Distributional FKF Transform for Spectral Modeling of Complex Supply Chain Dynamics

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Abstract—
This study proposes a convergent framework integrating AI, Blockchain, IoT, Digital Twins, quantum computing, and FKF spectral analysis for sustainable and resilient supply chains. AI supports prediction and optimization, Blockchain improves transparency and traceability, IoT enables real-time sensing, and Digital Twins facilitate simulation and adaptive disruption management. Quantum annealing addresses selected combinatorial logistics problems, including ULD configuration, while FKF methods characterize temporal shifts, modulation, multiscale dynamics, and lead-time variations. The integration establishes a closed-loop architecture linking sensing, spectral analysis, intelligence, simulation, trust, and optimization for adaptive logistics decision-making.

Keywords— Digital Transformation; Artificial Intelligence; Internet of Things; Blockchain; Digital Twin Technology; Quantum Computing; Intelligent Logistics; Supply Chain Transparency; Sustainable Supply Chains; Resilience; Smart Mobility; Intelligent Transportation Systems; Connected Vehicles; Mobility-as-a-Service; Sustainable Transportation; Multi-Scale Spectral Analysis; FKF Transform.

I. INTRODUCTION

Global supply chains are increasingly characterized by interconnected operations, uncertain demand, transportation delays, resource constraints, technological dependencies, and exposure to disruptions. These conditions require supply-chain systems that can simultaneously support sustainability, resilience, transparency, real-time visibility, and computationally intensive decision-making. The rapid development of Artificial Intelligence (AI), Internet of Things (IoT), Blockchain, Digital Twins, quantum computing, and advanced mathematical analysis provides an opportunity to address these requirements through an integrated technological and analytical framework.

Artificial Intelligence has emerged as an important enabler of sustainable logistics through demand forecasting, predictive analytics, intelligent optimization, anomaly detection, predictive maintenance, and resource-efficient decision-making. Digital Twin technology complements these capabilities by creating continuously updated virtual representations of physical assets, processes, transportation networks, and supply-chain operations. Such representations enable real-time monitoring, simulation, what-if analysis, disruption assessment, and adaptive decision-making. The integration of IoT, AI, and quantum computing further establishes connected smart-logistics ecosystems in which real-time operational information can be transformed into intelligent predictions and optimization decisions [23]. In parallel, Industry 5.0 extends digital transformation toward human-centric, sustainable, intelligent, and resilient operational systems [24].

Trust and information visibility are equally important in modern supply-chain management. AI–Blockchain integration can combine predictive intelligence with secure, traceable, and transparent information exchange, thereby supporting supply-chain transparency, traceability, coordination, and resilience [3]. Earlier communication and control technologies, including power-line carrier communication and controller-based systems, provide complementary foundations for sensing, communication, monitoring, and automated control [4], [6]. These technological developments demonstrate an evolutionary transition from isolated monitoring and control systems toward highly connected and intelligent supply-chain infrastructures.

II. LITERATURE REVIEW

Sustainability in transportation is another important dimension of this transformation. Smart mobility and intelligent transportation systems provide mechanisms for improving transportation efficiency, connectivity, and adaptive mobility [9]. Developments in electric-vehicle battery technologies contribute to the electrification and sustainability of transportation systems [10], while battery-sizing methodologies for plug-in hybrid electric vehicles support optimized energy utilization and vehicle performance [5]. Solar-assisted electric mobility provides an additional pathway for incorporating renewable energy into transportation systems [12], while solar-powered battery-electric hybrid vehicle architectures demonstrate the potential for combining renewable generation, battery storage, and hybrid propulsion [28]. These developments strengthen the relationship between sustainable mobility and energy-aware supply-chain operations.

The increasing computational complexity of logistics decisions has also stimulated interest in quantum computing. Quantum computing provides emerging opportunities for solving computationally demanding transportation and logistics problems, including routing, allocation, configuration, and disruption-related optimization [11]. Quantum annealing is particularly relevant to combinatorial logistics problems such as Unit Load Device (ULD) configuration and disruption management [8]. Hybrid quantum-classical approaches provide a practical implementation pathway by combining quantum optimization with established classical computing, simulation, and decision-support systems [7]. Such approaches are particularly suitable for supply chains in which large operational systems must continue to function while selected computationally difficult subproblems are transferred to quantum optimization.

Alongside these technological developments, a complementary mathematical foundation is provided by FKF-based spectral analysis. The FKL transform properties establish the underlying spectral structure for analyzing complex signals and positive scale-related variables [20]. The time-shift property of the FKF transform provides a mechanism for representing transportation delays, replenishment delays, and lead-time variations in the spectral domain [21]. Exponential modulation properties further enable the representation and analysis of frequency-shifted and periodic components within dynamic supply-chain signals [22]. These properties are relevant to logistics environments in which demand, inventory, transportation, production, and disruption signals may exhibit temporal shifts, oscillations, transient changes, and frequency-dependent behavior.

The mathematical framework has subsequently been extended to distributional and generalized settings. The distributional extension of the FKF transform provides a broader analytical basis for representing generalized and potentially irregular supply-chain signals [14]. Sequential convergence in the testing-function space establishes mathematical support for convergence and approximation within the two-sided FKF framework [15]. Multiscale spectral analysis extends the approach toward the identification of supply-chain behavior occurring at different temporal and operational scales [16]. Shift-invariant spectral analysis provides a specific framework for studying multi-echelon supply-chain lead times and delay structures [17], while the FKF spectral framework establishes relationships between spectral characteristics, supply-chain dynamics, and resilience [18]. Spectral differential properties provide an additional mechanism for analyzing dynamic changes and differential behavior in resilient supply-chain systems [19].

Further developments reported in [23]–[25] strengthen this mathematical foundation through additional treatment of distributional spectral differential properties, sequential convergence, and distributional extensions of the FKF transform. Together, these developments create a mathematical framework capable of supporting the analysis of temporal, delayed, multiscale, differential, and generalized supply-chain signals.

Consequently, this study proposes the convergence of AI, Blockchain, IoT, Digital Twins, quantum optimization, and FKF spectral intelligence within a unified supply-chain architecture. In this framework, IoT provides continuous operational sensing, FKF analysis extracts temporal and multiscale spectral characteristics, AI converts these characteristics into predictive and diagnostic intelligence, Blockchain supports trusted information exchange, Digital Twins provide simulation and scenario evaluation, and quantum optimization addresses selected computationally intensive logistics decisions. The resulting closed-loop architecture provides a foundation for sustainable, transparent, adaptive, and resilient supply-chain management.

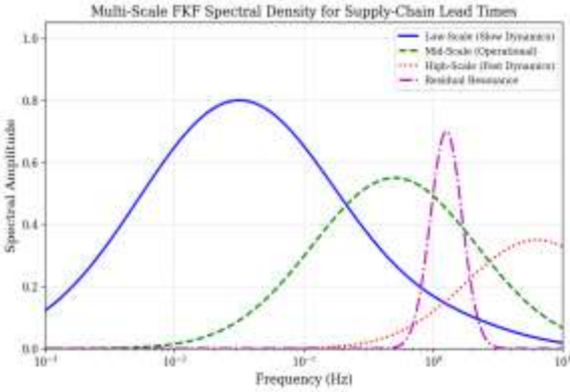

Figure 1. Multi-Scale FKF Spectral Density for Supply-Chain Lead Times (four curves: low-scale, mid-scale, high-scale, and residual resonance).

III. KEY CHARACTERISTICS

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 combines a Fourier transform in with a Kontorovich–Lebedev (KL) transform in , using spectral variables and . Its kernel is the product of the Fourier factor and the Macdonald function . The Fourier component captures temporal oscillations, frequencies, delays, and lead-time cycles, while the KL component represents positive scale, distance, inventory, demand, or disruption-intensity variables [6]. The Macdonald function satisfies the modified Bessel equation and, with the associated differential operator , obeys the eigenvalue relation

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 . The FKF kernel is the product

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

which provides the principal spectral property in the positive variable. For generalized functions, the transform is formulated through continuous pairing on a locally convex test-function space consisting of infinitely differentiable functions with suitable decay or growth controlled by weighted seminorms. This space contains , while its dual accommodates ordinary and slowly growing distributions [14], [23].

The Macdonald function satisfies the modified Bessel equation of order $\nu = iq$:

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

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 asymptotic 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 [14], [23]. Growth estimates of the form

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

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. The principal analytic features of the FKF transform follow from the product structure of its kernel and the classical properties of the Fourier and Kontorovich–Lebedev transforms. Continuity on the test-function space, sequential continuity on the dual, and an inversion formula of the schematic type

$$f(t,x) = (2\pi^2)^{-1} \int_{-\infty}^{\infty}\int_0^{\infty} F(s,q)\, e^{ist} q\, \sinh(\pi q)\, K_{iq}(x)\, dq\, ds$$

(under suitable growth restrictions) are established by standard density and continuity arguments. Parseval-type identities and convolution theorems follow similarly.

Consequently, the FKF transform extends by continuity or sequential continuity to generalized functions. Appropriate growth conditions characterize the transformed distribution classes and support inversion in suitable regions of the complex -plane. Its continuity, spectral differential properties, and inversion formula follow from the product structure of the kernel and the established theory of the Fourier and Kontorovich–Lebedev transforms [15], [22].

IV. INTELLIGENT DIGITAL TECHNOLOGIES FOR SUPPLY-CHAIN TRANSFORMATION

A progressive convergence of digital technologies aimed at improving supply-chain visibility, intelligence, sustainability, and resilience. Digital Twins have emerged as an important technology for developing resilient and adaptive supply chains because they enable continuously synchronized virtual representations of physical assets, processes, and networks [25]. Their ability to support real-time monitoring, predictive analysis, simulation, disruption assessment, and alternative-scenario evaluation makes them particularly suitable for complex global supply-chain environments.

AI provides the analytical intelligence required to transform operational data into predictions and optimization decisions. Research on AI applications in sustainable logistics emphasizes forecasting, optimization, resource efficiency, anomaly detection, and green supply-chain management. The combination of AI with IoT and Digital Twins enables continuous data acquisition, intelligent analysis, simulation, and adaptive management [23], [25]. Blockchain provides a complementary trust layer by improving information integrity, traceability, transparency, and coordination across distributed supply-chain networks [3].

These developments build upon earlier communication and control technologies. Power-line carrier communication demonstrates the application of communication technologies to monitoring and control problems [4], while controller-based systems provide complementary foundations for automated interaction and control [6]. Although these earlier technologies differ substantially from contemporary AI- and IoT-enabled systems, they represent an evolutionary foundation for the broader transition toward connected and intelligent operational infrastructures.

Industry 5.0 provides an additional conceptual dimension by emphasizing human-centric automation, sustainability, resilience, and collaboration between intelligent technologies and human decision-makers [24]. Thus, contemporary intelligent supply chains are increasingly viewed not simply as automated systems but as interconnected socio-technical systems combining sensing, analytics, automation, sustainability, and human-centered decision support.

Sustainable Transportation and Energy-Aware Logistics

Sustainable transportation represents an important component of resilient supply-chain transformation. Smart mobility and intelligent transportation systems integrate sensing, communication, automation, and intelligent decision-making to improve transportation efficiency and adaptability [9]. Electrification further supports sustainable mobility, with recent research addressing EV battery materials, battery-management systems, performance, and sustainability considerations [10].

Battery sizing is particularly important for hybrid transportation because energy-storage capacity directly affects vehicle performance, efficiency, and operating range. Research on plug-in hybrid electric-vehicle battery sizing provides an engineering foundation for optimized energy utilization in hybrid transportation systems [5]. Solar-assisted electric mobility extends this concept by incorporating renewable energy into hybrid vehicle architectures [12]. Similarly, solar-powered battery-electric hybrid vehicle architectures demonstrate how solar generation and battery-based propulsion can be integrated to support energy-efficient transportation [28].

These transportation developments have direct implications for sustainable logistics because transportation energy consumption, vehicle utilization, battery performance, and renewable-energy integration influence the environmental and operational performance of supply-chain networks. Digital transformation further strengthens these capabilities by enabling continuous monitoring, data-driven decision-making, and resilience-oriented management [13].

Quantum Computing and Optimization in Logistics

Conventional logistics optimization frequently involves computationally difficult combinatorial problems. Quantum computing has therefore emerged as a potential technological direction for transportation and logistics optimization, particularly for problems involving large solution spaces and complex constraints [11]. Quantum annealing offers a specific approach for exploring optimization landscapes and has been investigated for ULD configuration and disruption-related logistics problems [8].

However, practical adoption of quantum technologies requires integration with existing classical infrastructure. Hybrid quantum-classical strategies provide such an implementation pathway by allowing classical systems to perform data processing, scenario generation, constraint handling, and solution evaluation while quantum processors address selected optimization subproblems [7]. The IoT–AI–quantum convergence provides a broader ecosystem in which real-time operational data can feed intelligent analytics and quantum optimization.

Digital Twins can further strengthen this quantum-optimization architecture. A Digital Twin can represent the current state of a supply-chain network, generate disruption scenarios, formulate optimization problems, receive candidate solutions, and evaluate their operational consequences [28]. Quantum optimization can therefore function as one component within a larger closed-loop decision process rather than as an isolated computational technology. This integration creates opportunities for adaptive routing, resource allocation, configuration, inventory decisions, and disruption-response optimization [7], [8], [11].

V. FKF-BASED SPECTRAL ANALYSIS FOR SUPPLY-CHAIN DYNAMICS

A parallel mathematical research stream has developed around FKF-based spectral analysis. The FKL transform properties provide the mathematical basis for representing complex signals in a spectral domain involving temporal and scale-related characteristics [20]. The FKF time-shift property extends this capability by representing delayed signals through spectral transformation, making it relevant to transportation delays, replenishment cycles, and multi-echelon lead-time behavior [21]. Exponential modulation provides another important spectral property for identifying frequency-shifted or periodically modulated components in dynamic supply-chain signals [22].

The FKF framework has subsequently been extended beyond conventional functions toward generalized and distributional representations. The distributional extension provides a mathematical framework for handling generalized signals and irregular behavior that may arise in complex operational systems [14]. Sequential convergence in the associated testing-function space provides theoretical support for convergence and approximation of FKF representations [15]. These developments are important because real supply-chain signals may contain abrupt changes, sparse events, disruptions, discontinuities, and other behaviors that are difficult to represent using only conventional smooth-function assumptions.

Multiscale spectral analysis further extends FKF methods by examining patterns across different operational and temporal scales [16]. This is particularly relevant to supply chains because short-term demand fluctuations, medium-term inventory cycles, and long-term structural changes may coexist within the same system. Shift-invariant spectral analysis provides a specialized approach for analyzing multi-echelon lead-time behavior without losing the structural characteristics associated with temporal translation [17]. A broader FKF spectral framework connects these mathematical characteristics with supply-chain dynamics and resilience [18].

Spectral differential properties provide another analytical dimension by enabling the investigation of changes and differential behavior within distributional FKF representations [19]. The developments in [25] further strengthen this mathematical foundation by extending the treatment of spectral differential properties, sequential convergence, and distributional FKF representations. These contributions collectively establish a theoretical basis for applying FKF analysis to complex, delayed, impulsive, generalized, and multiscale supply-chain signals.

V. RESEARCH GAP AND INTEGRATED FRAMEWORK

Although the literature provides substantial development in each technological and mathematical domain, these streams are generally considered separately. Digital Twins emphasize virtual representation, simulation, and resilience [25]; AI focuses on prediction and optimization [29]; Blockchain addresses transparency and traceability [3]; IoT provides connected sensing [26]; quantum computing addresses computationally intensive optimization [7], [8], [11]; sustainable mobility addresses energy-efficient transportation, [9], [10]; and

FKF research establishes mathematical tools for spectral, distributional, temporal, differential, and multiscale analysis.

The major research opportunity therefore lies in their **systematic integration**. FKF spectral analysis can provide mathematically derived features describing delays, frequency components, modulation, temporal transitions, and multiscale behavior. These features can be supplied to AI models for prediction, anomaly detection, and resilience assessment. IoT can continuously provide the operational data required for spectral analysis, while Blockchain can provide trusted and traceable information exchange. Digital Twins can use the resulting intelligence to simulate disruptions and evaluate alternative responses. Quantum annealing can then optimize selected combinatorial decisions generated within these simulated scenarios [7].

Such an architecture creates a closed-loop supply-chain intelligence cycle:

IoT sensing → FKF spectral analysis → AI intelligence → Blockchain trust → Digital Twin simulation → Quantum optimization → operational decision → continuous sensing.

This integrated perspective extends the existing literature by connecting mathematical spectral intelligence with emerging digital and quantum technologies. It provides a foundation for analyzing complex supply-chain dynamics while simultaneously supporting prediction, simulation, optimization, sustainability, transparency, and resilience.

Overall, the reviewed literature demonstrates that the convergence of AI, Blockchain, IoT, Digital Twins, sustainable transportation technologies, quantum computing, and FKF spectral analysis can provide a comprehensive framework for next-generation supply-chain management. The proposed integration addresses not only technological modernization but also the fundamental requirements of resilient, adaptive, transparent, sustainable, and computationally intelligent global supply chains.

Global supply chains increasingly require technologies that jointly address sustainability, resilience, transparency, and complex optimization. AI supports green logistics through intelligent prediction and resource optimization, while Digital Twins enable dynamic monitoring, simulation, and adaptive resilience. IoT, AI, and quantum computing establish connected smart-logistics ecosystems [16], with Industry 5.0 emphasizing intelligent, sustainable, and human-centric operations. AI–Blockchain integration further improves transparency, traceability, and resilience [3], supported by earlier communication and control technologies [4], [6].

Smart transportation [9] and sustainable mobility developments involving EV batteries [10], battery sizing [5], solar-assisted mobility [12], and hybrid vehicle architectures extend intelligent logistics toward energy-aware operations. Quantum computing offers new opportunities for logistics optimization, while quantum annealing can address ULD configuration and disruption problems [8]; hybrid quantum-classical approaches provide practical implementation pathways [7]. These technologies collectively support resilient supply-chain transformation [13].

FKF-based spectral analysis provides a complementary analytical foundation. FKL properties [20], FKF time shifting [21], and exponential modulation [22] enable analysis of temporal, delay, and frequency characteristics. Distributional extensions [14], sequential convergence [15], spectral supply-chain frameworks [18], differential properties [19], shift-invariant lead-time analysis [17], and multiscale spectral analysis [16] strengthen the mathematical basis, with further developments. Consequently, the integration of AI, Blockchain, IoT, Digital Twins, FKF spectral intelligence, and quantum optimization provides a unified pathway toward sustainable, transparent, adaptive, and resilient supply-chain systems.

CONCLUSION

The convergence of AI, Blockchain, IoT, Digital Twins, quantum computing, and FKF spectral analysis provides a unified framework for sustainable and resilient logistics. AI enables intelligent prediction and optimization, Digital Twins support simulation and adaptive response, Blockchain improves transparency, quantum computing addresses complex optimization, and FKF analysis characterizes dynamic supply-chain behavior. Their integration establishes a closed-loop architecture connecting sensing, analysis, intelligence, simulation, and optimization. This approach offers a promising foundation for transparent, sustainable, adaptive, and resilient global supply-chain systems.

REFERENCES

1. H. M. Ozaktas, Z. Zalevsky, and M. A. Kutay, The Fractional Fourier Transform. Wiley, 2001.
2. L. B. Almeida, “The fractional Fourier transform and time-frequency representations,” IEEE Trans. Signal Process., vol. 42, no. 11, pp. 3084–3091, Nov. 1994.
3. A. Gulhane, “Artificial Intelligence and Blockchain Integration for Enhancing Supply Chain Transparency, Traceability, and Resilience,” Int. Res. J. Modernization Eng. Technol. Sci., vol. 6, no. 12, 2024, doi: 10.56726/IRJMETS65016.
4. A. Gulhane, “Power Line Carrier Communication Based Anti-Theft System,” Int. J. Res. IT Manage. (IJRIM), vol. 4, no. 12, pp. 1–11, 2014.
5. 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.
6. A. Gulhane, “Swipe Controller,” Int. J. Res. Eng. Appl. Sci. (IJREAS), vol. 4, no. 12, pp. 1–7, 2014.
7. A. Gulhane, “Navigating the Quantum Revolution in Logistics: Opportunities and Practical Applications in Supply Chain Management,” Int. J. Eng. Techn. (IJET), vol. 12, pp. 553–556, 2026, doi: 10.29126/ijet.2026.v12.i3.553.
8. 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.
9. 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.
10. A. Gulhane, “Recent Advances in Electric Vehicle Battery Technologies: Materials, Management Systems, and Sustainability Perspectives,” Int. J. Sci. Res. Eng. Manage. (IJSREM), vol. 9, no. 7, Jul. 2025, doi: 10.55041/IJSREM51198.
11. 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.
12. 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.
13. 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.
14. 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.
15. 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.
16. 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.
17. 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.
18. 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.
19. 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.
20. 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.
21. 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.
22. 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.
23. 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.
24. 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.
25. A. Gulhane, “The Future of Vehicles: Solar-Powered Battery Electric Hybrid Vehicle Architecture,” Tech Briefs Contest, 2020.
26. D. Ivanov, “Digital supply chain twins: Managing the ripple effect, resilience, and disruption risks by data-driven optimization, simulation, and visibility,” in Handbook of Ripple Effects in the Supply Chain. Springer, 2021, pp. 309–330.
27. R. G. Ghanem and P. D. Spanos, Stochastic Finite

Elements: A Spectral Approach. Springer-Verlag, 1991.
28. A. Gulhane, "Digital Twin Technology for Building Resilient and Adaptive Global Supply Chains: A Review," Int. Res. J. Modernization Eng. Technol. Sci., vol. 6, no. 12, 2024, doi: 10.56726/IRJMETS64992.
29. A. Gulhane, "Artificial Intelligence Applications in Sustainable Logistics and Green Supply Chain Management: A Bibliometric Review," Int. Res. J. Modernization Eng. Technol. Sci., vol. 6, no. 12, 2024, doi: 10.56726/IRJMETS65006.
30. D. Xiu, Numerical Methods for Stochastic Computations: A Spectral Method Approach. Princeton University Press, 2010.
31. 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.
32. S. M. Harle et al., "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.
33. S. M. Harle et al., "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.