Integrating FKF Transform, Artificial Intelligence, and Digital Twins for Adaptive Supply Chains

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How to Cite this Article:

SM, S. (2026). Integrating FKF Transform, Artificial Intelligence, and Digital Twins for Adaptive Supply Chains. International Journal of Creative and Open Research in Engineering and Management, <i>02</i>(8), 1-9. https://doi.org/10.55041/ijcope.v2i8.207

https://doi.org/10.55041/ijcope.v2i8.207

Abstract—
Supply-chain resilience requires coordinated sensing, intelligence, simulation, trusted data, and optimization. This study proposes an integrated architecture combining IoT, AI, Blockchain, Digital Twins, quantum computing, and FKF spectral analysis. IoT captures operational conditions, AI supports prediction, Blockchain strengthens traceability, and Digital Twins evaluate disruption scenarios. Quantum annealing addresses complex logistics decisions, while FKF analysis identifies temporal, spectral, and multiscale patterns. The proposed convergence provides a compact framework for adaptive, sustainable, and resilient logistics management.

Keywords— Artificial Intelligence; Blockchain Integration; Supply Chain Transparency; Traceability; Supply Chain Resilience; Smart Logistics; IoT; Digital Twins; Quantum Optimization; FKF Spectral Analysis.

I. INTRODUCTION

Global supply chains are evolving toward intelligent architectures capable of simultaneously addressing sustainability, resilience, transparency, and computational complexity. AI provides analytical and predictive capabilities for green logistics and resource optimization [32], while Digital Twins support continuous monitoring, simulation, and adaptive responses to disruptions [31]. The convergence of IoT, AI, and quantum computing strengthens smart logistics ecosystems [26], and Industry 5.0 promotes human-centric, sustainable, and intelligent logistics operations [27].

AI–Blockchain integration enhances transparency, traceability, provenance, and resilience [33], building upon earlier communication and control technologies [34], [36]. These capabilities increasingly intersect with smart transportation [9] and sustainable mobility, including electric-vehicle battery technologies [10], hybrid-vehicle battery sizing [35], solar-assisted mobility [12], and solar-powered vehicle architectures [28].

Complex logistics decisions such as routing, scheduling, packing, allocation, and ULD configuration require advanced optimization. Quantum computing offers emerging opportunities for transportation and logistics [11], while quantum annealing provides a practical approach for ULD configuration and disruption-related optimization [8]. Hybrid quantum-classical strategies provide a realistic pathway toward implementing these methods in current logistics environments [37]. Such technologies directly support broader supply-chain resilience objectives [13].

FKF-based spectral analysis provides an additional mathematical mechanism for representing complex supply-chain behavior. FKL properties [20], FKF time-shift analysis [21], and exponential modulation [22] enable analysis of delays, periodicity, and spectral changes. Distributional FKF theory [14], testing-space convergence [15], spectral representations [18], differential properties [19], shift-invariant lead-time analysis [17], and multiscale spectral analysis [16] provide a rigorous foundation. Related developments [23], [24], [25] extend these results. Hence, the integration of AI, Blockchain, IoT, Digital Twins, quantum optimization, and FKF spectral intelligence can establish sustainable, transparent, adaptive, and resilient supply-chain systems.

II. LITERATURE REVIEW

The literature demonstrates an increasing convergence between sustainability and digital transformation in supply-chain management. Digital Twins support dynamic modelling, simulation, and resilience [31], whereas AI contributes to sustainable logistics through intelligent prediction, optimization, and resource management [32]. AI–Blockchain integration addresses transparency, traceability, and resilience [33], supported by earlier communication and control technologies [34], [36]. These developments align with Industry 5.0's emphasis on human-centric intelligent logistics [27].

Sustainable mobility has become an important component of green logistics, with research addressing hybrid-vehicle battery sizing [35], smart transportation systems [9], EV battery technologies [10], solar-assisted electric mobility [12], and solar-powered hybrid vehicle architectures [28]. Digital transformation is increasingly recognized as essential for supply-chain resilience [13]. The resulting technological landscape requires computational methods capable of handling increasingly complex logistics decisions.

Quantum computing has therefore emerged as a promising optimization paradigm for transportation and logistics [11]. Quantum annealing has been applied conceptually to ULD configuration and disruption problems[33], [8], while broader quantum-logistics research emphasizes practical hybrid quantum-classical implementation [37]. Complementing these technologies, FKF research develops spectral tools for supply-chain analysis through FKL properties [20], temporal shifting [21], and exponential modulation [22]. Distributional extensions [14], sequential convergence [15], multiscale analysis [16], shift invariance [17], spectral frameworks [18], and differential properties [19] provide mathematical foundations further developed in [23]–[25]. The literature therefore supports an integrated research direction combining sustainability, resilience, spectral intelligence, and emerging digital and quantum technologies.

III. DISTRIBUTIONAL TRANSFORMS

Let $f(t, x)$ be a suitably restricted function or generalized function with $t \in \mathbb{R}$ and $x > 0$. The two-sided FKF transform is defined by

$$F(s,q) = (FKF\, f)(s,q) = \int_{-\infty}^{\infty}\int_{0}^{\infty} f(t,x)\, e^{-ist}\, K_{iq}(x)\, dx\, dt$$

where $s \in \mathbb{R}$ is the Fourier spectral variable, $q > 0$ is the KL spectral variable, and $K^{iq}(x)$ is the Macdonald function of imaginary order iq. The underlying domain is $\Omega = \{(t,x) : -\infty < t < \infty,\ 0 < x < \infty\}$. For distributions the transform is understood by continuous pairing with the FKF kernel and is defined on an open region Ω^f in the (s,q)-plane [22], [24].

The FKF kernel is the product

$$\Psi_{s,q}(t,x) = e^{-ist}\, K_{iq}(x).$$

The Fourier factor encodes temporal oscillations, frequencies and lead-time cycles; the KL factor, built from the Macdonald function, is adapted to positive scale, distance or intensity variables that arise ubiquitously in logistics networks [6], [36], [11]. The Macdonald function satisfies the modified Bessel equation of order $v = iq$:

$$(x^2\, \partial_x{}^2 + x\, \partial_x - x^2)\, K_{iq}(x) = -q^2\, K_{iq}(x),$$

which underpins the differential properties of the transform in the positive variable. Equivalently, introducing the operator

$$L_x = (-x^2 \partial_x{}^2 - x\, \partial_x + x^2),$$

one obtains the eigenvalue relation $L^x K^{iq} = -q^2 K^{iq}$.

Testing functions are infinitely differentiable on Ω and controlled by a countable family of seminorms of the schematic form

$$\gamma_{\{a,b,\alpha,k\}}(\varphi) = sup\_\{(t,x) \in \Omega\}\, |x^k\, D_t^{\{k_1\}} D_x^{\{k_2\}}\, \varphi(t,x)|\, \eta_{\{a,b,\alpha,k\}}(x)$$

where the weight η encodes exponential decay or polynomial growth compatible with the known asymptotics of the Macdonald kernel. The resulting space is a sequentially complete, countably multinormed, locally convex Hausdorff space that contains the compactly supported smooth functions $\mathcal{D}(\Omega)$. Its dual therefore contains the ordinary distributions (in the Zemanian sense) as well as distributions of slow growth, allowing the FKF transform to be extended by continuity (or by sequential continuity) to a wide class of generalized functions [25], [26]. Growth estimates of the form

$$|F(s,q)| \le C\,(1+|s|)^N\,(1+q)^M\,e^{a|s|+b\,q}$$

characterize the image of various distribution classes and guarantee the existence of an inverse transform on suitable horizontal strips in the complex *(s,q)*-plane.

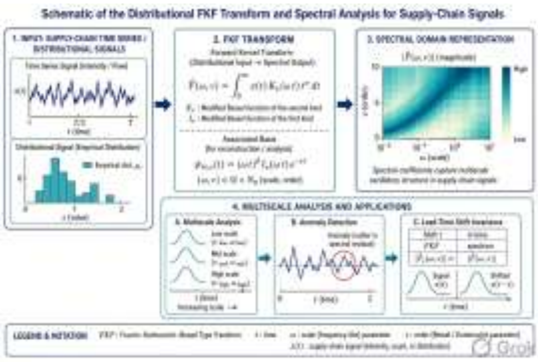

Figure 1. Schematic of the Distributional FKF Transform and spectral analysis pipeline for supply-chain signals, illustrating input time series and distributional signals, the FKF transform with Bessel kernels, spectral-domain representation, and downstream multiscale analysis, anomaly detection, and lead-time shift invariance.

IV. AI FOR SUSTAINABLE, INTELLIGENT LOGISTICS

AI provides powerful capabilities for transforming conventional logistics into sustainable and data-driven operations. Machine learning can improve forecasting, transportation planning, inventory management, energy utilization, and disruption prediction [32]. IoT-enabled sensing [26] and Digital Twins [31] enhance real-time visibility, while Blockchain-supported AI improves trustworthy information exchange and traceability [33]. Sustainable mobility applications involving EV batteries [10], battery sizing [35], smart transportation [9], and solar-assisted mobility [12] further demonstrate AI's potential for reducing environmental impacts. Supply-chain resilience [13] and Industry 5.0 [27] provide broader strategic contexts. Quantum optimization [7], [8], [11], [37] can address complex logistics decisions, while FKF spectral analysis [14]–[25] provides complementary representations of dynamic supply-chain behavior.

Figure 2. AI-driven architecture for sustainable and intelligent logistics, showing the central AI engine interacting with demand forecasting, inventory optimization, route planning, anomaly detection, energy efficiency, disruption prediction, IoT sensors, Blockchain trust layer, Digital Twin feedback, and sustainable mobility components.

V. ULD CONFIGURATION

Quantum computing is increasingly investigated for combinatorial logistics problems such as routing, allocation, scheduling, ULD configuration, and disruption optimization [34], [8], [11], [37]. Hybrid quantum-classical methods are particularly relevant for current hardware limitations, while IoT, AI, and quantum integration supports intelligent logistics ecosystems [26].

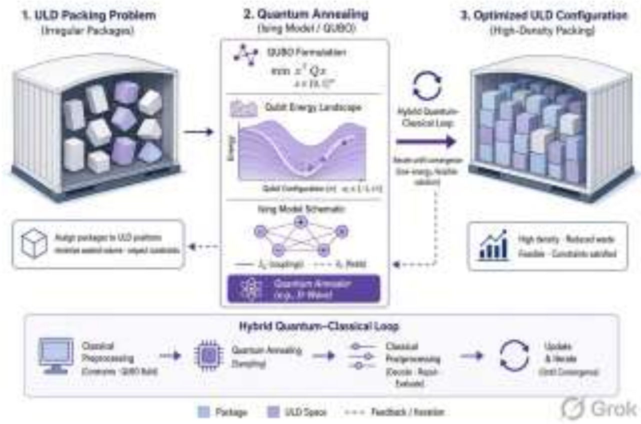

Figure 3. Quantum annealing approach to Unit Load Device (ULD) configuration: irregular packages are mapped to a QUBO / Ising formulation, solved on a quantum annealer within a hybrid quantum-classical loop, yielding high-density optimized packing that respects constraints and reduces wasted volume.

Digital Twins provide a complementary environment for real-time monitoring, scenario simulation, predictive analysis, and resilience management across interconnected supply-chain networks [31], [39]. Their sensor streams may include abrupt disruptions, sparse observations, and non-smooth operational changes. FKF distributional and spectral methods [14]–[25] can therefore support signal representation, spectral monitoring, anomaly identification, and model-error analysis. This convergence links quantum optimization with adaptive Digital Twin environments for resilient logistics.

VI. DIGITAL TWINS FOR RESILIENT AND SUSTAINABLE SUPPLY CHAINS

Digital Twins provide a powerful mechanism for representing and managing complex global supply chains through continuously synchronized virtual models [31]. They combine physical-system observations with computational models to support real-time monitoring, predictive analysis, what-if simulation, disruption assessment, and adaptive decision-making. In multi-echelon networks, Digital Twins can represent interactions among suppliers, manufacturers, warehouses, transport operators, distribution centers, and customers.

IoT technologies provide the sensing infrastructure required for synchronization, while AI transforms operational data into predictions and optimized decisions [32], [26]. AI applications include demand forecasting, anomaly detection, predictive maintenance, inventory optimization, route planning, and sustainability assessment. Blockchain can complement these capabilities by improving transparency, traceability, and data integrity across organizational boundaries [33]. Earlier communication and control technologies [34], [36] provide additional foundations for connected and monitored logistics systems.

Resilience is a major application area for Digital Twins because supply chains are exposed to disruptions such as transportation failures, demand shocks, equipment breakdowns, congestion, and external disturbances. Digital simulation enables organizations to evaluate disruption scenarios before implementing corrective actions and supports rapid recovery planning [13]. Industry 5.0 reinforces this direction by emphasizing intelligent, sustainable, human-centric, and adaptive logistics [27].

The sustainability dimension can be extended to transportation and energy systems. Smart mobility platforms [9], EV battery technologies [10], hybrid battery sizing [35], solar-assisted mobility [12], and solar-powered hybrid vehicle architectures [28] generate complex operational data that can be incorporated into Digital Twin environments. Such models can evaluate energy consumption, vehicle performance, charging requirements, and alternative mobility scenarios.

Digital Twins can also provide the computational environment in which quantum optimization is applied. Quantum computing has potential for difficult logistics problems [11], while quantum annealing can address ULD configuration and disruption-related optimization [8]. Hybrid quantum-classical strategies [7] enable optimized configurations to be generated externally and evaluated within the Digital Twin, creating a closed simulation-optimization cycle.

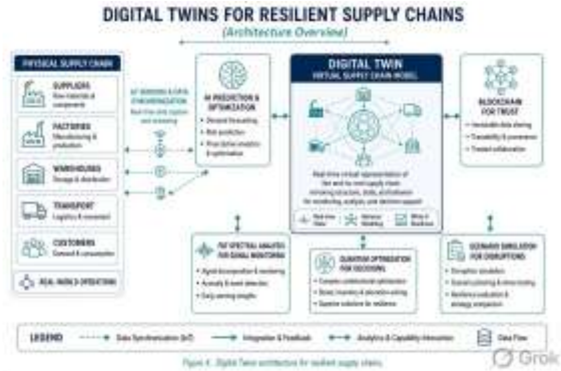

Figure 4. Digital Twins architecture for resilient supply chains, integrating the physical supply-chain layer (suppliers, factories, warehouses, transport, customers) with a central virtual model via IoT, supported by AI prediction, Blockchain trust, FKF spectral monitoring, quantum optimization, and scenario simulation for disruptions.

FKF-based analysis further strengthens the analytical capabilities of Digital Twins. FKL properties support supply-chain signal analysis [20], while FKF shifting [21] and modulation [22] describe delayed and frequency-dependent behavior. Distributional extensions [14], convergence theory [15], multiscale analysis [16], shift-invariant lead-time analysis [17], spectral frameworks [18], and differential properties [19], together with [23]–[25], enable rigorous spectral characterization of dynamic logistics signals. The resulting Digital Twin architecture therefore integrates physical sensing, mathematical analysis, AI intelligence, trusted data, and advanced optimization for resilient and sustainable supply-chain management.

VII. QUANTUM REVOLUTION IN LOGISTICS

We now examine technological domains in which distributional signals are commonplace and for which the distributional framework therefore supplies a natural analytic foundation. Quantum computing promises asymptotic advantages for combinatorial and sampling problems that dominate logistics planning: vehicle routing under uncertainty, multi-echelon inventory allocation, and high-dimensional scenario generation. Hybrid quantum–classical algorithms already demonstrate competitive performance on modestly sized instances, while longer-term roadmaps project substantial speed-ups as hardware matures.

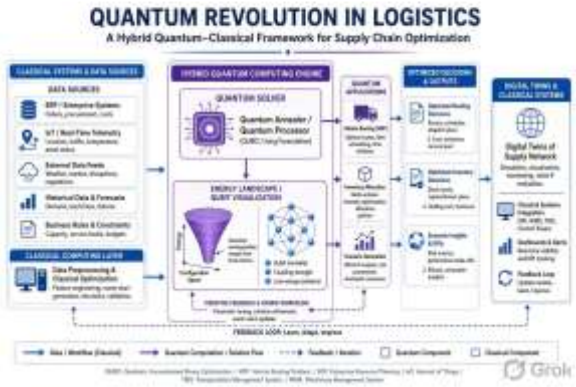

Figure 5. Hybrid quantum–classical framework for supply-chain optimization: classical data sources and preprocessing feed a quantum solver (annealer / processor) for vehicle routing, inventory allocation, and scenario generation; optimized decisions return to Digital Twins and classical enterprise systems within an iterative feedback loop.

The input data and intermediate states of quantum logistics solvers frequently exhibit singular statistical structure (sparse high-dimensional vectors, abrupt phase transitions in annealing trajectories). Embedding these objects in a distributional setting and applying the FKF transform offers a pathway for analytic post-processing, error diagnosis, and hybrid classical–quantum spectral filtering. Parallel investigations of quantum methods in transportation further underscore the breadth of the opportunity.

V. CONCLUSION

The integration of emerging digital and computational technologies can significantly transform sustainable logistics. AI improves forecasting, optimization, and resource efficiency, while IoT and Digital Twins enable continuous monitoring and adaptive management. Blockchain strengthens trusted information exchange, and quantum optimization provides opportunities for solving complex logistics problems. FKF spectral analysis adds advanced capabilities for understanding dynamic supply-chain behavior. Their convergence supports greener operations, improved visibility, greater resilience, and more responsive supply-chain decision-making.

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