Multi-Scale Supply Chain Resilience Modeling Using the FKF Transform and Digital Twins

Shinde SM
shindesanjaykumar3572@gmail.com

How to Cite this Article:

SM, S. (2026). Multi-Scale Supply Chain Resilience Modeling Using the FKF Transform and Digital Twins. International Journal of Creative and Open Research in Engineering and Management, <i>02</i>(8), 1-9. https://doi.org/10.55041/ijcope.v2i8.206

https://doi.org/10.55041/ijcope.v2i8.206

Abstract—
This study proposes a unified framework integrating AI, Blockchain, IoT, Digital Twins, quantum computing, and FKF spectral analysis for sustainable, transparent, and resilient supply chains. AI enables prediction and optimization; Blockchain ensures trusted traceability; IoT provides real-time sensing; Digital Twins support simulation; and quantum annealing addresses complex logistics optimization. FKF analysis captures temporal shifts, modulation, multiscale dynamics, and lead-time variations for AI-based spectral intelligence. The resulting sensing–analysis–intelligence–simulation–optimization architecture provides an adaptive pathway for efficient and resilient next-generation logistics

Keywords— Artificial Intelligence; Sustainable Logistics; Green Supply Chain; Blockchain; Digital Twins; Internet of Things; Quantum Computing; Quantum Annealing; FKF Transform; Supply Chain Resilience.

I. INTRODUCTION

Modern supply chains require intelligent, sustainable, transparent, and resilient decision-making under increasing disruption, demand variability, and operational complexity. Artificial Intelligence (AI) supports sustainable logistics through forecasting, optimization, anomaly detection, and resource-efficient decision-making [32], while Digital Twins enable real-time monitoring, simulation, prediction, and adaptive supply-chain management [31]. IoT, AI, and quantum computing further establish an integrated technological foundation for smart logistics ecosystems [26], complemented by Industry 5.0's emphasis on human-centric automation and intelligent logistics [27].

Blockchain can strengthen supply-chain transparency, traceability, and data integrity when integrated with AI [33], extending earlier developments in communication and intelligent control systems [34], [6]. In parallel, smart mobility and intelligent transportation technologies [9], together with advances in electric-vehicle batteries [10], battery sizing [35], solar-assisted mobility [12], and sustainable vehicle architectures [28], connect logistics optimization with energy efficiency and environmental sustainability.

The increasing computational complexity of routing, scheduling, packing, and ULD configuration motivates quantum approaches. Quantum computing and quantum annealing offer opportunities for difficult logistics optimization problems [11], including ULD configuration and disruption management [8], while practical quantum-revolution strategies emphasize hybrid quantum-classical implementation [7]. Supply-chain resilience provides the overarching objective for integrating these technologies [13].

A complementary spectral layer can characterize temporal, scale-dependent, and disruption-related supply-chain dynamics. FKL properties and supply-chain applications [20], FKF time shifting [21], and exponential modulation [22] provide mechanisms for analysing delays and frequency-domain variations. The distributional FKF framework establishes generalized representations [14], sequential convergence [15], spectral supply-chain analysis [18], and differential operators for resilient systems [19]. Shift-invariant lead-time analysis [17] and multiscale spectral analysis [16] further extend the framework. These developments, together with related FKF formulations [23]–[25], support a convergent architecture in which sensing, spectral analysis, AI intelligence, blockchain trust, Digital Twin simulation, and quantum optimization operate as interconnected layers for sustainable and resilient supply-chain management.

II. LITERATURE REVIEW

Research on intelligent logistics has progressively moved from isolated technological applications toward integrated digital supply-chain ecosystems. Digital Twin technology has been identified as an important mechanism for real-time monitoring, simulation, prediction, and resilient supply-chain management [31], while AI has been increasingly applied to sustainable logistics, forecasting, optimization, and green supply-chain operations [32]. The integration of AI with Blockchain further improves transparency, traceability, data integrity, and resilience [33]. Earlier developments in communication and control systems [34], [6] provide technological foundations for increasingly connected logistics environments.

Sustainable transportation research has expanded through battery sizing for hybrid vehicles [35], smart mobility and intelligent transportation systems [9], recent EV battery technologies [10], and solar-assisted mobility [12], complemented by solar-powered hybrid vehicle architectures [28]. Supply-chain resilience and digital transformation have consequently become interconnected research priorities [13]. Industry 5.0 further emphasizes intelligent, human-centric, and sustainable logistics [27].

Quantum computing introduces a new optimization dimension for transportation and logistics [11]. Quantum annealing has been examined for ULD configuration and disruption management [8], while practical applications of the quantum revolution emphasize hybrid quantum-classical approaches [7]. In parallel, FKF-based research provides a mathematical spectral layer through FKL properties [20], FKF time-shift analysis [21], and exponential modulation [22]. Distributional FKF theory [14], sequential convergence [15], multiscale spectral analysis [16], shift-invariant lead-time analysis [17], spectral frameworks [18], and spectral differential properties [19] establish a rigorous basis for supply-chain signal analysis, further extended in [23]–[25]. Collectively, the literature indicates a clear transition toward convergent architectures combining AI, Blockchain, IoT, Digital Twins, spectral intelligence, and quantum optimization for sustainable and resilient logistics..

III. PRELIMINARIES AND NOTATION

The distributional Laplace transform is defined as $F(s) = \langle f(t), e^{-st} \rangle$ for μ either zero or a complex number with positive real part.

If μ is zero or a complex number with positive real part, the K transform $F(y)$ is defined by $F(y) = \langle f(x), \left(xy\right)^{\frac{1}{2}} K_\mu(xy) \rangle$ Re $y > 0$where $K_\mu(z)$denotes the modified Bessel function of the third kind and order μ.

Similar to the K transformation, there is the I transformation $F(y) = \langle f(x), (xy)^{1/2} I_\mu(xy) \rangle$ where $I_\mu(z)$ denotes the modified Bessel function of the first kind and order $\mu > 1/2$.

We shall make considerable use of the differential operator

$$S_\mu = t^{-1/2} D t^{2\mu+1} D t^{\mu+1/2}$$

of second order i.e. $S_\mu = M_\mu N_\mu$, where M_μ and N_μ are defined in section 5.3 of Zemanian. The notation and terminology follow Zemanian.

This paper deals with distributional generalized FKF transform of distributional function f in dual space of LK_μ i.e. LK'_μ which is defined by

$$LK_\mu(f(x)) = F(s,y) = \langle f(x), e^{-s}(xy)^{1/2} K_\mu(xy) \rangle$$

for complex parameters s and y.

The RHS has sense for $f \in LK'_\mu$ and $e^{-s}(xy)^{1/2} K_\mu(xy) \in LK_\mu$.

The present paper mainly provides a representation theorem for the defined generalized transform.

IV. AI-DRIVEN SUSTAINABLE LOGISTICS AND GREEN SUPPLY-CHAIN MANAGEMENT

Artificial Intelligence (AI) has become a key technology for sustainable logistics, supporting demand forecasting, route optimization, resource allocation, predictive maintenance, and energy-efficient operations [32]. Its integration with IoT enables real-time collection and analysis of logistics data, while Digital Twins support simulation and adaptive decision-making [31], [26]. AI can also complement Blockchain to improve supply-chain transparency, traceability, and resilience [33]. Applications in smart mobility [9], electric-vehicle battery technologies [10], hybrid-vehicle battery sizing

International Journal of Creative and Open Research in Engineering and Management
ISSN: **3108-1754 (Online)**
Volume 02 Issue 08 August-2026 | Impact Factor: 3.5

[35], and solar-assisted transportation [12] demonstrate the growing role of intelligent systems in reducing energy consumption and environmental impact. These developments contribute to digitally enabled supply-chain resilience [13] and Industry 5.0 objectives [27]. Emerging quantum computing approaches [7], [8], [11] can further enhance AI-driven logistics optimization, while FKF-based spectral methods [14]–[25] offer additional tools for analyzing temporal, multiscale, and dynamic supply-chain patterns.

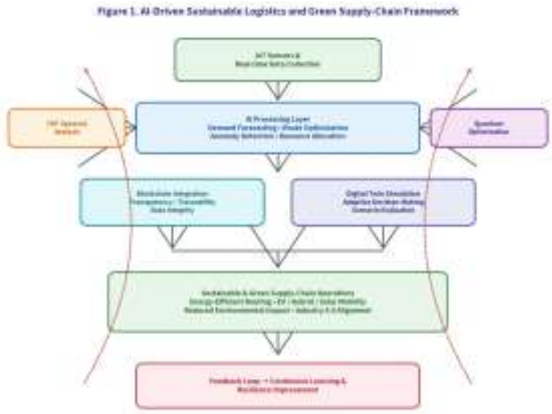

Figure 1. AI-Driven Sustainable Logistics and Green Supply-Chain Framework

V. IOT–AI–QUANTUM ARCHITECTURES

Quantum computing offers emerging capabilities for complex logistics optimization, including vehicle routing, inventory allocation, ULD configuration, and disruption management [7], [8], [11]. Hybrid quantum-classical approaches provide practical pathways for addressing computationally difficult supply-chain problems, while IoT–AI–quantum architectures strengthen real-time intelligent logistics [26]. Digital Twins complement these methods by continuously representing physical assets, processes, and multi-tier supply networks, enabling monitoring, simulation, prediction, and adaptive disruption response [31]. Because logistics and Digital Twin data may contain sparse, impulsive, and highly variable signals, FKF-based distributional methods provide a mathematical mechanism for spectral representation, filtering, anomaly detection, and residual analysis [14]–[25]. Together, quantum optimization and Digital Twins establish an adaptive framework for resilient supply-chain decision-making.

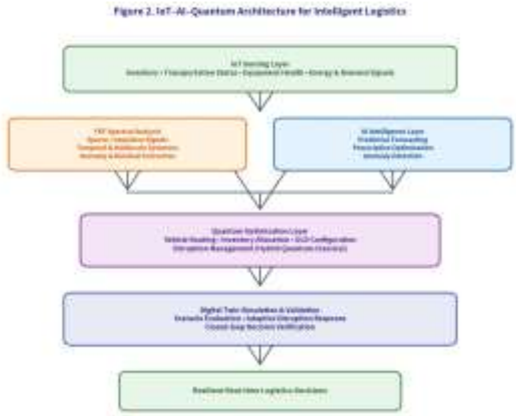

Figure 2. IoT–AI–Quantum Architecture for Intelligent Logistics

VI. BUILDING RESILIENT AND ADAPTIVE GLOBAL SUPPLY CHAINS

Digital Twin technology has emerged as an important component of digital supply-chain transformation, providing continuously updated virtual representations of physical assets, logistics processes, transportation networks, warehouses, and multi-tier supply-chain structures [31]. By integrating real-time operational data with simulation and analytical models, Digital Twins enable organizations to monitor system conditions, evaluate alternative scenarios, predict failures, and develop adaptive responses to changing supply-chain conditions.

The effectiveness of a Digital Twin depends on continuous data acquisition from connected assets. IoT sensors can provide information regarding inventory levels, transportation status, equipment conditions, energy consumption, demand fluctuations, and environmental conditions [26]. AI can transform these data streams into predictive and prescriptive insights, supporting demand forecasting, anomaly detection, predictive maintenance, route optimization, and resource allocation [32]. AI–Blockchain integration can further strengthen data integrity, transparency, traceability, and trust across distributed supply-chain participants [33].

Digital Twins are particularly valuable for resilience because disruptions may propagate across multiple tiers and geographic regions. A virtual supply-chain model can reproduce disruption scenarios, evaluate alternative transportation routes, identify bottlenecks, estimate recovery requirements, and support rapid reconfiguration. This capability aligns with broader research on digital transformation and supply-chain resilience [13]. Industry 5.0 further extends the concept by emphasizing intelligent automation, humanmachine collaboration, sustainability, and adaptive logistics operations [27].

The Digital Twin concept is also increasingly relevant to sustainable transportation and energy management. Smart mobility and intelligent transportation systems provide connected operational environments [9], while EV battery technologies [10], hybrid-vehicle battery sizing [35], and solar-assisted mobility [12] create new requirements for monitoring energy performance and vehicle-system interactions. Solar-powered hybrid vehicle architectures [28] further demonstrate how Digital Twins can support modelling, performance assessment, and sustainable mobility planning.

Digital Twins can also serve as an operational interface for advanced optimization. Quantum computing provides emerging capabilities for difficult transportation and logistics problems [11], while quantum annealing has particular relevance to ULD configuration and disruption optimization [8]. Hybrid quantum-classical approaches can connect Digital Twin-generated scenarios with quantum optimization processes, enabling difficult configurations to be optimized and subsequently re-evaluated within the simulated environment [7].

An additional analytical capability can be obtained by incorporating FKF-based spectral analysis into Digital Twin architectures. Supply-chain observations frequently contain temporal fluctuations, delays, abrupt disruptions, multiscale patterns, and irregular signals. FKL transform properties provide a basis for supply-chain analysis [20], while FKF time-shift [21] and exponential-modulation properties [22] enable the representation of delayed and modulated operational behavior. Distributional FKF theory [14], sequential convergence [15], multiscale spectral analysis [16], shift-invariant lead-time analysis [17], spectral supply-chain frameworks [18], and spectral differential properties [19] provide mathematical foundations for analyzing generalized and dynamic supply-chain signals. Related developments further extend these capabilities [23]–[25].

Thus, the Digital Twin can function as the central simulation and coordination layer within a convergent logistics architecture. IoT supplies real-time observations, FKF analysis extracts spectral characteristics, AI converts these characteristics into predictive intelligence, Blockchain establishes trusted data provenance, and quantum optimization addresses selected combinatorial decisions. The resulting feedback loop allows optimized decisions to be tested within the Digital Twin before operational deployment, supporting resilient, adaptive, transparent, and sustainable global supply chains.

Digital twins create continuously synchronized virtual replicas of physical supply-chain assets, processes, and multi-tier networks. They enable real-time monitoring, what-if simulation, predictive maintenance, and autonomous control. In global settings, multi-resolution twins support coordinated responses to disruptions that span continents.

Figure 3. Convergent Digital Twin Architecture for Resilient Global Supply Chains

Sensor streams that keep a digital twin synchronized routinely contain impulsive events—equipment failures, sudden congestion, or abrupt demand shocks. The representation theorem guarantees that the LK transform of these generalized inputs remains mathematically well-defined and can be reduced to operations on ordinary functions. Consequently, the transform can be incorporated into the twin's analytic engine for spectral monitoring of network health, early-warning indicators, and model-based residual analysis.

VI. CONCLUSION

This study demonstrates that the convergence of Artificial Intelligence, Blockchain, Internet of Things, Digital Twins, quantum computing, and FKF spectral analysis provides a promising foundation for next-generation logistics. AI enables intelligent prediction and optimization, Digital Twins support real-time simulation and adaptive decision-making, and Blockchain strengthens transparency and traceability. Quantum computing offers new possibilities for complex logistics optimization, while FKF-based spectral analysis provides mathematical tools for characterizing temporal, multiscale, and dynamic supply-chain behavior. Together, these technologies create an integrated

REFERENCES

[1] L. B. Almeida, "Product and convolution theorems for the fractional Fourier transform," IEEE Signal Processing Letters, vol. 4, pp. 15–17, 1997.

[2] Karhunen, K. (1947). Über lineare Methoden in der Wahrscheinlichkeitsrechnung. *Annales Academiae Scientiarum Fennicae. Series A. I, Mathematica-Physica*, 37, 1–79.

[3] Loève, M. (1978). *Probability Theory II* (4th ed.). Springer-Verlag.

[4] Heese, R., et al. (2026). Hybrid Quantum-Classical Optimization for Multi-Objective Supply Chain Logistics. *arXiv preprint arXiv:2602.05364*.

[5] Ivanov, D., Dolgui, A., & Sokolov, B. (2019). The impact of digital technology and Industry 4.0 on the ripple effect and supply chain risk analytics. *International Journal of Production Research*, 57(3), 829–846.

[6] Gulhane, A. (2014). Swipe Controller. *International Journal of Research in Engineering and Applied Sciences (IJREAS)*, *4*(12), 1–7.

[7] 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]

[8] Akarshan Gulhane, "Quantum Computing for Logistics Optimization: Annealing in Unit Load Device Configuration and Disruption," International Journal of Research Publication and Reviews, Vol. 7, Issue 6, pp. 4643–4648, June 2026. DOI: 10.55248/gengpi.07.0626.16a57.

[9] Akarshan Gulhane, "Smart Mobility and Intelligent Transportation Systems: Emerging Trends, Technologies, and Challenges," International Journal of Scientific Research in Engineering and Management (IJSREM), Vol. 9, Issue 11, Nov. 2025. DOI: 10.55041/IJSREM53436.

[10] 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.

[11] Akarshan Gulhane, "Quantum Computing in Transportation and Logistics: Current State, Industrial Applications, and Future Directions," International Journal of Scientific Research in Engineering and Management (IJSREM), Vol. 9, Issue 9, Sep. 2025. DOI: 10.55041/IJSREM52469.

[12] Akarshan Gulhane, "Solar-Assisted Electric Mobility: Design Framework and Performance Assessment of Sustainable Hybrid Vehicle Architectures," Int. J. Engg. Res. & Sci. & Tech., Vol. 21, No. 3, pp. 362–368, 2025. **DOI:** 10.56636/ijerst.2025.v21.i03.3594.

[13] Akarshan Gulhane, "Supply Chain Resilience in the Era of Digital Transformation: A Systematic Literature Review and Research Agenda," Int. J. Engg. Res. & Sci. & Tech., Vol. 21, No. 4, pp. 1058–1068, 2025. **DOI:** 10.56636/ijerst.2025.v21.i04.3812.

[14] Akarshan Gulhane, "Distributional Extension of the FKF Transform and Its Relevance to Supply-Chain Systems," International Journal of Creative and Open Research in Engineering and Management ISSN: 3108-1754 (Online) Volume 02 Issue 08 Augustl-2026 , DOI: https://doi.org/10.55041/ijcope.v2i8.137

[15] Akarshan Gulhane,"Sequential Convergence in the Testing Function Space of the Two-Sided FKF Transform," International Journal of Creative and Open Research in Engineering and Management ISSN: 3108-1754 (Online) Volume 02 Issue 08 Augustl-2026,
DOI: https://doi.org/10.55041/ijcope.v2i8.138

[16] Akarshan Gulhane," Spectral Analysis for Multi Scale Supply Chain Dynamics and ResidueBased Resonance Extraction in Hybrid-Vehicle Systems," International Journal of Creative and Open Research in Engineering and Management ISSN: 3108-1754 (Online) Volume 02 Issue 08 Augustl-2026, DOI: https://doi.org/10.55041/ijcope.v2i8.141

[17] Akarshan Gulhane," Shift-Invariant Spectral Analysis of Multi-Echelon Supply-Chain Lead Times via the FKF Transform," International Journal of Creative and Open Research in Engineering and Management ISSN: 3108-1754 (Online) Volume 02 Issue 08 Augustl-2026, DOI: https://doi.org/10.55041/ijcope.v2i8.136

[18] Akarshan Gulhane," Spectral Framework Based on the FKF Transform for Supply Chain Dynamics and Resilience," International Journal of Creative and Open Research in Engineering and Management ISSN: 3108-1754 (Online) Volume 02 Issue 08 Augustl-2026, DOI: https://doi.org/10.55041/ijcope.v2i8.140

[19] Akarshan Gulhane," Spectral Differential Properties of the Distributional FKF Transform with Applications to Resilient Supply-Chain Systems," International Journal of Creative and Open Research in Engineering and Management ISSN: 3108-1754 (Online) Volume 02 Issue 08 Augustl-2026, DOI: https://doi.org/10.55041/ijcope.v2i8.139

[20] Akarshan Gulhane," FKL Transform Key Properties, And Applications To Supply-chain Analysis," International journal of Engineering sciences and Advanced Technology, Published:11-12-2025, Issue: Vol. 25 No. 12 (2025), Page Nos: 596-605, DOI: Https://doi.org/10.64771/ijesat.2025.v25.i12.3816

[21] Akarshan Gulhane," Expanded Treatment Of The Time-Shift Property Of FKF Transform With Supply-Chain Applications," International journal of Engineering sciences and Advanced Technology, Published:11-12-2025, Issue: Vol. 25

No. 12 (2025), Page Nos: 606 – 616, DOI: Https://doi.org/10.64771/ijesat.2025.v25.i12.3817

[22] Akarshan Gulhane,“ The FKF Transform: Exponential Modulation Properties And Applications To Secure Digital Supply-Chain Networks,” International journal of Engineering sciences and Advanced Technology, Published:11-12-2025, Issue: Vol. 25 No. 12 (2025), Page Nos: 617 – 623, DOI: Https://doi.org/10.64771/ijesat.2025.v25.i12.3818

[23] Akarshan Gulhane, “Spectral Differential Properties of the Distributional FKF Transform with Applications to Resilient Supply-Chain Systems,” International Journal of Creative and Open Research in Engineering and Management ISSN: 3108-1754 (Online) Volume 02 Issue 08 Augustl-2026, DOI: https://doi.org/10.55041/ijcope.v2i8.139.

[24] Akarshan Gulhane, “Sequential Convergence in the Testing Function Space of the Two-Sided FKF Transform,” International Journal of Creative and Open Research in Engineering and Management ISSN: 3108-1754 (Online) Volume 02 Issue 08 Augustl-2026, DOI: https://doi.org/10.55041/ijcope.v2i8.138

[25] Akarshan Gulhane, “Distributional Extension of the FKF Transform and Its Relevance to Supply-Chain Systems,” International Journal of Creative and Open Research in Engineering and Management ISSN: 3108-1754 (Online) Volume 02 Issue 08 Augustl-2026, DOI: https://doi.org/10.55041/ijcope.v2i8.137

[26] Akarshan Gulhane, “Internet of Things, Artificial Intelligence, and Quantum Computing: A Convergent Framework for Smart Logistics Ecosystems,” International Journal of Engineering Science and Advanced Technology (IJESAT), Vol. 24, Issue 12, pp. 297–317, 2024. **DOI:** 10.64771/ijesat.2024.v24.i12.3372

[27] Akarshan Gulhane, “Industry 5.0 and Intelligent Logistics: Transforming Supply Chain Operations through Human-Centric Automation,” International Journal of Engineering Science and Advanced Technology (IJESAT), Vol. 24, Issue 12, pp. 287–296, 2024. DOI: 10.64771/ijesat.2024.v24.i12.3371

[28] Akarshan Gulhane, “The Future of Vehicles: Solar-Powered Battery Electric Hybrid Vehicle Architecture,” Tech Briefs Contest, 2020.

[29] B. N. Bhosale, M. S. Choudhary, works on double transforms of generalized functions.

[30] L. B. Almeida, “Product and convolution theorems for the fractional Fourier transform,” IEEE Signal Processing Letters, vol. 4, pp. 15–17, 1997.

[31] 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.

[32] 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.

[33] 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.

[34] Akarshan Gulhane, “Power Line Carrier Communication Based Anti-Theft System,” International Journal of Research in IT and Management (IJRIM), Vol. 4, Issue 12, pp. 1–11, 2014.

[35] Akarshan Gulhane, “Battery Sizing for Plug-in Hybrid Electric Vehicles — Formula Hybrid,” IEEE International Conference on Power, Control, Signals and Instrumentation Engineering (ICPCSI), pp. 368–372, 2017. DOI: 10.1109/ICPCSI.2017.8392317.

[36] A. H. Zemanian, Distribution Theory and Transform Analysis, McGraw-Hill, New York.

[37] A. H. Zemanian, Generalized Integral Transformations, Interscience, New York.

[38] H. M. Ozaktas, Z. Zalevsky, M. A. Kutay, The Fractional Fourier Transform, Wiley, 2001.

[39] L. B. Almeida, “The fractional Fourier transform and time-frequency representations,” IEEE Trans. Signal Process., vol. 42, pp. 3084–3091, 1994.