Artificial Intelligence-Enabled Digital Twins with FKF Spectral Analysis for Adaptive and Resilient Logistics

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Abstract—
The increasing complexity and uncertainty of global supply chains require adaptive logistics systems capable of continuously sensing, analysing, predicting, and responding to changing operational conditions. This study proposes an integrated Digital Twin–FKF transform framework for intelligent and resilient logistics, combining Digital Twins, IoT, AI, sustainable mobility, and quantum optimization with spectral analysis. Digital Twins provide dynamic representations of logistics assets and processes, enabling real-time synchronization and disruption scenario evaluation, while IoT and AI support intelligent monitoring, prediction, and decision-making. The FKF transform provides a joint temporal–scale spectral representation of supply-chain signals, This study introduces an FKF-enabled intelligent supply-chain framework integrating AI, Blockchain, IoT, Digital Twins, and quantum optimization. FKF spectral analysis captures shifts, modulation, multiscale behavior, and lead-time dynamics, providing features for AI-based prediction and resilience assessment.

Keywords— FKF Transform; Digital Twin Technology; Adaptive Global Supply Chains; Artificial Intelligence; Green Supply Chain Management; Blockchain Integration; swipe controller; Supply Chain Resilience; Quantum Revolution in Logistics; IoT; Quantum Optimization; Quantum Annealing; Sustainable Logistics; Spectral Analysis; Electric Vehicle Battery

I. INTRODUCTION

This study proposes an integrated perspective combining Digital Twins, IoT, AI, trusted data exchange, sustainable mobility, FKF spectral analysis, and quantum optimization for adaptive logistics [1], [2], [16], [17]. The framework aims to connect real-time physical-system observations with mathematical signal analysis and advanced optimization, enabling supply-chain states to be monitored, disruptions to be simulated, spectral characteristics to be identified, and complex decisions to be optimized within a continuous feedback environment. Digital Twin technology provides an important foundation for this transition by creating dynamic virtual representations of physical supply-chain processes and continuously incorporating operational information from logistics assets [1] , [25]. The integration of Internet of Things (IoT), Artificial Intelligence (AI), and advanced computational technologies further enables intelligent logistics ecosystems capable of responding to complex and uncertain environments [2], [16]. The increasing digitalization of logistics also requires reliable communication, transparency, and traceability across distributed supply-chain participants. AI can support demand forecasting, anomaly detection, resource optimization, and predictive decision-making [2], while blockchain can strengthen trusted information exchange and supply-chain traceability [3]. Communication technologies provide the underlying connectivity required for monitoring and control [19]. At the organizational level, Industry 5.0 extends intelligent logistics toward human-centric automation, resilience, and collaboration between people and intelligent systems [17]. These developments create an integrated technological foundation for adaptive supply-chain management.

Digital Twins are particularly relevant to resilience because they enable disruptions to be represented and evaluated virtually before recovery actions are implemented in the physical system [25]. Transportation delays, inventory fluctuations, equipment failures, capacity constraints, and demand changes can therefore be reproduced as alternative scenarios. The Digital Twin can compare potential responses and support faster recovery decisions. This capability can be extended to smart transportation and sustainable mobility, where intelligent transportation systems [22], EV battery technologies [6], hybrid-vehicle battery sizing [20], solar-powered hybrid architectures [18], swipe controller [4], and solar-assisted electric mobility [24] provide important modelling and optimization applications.

However, increasingly complex logistics decisions also involve large combinatorial search spaces. Quantum computing has therefore emerged as a promising computational paradigm for transportation and logistics optimization [23]. Quantum annealing can be applied to specialized problems such as Unit Load Device configuration and disruption management [21], while broader quantum-logistics research explores its potential for routing, scheduling, allocation, and resource optimization [5] ,[26]. Coupling quantum optimization with Digital Twins creates a hybrid quantum-classical decision architecture in which candidate solutions can be generated computationally and subsequently evaluated under realistic operational scenarios.

Beyond simulation and optimization, spectral analysis offers a complementary mathematical perspective for understanding dynamic supply-chain behaviour. Logistics signals can exhibit periodic demand, transportation delays, transient disturbances, multi-scale variations, and changing operational frequencies. The FKL transform provides a spectral framework for supply-chain analysis [13], while the FKF framework extends this approach to supply-chain dynamics and resilience [11]. Its time-shift property provides a mathematical basis for analysing delayed and multi-echelon lead-time behavior [10], [14], whereas exponential modulation can identify frequency-shifted and periodic components [15]. Multi-scale spectral analysis further supports identification of dominant patterns and resonance-related characteristics in complex supply-chain and hybrid-vehicle systems [9].

Recent developments in distributional FKF theory further strengthen this analytical foundation. The distributional extension enables generalized supply-chain signals to be represented within the transform framework [27], sequential convergence establishes mathematical properties of the associated testing-function space [28], and spectral differential properties support analysis of dynamic changes in transformed signals [12]. Multi-scale spectral analysis can additionally support the identification of dominant patterns and resonance-related characteristics in complex supply-chain and hybrid-vehicle systems [9].

II. TWO-DIMENSIONAL FKM/FKF TRANSFORM

The Fourier–Kontorovich–Lebedev (FKF) transform provides a joint temporal–scale spectral representation that is particularly suited to logistics signals possessing both oscillatory and multi-scale structure [11], [13]. For a suitable function $f(t,x)$, with $t \in \mathbb{R}$, $x > 0$, the two-sided transform may be defined by

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

Where, $s \in \mathbb{R}$, $q > 0$, $e^{-ist}$is the Fourier kernel, and $K_{iq}(x)$ is the Macdonald function of imaginary order.

Fourier Component and Sequential Representation

The temporal Fourier transform is first applied, after which the Kontorovich–Lebedev transform acts on the positive scale variable. Consequently, the FKF transform can be written sequentially, separating the temporal frequency variable ω from the positive-scale variable τ [11], [13]. Under appropriate admissibility and normalization conditions an inverse representation exists whose precise constant depends on the chosen KL normalization convention [13], [28]. The temporal Fourier transform is

$$\hat{f}(s,x) = \int_{-\infty}^{\infty} f\,(t,x)e^{-ist}\,dt.$$

The FKF transform can therefore be written sequentially as

$$\boxed{F(s,q) = \int_{0}^{\infty} \hat{f}\,(s,x)K_{iq}(x)\frac{dx}{x}}$$

which shows the separation between the temporal frequency variable s and the positive-scale variable q.

Inverse representation

Under appropriate admissibility and normalization conditions, the inverse transform can be represented schematically as

$$f(t,x) = \frac{1}{2\pi^2}$$

$$\boxed{\int_{-\infty}^{\infty} e^{ist} \int_{0}^{\infty} F\,(s,q)K_{iq}(x)\,q\sinh(\pi q)\,dq\,ds}$$

with the exact constant depending on the chosen KL normalization convention.

Supply-Chain Signal Representation

For a logistics signal, the variable t may represent time while x may represent inventory level, demand magnitude, transportation distance, capacity, safety-stock scale, or disruption intensity. The joint spectral representation (FKF f)(ω, τ) then encodes: temporal frequency content (via ω), KL spectral scale (via τ), periodic or oscillatory behaviors (peaks in the transform), and scale-dependent operational dynamics. Spectral shifts indicate delays or changes in logistics dynamics [9], [11], [13].

For a logistics signal $f(t,x)$, t can represent time, while $x > 0$ can represent inventory level, demand magnitude, transportation distance, capacity, safety-stock scale, or disruption intensity. Then

$$F(s,q) = \mathcal{F}_{FK}\{f(t,x)\}(s,q)$$

provides a joint spectral representation in which: s represents temporal frequency, q represents KL spectral scale, peaks in s indicate periodic or oscillatory behavior, changes in q indicate scale-dependent operational behaviors, spectral shifts can indicate delays or changes in logistics dynamics.

Time-shift property

If a signal undergoes a pure time shift, the FKF transform acquires a multiplicative phase factor e^{-iωτ₀} in the Fourier dimension [10], [14]. Thus a transportation or replenishment delay appears as a phase factor. Exponential modulation of a signal produces a corresponding frequency shift in the transform domain, which is useful for identifying frequency-shifted or periodic supply-chain components [15].

If $g(t,x) = f(t,-t_0x)$, then

$$\boxed{\mathcal{F}_{FK}\{f(t,-t_0x)\}(s,q) = e^{-ist_0}F(s,q)}$$

Thus, a transportation or replenishment delay t_0 appears as a phase factor in the Fourier dimension.

Exponential modulation

For

$$g(t,x) = e^{is_0t}f(t,x),$$

we obtain

$$\boxed{\mathcal{F}_{FK}\{e^{is_0t}f(t,x)\}(s,q) = F(s,-s_0q)}$$

This property is useful for identifying frequency-shifted or periodic supply-chain components.

Differential property of the KL kernel

The Macdonald function satisfies the modified Bessel equation. Consequently suitable differential operators acting in the positive-x domain are converted into multiplication by a simple algebraic factor of τ in the spectral domain [12]. This eigenvalue relationship is important for analysing dynamic changes inside a Digital Twin that continuously updates its spectral state. The Macdonald function satisfies the modified Bessel equation

$$x^2y'' + xy' - (x^2+\nu^2)y = 0.$$

For $\nu = iq$, this becomes

$$\boxed{x^2K_{iq}''(x) + xK_{iq}'(x) - (x^2-q^2)K_{iq}(x) = 0.}$$

Hence,

$$\left[x^2\frac{d^2}{dx^2}+x\frac{d}{dx}-x^2\right]K_{iq}(x)=-q^2K_{iq}(x).$$

This eigenvalue relationship is important for converting suitable differential operations in the positive x-domain into multiplication by $-q^2$ in the spectral domain.

Compact Digital-Twin formulation

For an adaptive logistics Digital Twin the physical signal can be represented as s(t, x) and its spectral state as S(ω, τ) = (FKF s)(ω, τ). This formulation supplies the mathematical link between FKF spectral analysis and Digital Twin-enabled adaptive logistics [1], [11], [25]. For an adaptive logistics Digital Twin, the physical signal can be represented as

$$f(t,x) = \text{logistics state at time } t \text{ and scale/intensity } x,$$

and its spectral state becomes

$$\boxed{F(s,q)=\mathcal{F}_{FK}[f(t,x)].}$$

A conceptual adaptive loop can therefore be expressed as

$$f(t,x)\longrightarrow F(s,q)\longrightarrow \text{spectral analysis} \longrightarrow \text{AI/optimization} \longrightarrow \text{Digital Twin decision} \boxed{\longrightarrow f_{\text{updated}}(t,x)}$$

This gives the mathematical link between FKF spectral analysis and Digital Twin-enabled adaptive logistics.

If by FKM you specifically mean a different transform than the **FKF** transform, give me its definition and I can formulate the exact equations accordingly.

for complex parameters s and y such that the kernel belongs to the testing space LKμ. The right-hand side is meaningful whenever f ∈ LK′μ and the kernel lies in LKμ. Because the kernel is intimately related to Meijer G-functions, the transform inherits analytic features of both the Laplace and the K-transforms and is therefore adapted to problems that combine exponential decay with Bessel-type singularity structure.

III. ADAPTIVE LOGISTICS SYSTEMS IN DIGITAL TWINS

The convergence of Digital Twins, intelligent sensing, spectral mathematics, sustainable mobility, and quantum optimization is creating a new generation of adaptive logistics systems capable of continuously observing, analyzing, and responding to changing supply-chain conditions [1], [16], [17]. Digital Twins establish dynamic virtual representations of physical supply-chain assets and processes, enabling real-time synchronization of vehicles, warehouses, inventories, production facilities, and transportation networks with their digital counterparts [1]. This capability transforms conventional planning systems into continuously updated environments for monitoring, simulation, prediction, and adaptive decision-making.

Within this framework, FKF provides a robust multi-sensor fusion mechanism that supports intelligent sensing across distributed Digital Twin nodes. Each local filter processes measurements from a distinct sensing modality (e.g., GPS, RFID, IoT inventory sensors, or vehicle telematics) while a master filter performs global fusion, preserving information integrity under intermittent connectivity typical of logistics networks. The local prediction step for the i-th sensor node is expressed as

$$\hat{x}_i(k|k-1) \;=\; \Phi(k)\,\hat{x}_i(k-1|k-1)$$

with the associated error covariance propagation

$$P_i(k|k-1) \;=\; \Phi(k)\,P_i(k-1|k-1)\,\Phi^T(k) + Q(k)$$

After the local measurement update, the global fusion performed by the master filter recovers the optimal combined estimate and covariance according to

$$P_g^{-1}(k|k) \;=\; \sum_{i=1}^{N} P_i^{-1}(k|k)$$

$$\hat{x}_g(k|k) \;=\; P_g(k|k)\sum_{i=1}^{N} P_i^{-1}(k|k)\,\hat{x}_i(k|k)$$

Here $\hat{x}_i$ and P_i denote the local state estimate and covariance, Φ is the state transition matrix, Q the process-noise covariance, and the subscript g identifies the globally fused quantities. These FKF transform enable the Digital Twin to maintain a consistent, uncertainty-aware representation of the physical logistics network [16], [19] even when individual sensors become temporarily unavailable or produce degraded measurements, thereby supporting continuous observation, analysis, and adaptive response across the supply chain [16].

IV. INTEGRATED DIGITAL TWIN AND SPECTRAL INTELLIGENCE FOR ADAPTIVE LOGISTICS

The sensing and communication foundation of such systems is provided by IoT and connected control technologies. IoT enables the collection of operational data from distributed logistics assets, while AI transforms these data into forecasts, anomaly detection, predictive maintenance, routing decisions, and resource-allocation strategies [2], [16]. Power-line carrier communication illustrates how communication signals can be used for monitoring and control applications [19]. Trustworthy information exchange is another important component: AI and blockchain can be combined to improve supply-chain transparency, traceability, information sharing, and resilience [3]. When these capabilities are integrated with Digital Twins, distributed stakeholders obtain a more consistent representation of supply-chain conditions while maintaining reliable information flows.

Digital Twin technology is especially valuable for resilience-oriented decision-making. When demand changes, transportation delays, equipment failures, capacity constraints, or other disruptions occur, the virtual environment can reproduce the affected operating conditions and evaluate alternative recovery strategies before they are implemented physically [25]. Industry 5.0 strengthens this perspective by emphasizing human-centric automation, intelligent collaboration, resilient logistics operations [17].

The framework also incorporates intelligent transportation and sustainable mobility. Smart mobility and intelligent transportation systems provide connected information concerning vehicles, traffic, infrastructure, and transportation operations [22]. EV battery technologies introduce variables related to battery performance, energy management, lifecycle considerations, and sustainability [6]. Battery-sizing methodologies for plug-in hybrid vehicles further support energy-aware modelling [20]. Solar-powered battery-electric hybrid architectures and solar-assisted electric mobility provide opportunities for evaluating renewable-energy utilization and hybrid-vehicle performance [18], [24]. Consequently, Digital Twins can simultaneously represent logistics flows, transportation states, energy consumption, and sustainability indicators.

For increasingly complex logistics decisions, quantum computing provides an emerging optimization layer [5], [23]. Quantum annealing can address difficult combinatorial problems such as Unit Load Device configuration and disruption-related logistics decisions [21]. Broader practical applications include optimization, scheduling, routing, allocation, and resource management [5], [26]. When coupled with Digital Twins, quantum optimization generates candidate decisions that are subsequently evaluated under realistic operational and disruption scenarios.

The analytical capability of the Digital Twin is further enhanced through FKF-based spectral analysis. Supply-chain signals frequently exhibit delays, oscillations, periodic demand patterns, transient changes, and multi-scale behaviour. The FKL transform supplies a mathematical framework for representing supply-chain characteristics in the spectral domain [13], while the FKF framework extends this analysis toward joint temporal and positive-variable representations [11]. The FKF time-shift property is particularly relevant to logistics lead-time analysis [10], [14]. Exponential modulation provides a complementary spectral mechanism for identifying frequency-shifted and periodic components [15]. Multi-scale spectral analysis can identify dominant structures and resonance-like behaviour [9]. A rigorous mathematical foundation is furnished by the distributional FKF framework [27], sequential convergence in the testing-function space [28], and spectral differential properties [12].

The proposed architecture can therefore be viewed as a closed-loop adaptive logistics ecosystem: IoT and communication technologies continuously acquire operational information [16], [19]; AI interprets and predicts system behaviour [2]; blockchain strengthens trusted information exchange [3]; Digital Twins reproduce physical logistics conditions [1]; FKF spectral analysis identifies temporal, delayed, and multi-scale characteristics [9]–[15], [27], [28]; and quantum optimization searches for improved decisions [5],

[21], [23], [26]. Sustainable mobility and energy models simultaneously evaluate transportation and environmental performance [6], [18], [20], [22], [24]. Additional AI and Digital Twin applications in related domains further illustrate the breadth of the underlying techniques [7], [8].

ion problem

V. DIGITAL TWIN-ENABLED ADAPTIVE LOGISTICS

Digital Twins transform conventional supply-chain management by creating dynamic virtual representations of physical logistics systems [1]. Unlike static planning models, Digital Twins continuously incorporate information from vehicles, warehouses, production facilities, inventories, and transportation networks, enabling real-time monitoring, simulation, predictive analysis, and adaptive decision-making. The integration of Internet of Things (IoT), Artificial Intelligence (AI), and quantum technologies further strengthens this digital environment by connecting physical operations with intelligent computational models [16].

IoT provides the real-time sensing and communication layer, while AI supports demand forecasting, anomaly detection, predictive maintenance, route optimization, and resource planning [2]. The development of intelligent communication and control mechanisms also provides an important technological foundation for connected logistics environments [4], [19]. Blockchain can complement these technologies by enabling transparent, traceable, and trusted information exchange among distributed supply-chain participants [3]. Such integration allows Digital Twins to maintain an evolving representation of operational conditions rather than relying only on historical or static datasets.

Adaptive Digital Twins are particularly valuable for supply-chain resilience. When transportation delays, equipment failures, demand fluctuations, or capacity disruptions occur, the virtual model can reproduce the affected conditions, estimate their consequences, and evaluate alternative recovery strategies before physical implementation [25]. Industry 5.0 further extends this concept by emphasizing human-centric automation, intelligent decision support, and resilient operational systems [17]. Thus, Digital Twins can serve as a bridge between real-time operational data and proactive resilience management.

The same architecture can be extended to sustainable transportation and mobility. Smart Mobility and Intelligent Transportation Systems provide connected traffic, vehicle, and transportation information [22]. EV battery technologies introduce variables related to battery performance, energy efficiency, management systems, and sustainability [6]. Battery-sizing methodologies for hybrid electric vehicles support Digital Twin models for energy-aware vehicle operation [20]. Solar-powered battery-electric hybrid architectures and solar-assisted electric mobility frameworks enable modelling of renewable-energy integration and sustainable transportation performance [18], [24].

For complex logistics decisions, Digital Twins can interact with quantum optimization technologies. Quantum computing provides emerging approaches for solving transportation and logistics optimization problems involving large and complex decision spaces [23]. Quantum annealing offers a practical approach for combinatorial optimization problems such as Unit Load Device configuration and disruption management [21]. More broadly, quantum technologies can be incorporated into logistics decision architectures to address routing, allocation, scheduling, and resource-configuration problems [5]. In a hybrid quantum-classical architecture, the Digital Twin generates realistic operational scenarios, quantum optimization searches for candidate decisions, and the resulting solutions are evaluated against simulated operational and resilience conditions.

FKF spectral analysis provides an additional analytical layer for adaptive Digital Twins. Supply-chain signals may contain delays, periodic patterns, transient variations, and multi-scale characteristics that are difficult to identify using conventional time-domain analysis. The FKL transform provides a mathematical basis for representing supply-chain behaviour in a spectral domain and examining variations associated with operational scales [13]. The FKF framework extends this approach to joint temporal and positive-variable spectral analysis, allowing complex logistics signals to be represented through complementary spectral variables [11]. The time-shift property of the FKF transform is particularly relevant to supply-chain lead-time analysis. Delays in demand, replenishment, transportation, and inventory responses can be represented through shift-related spectral relationships [14]. This provides a mathematical basis for shift-invariant analysis of multi-echelon supply-chain lead times [10]. Consequently, Digital Twins can detect and characterize propagation delays across supply-chain stages without requiring complete reconstruction of the signal in the physical domain.

Exponential modulation provides another useful spectral operation for identifying frequency-shifted or periodic supply-chain components [15]. Such characteristics may arise from recurring demand cycles, transportation schedules, production rhythms, or other periodic operational behaviors. Spectral analysis can additionally support multi-scale interpretation and resonance extraction in complex systems, including hybrid-vehicle and logistics-related applications [9]. These properties make FKF-based analysis suitable for monitoring changes in supply-chain signals and identifying emerging operational patterns within a Digital Twin.

A rigorous mathematical foundation is provided by the distributional extension of the FKF transform, which permits generalized or irregular supply-chain signals to be incorporated into the analytical framework [7]. Sequential convergence in the associated testing-function space establishes the mathematical conditions required for systematic transformation and approximation of such signals [8]. Spectral differential properties further enable the analysis of transformed derivatives and dynamic changes in supply-chain states [12]. These developments allow Digital Twin analytics to move beyond visualization and simulation toward mathematically grounded spectral monitoring.

The resulting architecture therefore combines Digital Twins, IoT, AI, blockchain, sustainable mobility, FKF spectral analysis, and quantum optimization within a unified adaptive logistics framework. Real-time sensing continuously updates the Digital Twin, AI interprets operational conditions, blockchain supports trusted information exchange, FKF analysis identifies temporal and multi-scale patterns, and quantum optimization addresses computationally intensive decision problems. The Digital Twin subsequently evaluates optimized decisions under realistic disruption and operating scenarios, creating a continuous feedback loop between sensing, spectral analysis, optimization, simulation, and adaptive control. Such integration provides a pathway toward resilient, sustainable, intelligent, and mathematically rigorous supply-chain systems [16], [21], [25].

VI. INTEGRATED MATHEMATICAL, DIGITAL, AND QUANTUM FOUNDATIONS FOR RESILIENT SUPPLY CHAINS

Recent research demonstrates that resilient and adaptive supply-chain management increasingly depends on the convergence of Digital Twins, artificial intelligence, blockchain, quantum computing, and intelligent sensing technologies. Digital Twin technology provides a virtual representation of physical supply-chain processes, enabling real-time monitoring, simulation, scenario evaluation, predictive analysis, and adaptive decision-making [1]. AI complements this capability through demand prediction, route and resource optimization, anomaly detection, and improved energy and operational efficiency, thereby supporting sustainable and green logistics [2]. The integration of AI with blockchain further strengthens transparency, traceability, data integrity, and resilience by enabling trustworthy information exchange across distributed supply-chain participants [3]. This provides a mathematical layer that complements the predictive and simulation capabilities of AI and Digital Twins [1], [2]. These capabilities can be incorporated into Digital Twin environments, where quantum-generated solutions can be simulated and evaluated against dynamic operational conditions before their implementation in the physical supply chain [1], [5]. Such integration creates a hybrid decision framework in which AI provides prediction and intelligence, Digital Twins provide simulation and feedback, blockchain provides trusted information, and quantum optimization addresses computationally intensive decision problems [3], [5].

The physical implementation of this architecture also requires reliable sensing, control, and energy-aware technologies. The Swipe Controller demonstrates an engineering approach to automated control and interaction, providing an example of how operational inputs can be acquired and translated into system actions [4]. Similarly, advances in electric-vehicle battery technologies emphasize the importance of battery management, energy efficiency, sustainability, and intelligent transportation systems [6]. These developments are particularly relevant to smart logistics, electric vehicle battery, where electric mobility, automated control, sensing infrastructure, and digital decision platforms increasingly operate as interconnected components. FKF spectral information can support such optimization by identifying dominant temporal and scale-dependent characteristics of operational data, which can then be incorporated into optimization and decision-making processes.

VII. A UNIFIED DIGITAL TWIN–FKF FRAMEWORK FOR INTELLIGENT AND RESILIENT LOGISTICS

Modern logistics is evolving toward continuously connected, analytically driven, and adaptive supply-chain ecosystems in which physical operations are dynamically represented, monitored, and optimized through digital technologies [1], [16], [17]. Digital Twin technology provides the central virtual representation of logistics assets and processes, enabling real-time synchronization of vehicles, warehouses, inventories, production facilities, and transportation networks [1]. The sensing and communication layer is supported by IoT and intelligent communication technologies [16], [19]. AI transforms the resulting data into demand forecasts, anomaly detection, predictive maintenance, routing decisions, and resource-allocation strategies [2]. A convergent IoT–AI–quantum architecture further connects sensing, intelligent analysis, and advanced optimization [16].

Trust and traceability are equally important. AI–blockchain integration strengthens transparency, traceability, information sharing, and resilience among supply-chain participants [3]. Digital Twins support resilience by reproducing disrupted operating conditions and testing alternative recovery strategies before physical implementation [25]. Industry 5.0 extends this capability through human-centric automation and resilient logistics operations [17].

Sustainable transportation is integrated into the same digital environment via smart mobility systems [22], EV battery models [6], hybrid-vehicle battery sizing [20], solar-powered hybrid architectures [18], and solar-assisted electric mobility [24]. For complex combinatorial decisions, quantum approaches address routing, allocation, scheduling, and resource configuration [5], [21], [23], [26].

The analytical capability of the Digital Twin is enhanced through FKF spectral methods. The FKL transform provides a spectral basis for analysing supply-chain characteristics [13]. The FKF spectral framework extends this analysis for supply-chain dynamics and resilience [11]. The time-shift property represents delayed demand, replenishment, transportation, and inventory responses [10], [14]. Exponential modulation enables frequency-shift analysis of periodic components [15]. Multi-scale spectral analysis identifies dominant structures and resonance-like behaviour [9]. The distributional extension [27], sequential convergence [28], and spectral differential properties [12] complete the rigorous mathematical foundation.

Technology Function Integration. The resulting architecture establishes a closed-loop intelligent logistics framework in which physical assets generate real-time data, AI interprets operational conditions, trusted communication supports information exchange, Digital Twins reproduce system behaviour, FKF analysis identifies spectral and multi-scale characteristics, and quantum optimization searches for improved decisions. The optimized decisions are reintroduced into the Digital Twin for simulation and resilience assessment. This continuous feedback mechanism transforms conventional Digital Twins into adaptive intelligence platforms capable of supporting prediction, spectral monitoring, disruption response, sustainable transportation, and computationally intensive optimization within a unified supply-chain environment [1]–[6], [9]–[28].

Technology–Function Integration

The resulting architecture establishes a closed-loop intelligent logistics framework in which physical assets generate real-time data, AI interprets operational conditions, trusted communication supports information exchange, Digital Twins reproduce system behaviour, FKF analysis identifies spectral and multi-scale characteristics, and quantum optimization searches for improved decisions. The optimized decisions can then be reintroduced into the Digital Twin for simulation and resilience assessment. This continuous feedback mechanism transforms conventional Digital Twins into adaptive intelligence platforms capable of supporting prediction, spectral monitoring, disruption response, sustainable transportation, and computationally intensive optimization within a unified supply-chain environment.problems.

CONCLUSION

Digital Twins are emerging as a powerful integrating and decision-support platform for connecting real-time sensing, artificial intelligence, trusted data management, and advanced optimization across complex supply-chain networks. Their combination with quantum computing enables complex logistics decisions to be formulated, simulated, evaluated, and iteratively refined within dynamic virtual representations of physical supply-chain operations. FKF spectral analysis further strengthens this architecture by identifying temporal shifts, modulation effects, multiscale patterns, frequency-dependent behavior, and operational changes that may not be readily visible in conventional analyses. By bringing these capabilities together, the proposed framework establishes an intelligent and adaptive decision environment in which supply-chain conditions can be continuously monitored, analyzed, predicted, and optimized, providing a practical foundation for sustainable, resilient, responsive, and data-driven supply-chain management.

REFERENCES

1. Akarshan Gulhane, “Digital Twin Technology for Building Resilient and Adaptive Global Supply Chains: A Review,” International Research Journal of Modernization in Engineering Technology and Science, Vol. 6, Issue 12, 2024. DOI: 10.56726/IRJMETS64992.
2. Akarshan Gulhane, “Artificial Intelligence Applications in Sustainable Logistics and Green Supply Chain Management: A Bibliometric Review,” International Research Journal of Modernization in Engineering Technology and Science, Vol. 6, Issue 12, 2024. DOI: 10.56726/IRJMETS65006.
3. Akarshan Gulhane, “Artificial Intelligence and Blockchain Integration for Enhancing Supply Chain Transparency, Traceability, and Resilience,” International Research Journal of Modernization in Engineering Technology and Science, Vol. 6, Issue 12, 2024. DOI: 10.56726/IRJMETS65016.
4. Gulhane, A. (2014). Swipe Controller. *International Journal of Research in Engineering and Applied Sciences (IJREAS)*, *4*(12), 1–7.
5. Akarshan Gulhane, “Navigating the Quantum Revolution in Logistics: Opportunities and Practical Applications in Supply Chain Management,” International Journal of Engineering and Techniques (IJET), Vol. 12, pp. 553–556, 2026. **DOI:** 10.29126/ijet.2026.v12.i3.553 [1, 2]
6. Akarshan Gulhane, “Recent Advances in Electric Vehicle Battery Technologies: Materials, Management Systems, and Sustainability Perspectives,” International Journal of Scientific Research in Engineering and Management (IJSREM), Vol. 9, Issue 7, Jul. 2025. DOI: 10.55041/IJSREM51198.
7. S. M. Harle, “Artificial Intelligence-Based Pavement Crack Detection: A Comprehensive Review of Machine Learning and Deep Learning Techniques,” Int. Res. J. Modernization Eng. Technol. Sci., vol. 8, pp. 50–69, Jan. 2026.
8. S. M. Harle, “Digital Twins and Artificial Intelligence for Sustainable Textile Raw Material Processing,” Int. Res. J. Modernization Eng. Technol. Sci., vol. 8, pp. 14–30, Jan. 2026.
9. A. Gulhane, “Spectral Analysis for Multi-Scale Supply Chain Dynamics and Residue-Based Resonance Extraction in Hybrid-Vehicle Systems,” Int. J. Creative Open Res. Eng. Manage., vol. 2, no. 8, Aug. 2026, doi: 10.55041/ijcope.v2i8.141.
10. A. Gulhane, “Shift-Invariant Spectral Analysis of Multi-Echelon Supply-Chain Lead Times via the FKF Transform,” Int. J. Creative Open Res. Eng. Manage., vol. 2, no. 8, Aug. 2026, doi: 10.55041/ijcope.v2i8.136.
11. A. Gulhane, “Spectral Framework Based on the FKF Transform for Supply Chain Dynamics and Resilience,” Int. J. Creative Open Res. Eng. Manage., vol. 2, no. 8, Aug. 2026, doi: 10.55041/ijcope.v2i8.140.
12. A. Gulhane, “Spectral Differential Properties of the Distributional FKF Transform with Applications to Resilient Supply-Chain Systems,” Int. J. Creative Open Res. Eng. Manage., vol. 2, no. 8, Aug. 2026, doi: 10.55041/ijcope.v2i8.139.
13. A. Gulhane, “FKL Transform: Key Properties and Applications to Supply-Chain Analysis,” Int. J. Eng. Sci. Adv. Technol., vol. 25, no. 12, pp. 596–605, Dec. 2025, doi: 10.64771/ijesat.2025.v25.i12.3816.

14. A. Gulhane, "Expanded Treatment of the Time-Shift Property of FKF Transform with Supply-Chain Applications," Int. J. Eng. Sci. Adv. Technol., vol. 25, no. 12, pp. 606–616, Dec. 2025, doi: 10.64771/ijesat.2025.v25.i12.3817.
15. A. Gulhane, "The FKF Transform: Exponential Modulation Properties and Applications to Secure Digital Supply-Chain Networks," Int. J. Eng. Sci. Adv. Technol., vol. 25, no. 12, pp. 617–623, Dec. 2025, doi: 10.64771/ijesat.2025.v25.i12.3818.
16. A. Gulhane, "Internet of Things, Artificial Intelligence, and Quantum Computing: A Convergent Framework for Smart Logistics Ecosystems," Int. J. Eng. Sci. Adv. Technol. (IJESAT), vol. 24, no. 12, pp. 297–317, 2024, doi: 10.64771/ijesat.2024.v24.i12.3372.
17. A. Gulhane, "Industry 5.0 and Intelligent Logistics: Transforming Supply Chain Operations through Human-Centric Automation," Int. J. Eng. Sci. Adv. Technol. (IJESAT), vol. 24, no. 12, pp. 287–296, 2024, doi: 10.64771/ijesat.2024.v24.i12.3371.
18. A. Gulhane, "The Future of Vehicles: Solar-Powered Battery Electric Hybrid Vehicle Architecture," Tech Briefs Contest, 2020
19. A. Gulhane, "Power Line Carrier Communication Based Anti-Theft System," Int. J. Res. IT Manage. (IJRIM), vol. 4, no. 12, pp. 1–11, 2014.
20. A. Gulhane, "Battery Sizing for Plug-in Hybrid Electric Vehicles — Formula Hybrid," in Proc. IEEE Int. Conf. Power, Control, Signals Instrum. Eng. (ICPCSI), 2017, pp. 368–372, doi: 10.1109/ICPCSI.2017.8392317.
21. A. Gulhane, "Quantum Computing for Logistics Optimization: Annealing in Unit Load Device Configuration and Disruption," Int. J. Res. Publ. Rev., vol. 7, no. 6, pp. 4643–4648, Jun. 2026, doi: 10.55248/gengpi.07.0626.16a57.
22. A. Gulhane, "Smart Mobility and Intelligent Transportation Systems: Emerging Trends, Technologies, and Challenges," Int. J. Sci. Res. Eng. Manage. (IJSREM), vol. 9, no. 11, Nov. 2025, doi: 10.55041/IJSREM53436.
23. A. Gulhane, "Quantum Computing in Transportation and Logistics: Current State, Industrial Applications, and Future Directions," Int. J. Sci. Res. Eng. Manage. (IJSREM), vol. 9, no. 9, Sep. 2025, doi: 10.55041/IJSREM52469.
24. A. Gulhane, "Solar-Assisted Electric Mobility: Design Framework and Performance Assessment of Sustainable Hybrid Vehicle Architectures," Int. J. Eng. Res. Sci. Technol., vol. 21, no. 3, pp. 362–368, 2025, doi: 10.56636/ijerst.2025.v21.i03.3594.
25. A. Gulhane, "Supply Chain Resilience in the Era of Digital Transformation: A Systematic Literature Review and Research Agenda," Int. J. Eng. Res. Sci. Technol., vol. 21, no. 4, pp. 1058–1068, 2025, doi: 10.56636/ijerst.2025.v21.i04.3812.
26. R. Sharma, R. Katukam, and A. Nagulapally, "Bridging the Linear-Quadratic Gap: A Quantum-Classical Hybrid Approach to Robust Supply Chain Design," arXiv preprint arXiv:2601.04095, 2026.
27. A. Gulhane, "Distributional Extension of the FKF Transform and Its Relevance to Supply-Chain Systems," Int. J. Creative Open Res. Eng. Manage., vol. 2, no. 8, Aug. 2026, doi: 10.55041/ijcope.v2i8.137.
28. A. Gulhane, "Sequential Convergence in the Testing Function Space of the Two-Sided FKF Transform," Int. J. Creative Open Res. Eng. Manage., vol. 2, no. 8, Aug. 2026, doi: 10.55041/ijcope.v2i8.138.
29. R. Sharma, R. Katukam, and A. Nagulapally, "Bridging the Linear-Quadratic Gap: A Quantum-Classical Hybrid Approach to Robust Supply Chain Design," arXiv preprint arXiv:2601.04095, 2026.