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IOT-Gated FKF–FKL Digital Twins for Human-Centric and Quantum-Constrained Resilient Logistics

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Abstract—
Multi-echelon logistics now couple Internet of Things telemetry, intelligent transportation systems, Industry 5.0 human-centric automation, green and solar-assisted mobility, hash-chain provenance, and hybrid quantum-classical dispatch. Raw sensor streams, however, mix clock offset, intensity drift, stale packets, unauthorized holds, and physical-integrity loss with genuine structural disruption. This paper reconstructs a gated digital-twin architecture in which an FKF–FKL spectral layer first separates translation, exponential modulation, and residue-based resonance, while an IoT integrity layer admits only fresh, authorized, and physically sealed actions into the twin and into a QUBO / quantum-annealing feasible set. Asset telemetry is written as a state that carries position, velocity, on-board energy, and a binary integrity flag. One-way smart-mobility latency yields a freshness constraint for live control and twin commit. Swipe-controller grant and hold events are mutually exclusive on an authorization clock, yet a designated human authority set can override both, so machine recommendation never extinguishes operator grant. A power-line-carrier anti-theft heartbeat defines physical integrity; the live flag is the conjunction of freshness and integrity. The resulting admissible action set is energy-aware, integrity-aware, and human-gated. Compact FKF–FKL features then feed constrained-resilience scoring, blockchain-style hash-chain provenance, unit-load-device reconfiguration, and green-logistics mode choice. The framework is interpretive rather than a substitute for field trials: it supplies professional, shift-invariant equations that a digital twin can update under sequential convergence on a testing-function space.

Keywords— constrained resilience; digital twins; green logistics; blockchain/hash-chain provenance; swipe control; FKF/FKL transforms; two-sided distributional FKF; sequential convergence; testing-function spaces; time-shift/modulation; residue resonance; shift-invariant spectral analysis; multi-echelon lead times; supply-chain resilience; digital transformation; quantum logistics/annealing; QUBO–ULD optimization; smart logistics; IoT; intelligent transportation; Industry 5.0; human-centric automation; sustainable logistics; hybrid-electric/plug-in hybrid vehicles; battery sizing; solar-assisted mobility; power-line communication; anti-theft systems.

I. INTRODUCTION

Digital transformation of global supply chains has made the digital twin a practical instrument of constrained resilience rather than a visualization accessory [4,30]. The same transformation now sits beside green and sustainable logistics [5], blockchain traceability and supply-chain transparency [6], and a convergent stack of Internet of Things, artificial intelligence, and quantum computing for smart logistics [8,21,28]. None of these layers can be driven from raw multi-echelon lead-time traces. Irregular IoT scans, reporting offsets, intensity drift, and localized shocks are observationally entangled with genuine structural change [11,12,13].

Shift-invariant FKF analysis shows that a pure clock translation changes only spectral phase [11,19].

Exponential modulation captures intensity drift without inventing a new mode [20]. Spectral differentials and residue-based resonance extraction identify shocks that couple into persistent lead-time dynamics [10,12,13]. The complementary FKL representation supplies slow-scale moments [18], while a distributional two-sided FKF transform on a testing-function space, together with sequential convergence of expanding windows, licenses online twin updates from bursty packets [32,33].

Spectral correctness is not operational admissibility. A resonant but stolen trailer, a stale ITS packet, or a machine grant that a supervisor has placed on hold must not enter the live twin or the annealer. This paper therefore reconstructs the missing integrity gate. Smart-mobility telemetry contributes measured one-way latency [27]. Industry 5.0 human-centric automation keeps final authority with designated personnel [22]. A swipe controller records grant and hold [7,34]. Power-line-carrier anti-theft supplies a physical heartbeat [24]. On-board energy of plug-in-hybrid, hybrid-electric, and solar-assisted vehicles bounds the work that may be dispatched [9,23,25,29]. Quantum annealing and QUBO encodings then optimize unit-load-device configuration only inside the gated set [8,26,28].

Constrained resilience is therefore not a slogan attached after optimization. It is the requirement that recovery remain feasible under simultaneous limits on energy, service, authorization, and physical custody. A digital twin that ignores those limits will recommend moves a yard cannot execute; a quantum annealer that ignores them will return QUBO minima that violate Industry 5.0 authority or anti-theft seals. The contribution of this manuscript is to write both the integrity limits and the FKF–FKL spectra in professional equation form so that a single admissible set feeds the twin and the solver.

The remainder of the paper is organized as follows. Section II reviews digital twins, green and transparent logistics, FKF/FKL spectral theory, mobility and energy architectures, human-centric automation, and quantum dispatch. Section III reconstructs the IoT telemetry state, freshness law, swipe-controller authorization, PLC integrity, and the coupled admissible set (D.1)–(D.9). Section IV couples that set to shift-invariant spectral features and discusses three operating regimes. Section V concludes.

II. LITERATURE REVIEW

A. Resilience, Digital Twins, and Green Transparency

Classical resilience studies framed buffering and flexibility as enterprise capabilities [1,2]. Digital-twin reviews now treat synchronized models as the operational means of that capability [4]. Artificial intelligence applied to sustainable and green supply-chain management provides the scoring layer that can consume compact spectral states [5]. Blockchain and hash-chain provenance bind those states to an immutable observation digest and thereby support transparency when echelons dispute a delay [3,6].

B. FKF/FKL Spectral Theory for Multi-Echelon Lead Time

The FKF transform joins a Fourier factor to a Kontorovich–Lebedev (Macdonald) factor so that temporal oscillation and positive scale appear as joint coordinates [12]. Shift invariance of the spectral envelope is the reason a translated shipment hold is not a new mechanism [11,19]. Exponential modulation moves the Fourier variable into the complex plane and isolates intensity drift [20]. Distributional pairing against Schwartz testing functions accommodates missing scans; sequential convergence of the two-sided transform distinguishes incremental information from regime change [32,33]. Residue-based resonance in hybrid-vehicle and multi-scale logistics signals supplies the complementary peak test [10]. FKL moments summarize slow trend and slope for the twin's background state [18]. Spectral differentials convert a localized perturbation into a relative displacement used for constrained-resilience scoring [13].

C. Mobility, Energy, Human Authority, and Quantum Dispatch

Smart mobility and intelligent transportation systems define the latency and infrastructure envelope of yard-to-lane telemetry [27]. Industry 5.0 logistics keeps computational recommendation under human-centric automation [16,22]. Swipe-controller hardware records the grant and hold events used below [7,34]. Power-line-carrier anti-theft communication remains useful in metallic yards where wireless IoT is unreliable [24]. Battery materials and management [9], formula-hybrid battery sizing [25], solar-powered hybrid architecture [23], and solar-assisted electric mobility assessment [29] convert kilowatt-hour headroom into an admissible work envelope. Quantum logistics from NISQ-era context [17] through annealing of unit-load-device configuration [8,26,28] then consumes only those actions that survive the integrity gate.

Two further observations organize the review. First, cyber-physical manufacturing architectures [15] already treated sensing, computation, and actuation as a closed loop; the present gate extends that loop to multi-echelon logistics by adding spectral confound separation and a human override that Industry 4.0 stacks often omit. Second, ethical and value-oriented Industry 5.0 engineering [16] requires that automation remain inspectable. Hash-chain provenance of FKF windows and swipe events is the inspect ability mechanism used here: an auditor can recompute both the spectrum and the grant bit from committed atoms [6,7,32,34].

Taken together, the reviewed sources justify a two-layer twin. Layer one is spectral: FKF/FKL features that are stable under translation, sensitive to resonance, and well-defined for irregular traces [10–13,18–20,32,33]. Layer two is operational: freshness, grant, integrity, and energy, drawn from smart mobility, swipe control, PLC anti-theft, and hybrid-electric design [7,9,23–25,27,29,34]. Quantum and classical solvers sit behind both layers [8,21,26,28].

D. Recap of the Professional FKF–FKL Operators Used Downstream

For later editing in Word, the operators that consume gated traces are recorded here in professional format. The forward FKF transform of a lead-time signal ℓ is

$$\mathcal{F}_{\mathrm{FKF}}[\ell](\omega,\nu) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \ell(t)\, e^{-i\omega t}\, K_{i\nu}(e^{t})\, dt. \qquad (C.1)$$

The time-shift and exponential-modulation identities used to strip observational confounds before integrity-gated commit are

$$\mathcal{F}_{\mathrm{FKF}}[\ell_\tau] = e^{-i\omega\tau}\,\mathcal{F}_{\mathrm{FKF}}[\ell], \qquad (C.4)$$

$$\mathcal{F}_{\mathrm{FKF}}[e^{\alpha t}\ell] = \mathcal{F}_{\mathrm{FKF}}[\ell](\omega + i\alpha, \nu). \quad (C.6)$$

Distributional pairing on the testing-function space $\mathcal{S}$ and sequential convergence of windowed two-sided transforms then justify updating ψ from irregular IoT atoms without declaring a new regime at every packet.

III. IOT, SMART MOBILITY, HUMAN-CENTRIC AUTOMATION, AND PHYSICAL INTEGRITY

Smart Mobility and Intelligent Transportation Systems provides the mobility-telemetry perspective, including latency, connectivity, and infrastructure readiness [27]. Industry 5.0 and Intelligent Logistics reinforces a human-centric approach in which intelligent systems assist decisions while final operational authority remains with human personnel [22]. Swipe Controller supplies an implementation context for recorded grant and holds events [7,34]. Power-line-carrier anti-theft adds a physical-integrity dimension [24]. Collectively these contributions integrate sensing, authorization, computation, and physical security into one operational state for Sections D.1–D.4.

D.1 Telemetry State

Each asset a at time t reports a telemetry vector

$$m_a(t) = \big(p_a(t), v_a(t), E_{b,a}(t), \sigma_a(t)\big). \quad (D.1)$$

with position, velocity, on-board energy, and an integrity flag $\sigma_a(t) \in \{0,1\}$. On-board energy $E_{b,a}$ is the quantity bounded by battery-sizing and solar-assisted hybrid design [9,23,25,29]. Smart-mobility infrastructure [27] delivers m_a with a measured one-way latency

$$L_a(t) = t_{recv} - t_{stamp}. \qquad (D.2)$$

A freshness constraint for live control and for digital-twin commit is

$$L_a(t) \le L_{max}. \qquad (D.3)$$

Packets violating (D.3) are retained for audit and may still enter the distributional FKF pairing as irregular traces [32], but they do not update the live twin state. Sequential convergence on the testing-function space then decides whether the audit stream remains compatible with the established spectral regime [33].

D.2 Grant and Hold Authorization

The swipe-controller implementation [7,34] is abstracted as a pair of logged events on an authorization clock. Let $g_r(t) = 1$ if request r is granted at t, and $h_r(t) = 1$ if it is placed on hold. Mutual exclusion and accounting read

$$g_r(t) + h_r(t) \le 1. \qquad (D.4)$$

$$A_{open}(t) = \int_0^t \big(g_r(\tau) - h_r(\tau)\big)\, d\tau. \qquad (D.5)$$

Human-centric automation [22] requires that a designated authority set $\mathcal{U}$ can override both grant and hold. Writing $u \in \mathcal{U}$ for an authorized operator action,

$$g_r(t) \leftarrow g_r(t) \vee 1_{\{u\ \text{grants}\ r\}}. \qquad (D.6)$$

An analogous rule holds for hold. The logical disjunction is the mathematical statement that machine recommendation never extinguishes human grant authority the defining Industry 5.0 constraint on the subsequent QUBO.

D.3 Physical Integrity and PLC Anti-Theft

The power-line-carrier anti-theft layer [24] is represented by a binary integrity process $\iota_a(t)$ that equals 1 only when the expected carrier heartbeat is present and the sealed-path checksum matches:

$$\iota_a(t) = 1_{[|s_a(t) - s_{a*}(t)| \le \varepsilon_{PLC}]}. \qquad (D.7)$$

The telemetry flag in (D.1) is then the conjunction of communication freshness and physical integrity:

$$\sigma_a(t) = 1_{[L_a(t) \le L_{max}]} \cdot \iota_a(t). \quad \text{(D.8)}$$

Any assignment that would move an asset with $\sigma_a(t) = 0$ is added to the forbidden set of the dispatch model, so physical-integrity failure is visible both to the annealer and to the twin. Hash-chain provenance commits the heartbeat residue together with the FKF window that contained it [6].

D.4 Coupled Sensing–Computation Loop

Latency, authorization, and integrity do not sit beside the optimizer; they bound it. The admissible action set at t is

$$U_{adm}(t) = \{u: E_{work}(u) \le E_{avail}(t) - E_{reserve}, \ \sigma_a(t) = 1, \ g_u(t) = 1\}. \quad \text{(D.9)}$$

Equation (D.9) is the human-centric, energy-aware, integrity-aware gate through which every quantum or classical dispatch must pass [8,26]. The reserve term protects battery and solar-assisted headroom so that green-logistics mode shifts remain feasible after a shock [5,29].

IV. SPECTRAL COUPLING, RESULTS, AND DISCUSSION

Once an action lies in U_{adm}, the twin updates a compact FKF–FKL state. Let $\psi = (\mu_0, \mu_1, \rho_{peak}, \omega^*)$ collect low-order FKL moments with the dominant FKF modulus and its frequency [12,18]. The time-shift property implies $\psi(\ell_\tau) = \psi(\ell)$ for a pure translation [11,19]. After compensation of exponential intensity [20], residual spectral displacement

$$\Delta_{spec}(\omega) = \frac{\|\mathcal{F}_{FKF}[\ell]\|_{KL}}{\|\mathcal{F}_{FKF}[\ell]\|_{KL} + \varepsilon_0} \quad (4)$$

together with FKL concentration declares residue-based resonance [10,13]. Three qualitative regimes follow.

Regime I — gated translation. Freshness, grant, and PLC integrity all hold; the FKF envelope is unchanged; only phase moves. The twin commits ψ without raising a new-mechanism alarm. This is the desired digital-twin behavior under reporting offset or synchronized shipment hold.

Regime II — intensity or energy drift. Exponential modulation or a change in $E_{b,a}$ rescales amplitude or the FKL centre of gravity, yet U_{adm} remains nonempty because reserve energy and human grant are intact. Green-logistics mode choice may shift volume onto solar-assisted or plug-in-hybrid legs without a QUBO restart.

Regime III — integrity or resonance failure. Either $\sigma_a = 0$ (stale packet, missing PLC heartbeat, or hold) or Δ_{spec} exceeds threshold with concentrated FKL residue. The action is excluded from U_{adm} and, if resonance persists across sequentially convergent windows [33], the hybrid annealer is invoked on a QUBO whose quadratic terms penalize simultaneous use of resonant unit-load-device slots [26].

These regimes are theoretical consequences of (D.1)–(D.9) together with published FKF/FKL properties; they are not a substitute for a labelled industrial trial. Their value is diagnostic separation: observational confound, energy drift, authorization conflict, physical-integrity loss, and structural resonance are no longer collapsed into a single anomaly flag. That separation is what makes constrained resilience computable inside a digital twin [4–13,18–30,33,34].

A practical implementation remark follows. Digital-twin commit should write four fields per window: the feature vector ψ, the freshness bit of (D.3), the grant bit of (D.6), and the PLC bit of (D.7). The hash-chain leaf is the concatenation of those fields with the atomic observation times that entered the distributional pairing [6,32]. Downstream AI scoring for green logistics can then be trained on ψ alone when integrity is one, and must be frozen when integrity is zero, preventing a stale or stolen asset from teaching the predictor a spurious lead-time mode [5]. Unit-load-device QUBO variables are instantiated only for assets with $\sigma_a = 1$ and $g_u = 1$, which keeps the Ising graph small enough for contemporary annealers [26,28].

The discussion is qualitative because the governing properties are identities and implications, not estimated elasticities. That is appropriate for a reconstruction paper whose purpose is to restore missing equations and to place every required reference in a citable scholarly form. Quantitative thresholds remain a calibration task for a subsequent instrumented yard study.

V. CONCLUSION

This paper reconstructed a complete, professionally typeset gate between IoT sensing and quantum-constrained dispatch. The telemetry state (D.1), latency and freshness laws (D.2)–(D.3), swipe-controller authorization (D.4)–(D.6), PLC integrity (D.7)–(D.8), and the admissible set (D.9) make human-centric Industry 5.0, smart mobility, anti-theft integrity, and energy limits first-class constraints. Coupled to shift-invariant FKF analysis, FKL moments, distributional pairing, and sequential convergence, the same gate feeds digital-twin commit, hash-chain provenance, green-logistics mode choice, and unit-load-device annealing. Future work is empirical calibration of L_{max}, ε_{PLC}, and resonance thresholds on live yard traces, and uncertainty-aware twins that carry those thresholds as random measures.

REFERENCES

[1] Christopher, M., & Peck, H. (2004). Building the resilient supply chain. *The International Journal of Logistics Management*, 15(2), 1–14.

[2] Sheffi, Y., & Rice, J. B. (2005). A supply chain view of the resilient enterprise. *MIT Sloan Management Review*, 47(1), 41–48.

[3] Saberi, S., Kouhizadeh, M., Sarkis, J., & Shen, L. (2019). Blockchain technology and its relationships to sustainable supply chain management. *International Journal of Production Research*, 57(7), 2117–2135.

[4] Akarshan Gulhane (2024). 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, no. 12, **DOI** 10.56726/IRJMETS64992.

[5] Akarshan Gulhane (2024). 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, no. 12, **DOI** 10.56726/IRJMETS65006.

[6] Akarshan Gulhane (2024). 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, no. 12, **DOI** 10.56726/IRJMETS65016.

[7] Akarshan Gulhane (2014). SWIPE CONTROLLER. International Journal of Research in Engineering and Applied Sciences (IJREAS), vol. 4, no. 12, pp. 1–7, **URL** indianjournals.com/article/ijreas-4-12-001.

[8] Akarshan Gulhane (2026). Navigating the Quantum Revolution in Logistics: Opportunities and Practical Applications in Supply Chain Management. International Journal of Engineering and Techniques, vol. 12, no. 3, pp. 553–556, **DOI** 10.29126/ijet.2026.v12.i3.553.

[9] Akarshan Gulhane (2025). 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, no. 7, **DOI** 10.55041/IJSREM51198.

[10] Akarshan Gulhane (2026). 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, **DOI** 10.55041/ijcope.v2i8.141.

[11] Akarshan Gulhane (2026). 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, vol. 2, no. 8, **DOI** 10.55041/ijcope.v2i8.136.

[12] Akarshan Gulhane (2026). Spectral Framework Based on the FKF Transform for Supply Chain Dynamics and Resilience. International Journal of Creative and Open Research in Engineering and Management, vol. 2, no. 8, **DOI** 10.55041/ijcope.v2i8.140.

[13] Akarshan Gulhane (2026). 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, vol. 2, no. 8, **DOI** 10.55041/ijcope.v2i8.139.

[14] Min, H. (2010). Artificial intelligence in supply chain management: Theory and applications. *International Journal of Logistics Research and Applications*, 13(1), 13–39.

[15] Lee, J., Bagheri, B., & Kao, H.-A. (2015). A cyber-physical systems architecture for Industry 4.0-based manufacturing systems. *Manufacturing Letters*, 3, 18–23.

[16] Longo, F., Padovano, A., & Umbrello, S. (2020). Value-oriented and ethical technology engineering in Industry 5.0. *Applied Sciences*, 10(12), 4182.

[17] Preskill, J. (2018). Quantum computing in the NISQ era and beyond. *Quantum*, 2, 79

[18] Akarshan Gulhane (2025). FKL Transform Key Properties, And Applications To Supply-chain Analysis. International journal of Engineering sciences and Advanced Technology, vol. 25, no. 12, pp. 596–605, **DOI** 10.64771/ijesat.2025.v25.i12.3816.

[19] Akarshan Gulhane (2025). Expanded Treatment Of the Time-Shift Property Of FKF Transform With Supply-Chain Applications. International journal of Engineering sciences and Advanced Technology, vol. 25, no. 12, pp. 606–616, **DOI** 10.64771/ijesat.2025.v25.i12.3817.

[20] Akarshan Gulhane (2025). 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, **DOI** 10.64771/ijesat.2025.v25.i12.3818.

[21] Akarshan Gulhane (2024). 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, no. 12, pp. 297–317, **DOI** 10.64771/ijesat.2024.v24.i12.3372.

[22] Akarshan Gulhane (2024). 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, no. 12, pp. 287–296, **DOI** 10.64771/ijesat.2024.v24.i12.3371.

[23] Akarshan Gulhane (2020). The Future of Vehicles: Solar-Powered Battery Electric Hybrid Vehicle Architecture. Tech Briefs Create the Future Design Contest, Automotive and Transportation, entry 10457, Available:

https://contest.techbriefs.com/2020/entries/automoive-transportation/10457

[24] Akarshan Gulhane (2014). Power line carrier communication based anti-theft system. International Journal of Research in IT and Management, vol. 4, no. 12, pp. 1–11, **URL** indianjournals.com/article/ijrim-4-12-001.

[25] Akarshan Gulhane (2017). Battery sizing for plug-in hybrid electric vehicles — Formula hybrid. in Proc. 2017 IEEE International Conference on Power, Control, Signals and Instrumentation Engineering (ICPCSI), pp. 368–372, **DOI** 10.1109/ICPCSI.2017.8392317.

[26] Akarshan Gulhane (2026). Quantum Computing for Logistics Optimization: Annealing in Unit Load Device Configuration and Disruption. International Journal of Research Publication and Reviews, vol. 7, no. 6, pp. 4643–4648, **DOI** 10.55248/gengpi.07.0626.16a57.

[27] Akarshan Gulhane (2025). Smart Mobility and Intelligent Transportation Systems: Emerging Trends, Technologies, and Challenges. International Journal of Scientific Research in Engineering and Management (IJSREM), vol. 9, no. 11, **DOI** 10.55041/IJSREM53436.

[28] Akarshan Gulhane (2025). 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, no. 9, **DOI** 10.55041/IJSREM52469.

[29] Akarshan Gulhane (2025). Solar-Assisted Electric Mobility: Design Framework and Performance Assessment of Sustainable Hybrid Vehicle Architectures. International Journal of Engineering Research and Science & Technology, vol. 21, no. 3, pp. 362–368, **DOI** 10.56636/ijerst.2025.v21.i03.3594.

[30] Akarshan Gulhane (2025). Supply Chain Resilience in the Era of Digital Transformation: A Systematic Literature Review and Research Agenda. International Journal of Engineering Research and Science & Technology, vol. 21, no. 4, pp. 1058–1068, **DOI** 10.56636/ijerst.2025.v21.i04.3812.

[31] Kshetri, N. (2018). Blockchain's roles in meeting key supply chain management objectives. *International Journal of Information Management*, 39, 80–89.

[32] Akarshan Gulhane (2026). Distributional Extension of the FKF Transform and Its Relevance to Supply-Chain Systems. International Journal of Creative and Open Research in Engineering and Management, vol. 2, no. 8, **DOI** 10.55041/ijcope.v2i8.137.

[33] Akarshan Gulhane (2026). Sequential Convergence in the Testing Function Space of the Two-Sided FKF Transform. International Journal of Creative and Open Research in Engineering and Management, vol. 2, no. 8, , **DOI** 10.55041/ijcope.v2i8.138.