Hybrid FKF–FKL Transform Framework for Digital-Twin Battery Systems, Smart Mobility, And Resilient Quantum Logistics

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How to Cite this Article:

AA, G. (2026). Hybrid FKF–FKL Transform Framework for Digital-Twin Battery Systems, Smart Mobility, And Resilient Quantum Logistics. International Journal of Creative and Open Research in Engineering and Management, <i>02</i>(9), 1-9. https://doi.org/10.55041/ijcope.v2i9.107

https://doi.org/10.55041/ijcope.v2i9.107

Abstract—

Battery systems, smart mobility, and resilient logistics generate observations that are temporal, scale-dependent, delayed, incomplete, and operationally constrained. This paper constructs a mathematical framework from the two-sided FKF transform, its time-shift property, and the testing-function-space and sequential-convergence foundations of the hybrid Fourier–Macdonald construction. The central construction uses a product kernel formed from a two-sided Fourier factor and an imaginary-order Macdonald factor. The Fourier coordinate represents temporal oscillation and delay, while the KL coordinate represents positive physical or operational scale. The resulting framework is extended to generalized observations so that impulses, switching events, abrupt demand shocks, and incomplete telemetry can be represented without forcing every event into a smooth classical signal. The theory is connected to automotive and electric-vehicle battery systems, smart mobility and intelligent transportation systems, spectral supply-chain analysis, quantum transportation and logistics, artificial intelligence and green supply chains, AI–blockchain traceability, digital twins, and resilience theory. Quantum annealing and QUBO formulation are placed after spectral validation, physical feasibility, and provenance checks. The proposed architecture therefore distinguishes prediction from authorization and treats quantum optimization as a downstream decision mechanism. Expanded operator relations are developed for delay, differentiation, residual spectra, resonance, energy feasibility, provenance, and binary logistics decisions. The framework provides a common mathematical language for battery telemetry, mobility states, multi-echelon delays, digital-twin residuals, and constrained quantum dispatch.

Keywords: FKF transform, FKL transform, testing-function space, Macdonald function, distributional transform, sequential convergence, time-shift operator, spectral resonance, digital twin, electric-vehicle battery, smart mobility, supply-chain resilience, blockchain provenance, quantum annealing, QUBO

I. INTRODUCTION

The transition toward electrified mobility and digitally coordinated logistics has changed the mathematical character of operational data. Battery voltage, current, state of charge, temperature, traction power, vehicle motion, inventory, demand, communication status, and recovery actions are generated at different temporal resolutions and physical scales. Battery technology reviews emphasize that useful energy, power capability, thermal state, ageing, materials, and management logic must be considered together [32], [14], [9]. Smart mobility and intelligent transportation systems introduce additional connected observations and route-level interactions [13]. In resilient supply chains, disturbances propagate through multiple echelons and are affected by visibility, recovery capacity, digital transformation, and coordination [30], [31], [17].

The difficulty is not merely computational. A demand shock is not mathematically identical to a switching impulse, a theft pulse, a communication delay, or a gradual battery degradation trajectory [8]. A framework that smooths all of these signals into a common time series can lose the distinction between event type and physical scale. The two-sided FKF framework offers a route around this problem by combining temporal Fourier structure with the positive-scale structure of the KL/Macdonald component [25], [24], [19].

The purpose of this paper is to construct that mathematical foundation first and then connect it to applications. The transform is not introduced as a decorative analytical tool. Instead, the testing-function topology determines what observations are admissible; the distributional extension determines how impulsive observations are handled [18], [23]; the shift theorem determines how delay is represented [25], [21]; and the transformed residual determines how a digital twin can be checked [5], [20]. Only after those conditions are evaluated is a quantum optimization problem constructed [15], [11], [12].

The resulting architecture is organized around the principle that prediction is not authorization. AI can predict a state or propose a recovery action [6], [27], while a digital twin reconstructs the state [5] and blockchain records provenance [7]. The mathematical gate must then verify spectral consistency and physical feasibility before the binary decision is passed to a quantum optimizer [15], [11]. Industry 5.0 interpretations further require a human-centric authorization layer after combinatorial search [28].

The paper contains five technical sections. Section 2 defines the mixed transform and testing topology. Section 3 expands the operator theory of delay, differentiation, generalized observations, and spectral resonance. Section 4 develops the application mapping to batteries, smart mobility, supply chains, and digital twins. Section 5 constructs the integrity-constrained QUBO architecture and explains the role of quantum annealing. The conclusion identifies the mathematical and application-level contributions.

2. HYBRID FKF–FKL MATHEMATICAL SETTING

2.1 Mixed domain and product kernel

Let Ω be the half-strip consisting of an unrestricted temporal coordinate and a strictly positive scale coordinate. The positive coordinate is intentionally separated from time because energy, inventory, demand, capacity, distance, and payload are not naturally signed quantities [32], [24].

For an admissible field f(t,x), the mixed transform is defined by the Fourier factor in t and the imaginary-order Macdonald factor in x. The FKL properties supply the scale-side calculus, while the two-sided FKF construction supplies the temporal and sequential framework [25], [19], [24].

2.2 Testing-function topology and sequential convergence

Let T_FKF denote a testing-function space whose seminorms control temporal decay, positive-scale behavior, and the derivatives needed by the transform. The precise weights and KL-compatible differential operator are selected consistently with the sequential-convergence constructions for the two-sided FKF transform [19]. The significant point is that convergence is defined through all relevant seminorms. Thus f_n converges to f in the testing space when every defining seminorm of their difference tends to zero. This creates a mathematical environment in which increasingly refined numerical or telemetry observations can converge without requiring uniform pointwise behavior at every sample [19], [18].

2.3 Distributional dual

The continuous dual T_FKF′ permits generalized states. For example, an ordinary state can be augmented by an instantaneous event using a product of Dirac distributions [18], [23]. This construction is important in cyber-physical applications because switching, theft detection, communication loss, contact events, and abrupt demand disturbances can be sparse or impulsive [8], [26]. The generalized formulation keeps such events mathematically distinct until a controlled regularization or classification stage is introduced.

3. EXPANDED OPERATOR THEORY: DELAY, DISTRIBUTIONS, AND SPECTRAL STRUCTURE

3.1 Translation operator and phase law

Define the temporal translation operator τ_L by shifting the input without changing its positive-scale coordinate. The transform of the shifted state follows directly from the Fourier factor [25]. The modulus therefore obeys an invariance law for pure translation. If θ(s,q) denotes an unwrapped phase on a usable frequency region, then the phase difference caused by a delay L is Δθ(s,q) = −sL. Hence a delay estimate can be obtained from the slope of phase with respect to the temporal spectral variable [25], [21].

This is a stronger interpretation than simply stating that the transform has a shift property. It identifies delay as a measurable spectral phase quantity while leaving the KL coordinate available for scale classification [24], [21].

3.2 Multi-stage delay composition

Suppose a signal propagates through N operational stages with delays L1, …, LN. Repeated application of the shift operator gives a cumulative phase multiplier [25], [21]. The result maps naturally to multi-echelon supply chains. An observed downstream disturbance can retain a record of accumulated propagation delay even when its time-domain waveform has changed because of aggregation, buffering, replenishment, or local control. Resilience studies motivate this interpretation [30], [31], [17], while FKF delay and shift-invariant spectral analysis supply the mathematical mechanism [25], [22].

3.3 Differentiation and transformed dynamics

For suitable test functions or distributional states, differentiation in time is transferred to multiplication in the Fourier coordinate [23]. Consequently, a temporal differential equation can be converted into an algebraic spectral relation. For a mixed operator A acting on time and positive scale, the multiplier Λ summarizes the temporal and scale response of the model. This representation provides a common route for comparing battery dynamics, vehicle trajectories, inventory evolution, and transformed residuals [32], [14], [20].

3.4 Distributional continuity and event preservation

Consider a sequence of observations f_n converging to f in T_FKF. Continuity of the transform means that the associated transformed sequence converges in the corresponding transform topology [19], [18]. This matters for incomplete digital-twin observations because convergence can be formulated at the level of test-function action rather than individual samples [5]. An impulsive event should therefore be retained as a generalized contribution until the model explicitly applies a smoothing or measurement operator [18]. This prevents an arbitrary preprocessing step from deciding in advance whether a pulse is a theft event, a control switch, a sensor artifact, or a genuine demand shock [8].

3.5 Spectral residual and resonance functional

Let z_obs and z_twin denote observed and reconstructed states. Their residual is transformed and evaluated using a nonnegative weight W(s,q). A normalized concentration measure can be used to compare residual strength against the local twin magnitude [5], [20]. A threshold $\rho > \gamma$ identifies a candidate spectral anomaly. Localized peaks or residue concentrations can be interpreted as signatures of multi-scale resonance [20], [22]. The framework deliberately avoids identifying every amplitude increase as the same failure. Temporal frequency, positive scale, phase, and localization remain available as classification variables [21], [23].

3.6 Regularization and stability

Noisy measurements can be regularized before transformation by a controlled smoothing operator G_σ. The objective is not maximum smoothness but stability: frequencies that amplify differentiation noise should be reduced while physically meaningful spectral concentrations should remain detectable [19], [23], provided the chosen topology and kernel assumptions permit the limit. This establishes a principled place for regularization within the theory and prevents smoothing from being confused with the underlying FKF/FKL representation [24].

4. EXPANDED APPLICATION THEORY FOR BATTERIES, SMART MOBILITY, SUPPLY CHAINS, AND DIGITAL TWINS

4.1 Battery state as a mixed temporal-scale field

Battery systems contain states with different physical dimensions and characteristic time scales. Reviews of automotive and electric-vehicle batteries motivate simultaneous consideration of stored energy, state of charge, power, temperature, charging behavior, management systems, and ageing [32], [14], [29]. Introduce a normalized positive scale x so that observations can be represented as z(t,x). The hybrid transform then separates temporal behavior from energy-related scale behavior [24].

A charging delay Lc modifies phase through exp(−isLc), whereas an energetic rescaling changes the q-domain structure [25]. This separation can be used to distinguish a delayed but otherwise consistent battery trajectory from a trajectory whose energy scale or capacity envelope has changed [32], [14].

4.2 Energy feasibility and pack envelope

A transform-domain anomaly should not automatically become an operational command. Let usable energy be E_use and the pack limits be E_min and E_max. A recovery action is physically feasible only when its predicted trajectory remains inside the pack and ageing envelope [14], [9], [16]. Thus spectral admissibility and energy feasibility are complementary: the first checks whether the observed and reconstructed signals agree structurally; the second checks whether the resulting state is physically permissible [5], [29].

4.3 Smart mobility and ITS representation

Smart mobility systems combine vehicle motion, route information, communication, sensing, charging infrastructure, and traffic conditions [13]. Let v(t) be velocity and P_tr(t) traction power. The temporal Fourier coordinate can represent drive-cycle oscillations, switching patterns, and periodic traffic effects, while the positive-scale coordinate can represent distance, mass, energy, or power [13], [16]. The benefit of the hybrid representation is that two vehicles can exhibit similar temporal oscillations while having different energy or payload scales. The q coordinate supplies an additional discriminant that is unavailable in a purely temporal spectrum [20], [24]. Connected IoT and intelligent-logistics telemetry further populate the same mixed domain [27], [28].

4.4 Multi-echelon supply-chain dynamics

Let $D_k(t,x)$ denote a demand or flow field at echelon k. If stage k introduces a delay L_k, the phase after N stages contains the accumulated delay [25], [21]. The positive-scale coordinate remains available for demand magnitude, inventory, or capacity effects. This creates a mathematical distinction between delay propagation and scale amplification, which is valuable for resilience studies [30], [31], [17].

4.5 Digital-twin residual architecture

Let the digital twin produce z_{twin} from historical data, physics, AI prediction, or a hybrid estimator [5], [6]. The spectral consistency gate has an important operational consequence: an AI prediction can be useful without being authorized [6], [27]. A prediction becomes a candidate input to the decision layer only after the twin residual satisfies the prescribed tolerance. This directly connects AI and digital-twin applications with the mathematical residual operator [5], [20], [7].

4.6 Blockchain provenance as an independent constraint

Let h_k represent a provenance state associated with an ordered telemetry sequence. A decision therefore requires both spectral evidence and traceable provenance [7]. Blockchain technology is used to preserve evidence and ordering, while the FKF/FKL framework evaluates the mathematical consistency of the state [7], [27]. These functions should not be conflated: provenance can show where data came from, but it cannot by itself establish physical feasibility [5], [31]. Interface-level control events, including physical anti-theft pulses, remain distributional until classified [8], [10].

4.7 Resilience decision space

The admissible action set joins the mathematical residual, provenance condition, and physical envelope [30], [17]. A recovery action outside this set is rejected before combinatorial optimization. This architecture gives a formal interpretation to resilient decision-making: resilience is not merely the ability to react quickly, but the ability to react within a validated state space [5], [28], [31].

5. EXPANDED INTEGRITY-CONSTRAINED QUANTUM LOGISTICS ARCHITECTURE

5.1 Separation of state estimation and binary optimization

Quantum logistics applications involve binary decisions such as assignment, placement, recovery selection, and unit-load configuration [15], [11], [12]. These decisions should be separated from continuous states such as battery energy, temperature, inventory, and spectral residuals. The continuous state defines the admissible region, while the binary vector determines the selected operational pattern [12], [27]. This prevents a binary solver from implicitly correcting an invalid physical prediction [14], [9].

5.2 QUBO construction

Let C(y) be the operational cost. Hard constraints are transferred into nonnegative quadratic penalties, producing an unconstrained quadratic form required by an annealing formulation [12], [11]. The penalty weights must be sufficiently large to discourage infeasible states without destroying useful cost differences among feasible states [15].

5.3 Energy-aware logistics optimization

Battery and vehicle constraints can enter the QUBO only after continuous feasibility has been evaluated [32], [14], [13]. For a route r, let $E_{req}(r)$ be the predicted mission energy and E_{res} the required reserve. A route violating the energy-reserve inequality should be excluded or heavily penalized before annealing. The same principle applies to thermal limits, charging availability, payload capacity, and other physical conditions [14], [16].

5.4 Spectral preconditioning of recovery decisions

The spectral residual can be mapped into a decision-specific disturbance score Φ_j [20], [22]. This does not mean that the quantum processor performs spectral diagnosis. The classical spectral layer changes the decision landscape before binary optimization [21], [23]. The annealer then searches for a low-cost configuration under the constraints derived from the validated state [12], [11].

5.5 ULD and disruption configuration

For unit-load-device configuration, binary variables may encode object-to-slot assignment, recovery selection, or placement choices [12]. Representative constraints include payload, volume, geometry, center-of-gravity, adjacency, stacking, and structural limitations. The purpose of FKF/FKL preconditioning is to determine whether the disruption state and its propagation justify the candidate recovery scenario [25], [21], [22]. The purpose of the QUBO is to select an efficient feasible configuration [12], [27].

5.6 Prediction is not authorization

The complete decision chain can be represented as a composition of operators. Here F_FKF produces the hybrid spectral representation [25], [19], [24]; D evaluates digital-twin consistency [5]; E checks physical and energy feasibility [32], [14]; P checks provenance [7]; and S applies spectral admissibility [20], [22]. A binary optimizer receives only the resulting admissible decision space [15], [12].

The distinction is central to a human-centric Industry 5.0 interpretation [28]. AI prediction can identify a likely recovery state [6]; the transform can test its consistency [19], [18]; the physical layer can reject an impossible state [32], [9]; blockchain can establish traceability [7]; and quantum annealing can optimize among remaining alternatives [11], [12]. Human authorization can then be applied as the final operational control [28], [27].

5.7 Integrated architecture and research implications

The application layers form a coherent pipeline. Battery technology supplies physical energy states [32], [14], [16]. Smart mobility and ITS provide connected transportation telemetry [13], [27]. Spectral analysis provides multi-scale disturbance and resonance information [20], [22], [23]. AI, blockchain, and digital twins supply prediction, provenance, and state reconstruction [5], [6], [7]. Supply-chain resilience provides the recovery objective [30], [31], [17]. Quantum computing and annealing provide combinatorial optimization [15], [11], [12]. FKF theory and its time-shift and sequential-convergence foundations provide the mathematical backbone [25], [19], [18].

This ordering prevents three common category errors. First, a large prediction is not automatically a feasible physical state. Second, an impulse or integrity event is not automatically a demand disturbance [8], [18]. Third, a low-cost binary solution is not automatically a valid operational solution [12], [11]. The mathematical gate preserves these distinctions before optimization [22], [28].

CONCLUSION

This paper constructs a mathematical bridge between two-sided FKF transform theory and the application domains of battery systems, smart mobility, digital twins, resilient logistics, and quantum decision architectures. The product kernel separates temporal oscillation from positive-scale structure, the testing-function topology provides a controlled convergence setting, and the distributional dual permits generalized observations. The time-shift theorem converts physical delay into a spectral phase factor, while the magnitude invariance of pure translation provides a useful separation between delay and amplitude effects.

The expanded application theory demonstrates how the same operator structure can represent battery energy and thermal states, smart-mobility telemetry, multi-echelon demand propagation, digital-twin residuals, and disruption signatures. AI and blockchain are assigned complementary roles of prediction and provenance, while digital-twin residuals provide a mathematical consistency check. Quantum annealing is deliberately placed downstream of these checks and is used to optimize binary logistics decisions only within an admissible physical and informational state space.

The main contribution is therefore an integrated operator-to-decision architecture rather than a claim that any single technology solves resilience. The mathematical layer identifies structure, the physical layer establishes feasibility, the provenance layer preserves evidence, and the quantum layer searches the validated decision space. Future work should prove sharper stability and inversion results for selected weighted testing spaces, quantify noise and missing-data effects, develop fractional and adaptive FKF/FKL operators, and validate the proposed spectral-to-QUBO interface using real battery, ITS, and multi-echelon logistics datasets.

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