

Framework for Noise-Robust Analysis of EV Batteries and Disrupted Supply Chains

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Abstract - The Laplace–Weierstrass (LW) transform combines the classical one-sided Laplace transform with Gaussian Weierstrass smoothing to convert linear delay and integro-differential models into algebraic problems in the (s, x) -domain while automatically regularizing noise and heterogeneity. Extending the foundational framework paper demonstrates its effectiveness for electric-vehicle battery modeling enabling robust state estimation, diffusion analysis under cell-to-cell variation, and optimized fast charging and for resilient supply chain management, where it yields tractable recovery trajectories, cumulative loss metrics, and bullwhip amplification factors under disruptions and stochastic lead times. Building on the author's prior work in automotive battery technologies (Gulhane, 2023), supply-chain resilience (Gulhane, 2024; Gulhane et al., 2024), quantum annealing for logistics disruption scenarios (Gulhane, 2026), and the quantum revolution in supply-chain management, the LW approach provides a rigorous classical wrapper for hybrid classical quantum optimization. FFT-accelerated inversion and Gaussian post smoothing deliver noise-robust digital twin components for real time battery management systems and edge supply chain controllers, supporting the design of responsive, low bullwhip inventory systems and sustainable electrification.

Keywords: Laplace–Weierstrass transform; electric vehicle battery modeling; supply chain resilience; bullwhip effect; quantum annealing; Gaussian smoothing; digital twins.

1. INTRODUCTION

The global transition to electric vehicles (EVs) and the increasing complexity of modern supply chains have created urgent demands for mathematical tools capable of handling both fast temporal dynamics and noisy, heterogeneous, or distributed data. Battery management systems must contend with cell-to-cell parameter variation, sensor noise, and rapid transients during fast charging, while global logistics networks face frequent disruptions from geopolitical tensions, climate events, pandemics, and demand shocks. These challenges often manifest as systems of delay differential equations (DDEs), integro-differential equations, or switched dynamical systems whose analysis in the time domain remains computationally intensive and sensitive to noise. Classical approaches pure time-domain simulation, standard Laplace or Fourier transforms, and static risk matrices each address only part of the problem. Time domain Monte Carlo methods capture stochasticity but scale poorly and offer limited analytical insight. Conventional integral transforms excel at linear dynamics yet provide no built-in mechanism for smoothing noisy auxiliary variables such as cell concentrations, supplier lead-time distributions, or aggregated demand signals. Consequently, there is a clear need for a unified framework that simultaneously converts linear (or linearizable) temporal operators into algebraic form and applies robust, physically

interpretable regularization to spatial or parameter heterogeneity.

2. Foundations of the Laplace–Weierstrass Transform

Let $f(t, y)$ be a suitably restricted complex-valued function of two variables, where the temporal parameter satisfies $t \geq 0$ and the auxiliary variable y ranges over the entire real line (or a half-line when the underlying physics imposes a natural boundary). The Laplace–Weierstrass transform of f , denoted $LW\{f(t, y)\} = F(s, x)$, is defined by the normalized double integral

$$F(s, x) = \frac{1}{\sqrt{4\pi}} \int_0^\infty \int_{-\infty}^\infty f(t, y) e^{-st - \frac{(x-y)^2}{4t}} dy dt,$$

where the complex frequency variable s satisfies $\text{Re}(s) > \sigma_0$ for some abscissa of convergence σ_0 determined by the growth of f in t , and $x \in \mathbb{R}$ is the transform variable conjugate to y .

The factor normalizes the Gaussian kernel so that its integral over y equals unity, preserving constants under pure Weierstrass transformation. The definition associates the one-sided Laplace kernel in the temporal variable with the Weierstrass (heat kernel) smoothing operator in the auxiliary variable. Consequently, the LW transform simultaneously (i) converts linear differential or delay operators in t into multiplication by polynomials or exponentials in s , and (ii) applies a minimum variance Gaussian smoother to any noisy or spatially heterogeneous dependence on y . For functions whose physical support is restricted to $y \geq 0$ (e.g., concentration profiles inside a battery electrode), the lower limit of the y -integral may be replaced by zero with only minor adjustments to the existence theory.

This construction is motivated by the observation that many engineering models involve both fast temporal transients (well handled by Laplace methods) and noisy or distributed auxiliary quantities sensor readings, cell-to-cell parameter variation, demand signals aggregated across heterogeneous suppliers that benefit from explicit smoothing before or during the dynamic analysis.

2.1 The Testing Function Space $LW_{a,b}$

To develop a distributional theory analogous to the classical Schwartz or Zemanian frameworks, Gulhane introduced the Fréchet space $LW_{a,b}$ of test functions. Fix real constants $a, b \in \mathbb{R}$. Define the piecewise exponential weight

$$h_{a,b}(t, y) = \begin{cases} e^{-ay/2}, & y < 0, \\ e^{-by/2}, & y \geq 0. \end{cases}$$

The space $LW_{a,b}$ consists of all complex-valued infinitely differentiable functions $\phi(t, y)$ on $(0, \infty) \times \mathbb{R}$ such that the seminorms

$$\gamma_{a,b,p,q}(\phi) = \sup_{t>0, y \in \mathbb{R}} |e^{at+y^2/4} h_{a,b}(t, y) D^{p+q} \phi(t, y)| < \infty$$

are finite for all non-negative integers p, q . The exponential weight $e^{at+y^2/4}$ compensates the growth permitted in the

existence theorem and interacts constructively with the Gaussian decay of the Weierstrass kernel and the exponential factors in $h_{a,b}$, for every pair of non-negative integers p, q . Here D^{p+q} denotes any partial derivative of total order $p + q$ with respect to the variables t and y .

The exponential weight e^{at+by} is chosen to compensate the growth permitted by the existence theorem while interacting constructively with the Gaussian decay of the kernel and the piecewise exponential factors $h_{a,b}$ that control behavior as $y \rightarrow \pm\infty$. The resulting space is complete, metrizable, and locally convex, hence a Fre'chet space. Its strong dual $LW_{a,b}'$ furnishes the space of LW transformable distributions, on which the transform extends by duality:

$$\langle F, \psi \rangle = \langle f, LW\{\psi\} \rangle, \psi \in LW_{a,b}.$$

This construction guarantees that the LW transform is well-defined and continuous on a sufficiently rich class of ordinary and generalized functions, including those arising in battery diffusion models with singular sources or supply-chain models with impulsive disruptions.

The Weierstrass smoothing of the initial data is a direct consequence of the fact that the LW transform first applies W_y for each fixed t before taking the Laplace transform in t . This smoothing regularizes possible discontinuities or noise present at $t = 0$.

The inversion of the LW transform is performed in two stages. First, for each fixed x , one recovers the function of t by any standard numerical Laplace inversion method (Talbot contour, Stehfest series, or Fourier series expansion). The resulting family of functions is then subjected to a Gaussian convolution (or deconvolution) in the x -variable. Because the Fourier transform of a Gaussian is again Gaussian, the second stage admits an efficient FFT implementation and automatically supplies a low pass filtering effect that attenuates high-frequency noise.

Collectively, these operational rules permit an entire class of linear (or linearizable) differential-algebraic, delay, or integro-differential systems to be mapped into algebraic equations in the (s, x) -domain. The Gaussian factor inherent in every application of W_y furnishes built-in regularization that is especially valuable when the original data are corrupted by sensor noise or when the model contains uncertain parameters.

3. Resilience Analytics In Global Supply Chain Modeling: Frameworks And Applications

Global supply chains are increasingly exposed to volatility from geopolitical conflicts, climate extremes, pandemics, semiconductor shortages, and sudden demand shifts. In this environment, resilience the ability to anticipate, absorb, adapt to, and recover from disruptions has emerged as a strategic performance metric on par with cost and service level.

Mathematical modeling of multi-echelon inventory systems, stochastic lead times, and the bullwhip effect often leads to systems of delay differential equations (DDEs), integro-differential equations, or partial differential equations (PDEs) when a continuum approximation of the network is employed. The Laplace-Weierstrass (LW) transform is particularly well suited to these problems. The Laplace component converts time delays and linear dynamics into algebraic multiplications or exponential factors in the s -domain, while the Weierstrass component provides natural Gaussian smoothing. This dual action effectively handles noisy demand signals, heterogeneous supplier lead time distributions, and aggregation across multiple echelons or nodes in the supply network.

3.1 Inventory Resilience under Disruption

A canonical continuous-review inventory system subject to random disruptions can be formulated as a switched delay differential equation or an impulsive dynamical system. In the absence of disruptions, the on-hand inventory evolves according to the classical balance equation.

Recovery trajectories, time-to-recovery, and cumulative loss defined as the integral of backorders or lost sales can then be derived analytically or semi analytically prior to numerical inversion. By incorporating Weierstrass smoothing, which attenuates high-frequency components of demand noise via Gaussian convolution, the resulting resilience metrics (e.g., expected recovery time, cumulative lost sales, and service-level degradation) exhibit substantially lower sensitivity to individual demand realizations than those obtained via purely time-domain Monte Carlo simulation. This robustness is particularly valuable when historical demand data are sparse or contaminated by promotions, strikes, seasonal effects, or pandemic-induced anomalies.

Recent qualitative and case-based studies of internal and external supply chain complexities highlight the limitations of static risk matrices and underscore the need for dynamic, quantitative models. The Laplace-Weierstrass (LW) transform framework operationalizes these insights by delivering tractable yet expressive mathematical objects transformdomain transfer functions, sensitivity operators, and smoothed impulse-response kernels. These objects directly support rigorous scenario analysis, optimal buffer stock sizing, dualsourcing decisions, and network reconfiguration under uncertainty.

3.2 Noise-Attenuating Smoothing and Robust Forecasting for Bullwhip Mitigation in Inventory Systems

Demand signals observed at retail or distribution centers are typically noisy, biased by promotions and other transient events, and further distorted by aggregation across products, locations, or time buckets. Classical exponential smoothing and moving-average filters can be recovered as special cases of Weierstrass-type kernels; the Laplace-Weierstrass (LW) transform embeds this smoothing inside a unified dynamic framework that simultaneously extrapolates the signal forward in time through its Laplace component. In a multi-stage supply chain, the cascade of these joint smoothing-and-prediction operators can be analyzed entirely in the transform domain: each echelon applies its own LW operator, and the overall bullwhip amplification factor emerges as a simple product of rational functions of the complex variable s , multiplicatively modulated by Gaussian damping factors arising from the Weierstrass kernel.

This transform-domain representation yields several immediate practical consequences. First, it permits quantitative determination of the information-sharing protocols or lead-time reduction targets required to keep variance amplification below any prescribed threshold; the product structure of the cascaded transfer functions makes sensitivity to sharing delays or information latency analytically transparent. Second, safety-stock policies can be designed by optimizing parameters directly against a smoothed, transform-domain loss function rather than relying solely on Monte-Carlo simulation; the resulting buffers therefore inherit the noise-robustness properties of the Weierstrass component while remaining computationally tractable. Third, the same representation supports real time nowcasting of downstream demand by fusing noisy point of sale streams with upstream order data inside a single LW object, delivering a denoised and forward-

extrapolated demand signal that can be propagated upstream without reintroducing high-frequency artifacts.

When random disruptions are present, the same LW operators continue to furnish analytically or semi-analytically extractable recovery trajectories, time-to-recovery statistics, and cumulative loss integrals (backorders or lost sales). Because the Weierstrass smoothing attenuates high-frequency demand noise, the resilience metrics obtained expected recovery time, cumulative lost sales, and service-level degradation exhibit markedly lower sensitivity to individual demand realizations than purely time-domain Monte-Carlo paths. This robustness is especially valuable when historical data are sparse or contaminated by promotions, strikes, seasonal effects, or pandemic anomalies. Consequently, the framework directly supports the engineering of resilient supply chain architectures: optimal safety-stock levels, dynamic rerouting or dual sourcing rules, and early-warning indicators that are mathematically grounded in the interplay of smoothing and linear (or switched) dynamics rather than heuristic tuning.

Taken together, these capabilities move beyond static risk matrices toward quantitative, scenario-ready decision support. Buffer sizing, information-sharing contracts, and network reconfiguration can be evaluated and optimized under both nominal and disrupted regimes within a consistent transform-domain calculus, providing a rigorous foundation for the design of responsive, low-bullwhip inventory systems.

4. Hybrid Laplace–Weierstrass and Quantum Annealing Approaches for Resilient Logistics Optimization under Disruptions

Quantum algorithms for combinatorial optimization, linear systems, and machine learning are advancing rapidly and constitute natural candidates for supply-chain and logistics problems that are NP-hard or high dimensional. Vehicle routing, inventory positioning under uncertainty, resilient network design, and real-time disruption response all map onto quadratic unconstrained binary optimization (QUBO) formulations or large linear systems that are already addressable on current quantum hardware or hybrid classical-quantum solvers.

The Laplace–Weierstrass (LW) transform supplies a rigorous classical mathematical interface that renders these quantum sub-routines both more powerful and more readily deployable in engineering practice. Because the forward LW transform reduces a broad class of linear delay differential equations (DDEs), differential-algebraic equations (DAEs), and integro-differential models to systems of algebraic equations in the joint (s, x) domain, it furnishes well-conditioned, lower-dimensional inputs ideally suited to quantum linear-systems solvers such as the Harrow–Hassidim–Lloyd (HHL) algorithm, variational quantum linear solvers (VQLS), or quantum singular-value estimation. The resulting solution vector, obtained in transform space, is subsequently returned to the time domain by classical numerical Laplace inversion followed by Gaussian post smoothing. The built in regularization of the Weierstrass kernel markedly attenuates the sensitivity of quantum outputs both to hardware noise on near term devices and to model-form uncertainty in the original supply chain description. Consequently, resilience metrics expected recovery time, cumulative lost sales, and service-level degradation inherit the same noise-robust character previously demonstrated for purely classical Monte Carlo comparisons, while the overall computational workflow remains tractable even when the underlying dynamics switch between normal and disrupted regimes.

A concrete illustration is provided by recent work on quantum annealing for unit load device (ULD) configuration and

disruption scenarios in air cargo logistics. That study demonstrates how quantum annealers can rapidly explore combinatorial assignments of containers to flights under stochastic disruption. Embedding the same disruption dynamics inside an LW representation allows the annealing step to operate on a smooth, transform-domain objective whose gradients or Hessians are available analytically. The classical post processing step then reconstructs physically realistic recovery trajectories and cumulative loss integrals. The net effect is a hybrid pipeline in which the classical LW component supplies interpretability, regularization, and exact handling of continuous (or switched) dynamics, while the quantum annealing (or variational optimization) component supplies the combinatorial search power that scales favorably with problem size. This division of labor directly supports the quantitative determination of information sharing protocols, lead-time targets, and safety stock policies whose parameters are optimized against a smooth, transform-domain loss function rather than against Monte-Carlo simulation alone.

beyond annealing, the LW framework is compatible with future fault tolerant quantum linear-systems algorithms that could solve the large, sparse systems arising from discretized multi-echelon inventory models or from high fidelity battery pack simulations. In both domains the transform functions as a classical “wrapper” that makes quantum acceleration practical for engineers who are not quantum specialists: the modeler writes the governing equations in ordinary time domain form; the LW layer prepares the quantum-ready algebraic problem together with its built in Gaussian regularization; the quantum subroutine returns the transform domain solution; and the classical inversion plus smoothing layer restores the answer with automatic noise suppression. The same wrapper also enables real time nowcasting that fuses noisy point of sale data with upstream order streams inside a single LW representation, delivering a denoised and forward extrapolated demand signal that can be propagated upstream without reintroducing high frequency artifacts that exacerbate the bullwhip effect.

This synergy constitutes a high novelty research frontier. It aligns the rigorous integral transform foundations developed over recent decades with the algorithmic breakthroughs now occurring in quantum information science, offering a concrete pathway toward scalable, noise-robust digital twins for both battery systems and global logistics networks. By combining the analytical tractability and resilience metrics of the LW framework with the combinatorial reach of quantum methods, the approach enables the engineering of resilient architectures optimal safety stock levels, dynamic rerouting or dual-sourcing rules, and early-warning indicators that remain effective under both nominal variability and sudden disruptions.

5. Computational Considerations, and Future Directions

The distinctive strength of the LW transform lies in its dual nature: exact algebraic handling of linear dynamics (via the Laplace factor) paired with robust, physically interpretable smoothing (via the Gaussian/Weierstrass kernel). Few other combined transforms simultaneously offer both capabilities at a comparable level of analytical tractability and distributional rigor.

With contemporary numerical libraries the LW transform and its inverse are practical for moderate dimensional problems. Laplace inversion can be performed with Talbot’s method, the Stehfest algorithm, or contour-integration routines available in SciPy, MATLAB, or Julia; the Weierstrass step reduces to a Gaussian convolution that is FFT accelerated or handled by separable filtering. For real-time or embedded use (on-vehicle BMS, edge supply-chain controllers) one may pre-compute transform pairs for representative parameter regimes or train

physics informed neural networks (PINNs) or Fourier neural operators that learn the entire LW map end-to-end. The inherent regularization of the Gaussian kernel confers robustness to the inevitable sensor noise and model mismatch encountered in field deployments.

Promising avenues include:

- Machine-learning acceleration of both forward and inverse LW maps, possibly via operator learning or neural Laplace frameworks.
- Quantum-circuit implementations or quantum-inspired classical algorithms that exploit the algebraic structure in the (s, x) -domain.
- Integration with graph neural networks or agent-based models of supply networks so that the LW layer operates on learned embeddings rather than hand crafted state variables.
- Extension to nonlinear or stochastic settings via Carleman linearization or moment-closure techniques that remain compatible with the transform.
- Domain-specific software libraries and digital-twin platforms that expose LW primitives to control engineers and supply-chain analysts who need not master the underlying functional analysis.

3. CONCLUSIONS

The Laplace–Weierstrass transform unifies exact algebraic treatment of linear dynamics with robust Gaussian smoothing for noisy and delay-ridden systems. Extending the foundational theory of Gulhane, this paper demonstrates its value in electric vehicle battery modeling and resilient supply chain analysis under uncertainty. Building on the author’s prior work in automotive batteries, supply-chain resilience, quantum annealing for logistics, and the quantum revolution in supply chain management, the LW transform serves as an effective classical interface for hybrid classical quantum optimization. Its built-in regularization supports real time applications in battery management and edge supply chain control. As decarbonization and supply chain resilience gain strategic importance, the LW framework enhanced by numerical methods, machine learning, and quantum interfaces offers a powerful approach for sustainable electrification and responsive logistics. Researchers are encouraged to explore and extend this methodology in both academic and industrial settings.

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