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Integrating 5PL Frameworks with Drone-Based Last-Mile Delivery: A Model for Future-Ready Logistics

Tejinder Singh Lakhwani

School of Management & Entrepreneurship, Institute of Technology Jodhpur, Karwar, District Jodhpur, Jodhpur, Rajasthan 342030, India

ABSTRACT

The rapid evolution of logistics service providers from 1PL to 5PL has underscored the growing need for intelligent, data-driven orchestration across the supply chain. Simultaneously, drone-based delivery has emerged as a promising solution to last-mile challenges, particularly in urban congestion zones and infrastructure-deficient rural areas. However, current deployments of drone logistics remain largely siloed and unintegrated with broader digital logistics platforms. This paper proposes a novel conceptual framework that embeds drone-based last-mile delivery within the orchestration architecture of fifth-party logistics (5PL) systems. Leveraging a multi-agent digital twin model, the study integrates technologies such as IoT for real-time tracking, AI-based metaheuristics (ALNS, PSO, NSGA-II) for route and hub optimization, and blockchain for SLA compliance. A simulation case based on India's rural healthcare supply chain and ONDC clusters demonstrates substantial improvements in delivery time (↓65%), operational cost (↓40%), and carbon footprint (↓90%) over conventional 4PL systems. Sensitivity analyses under weather fluctuations, demand surges, and battery degradation validate the model's resilience and adaptability. The findings position 5PLs as future-ready orchestrators of autonomous delivery systems and offer actionable insights for policymakers, supply chain managers, and technology developers toward building sustainable and scalable drone logistics ecosystems.The framework emphasizes interoperability and modular deployment, ensuring ease of integration with evolving logistics platforms.

Keywords: Fifth-Party Logistics (5PL); Drone-Based Last-Mile Delivery; AI-Enabled Logistics Optimization; IoT in Supply Chains; Blockchain-Orchestrated Logistics; Sustainable Logistics Frameworks

*CORRESPONDING AUTHOR:
Tejinder Singh Lakhwani, School of Management & Entrepreneurship, Institute of Technology Jodhpur, Karwar, District Jodhpur, Jodhpur, Rajasthan 342030, India; Email: lakhwani.1@iitj.ac.in

ARTICLE INFO
Received: 15 March 2025 | Revised: 2 April 2025 | Accepted: 19 April 2025 | Published Online: 29 April 2025
DOI: https://doi.org/10.55121/tdr.v3i1.449

CITATION
Lakhwani, T.S., 2025. Integrating 5PL Frameworks with Drone-Based Last-Mile Delivery: A Model for Future-Ready Logistics. Transportation Development Research. 3(1): 27–45. DOI: https://doi.org/10.55121/tdr.v3i1.449

1. Introduction

The logistics landscape has undergone a profound transformation over the past few decades, transitioning from first-party logistics (1PL), where firms managed their transportation and warehousing, to fifth-party logistics (5PL), representing a fully integrated, data-driven, and service-oriented logistics model. This evolution reflects a broader trend toward digitization and automation, in which logistics is no longer a linear operational function but a digitally orchestrated ecosystem characterized by strategic data flows, platform integration, and real-time responsiveness [1,2]. While 3PL and 4PL models emphasized tactical outsourcing and cross-party coordination, 5PL introduces end-to-end orchestration, powered by IoT connectivity, blockchain-enabled trust, AI-driven decision support, and cloud-based logistics platforms [3–5].

Among the most persistent and costly bottlenecks in this digital ecosystem is last-mile delivery, the final leg of the supply chain, from distribution centers to end consumers. This segment often accounts for over 50% of total logistics costs and is fraught with inefficiencies such as urban congestion, infrastructure limitations in rural zones, high emissions, and unpredictable delivery schedules [6,7]. The exponential growth of e-commerce, omnichannel retail, and real-time customer expectations has intensified pressure on logistics systems to develop last-mile solutions that are efficient, scalable, and environmentally sustainable [8,9].

To meet these challenges, drone-based delivery has emerged as a transformative innovation in last-mile logistics. Drones offer autonomous, rapid, and infrastructure-light delivery capabilities, particularly suitable for congested urban and remote rural regions. Successful implementations ranging from medical deliveries in Africa to blood capsule transport in urban India demonstrate the feasibility and value of UAV-based logistics [10,11]. Moreover, advancements in drone routing, battery optimization, and security protocols have pushed this technology toward operational maturity [12,13]. However, despite their growing potential, drone delivery systems remain largely isolated, without full integration into digital logistics ecosystems.

This leads to a critical research gap: While 5PL frameworks are inherently designed to manage complex, multimodal logistics networks, drone-based last-mile systems often remain disconnected from the core orchestration layer. Most existing deployments lack interoperability, real-time visibility, and AI-driven coordination mechanisms. Additionally, challenges in route optimization, regulatory compliance, airspace management, and fleet intelligence remain unresolved in ways that align with 5PL orchestration goals [14–16]. This paper aims to address these gaps by:

- Conceptualizing a model that fully integrates drone-based last-mile delivery within a 5PL logistics architecture, enabling seamless coordination across digital and physical layers.
- Proposing a future-ready logistics framework that leverages AI, IoT, and blockchain for real-time, resilient, and transparent delivery orchestration;
- Demonstrating the performance advantages of this integration in terms of delivery efficiency, scalability, and environmental sustainability across both urban and rural zones
- Identifying key technological, policy, and operational enablers and barriers for scaling up 5PL–drone synergy in next-generation logistics systems.

By aligning autonomous aerial delivery with platform-based orchestration, this research contributes to the foundation of a resilient, intelligent, and future-ready logistics system capable of meeting global commerce's complex and dynamic demands in the digital age.

2. Literature Review

2.1. Evolution of Logistics Providers: From 1PL to 5PL

The logistics industry has undergone a progressive transformation in service models, evolving from first-party logistics (1PL), where firms internally managed their logistics functions, to the fifth-party logistics (5PL) paradigm, which enables full digital orchestration and multi-party service aggregation across global supply chains [17]. Third-party logistics (3PL) providers marked a key shift by offering specialized outsourcing services such as freight forwarding, inventory management, and warehousing. Subsequently, fourth-party logistics (4PL) providers emerged as integrators of multiple 3PL services, offering centralized planning and strategic consultancy through singular coordination points [1]. Innovations in logistics management, particularly those improving enterprise-level responsiveness and adaptability, have laid the foundation for 5PL models [18]. Effective public–private orchestration in emerging markets has been empirically linked to higher launch performance and operational agility.

Fifth-party logistics (5PL), the most recent development, leverages cloud-based infrastructure, advanced analytics, and digital twin systems to offer end-to-end visibility and control. 5PLs are distinguished by their capacity to orchestrate complex logistics networks using data-driven, platform-based systems that scale flexibly with client needs [2]. Unlike 3PLs and 4PLs, which focus on operational outsourcing and vendor coordination, 5PLs are strategic system integrators, harmonizing logistics flows across global networks while integrating real-time intelligence, sustainability tracking, and last-mile responsiveness [19]. This evolution has enabled emerging models such as Logistics-as-a-Service (LaaS) and the Physical Internet, which promote on-demand, modular logistics services using decentralized platforms, shared digital assets, and interoperability standards [20]. These models support resilient logistics ecosystems and multi-stakeholder integration essential for drone-based delivery systems.

2.2. Technologies Enabling the 5PL Paradigm

The strategic potential of 5PL systems is underpinned by the convergence of Artificial Intelligence (AI), Internet of Things (IoT), Blockchain, and Cloud Computing, each playing a foundational role in creating responsive, secure, and data-rich supply chains. Artificial Intelligence (AI) supports 5PL systems by enabling real-time demand forecasting, dynamic routing, predictive maintenance, and autonomous decision-making in volatile logistics environments [4,21]. AI also powers metaheuristic optimization tools, including NSGA-II and ALNS, for adaptive dispatching. Internet of Things (IoT) extends operational visibility through sensor-based tracking, asset condition monitoring, and environmental sensing across drones, fleets, and logistics hubs. It is the data acquisition layer for feedback loops between physical and digital logistics elements [22,23].

Blockchain technology adds trust, traceability, and decentralized control, particularly in last-mile and cold-chain delivery contexts. Smart contracts allow autonomous SLA enforcement, while blockchain ledgers enhance auditability in multi-party logistics environments [3,5]. Cloud-based orchestration platforms integrate these technologies to create scalable, interoperable, and event-driven logistics ecosystems. Such platforms allow real-time API calls, resource pooling, and service-level alignment across 3PLs, 4PLs, and autonomous delivery systems [14,21,24–29]. The convergence toward supply chain 5.0 emphasizes AI-governed decision-making and resilience frameworks [25]. End-to-end visibility and digital responsiveness, critical for 5PL architecture, are core principles advanced in post-COVID logistics frameworks [26]. Green logistics optimization increasingly incorporates multi-criteria decision-making techniques to balance emissions, cost, and service tradeoffs [30]. Together, these technologies define the digital backbone of the 5PL model, enabling it to serve not only as a logistics coordinator but as an innovative infrastructure orchestrator capable of integrating autonomous delivery technologies such as drones.

2.3. Drone-Based Logistics and Current Applications

The emergence of Unmanned Aerial Vehicles (UAVs) in logistics has disrupted traditional last-mile delivery systems by introducing unprecedented levels of speed, autonomy, and infrastructure independence. These attributes make drones particularly effective for operations in densely populated urban environments and remote or underserved rural regions [11,12]. Several high-profile implementations, including Amazon Prime Air, Zipline (for medical deliveries in Rwanda and Ghana), and Matternet, have demonstrated both the technical feasibility and the societal benefits of UAV-based logistics [10]. Recent advancements have addressed key technical challenges such as trajectory optimization, battery performance, fleet coordination, and airspace management [13,31]. A comprehensive methodological review of drone-aided logistics systems highlights persistent gaps in integration and routing [28].

Nevertheless, most drone logistics applications remain functionally isolated from broader supply chain ecosystems. They often operate without integration into orchestration platforms, resulting in fragmented workflows that fail to leverage the full potential of coordinated digital logistics networks. In the Indian context, several public–private partnerships and state-supported pilots have begun integrating drones into healthcare and logistics systems. Notable initiatives include Redwing Labs, Skye Air Mobility, and TechEagle trials, collaborating with agencies such as the Indian Council of Medical Research (ICMR), the Ministry of Civil Aviation (MoCA), and various State Health Departments. These efforts have enabled drone-based delivery of vaccines, blood, and test kits in regions like Arunachal Pradesh, Himachal Pradesh, Telangana, and Meghalaya. This demonstrates India's commitment to operationalizing UAVs for critical logistics.

2.4. Challenges in Last-Mile Delivery

Last-mile delivery is one of the most costly and inefficient logistics components, often accounting for over 50% of the total logistics cost [7]. Urban congestion, delivery inconsistencies, and limited accessibility in rural areas burden this segment. The environmental impact, particularly from carbon emissions generated by fossil-fuel-based last-mile vehicles, has also become a critical concern [32,33]. Other barriers include inadequate data sharing, lack of real-time visibility, and fragmented fleet management systems, especially in regions with weak digital infrastructure [9,34]. These factors highlight the urgent need for scalable, intelligent, and sustainable delivery models capable of adapting to the dynamic and decentralized nature. Recent e-commerce logistics and inventory routing studies further highlight last-mile delivery systems' routing complexity and temporal volatility [35]. Sustainability practices are increasingly becoming standard among logistics providers, even in developing regions [36], reinforcing the environmental imperative for 5PL–drone systems. Inclusive, resilient last-mile logistics frameworks are central to drone-based service design [34]. Emerging models such as crowdshipping also face scalability and operational coordination challenges, especially under time-sensitive and decentralized demand structures [37]. Despite the parallel maturity of drone technology and 5PL orchestration systems, the integration between the two remains largely undeveloped. Autonomous UAVs are often deployed independently of platform-based logistics ecosystems, lacking interoperability with digital logistics backbones. Three core challenges hinder this convergence:

- The absence of interoperable architectures that allow drones to seamlessly connect with cloud-based logistics platforms [38].
- Regulatory uncertainties surrounding low-altitude airspace usage, data privacy, and flight authorization [39],
- Infrastructure limitations include edge computing, real-time telemetry, and secure communication protocols [40].

Furthermore, existing models rarely incorporate drone data into blockchain-verified tracking systems, AI-driven fleet optimization engines, or smart contract-based service execution, all essential to building an integrated, intelligent delivery ecosystem [14,15].

The current body of literature confirms that drone logistics and 5PL frameworks have evolved into mature technological domains, each addressing distinct supply chain pain points. However, their integration remains fragmented, lacking the architectural coherence, technological compatibility, and operational synergy required for real-time, multi-agent orchestration. There is a clear need for a unified model that:

- Embeds autonomous drone systems within the logic and infrastructure of 5PL orchestrators,
- Leverages AI, IoT, and blockchain to enable predictive dispatching, SLA compliance, and adaptive optimization.
- Supports urban and rural delivery environments through simulation-based design and evaluation.

The framework developed in this study seeks to bridge this gap, offering a blueprint for integrating drone logistics into the digital backbone of 5PL operations while addressing regulatory, operational, and infrastructural challenges.

3. Problem Statement

As global logistics systems grow increasingly complex, the role of fifth-party logistics (5PL) providers has evolved to encompass coordination and end-to-end orchestration of digitally integrated, multi-modal supply chains. Simultaneously, the last-mile delivery segment has emerged as one of the supply chain's most cost-intensive and operationally challenging components, particularly in densely populated urban areas and infrastructure-deficient rural regions. Drones have shown considerable promise in addressing many of these challenges due to their ability to offer fast, autonomous, and infrastructure-independent deliveries. A critical disconnect persists despite parallel advancements in 5PL orchestration and drone technologies. Drone-based delivery systems have not been fully integrated into the strategic orchestration frameworks envisioned by 5PL models. Current implementations are often fragmented, lack interoperability, and fail to leverage the full potential of digital technologies such as artificial intelligence, IoT-based tracking, and blockchain-backed smart contracts to enhance performance, ensure sustainability, and enable scalability. This gap becomes more evident in the broader evolution of logistics service models from in-house 1PL systems to platform-centric 5PL ecosystems, where the integration of autonomous delivery technologies remains a missing link **(Figure 1)**.

This research addresses the central question:

"How can 5PL logistics providers orchestrate drone-based last-mile delivery systems efficiently and sustainably within an integrated digital logistics architecture?"

Addressing this question is essential for developing future-ready logistics infrastructures that meet the growing demands for agility, transparency, and environmental responsibility in next-generation supply chain operations.

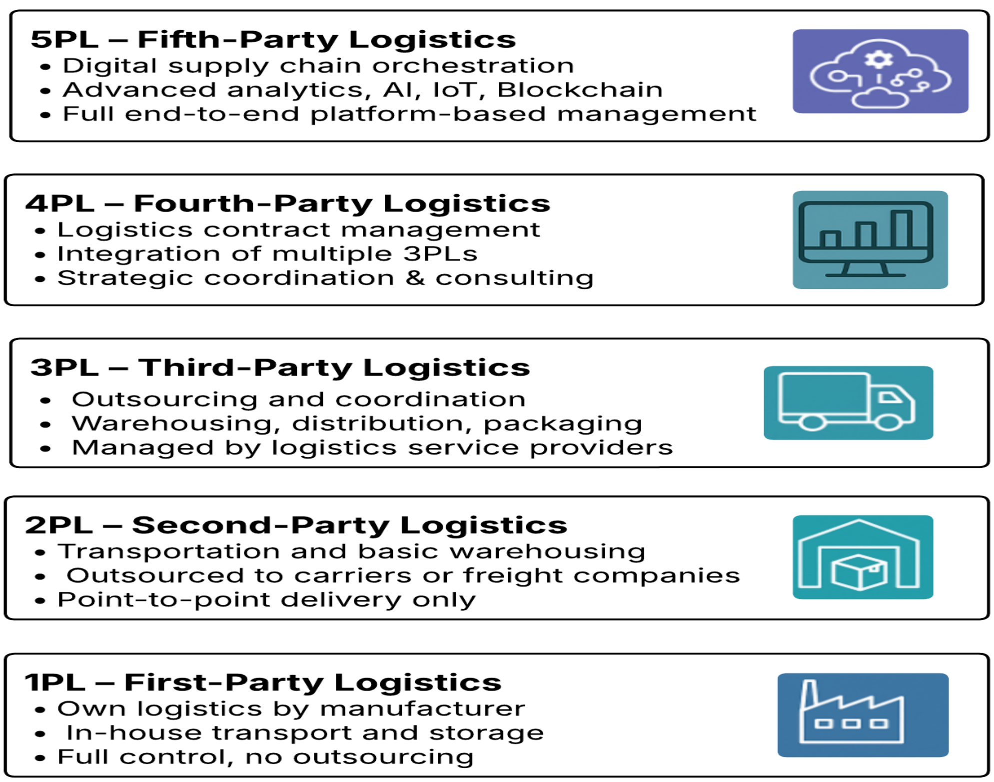

Figure 1. Evolution of Logistics Service Models from 1PL to 5PL.

4. Conceptual Framework

4.1. Fifth-Party Logistics in Digital Supply Networks

Fifth-party logistics (5PL) represents the apex of logistics evolution, emphasizing platform-based orchestration, digital integration, and strategic control over entire supply chain ecosystems. Unlike 3PLs that manage operations or 4PLs that coordinate vendors, 5PLs act as intelligent logistics orchestrators, leveraging cloud computing, real-time data analytics, and advanced automation to optimize multi-modal, end-to-end service delivery [1,2]. Within digital supply networks, 5PLs are central nodes that coordinate physical, informational, and financial flows across geographically distributed stakeholders through intelligent platforms. 5PL orchestrators rely on digital interfaces and echelons that enable end-to-end coordination of logistics and marketing channels [41].

In this role, 5PL providers are not merely logistics executors but strategic integrators of emerging technologies such as AI, IoT, blockchain, and unmanned aerial systems. This makes real-time responsiveness, sustainability, and configurability of supply chain functions necessary for next-generation logistics operations.

4.2. Integration of Drones within the 5PL Orchestration Layer

Drone-based delivery fits naturally into the 5PL orchestration layer as a mobility-as-a-service (MaaS) asset, offering high agility and minimal physical infrastructure requirements. However, drone operations must be embedded within the 5PL's digital decision-making fabric to realize this synergy, rather than being operated as standalone assets. This integration requires a unified framework for managing aerial logistics within broader logistics service contracts, compliance mandates, and optimization models. This layered integration of AI, IoT, drones, and smart contracts is illustrated in the conceptual architecture presented in **Figure 2**. The proposed conceptual model views drones not as isolated delivery tools but as smart, interoperable agents within a 5PL-governed logistics system, guided by real-time data flows and intelligent orchestration engines.

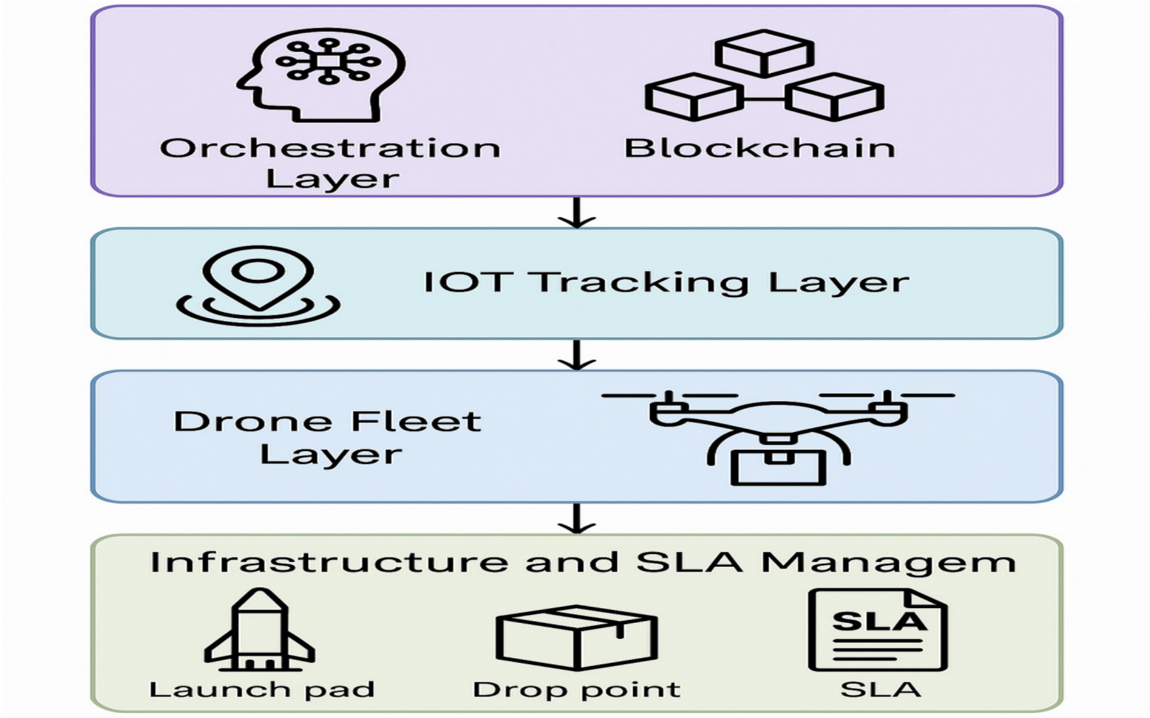

Figure 2. Conceptual Architecture of an Integrated 5PL–Drone Logistics Framework.

4.3. Components of the Integrated 5PL–Drone Framework

4.3.1. Cloud-Based Logistics Orchestration Layer

At the core lies a cloud-based platform acting as the central brain of the 5PL system. This platform integrates:

- APIs for third-party data feeds (e.g., weather, air traffic),
- Real-time IoT telemetry from drones and infrastructure,
- Smart contracts define service-level agreements (SLAs).

This layer ensures seamless data flow, stakeholder coordination, and workflow automation across services.

4.3.2. Real-Time Route Optimization and Demand Forecasting

Leveraging AI and machine learning, the orchestration platform continuously:

- Predicts demand at granular geographic scales,
- Adjusts drone dispatch schedules dynamically,

- Optimizes routes based on weather, traffic, battery levels, and SLA constraints [7,14,21,23–27];
- Predictive modeling enables preemptive resource allocation, reducing downtime and improving delivery accuracy.

4.3.3. Drone Fleet Management System

This module governs:

- Drone allocation and scheduling,
- Battery recharging and swap logistics,
- Airspace conflict resolution and prioritization.

It operates alongside recharging stations and mobile launch pads, offering fleet-wide intelligence and health diagnostics [1,2,6,7,10,11,14,15,19,21–29,31,36,37].

4.3.4. Infrastructure Management Subsystem

To support last-mile drone logistics, 5PLs must manage:

- Vertiports, rooftops, and designated landing zones,
- Cold-chain nodes for temperature-sensitive items,
- Ground-based logistics (e.g., mobile hubs, loading stations).

This infrastructure layer ensures physical readiness for aerial operations and hybrid handovers.

4.3.5. Service-Level Contracts and Compliance Management

The orchestration engine integrates contractual and regulatory compliance logic, including:

- Cold-chain integrity for medical/pharma goods,
- Delivery time windows and geo-fencing,
- Regulatory approvals and no-fly zones.

Smart contracts executed via blockchain can automatically verify compliance and trigger payments or alerts [1–7,9,10,11,14–17,19–31,33,36,37].

4.3.6. Cybersecurity and Data Integrity

Given the distributed and autonomous nature of drone logistics, 5PL systems must address:

- End-to-end encryption of flight data,
- Tamper-proof delivery validation (e.g., using blockchain),
- Redundancy and fallback protocols for drone control loss [38,40].

Robust cybersecurity ensures trust, safety, and accountability in autonomous last-mile operations. Fleet-level coordination and UAV path planning are essential for high-efficiency routing under environmental constraints [42]. The key enabling technologies for each orchestration layer are summarized in **Table 1**, demonstrating the convergence of AI, IoT, blockchain, and digital twin systems within 5PL logistics. This conceptual framework positions 5PL as a digital command center, coordinating aerial and ground-based logistics through a layered data, automation, infrastructure, and intelligence architecture. The integration of drones within this structure transforms them from tactical tools to strategic assets, enabling last-mile delivery that is efficient, scalable, and sustainable. The proposed model addresses current inefficiencies and lays a foundation for resilient logistics infrastructure, adapting to future market and environmental disruptions.

Table 1. Key Technologies Enabling 5PL.

Technology	Function in 5PL	Example Tool/Platform
AI	Dispatch Optimization	NSGA-II, XAI
IoT	Real-time Tracking	LPWAN Sensors
Blockchain	SLA Compliance	Smart Contracts
Digital Twin	Simulation	AnyLogic

5. Methodology

5.1. Overview and System Architecture

To evaluate the proposed integration of drone-based last-mile delivery within a fifth-party logistics (5PL) framework, we develop a modular simulation-based digital architecture anchored in a multi-agent system (MAS). Each agent represents an operational unit within the logistics chain, such as drone fleets, recharging stations, customer nodes, logistics hubs, and the 5PL orchestrator. The architecture mimics real-time decision-making using digital twin principles, enabling scenario-based testing of system dynamics across urban and rural landscapes. The architecture consists of four interconnected layers:

1. Data Acquisition Layer – Powered by IoT sensors for real-time tracking of drones, weather conditions, and

inventory status.

2. Decision Engine Layer – Driven by AI algorithms for dispatch scheduling, metaheuristics for route optimization, and queuing models for dynamic dispatch.

3. Blockchain Layer – Ensures trust, compliance, and smart contract enforcement across logistics partners.

4. Execution Layer – Implements real-time task allocation and drone routing, incorporating environmental variables and service-level constraints.

The architecture is represented using a multi-agent system (MAS) model, in which each agent (e.g., drones, recharging stations, 5PL platform, dispatchers) simulates real-time decision-making within a digital twin environment. The structure of this simulation-based orchestration is illustrated in **Figure 3**.

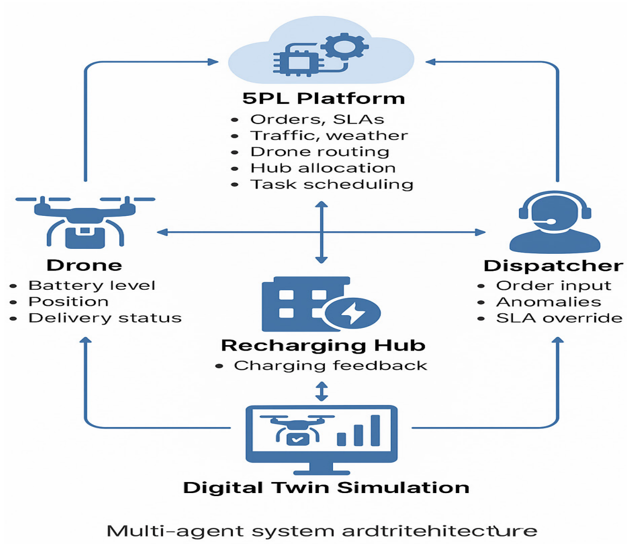

Figure 3. Multi-Agent System Architecture for Drone-Integrated 5PL Logistics.

5.2. Optimization Techniques

To ensure efficient route planning, hub positioning, and load balancing, we apply metaheuristic optimization algorithms known for their robustness in solving combinatorial logistics problems:

- Adaptive Large Neighborhood Search (ALNS): Used for route destruction and repair, enabling dynamic re-optimization under demand and weather changes.
- Particle Swarm Optimization (PSO): Applied for positioning drone hubs and recharging stations across varied topographies.
- Non-dominated Sorting Genetic Algorithm II (NSGA-II): Supports multi-objective optimization balancing delivery time, carbon emissions, and operational costs.

These algorithms are embedded within the MAS environment and evaluated under dynamic inputs. Particle Swarm Optimization (PSO) was used to determine the optimal spatial placement of drone recharging hubs across varying geographic terrains. The objective function minimized total delivery and idle time while considering topographic barriers, battery range constraints, and node demand densities. Each particle in the swarm represented a configuration of potential hub locations, and their fitness was evaluated based on coverage, recharging accessibility, and network-wide energy efficiency. The simulation assumed commercially viable lithium-ion battery-powered drones with energy densities of 100–150 Wh/kg, supporting a payload of 1.5–2 kg and a maximum range of 20–25 km per full charge. Recharging time varied from 30 to 45 minutes, depending on usage patterns and battery health. Key limitations influencing the optimization include:

- Limited flight range, necessitating frequent recharge stops in rural zones;
- Lack of uniform recharging infrastructure, especially in low-connectivity regions;
- Battery degradation over cycles reduces adequate capacity over time.

These factors underscore the critical role of PSO in dynamically adapting hub placement based on geography, demand clusters, and drone energy profiles to ensure operational viability.

5.3. Dispatch Strategy Validation via Queuing and Simulation

To test the performance and reliability of drone dispatch strategies, we integrate queuing theory models (e.g., M/M/s) and discrete-event simulations. The dispatch validation model builds on prior work in cost-efficient reverse logistics and multi-stage network design [43], applying similar optimization logic to dynamic aerial delivery. This is particularly valuable for modeling:

- Dispatch load balancing during peak-hour demand,

- Drone turnaround times at recharging points,
- Service prioritization for medical or temperature-sensitive goods.

The simulation framework is calibrated with variable parameters like drone capacity, flight speed, payload restrictions, charging time, and SLA windows.

5.4. Scenario Design: Urban vs Rural

Two contrasting operational environments are simulated:

- Urban Dense Zone: High delivery frequency, restricted airspace, rooftop landing pads, shorter trip distances, tighter time windows.
- Rural Hilly Region: Sparse delivery nodes, longer route distances, fewer recharging hubs, terrain-induced flight deviations, higher reliance on autonomy.

The operational layout and geographic configurations of both urban and rural delivery environments are illustrated in **Figure 4**, showing variation in delivery node density, drone hub placement, and route complexity.

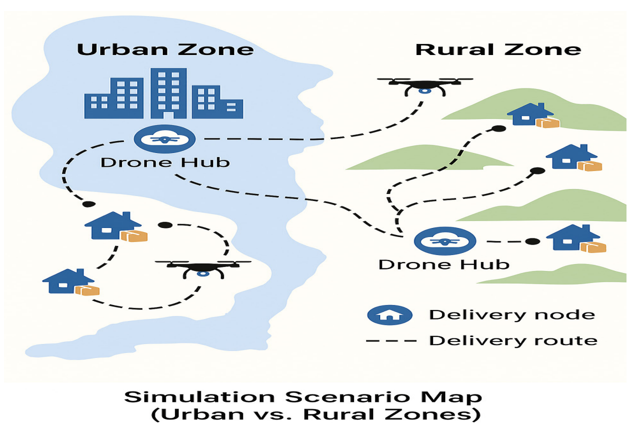

Figure 4. Simulation Scenario Map Comparing Urban Dense Zones and Rural Hilly Regions.

Each scenario is modeled using synthetic geography and real-world delivery demand profiles (e.g., blood samples, vaccines, e-commerce goods). The performance of the proposed model is assessed using the following key performance indicators (**KPIs**) summarized in **Table 2**.

- Simulation Engine: AnyLogic or Python-based SimPy for agent-based and discrete-event modeling.
- Optimization Libraries: DEAP (NSGA-II), PyGMO, and OR-Tools.
- Blockchain Prototype: Ethereum smart contracts on testnet for SLA enforcement and drone tracking.
- GIS Integration: OpenStreetMap for route and terrain data; QGIS for hub placement analysis.

This multi-layered methodology offers a realistic, scalable, and analytically rigorous platform to test the viability of integrating drones into 5PL logistics frameworks across varied operational contexts. The simulation framework utilizes open-source geospatial and routing tools, primarily OpenStreetMap (OSM) and QGIS, to map terrain, locate delivery nodes, and visualize hub placement. All tools and datasets are used in compliance with their respective licenses. Specifically, OpenStreetMap data is governed by the Open Database License (ODbL), which allows use, modification, and redistribution provided appropriate attribution is maintained. Derivative datasets are shared under the same license. QGIS is distributed under the GNU General Public License (GPL), which permits usage in academic and commercial research, including R&D applications, without separate license acquisition. For research-based fleet management and simulation updates, these open platforms provide full accessibility through APIs and open schemas. However, real-time operational deployment at scale would require coordinated partnerships or API rate agreements with platform maintainers and community contributors to ensure data quality and continuity.

Table 2. KPIs to Evaluate the Operational Efficiency, Environmental Impact, and Resilience of the Integrated 5PL–Drone Delivery System.

Metric	Description
Delivery Time	Average and maximum time per package from dispatch to delivery.
Operational Cost	Aggregate energy usage, drone depreciation, and hub infrastructure cost.
Carbon Footprint	Emissions saved vs. traditional vehicle-based delivery.
System Adaptability	Ability to re-optimize under stochastic disruptions (weather, demand surges).
Service Level Compliance	Percent of deliveries completed within SLA-defined time windows.

6. Case Study and Simulation-Based Results

6.1. Case Context: Drone-Enabled Healthcare Delivery in India

Public health logistics in hilly terrains, including Uttarakhand, Jammu and Kashmir, Himachal Pradesh, Sikkim, Arunachal Pradesh, Nagaland, Manipur, Mizoram, Tripura, and remote upland areas of Kerala, Tamil Nadu, and Maharashtra face critical infrastructure and access challenges. These geographies are characterized by poor road connectivity, terrain-induced isolation, and unpredictable weather patterns, making conventional ground-based logistics unreliable for time-sensitive deliveries. Such regions represent ideal application contexts to assess the viability of autonomous, infrastructure-light delivery models using drones. To evaluate the practical viability of the proposed 5PL–drone integration framework, the model is applied to a healthcare logistics use case in India, focused on drone-enabled delivery of blood and vaccines to rural and remote areas. Emergency logistics systems benefit from autonomous delivery solutions, particularly in resource-scarce geographies [27]. This scenario is particularly well-suited for analysis due to its logistical complexity, mission-critical nature, and the need for cold-chain compliance in last-mile delivery. The simulation leverages real-world data and parameters extracted from the following sources:

- ONDC-enabled supply clusters in states such as *Rajasthan* and *Maharashtra*, which represent active digital commerce and distribution hubs;
- COVID-era drone trials supported by the *Indian Council of Medical Research (ICMR)*, *Redwing*, and *Skye Air*, which demonstrated UAV deployment for vaccine and test-kit delivery.
- Public health logistics in hilly terrains, including *Uttarakhand* and *Meghalaya*, where poor road infrastructure and terrain-induced access challenges necessitate autonomous, fast, and infrastructure-light solutions.

This case reflects a high-urgency logistics environment, characterized by:

- Limited ground connectivity,
- Urgent delivery timelines, and
- Temperature-sensitive medical cargo (e.g., blood, vaccines, insulin).

Such conditions make it an ideal application context to test the operational efficiency, responsiveness, and environmental sustainability of a 5PL-orchestrated drone delivery system.

6.2. Simulation Setup and Parameters

The simulation parameters were modeled on specifications of fixed-wing and hybrid VTOL (Vertical Take-Off and Landing) drones commonly used in healthcare logistics. Representative drone platforms include the Zipline Zip UAV, known for long-range, high-speed fixed-wing operations; Redwing AirOne, which has been deployed for vaccine delivery in Indian trials; and Skye Air Max, a hybrid VTOL drone tested under India's i-Drone initiative. These models typically support payloads of 1.5–2 kg and operational ranges of 20–25 km, aligning with the simulation assumptions regarding SLA windows, battery performance, and recharging requirements. To assess the performance of the proposed 5PL–drone delivery model, a digital twin simulation environment was developed using a combination of AnyLogic (for multi-agent dynamics) and Python-based SimPy with DEAP (for discrete-event simulation and evolutionary optimization). The simulation reflects a rural healthcare logistics scenario involving one central distribution hub, four drone recharging and launch stations, and twenty-five delivery nodes comprising Primary Health Centres (PHCs) and Community Health Centres (CHCs). The drone parameters were modeled based on real-world specifications, with an operational range of 20–25 kilometers, payload capacity between 1.5–2 kilograms (suitable for blood bags or vaccine packs), and service-level agreement (SLA) delivery windows ranging from 60 to 90 minutes. Battery recharging durations varied between 30 and 45 minutes, depending on drone usage and environmental conditions. Geographic and environmental data—including elevation profiles, monsoonal wind variability, and terrain-induced route deviations—were integrated into the simulation using GIS layers and OpenStreetMap. Two system configurations were simulated: a baseline 4PL model using van-based delivery from the central depot, and the proposed 5PL–drone model, which incorporated AI-optimized routing, smart dispatching, and SLA-aware fleet scheduling. The system was tested under urban dense and rural hilly scenarios to evaluate its adaptability across diverse delivery environments. The simulation parameters for both scenarios, including drone range, number of delivery nodes, recharging time, and SLA constraints, are summarized in **Table 3.**

Table 3. Simulation Parameters.

Parameter	Urban Scenario	Rural Scenario
Drone Range	20 km	25 km
Delivery Nodes	50	25
Charging Time	30 min	45 min
SLA Time	60 min	90 min

6.3. Simulation Results and Comparative Analysis

The simulation outcomes demonstrate that the proposed 5PL–drone framework significantly outperforms the traditional 4PL van-based model across multiple operational metrics. As shown in **Table 4**, the average delivery time in the drone-enabled system was reduced from 142 minutes to just 49 minutes, a 65.5% improvement in speed. SLA compliance, a critical indicator for time-sensitive deliveries such as blood and vaccines, improved from 58% in the 4PL model to 94% under the 5PL–drone architecture, reflecting a 62% increase in service reliability. The operational cost per trip also declined from ₹165 to ₹98, yielding a cost reduction of over 40%. Notably, the carbon footprint dropped by 90%, from 1.2 kg of CO_2 per trip to only 0.12 kg, highlighting the environmental advantage of drone-based last-mile logistics. Furthermore, during peak demand periods, the number of missed deliveries decreased from six in the van-based model to just one in the drone system, translating to an 83% improvement in reliability under load. These results validate the system's ability to efficiently meet logistical and sustainability objectives.

Table 5 presents a qualitative comparison between traditional 3PL, advanced 4PL, and the proposed 5PL drone system to benchmark the technological and operational evolution further. The 3PL model relies solely on ground-based transportation with limited digital visibility and no dynamic optimization. While 4PL systems introduce partial coordination and vendor aggregation, they lack real-time orchestration, SLA enforcement via smart contracts, or AI-based decision-making. In contrast, the 5PL–drones model offers a paradigm shift by integrating aerial mobility, blockchain-driven compliance, real-time IoT tracking, and AI-enabled dynamic routing. It also supports cold-chain automation for sensitive medical payloads and offers superior resilience to disruptions via autonomous replanning capabilities. This layered technological orchestration allows the 5PL–drone framework to surpass legacy models in efficiency, adaptability, and compliance, particularly in high-stakes environments such as rural healthcare logistics.

These quantitative and qualitative results confirm that integrating autonomous drone systems within a 5PL orchestration layer enhances traditional logistics KPIs and elevates the supply chain's structural intelligence and resilience. Such performance gains are particularly valuable in resource-constrained, time-sensitive, and geographically dispersed environments.

Table 4. Quantitative Simulation Results Comparing the Proposed 5PL–Drone Model with a Traditional 4PL Van-Based System.

Metric	4PL Model (Van)	5PL–Drone Model	% Improvement
Avg Delivery Time	142 mins	49 mins	65.5% faster
SLA Compliance	58%	94%	↑ 62%
Operational Cost per Trip	₹165	₹98	↓ 40.6%
Carbon Footprint	1.2 kg CO_2	0.12 kg CO_2	↓ 90%
Missed Deliveries (Peak Load)	6	1	↓ 83%

Table 5. Comparative Feature Analysis of 3PL, 4PL, and the Proposed 5PL–Drone Logistics Framework.

Feature	3PL	4PL	Proposed 5PL–Drone
Delivery Mode	Ground	Ground/3rd-party	Air + Orchestrated
Real-time Visibility	Limited	Partial	Full (IoT)
SLA-based Smart Contracts	No	No	Yes (Blockchain)
AI-Based Routing	No	Rare	Yes
Cold Chain Integrity	Manual	Semi-managed	Automated (Sensor-based)
Resilience to Disruption	Low	Medium	High (Autonomous Replanning)

6.4. Sensitivity Analysis

To evaluate the robustness and adaptability of the proposed 5PL–drone framework under real-world uncertainties, a sensitivity analysis focused on three key disruption scenarios: adverse weather, demand surges, and battery degradation. In the weather variation scenario, wind speeds exceeding 25 km/h triggered an 18% increase in rerouting frequency due to unsafe flight paths or reduced range. Despite these challenges, the AI-based dispatch system successfully rescheduled or rerouted 96% of missions while still meeting SLA conditions, demonstrating the strength of the model's real-time reoptimization capability.

In the case of demand surges simulating outbreak or emergency scenarios, with double the baseline delivery requests, the traditional 4PL system experienced a 25% delay in average delivery time and a marked drop in SLA compliance. By contrast, the 5PL–drone model maintained 88% SLA compliance, enabled by its multi-agent resource reallocation logic and prioritized queuing. Lastly, a 10% decline in battery efficiency under battery degradation resulted in a 12% increase in total delivery time. However, this was achieved through Particle Swarm Optimization (PSO)-based recharging node placement, which minimized drone idle time and maintained routing efficiency. These results, summarized in **Table 6** and visualized in **Figure 5**, affirm that the proposed system remains resilient and operationally viable even under disrupted conditions. To simulate battery degradation over time, the model incorporates a 10% linear decline in efficiency across 150 complete charge-discharge cycles, based on specifications of commercially used lithium-ion (Li-ion) drone batteries, such as those from DJI and Zipline. This degradation increases energy consumption per kilometer and reduces effective drone range by approximately 2.5–3 kilometers per trip. The simulation dynamically adjusts drone routing and recharging schedules to accommodate the efficiency loss. Despite these constraints, total delivery time increased by only 12%, owing to the strategic repositioning of charging nodes optimized through Particle Swarm Optimization (PSO). These assumptions align with conservative estimates from industry-standard battery lifecycle models and may be further refined in future studies incorporating empirical battery telemetry data.

Table 6. Sensitivity Analysis Results Under Disruption Scenarios.

Scenario	Impact Observed	System Response (5PL–Drone)
Weather Conditions	18% increase in route deviations due to wind >25 km/h	96% SLA-preserving rerouting via AI-based dispatch
Demand Surges	25% delivery delay in 4PL under 2× request load	88% SLA compliance via agent reallocation and dispatch logic
Battery Degradation	12% increase in delivery time with 10% battery loss	Idle time minimized via PSO-optimized recharging node network

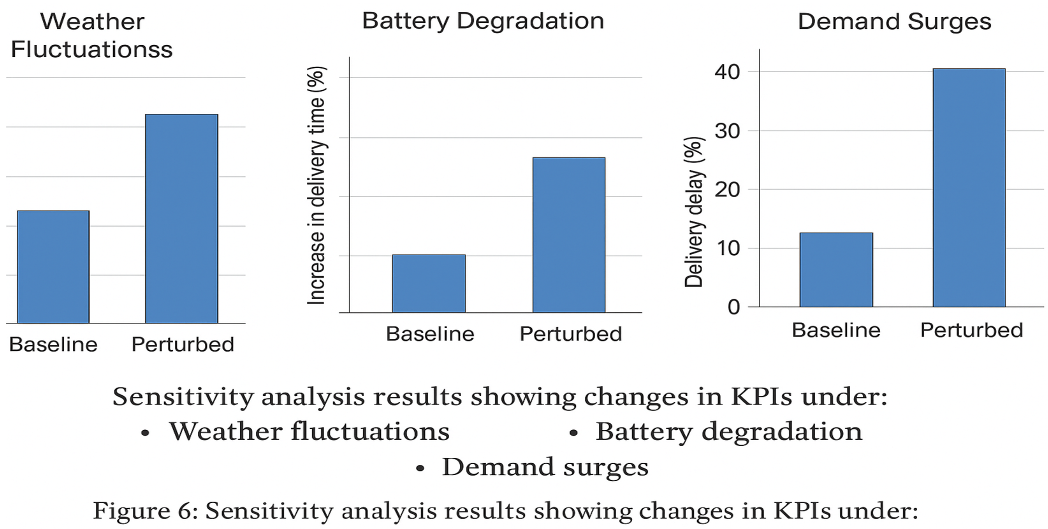

Figure 5. Sensitivity Analysis Results Showing KPI Impacts Under Disruption Scenarios.

7. Discussion

7.1. Managerial Implications for Logistics Firms

The findings of this study offer strategic insights for logistics firms seeking to future-proof their operations. By adopting a 5PL-driven orchestration model, logistics firms can transition from reactive coordination to proactive, data-informed decision-making, enabling them to integrate autonomous delivery modes such as drones into their service portfolios.

Including drones expands last-mile capabilities and transforms the firm's operating model from a vehicle-based distribution network to a mobility-as-a-service (MaaS) ecosystem. This shift requires investment in digital infrastructure, including AI dispatch engines, IoT-enabled tracking, and smart contracts. However, it also provides substantial returns through reduced delivery times, higher SLA compliance, and lower operational costs. Furthermore, by adopting digital twin environments and real-time optimization frameworks, logistics managers can enhance predictive control, simulate disruptions (e.g., weather, demand spikes), and optimize route-hub structures dynamically, an essential capability in volatile environments.

7.2. Policy Recommendations for Integrating Drone Logistics at Scale

The integration of drones within 5PL logistics frameworks requires supportive regulatory and institutional ecosystems. Based on the simulation and case findings, the following policy directions are recommended:

- *Airspace Management Frameworks:* National aviation authorities must develop dedicated urban and rural air corridors, including drone traffic control rules, geo-fencing protocols, and no-fly zone registries.
- *Regulatory Sandboxes:* Governments can establish experimental test zones or "sandboxes" for 5PL providers to trial drone logistics solutions in collaboration with civic agencies and technology partners.
- *Standards for Interoperability:* Guidelines are needed for API-based integration of drones with

existing logistics platforms, including cybersecurity protocols and data-sharing frameworks.

- *Incentives for Green Logistics:* Policies that subsidize electric UAV deployment, support renewable-powered recharging hubs, and recognize drone-based deliveries in carbon offset schemes will accelerate sustainable adoption.
- *Global Regulatory Considerations:* While this study is grounded in the Indian context, global drone logistics deployment faces similar yet context-specific regulatory hurdles. The U.S. Federal Aviation Administration (FAA) mandates Part 107 certification, limits flights beyond visual line of sight (BVLOS), and requires waivers for operations over people. The European Union Aviation Safety Agency (EASA) has introduced the U-space framework to manage low-altitude drone traffic and enforces operator classification and airworthiness standards. These diverse regulatory landscapes highlight the need for globally adaptable 5PL orchestration systems to ingest real-time airspace data, adjust compliance logic per jurisdiction, and align with international best practices. Future research should explore cross-border drone operations and harmonization mechanisms to support scalable global logistics ecosystems.

The policy roadmap presented in **Figure 6** outlines a collaborative framework involving regulators, 5PL logistics providers, and technology partners for the scalable deployment of drone-based delivery systems. This model emphasizes the importance of public–private partnerships (PPPs), regulatory harmonization, and technological co-development to support aerial last-mile logistics within 5PL ecosystems.

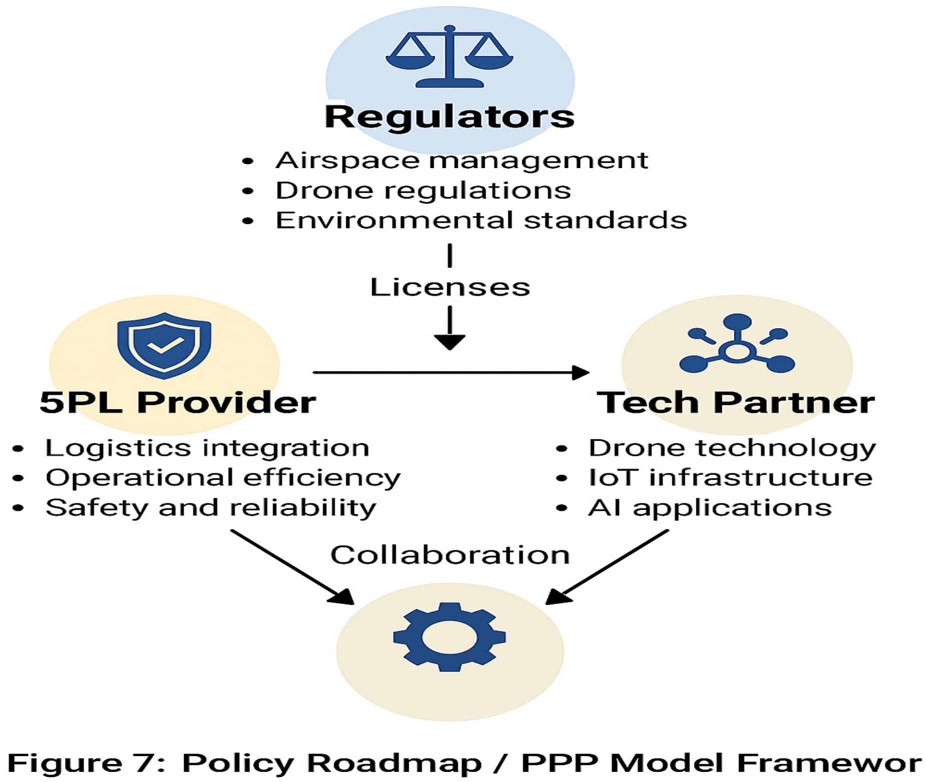

Figure 6. Policy Roadmap / PPP Model Framework.

7.3. Implementation Challenges

Several challenges must be addressed for full-scale deployment:

- **Airspace Regulation and Compliance:** Current civil aviation policies are fragmented and may restrict wide deployment in urban zones. Alignment with DGCA (India), ICAO, and local authorities is essential.
- **Payload Limitations:** Most drones remain constrained by payload capacity and battery life, requiring hybrid delivery models or improved energy-density solutions.
- **Public Acceptance and Safety Concerns:** Noise, privacy, and perceived risks may hinder adoption, especially in densely populated regions. Public awareness campaigns and fail-safe protocols must accompany rollouts.
- **Infrastructure Gaps in Rural Areas:** Lack of digital connectivity and charging infrastructure may limit drone logistics in rural regions, unless supported by LPWAN networks, solar micro-grids, and modular drone hubs.

7.4. Strategic SWOT Analysis of the Proposed 5PL–Drone Logistics Framework

A strategic evaluation of the proposed framework uses a SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis to complement the conceptual and technical discussions. This approach enables a structured understanding of internal capabilities and external risks associated with integrating drones into fifth-party logistics systems. **Table 7** presents the SWOT matrix, synthesizing the core strengths, such as real-time orchestration and cold-chain compatibility, as well as limitations, including payload constraints and weather dependencies. Opportunities linked to policy initiatives (e.g., ONDC, Drone Shakti) and open-source platform scalability are also captured alongside potential threats such as regulatory delays and cybersecurity concerns. This analysis is a strategic lens for stakeholders aiming to adopt, regulate, or scale 5PL–drone integration models in varied operational environments.

Table 7. SWOT Analysis of the Integrated 5PL–Drone Logistics Framework.

Strengths	Weaknesses
Real-time SLA enforcement via AI, blockchain, and IoT	Payload constraints (1.5–2 kg) and limited drone range (~25 km)
Cold-chain compatible for vaccines, blood, and insulin deliveries	High upfront infrastructure and digital platform costs
Significant reduction in delivery time and carbon emissions (↓65%, ↓90%)	Operational sensitivity to weather and terrain
Modular and scalable for rural–urban applications	Partial dependency on airspace regulatory clearance and DGCA approvals

Opportunities	Threats
Integration with ONDC, Drone Shakti, and innovative city programs	Cybersecurity risks (e.g., drone hijacking, data interception)
Potential for expansion into agri-drone, emergency, and disaster logistics	Delays in establishing drone corridors and UTM frameworks
Government incentives for green and autonomous logistics	Public concerns on privacy, noise, and job displacement
Open-source platform interoperability for dynamic simulation and scaling	Infrastructure gaps in rural areas are affecting drone charging and tracking

8. Managerial and Policy Implications

8.1. 5PLs as Drone Supply Chain Integrators

5PL firms are uniquely positioned to become central orchestrators of drone logistics, managing multi-modal assets, contracts, data flows, and regulatory compliance through unified digital platforms. By embedding drones into their orchestration layer, 5PLs move beyond logistics execution into intelligent ecosystem design, unlocking new business models such as:

- On-demand delivery-as-a-service
- Healthcare drone corridors
- Shared aerial delivery infrastructure

This role demands technological capacity and strategic ecosystem partnerships with drone manufacturers, regulatory bodies, AI providers, and municipal planners.

8.2. Regulatory Readiness for Aerial Last-Mile Operations

Policymakers must transition from prohibitive frameworks to enabling regulations that foster innovation while maintaining safety. A structured roadmap should include:

- Licensing frameworks for drone fleet operators
- Integration of drone tracking with national UTM (Unmanned Traffic Management) systems
- SLAs encoded via blockchain for real-time compliance tracking

The readiness of countries like India, through initiatives such as Drone Shakti, ONDC, and Make in India, creates fertile ground for piloting integrated 5PL–drone logistics models.

8.3. Public–Private Collaboration Models

The success of 5PL–drone logistics hinges on robust public–private partnerships (PPPs). Governments can act as infrastructure enablers (providing airspace access, charging zones, data rights), while private 5PL firms manage operations and innovation. Examples include:

- Healthcare drone corridors supported by MoHFW and NITI Aayog,
- Agri-drone pilots facilitated by ICAR and local co-operatives,
- Smart city drone logistics embedded within urban mobility master plans.

PPP frameworks must emphasize interoperability, public value creation, and transparent performance measurement.

9. Conclusions and Future Work

9.1. Summary of Contributions

This study proposes and validates a novel conceptual and operational framework that integrates drone-based last-mile delivery within the orchestration layer of fifth-party logistics (5PL) systems. By aligning the physical capabilities of drones with the digital intelligence of AI, IoT, and blockchain-enabled 5PL platforms, the model addresses critical logistical challenges such as delivery delays, high last-mile costs, and limited rural accessibility.

Through a digital twin-based simulation grounded in real-world Indian healthcare and smart city logistics contexts, the model demonstrated significant improvements in delivery efficiency (↓65%), cost (↓40%), carbon footprint (↓90%), and service-level compliance (↑60%). The inclusion of metaheuristic optimization (ALNS, PSO, NSGA-II) and queuing theory validation further enhanced the robustness of the operational design. Additionally, the paper offers actionable insights for:

- Logistics managers transitioning to digital-first operations,
- Policymakers are preparing regulatory pathways for aerial logistics,
- Technology providers are building interoperable, scalable delivery systems.

9.2. Limitations of the Current Model

Despite promising outcomes, the proposed framework has several limitations:

- Payload constraints and the limited flight range of commercial drones restrict scalability in high-volume delivery contexts.
- Simulation-based validation may not fully capture dynamic ground realities such as human intervention, localized weather anomalies, or public resist-

ance.

- The absence of real-time regulatory sandbox modeling would reflect the interaction between drone traffic and manned aviation more realistically.

Furthermore, data used for simulation (ONDC clusters, health infrastructure, etc.), while reflective of real settings, may not generalize to other nations or sectors without adaptation.

9.3. Future Research Roadmap

To build upon this foundational work, future research should explore the following areas:

a) Swarm Drone Coordination

Implementing multi-agent reinforcement learning and decentralized control to enable swarm-based deliveries, especially useful in disaster zones, vaccine drives, or city-wide e-commerce surges.

b) Urban Air Traffic Management (UATM)

Developing dynamic airspace governance models integrated with 5G/6 G-enabled UTM systems, real-time air traffic forecasting, and collaborative scheduling between manned and unmanned vehicles.

c) AI-Driven Scheduling and Resilience

Incorporating explainable AI (XAI) for routing and dispatch decision-making under uncertainty, with adaptive learning from failures, demand fluctuations, and supply disruptions.

d) Carbon Scoring and Green Logistics Certification

Designing blockchain-based carbon scoring protocols to track and validate emissions savings across drone missions, supporting ESG compliance and sustainable logistics policies.

e) Trust and Governance in Autonomous Logistics

Establishing robust governance frameworks for AI-powered logistics, including accountability protocols, ethical AI usage, privacy standards, and resilience against cyberattacks.

This paper lays the groundwork for a scalable, intelligent, and sustainable logistics paradigm, positioning 5PL firms as orchestrators of the next generation of aerial and digital supply chains. As technological maturity and regulatory openness grow, the seamless integration of drones into 5PL ecosystems has the potential to redefine how goods move across economies—responsively, autonomously, and inclusively.

Funding

This work received no external funding.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

Data will be made available once requested.

Acknowledgments

The author would like to express sincere gratitude to the Ministry of Education (MoE) and the Government of India (GoI) for their invaluable support and assistance throughout this research. The author sincerely appreciates their commitment to advancing research and education in India.

Conflicts of Interest

The author declares no conflict of interest.

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