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DRONE-BASED DELIVERY IN LOGISTICS

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Abstract: This systematic review synthesizes peer-reviewed and policy literature (2025–2026) on drone-based last-mile delivery, emphasizing economic viability, life-cycle environmental impacts, and regulatory constraints. A structured search across Scopus, Web of Science, ScienceDirect and selected policy portals yielded 32 studies for in-depth analysis. Results show that unmanned aerial vehicles (UAVs) provide meaningful operational advantages — notably delivery speed and reach for lightweight and urgent shipments — while environmental benefits are conditional on operational context and energy sources. Techno-economic studies indicate drones are financially attractive in niche applications (medical, emergency, remote delivery), but high capital expenditures, infrastructure needs, and regulatory fragmentation limit scale-up. The review concludes with concrete policy and business recommendations and highlights priority research directions, including integrated LCA–TEA–network modeling and large-scale real-world pilots.

Keywords: drone delivery; UAV logistics; last-mile delivery; life-cycle assessment (LCA); techno-economic analysis (TEA); regulation; hybrid logistics

Introduction

Global logistics systems have been rapidly transformed by digitalization, automation, and novel mobility technologies. Among the supply-chain stages, **last-mile delivery** stands out as both the costliest and most logistically complex segment: it faces traffic congestion, low load factors, and rising greenhouse-gas emissions per parcel delivered [1]. In response, unmanned aerial vehicles (UAVs, or drones) are proposed as a potential technological solution for selected last-mile tasks: lightweight parcels, time-sensitive shipments, and deliveries to infrastructure-poor locations. Major logistics and tech firms have piloted drone delivery systems (e.g., Amazon Prime Air, DHL, Wing) while specialist operators (e.g., Zipline) have scaled medical deliveries in low-connectivity settings [2]. Recent policy developments — notably EU U-Space rules for low-altitude traffic management — indicate regulatory frameworks are evolving to accommodate commercial drone operations.

Nevertheless, there remains uncertainty about the net economic and environmental benefits of drone delivery at scale. Life-Cycle Assessments (LCA) and Techno-Economic Analyses (TEA) published recently point to **context-dependent** outcomes: drones may reduce CO_2 per parcel under some conditions but can be inferior in dense urban networks where load consolidation and vehicle capacity drive efficiency [3].

Technological and operational research

Recent progress in battery energy density, autonomous navigation, and detect-and-avoid systems has extended practical drone capability (payloads ~2–5 kg; typical ranges 15–30 km under favorable conditions) [5–6]. Multi-drone coordination and AI-based routing permit denser operations, but meteorological sensitivity and limited payload capacity remain key constraints. Algorithmic contributions (Flying Sidekick TSP, multi-trip VRPs) have defined planning models for truck–drone hybrids and multi-drone fleets [2,9,10].

Environmental evidence — LCA studies

A structured review of LCA studies (2025) indicates drones can lower per-parcel CO_2 in rural/low-density areas and when electricity for charging is low-carbon; however, cradle-to-grave boundaries that include battery manufacture, replacement and infrastructure build-out reduce the apparent advantage in many scenarios [3]. In urban high-density contexts, electric vans often outperform drones per parcel because of higher payload aggregation and fewer repeated trips.

Economic analyses — TEA and cost models

TEA literature shows conditional cost competitiveness: drones reduce labor costs by automation but require significant CAPEX (fleet, charging hubs, UTM integration). Hybrid models (truck + drone) frequently show the best compromise — trucks for bulk legs, drones for point-delivery to reduce time-to-delivery and reach constrained clients [2,4].

Regulatory & policy landscape

Regulatory regimes remain the gating factor. The European U-Space framework is among the most advanced, offering a path to safe urban drone operations via layered services for traffic management, authorization and monitoring [EASA]. Other jurisdictions are patchy; pilot permits remain common practice. The rapid scale-up of medical drone networks (e.g., Zipline) shows how public-private agreements and purpose-specific regulation can accelerate deployment.

Synthesis and research gaps

Despite growing work, integration across LCA, TEA and operational network models is rare. Few studies evaluate **real-world, large-scale** operations; most remain simulations, pilot case studies, or pre-commercial rollouts. Comparative studies across governance regimes (developed vs developing contexts) are limited and merit attention.

Results

Operational performance

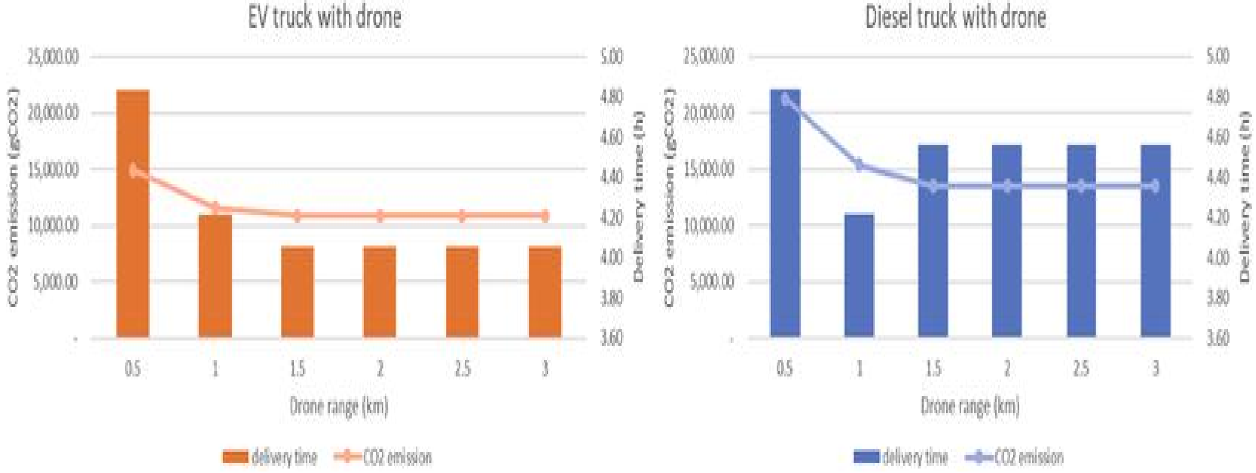
Simulations and pilot data show drones reduce point-to-point time by **~30–60%** for parcels <2 kg over distances <20 km relative to ground vans (due to straight-line routing and avoidance of road congestion). Drones also enable deliveries to locations inaccessible to ground vehicles (remote clinics, disaster zones) — a key advantage validated by Zipline's large-scale medical missions.

Environmental impacts (LCA synthesis)

LCA syntheses report: when charged from **low-carbon grids**, drones often produce lower cradle-to-gate CO_2 per parcel in low-density areas. However, if grid electricity is fossil-fuel heavy, or when battery production and replacement rates are accounted for, the CO_2 advantage shrinks or disappears. Aggregation effects in urban centers (many deliveries on a single van route) favor ground vehicles in dense deliveries [3].

Key drivers: energy mix for charging; parcel weight; route density; battery lifetime and recycling assumptions.

Figure 1 — Comparative environmental performance (example LCA chart)



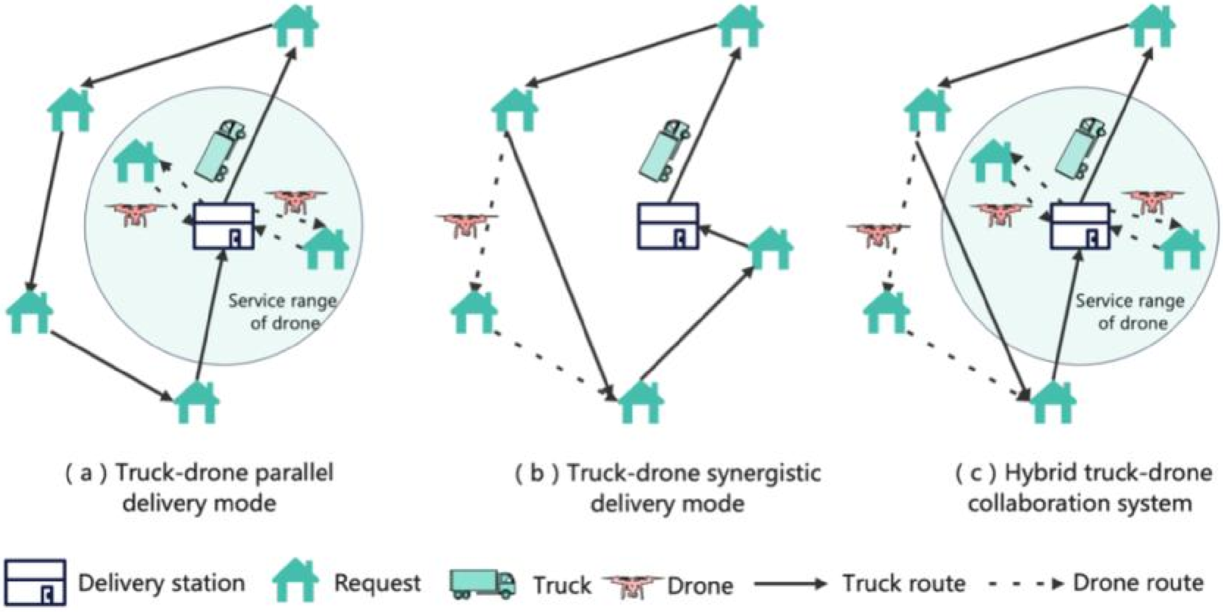
Economic outcomes (TEA synthesis)

TEAs reveal drones can reduce marginal operating costs in contexts with high labor costs and low parcel weight/time sensitivity. But significant fixed costs (fleet procurement, charging infrastructure, UTM integration) entail long payback periods unless volumes or value-added use cases (medical deliveries) justify investment.

Regulatory & safety constraints

Regulatory fragmentation (lack of harmonized cross-border rules) and conservative restrictions (visual line-of-sight, altitude and no-fly zones) remain major barriers. Advanced frameworks (U-Space) show one path to managed urban operations, but implementation and certification processes are resource-intensive for operators and authorities.

Figure 2 — Hybrid truck–drone logistics conceptual diagram

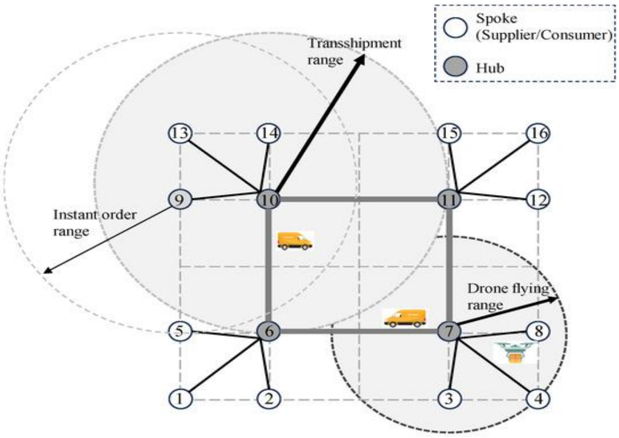


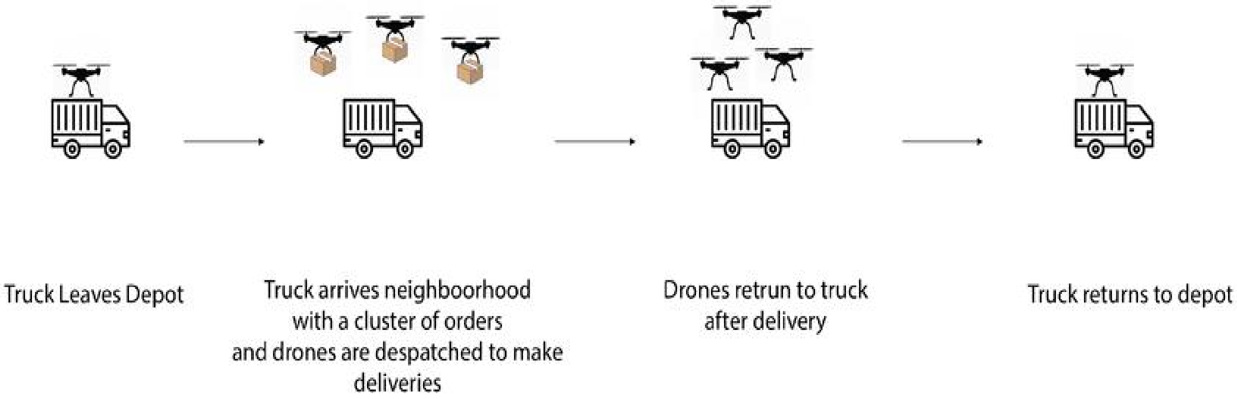
(a) Truck-drone parallel delivery mode

(b) Truck-drone synergistic delivery mode

(c) Hybrid truck-drone collaboration system

conceptual architecture showing depot → truck trunk → drone spokes; indicates charging hub & UTM control node.





Conclusion

This systematic review synthesizes current scientific evidence and policy developments (2025–2026) regarding drone-based last-mile delivery. Drones present **conditional advantages**: they are operationally compelling for light, urgent shipments and in reach-limited environments, and environmentally preferable under low-carbon charging and favorable operational assumptions. Nevertheless, **economic viability at scale** is constrained by CAPEX, infrastructure needs, and regulatory fragmentation. The pragmatic path forward is **targeted deployment** within hybrid logistics systems, accompanied by regulatory sandboxes, green charging incentives, and integrated empirical evaluations. Future work should emphasize real-world pilots, cross-disciplinary modeling, and policy experiments to determine whether drones can move from niche to mainstream components of sustainable logistics.

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