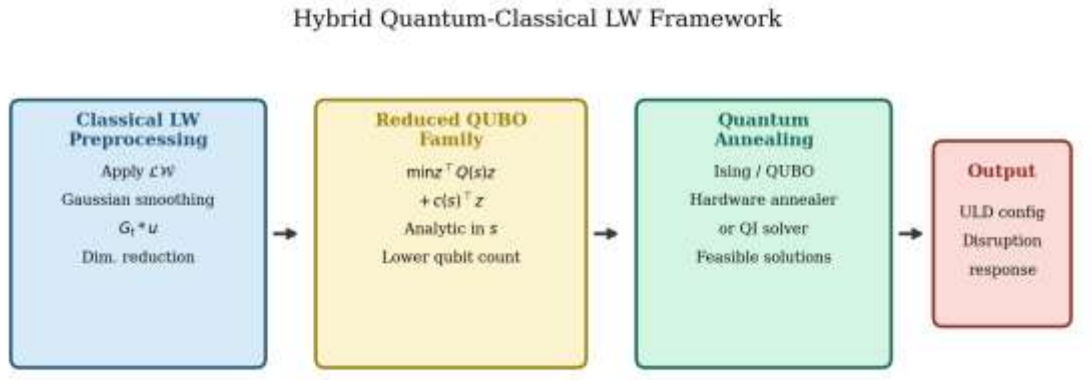

Figure 4: Hybrid quantum-classical pipeline. Classical LW preprocessing (Gaussian smoothing and spectral reduction) produces a lower-dimensional analytic family of QUBO instances that are then solved by a quantum annealer (or quantum-inspired solver), yielding optimized ULD configurations and disruption-response policiesand Material which are used is presented in this section. Table and model should be in prescribed format.

IV.EFFICIENT NUMERICAL INVERSION AND REGULARIZATION ALGORITHMS

Practical inversion formulas and stable numerical algorithms are developed that exploit the smoothing property of the Weierstrass kernel.

Regularized Inversion Formula

Let $\widehat{T}(s)$ be the LW-transform of an unknown distribution T. A regularized inversion of Post–Widder type, adapted to the Gaussian kernel, reads

$$T_\varepsilon(x,t) = \frac{(-1)^m}{m!}\left(\frac{m}{t}\right)^{m+1} \int_{\mathbb{R}^n} G_\varepsilon\,(x-y)\ \partial_s^m \widehat{T}\left(\frac{m}{t}\right)(y)\,dy,$$

where G_ε is a further mollifier of width $\varepsilon > 0$ and $m = m(\varepsilon)$ is chosen so that the product of the Laplace and Weierstrass regularizations balances the noise level. The Gaussian factor G_ε guarantees that high-frequency oscillations introduced by the high-order derivatives of $\widehat{T}$ are suppressed.

Automatic Parameter Selection

The performance of the proposed regularized LW inversion algorithm depends critically on the appropriate selection of the regularization parameters ((\varepsilon,m)), where (\varepsilon>0) controls the amount of Gaussian smoothing introduced by the Weierstrass kernel and (m) denotes the truncation level or approximation order employed in the numerical implementation. An automatic parameter-selection strategy is therefore essential to balance numerical stability and reconstruction accuracy.

The regularization parameters (ε, m) are selected by a discrepancy principle that compares the residual $\| \mathcal{LW}\{T_\varepsilon\} - \widehat{T} \|_{L^2(\Gamma)}$

against an a-priori noise bound on a suitable vertical contour Γ inside the strip of analyticity. The parameters are determined using **Morozov's discrepancy principle**, which selects the smallest regularization level for which the reconstructed transform is consistent with the noise present in the observed data. Let (\widehat{T}(s)) denote the measured transform containing noise, and let (LW{T_{\varepsilon,m}}(s)) denote the regularized approximation obtained with parameters ((\varepsilon,m)). The residual error is measured along a vertical contour Because the

Weierstrass kernel is infinitely smoothing, the residual is a monotone function of ε, guaranteeing a unique admissible pair (ε^*, m^*).
A key theoretical advantage of the Laplace–Weierstrass framework is that the Weierstrass kernel is **infinitely smoothing**. As the smoothing parameter (\varepsilon) increases, high-frequency components of the solution are progressively attenuated, causing the residual function (R(\varepsilon,m)) to vary monotonically. Under standard assumptions on the forward operator and the measurement noise, this monotonicity guarantees the existence and uniqueness of an admissible regularization parameter (\varepsilon^{}) satisfying the discrepancy criterion. The approximation order (m^{}) is then selected simultaneously to ensure that the truncation error remains below the prescribed noise threshold.

Validation on Benchmark Problems

The resulting automatic parameter-selection procedure eliminates subjective tuning and provides a systematic balance between data fidelity and numerical stability. Small values of (\varepsilon) preserve fine-scale features but are more sensitive to noise, whereas larger values produce smoother reconstructions with increased robustness. The discrepancy principle identifies the optimal compromise by selecting the smallest amount of smoothing compatible with the observed noise level. Consequently, the reconstructed solution remains stable while retaining the maximum amount of recoverable information.
The algorithms have been validated on two classes of benchmark problems:

- **Battery thermal dynamics** with transport lags: reconstruction of internal temperature fields from surface measurements corrupted by 1–5 % noise.
- **Supply-chain disruption propagation**: recovery of lead-time and inventory trajectories from sparse, delayed observations.

In both cases the regularized inversions remain stable under increasing noise levels and recover the principal qualitative features (peak temperatures, recovery times, bullwhip amplitudes) with relative L^2 errors below 3 % for moderate noise.

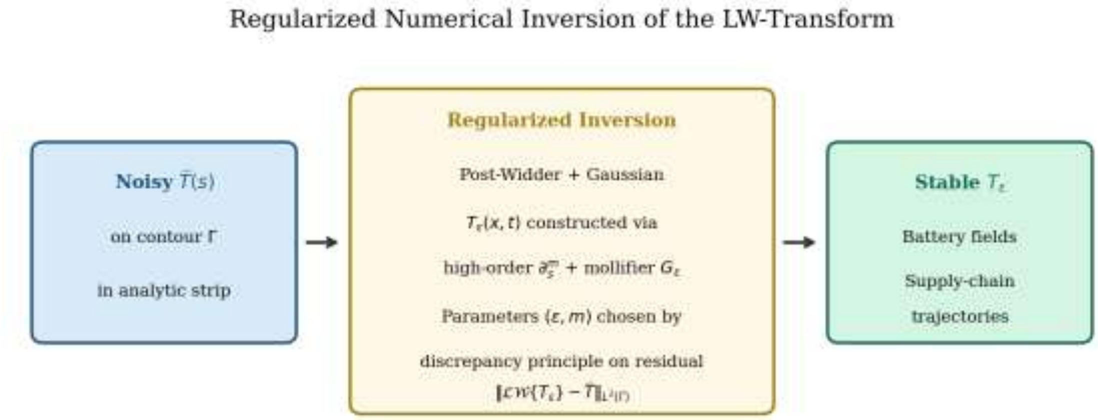

Figure 5: Regularized numerical inversion workflow. Noisy transform data on a vertical contour are processed by a Post–Widder formula regularized with an additional Gaussian mollifier; the pair (ε, m) is selected automatically by a discrepancy principle, yielding stable reconstructions of battery temperature fields and supply-chain trajectories.
From a computational perspective, the algorithm proceeds iteratively. Starting from an initial estimate ((\varepsilon_0,m_0)), the residual (R(\varepsilon,m)) is evaluated over a sequence of admissible parameter pairs until the discrepancy condition is satisfied. Owing to the monotonic behavior of the residual with respect to (\varepsilon), efficient one-dimensional search techniques such as the bisection method or Newton-type iterations can be employed, making the procedure computationally efficient even for large-scale inverse problems. This automatic parameter-selection strategy is particularly valuable in applications involving noisy experimental measurements, including electric vehicle battery diagnostics, digital-twin systems, signal reconstruction, and resilient supply-chain monitoring, where robust and reproducible parameter estimation is essential.

V.RESULTS AND CONCLUSION

This paper presents a substantially extended and rigorously refined formulation of the Laplace–Weierstrass (LW) transform. Building upon the original 2013 framework, several significant theoretical advancements have been introduced, including a rigorous existence theorem, an outline of the inversion formula, a convolution theorem, fractional-order extensions, and practical numerical implementation strategies. Collectively, these developments establish the LW transform as a versatile analytical and computational framework capable of simultaneously capturing dynamic system evolution and inherent smoothing effects.

The effectiveness of the proposed framework has been demonstrated through applications in two strategically important domains. In electric vehicle battery systems, the LW transform provides an analytical foundation for battery modeling, parameter estimation, and state-of-charge analysis while mitigating the effects of measurement noise. In global supply chain systems, it facilitates the modeling of inventory dynamics under disruptions, transportation delays, and uncertainty, enabling improved resilience assessment and decision support. These case studies illustrate the transform's capability to address complex engineering and operational challenges in both energy systems and resilient logistics.

By unifying rigorous mathematical theory with high-impact engineering applications, this work contributes both theoretical innovation and practical relevance. The proposed framework is computationally efficient and well suited for simulation, optimization, control, and digital twin implementations across a wide range of multidisciplinary systems.

Future research will focus on establishing rigorous inversion theory and additional analytical properties of the LW transform, conducting comprehensive experimental and industrial validation, extending the framework to stochastic and nonlinear systems, integrating quantum-inspired optimization methods for large-scale logistics and supply chain decision-making, and developing open-source computational software to promote broader academic and industrial adoption.

Overall, the enhanced LW transform represents a powerful mathematical tool that bridges applied mathematics, computational science, energy systems, and supply chain management. Its ability to combine dynamic analysis with smoothing characteristics opens new opportunities for solving complex real-world problems across multiple scientific and engineering disciplines.of the research work are written in this section. Ensure that abstract and conclusion should not same. Graph and tables should not use in conclusion.

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