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UAVs for Medical Drug Delivery: Survey of Path Planning Technologies

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Abstract

Unmanned aerial vehicles (UAVs) are being increasingly used for medical logistics, but planning goes beyond shortest path routing due to strict safety, reliability, and regulatory requirements. This paper provides a systematic literature review of the literature on UAV medical delivery planning studies published between 2021 and 2026 and provides the literature classification based on a multi-layer decision framework that includes trajectory viability, routing and scheduling, logistics system coordination, and dynamic resilient operations. The literature is reviewed to compare deterministic optimization, heuristic search, learning-based adaptation, and multi-modal approaches, with emphasis on the trade-offs between optimality, scalability, adaptability, and certifiability. In addition to vehicle-level routing, the literature review covers network design, environmental uncertainty, privacy, and acoustic constraints, and provides a cross-national regulatory comparison. The literature survey concludes that UAV medical delivery planning is a problem of cyber-physical-legal co-design, which demands regulation-aware and reliability-focused decision architectures.

Keywords: UAV medical delivery; path planning; healthcare logistics; regulatory compliance; multi-layer decision framework.

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1 Introduction

Unmanned aerial vehicles (UAVs) are increasingly being used for medical logistics to transport blood products, vaccines, diagnostic samples, and other time-sensitive pharmaceuticals (Barbieri et al., 2022). Sub-Saharan Africa currently has the highest concentration of UAV deployments for medical logistics, particularly in Rwanda and Ghana (Singh et al., 2026). Unlike traditional parcel delivery, medical missions require extremely strict conditions for safety, reliability, traceability, and regulatory compliance (Grote & Cherrett, 2025). Medical delivery planning for UAVs cannot be simplified to the shortest path problem; instead, it requires extremely tightly coupled decisions on trajectory feasibility, routing and scheduling, energy optimization, multi-vehicle coordination, and aviation regulatory compliance (Dewmini et al., 2023).

There have been some paradigms suggested in recent literature for methodological frameworks of medical delivery planning for UAVs, which include deterministic optimization, heuristic/metaheuristic search, learning-based autonomy, and hybrid multi-modal logistics systems (Li et al., 2022; Park et al., 2018). While each paradigm has its own distinct advantages, none of them are comprehensive. On the one hand, optimization models are mathematically rigorous but not scalable; on the other hand, heuristic models are more computationally efficient but lack guarantees of performance; learning-based autonomy models are more flexible but plagued by certification and generalization challenges; and hybrid logistics systems are more complex in terms of multi-vehicle coordination. Moreover, airspace constraints are inherently restrictive of the feasible set of flight trajectories, such that route planning becomes an optimization problem of joint compliance (Kotwicz Herniczek & German, 2022).

The survey provides a literature review of research on UAV medical delivery planning published between 2021 and 2026. The literature is organized based on the decision level at which planning intelligence is incorporated, including deterministic optimization, approximate search, data-driven adaptation, and integrated logistics coordination, and supplemented by a cross-national regulatory analysis.

However, aside from path planning at the vehicle level, the large-scale deployment of medical UAVs also requires modeling at the network level and socio-technical analysis (Narayanan et al., 2022). These include strategic considerations such as the location of launch sites, charging station allocation, intermodal connectivity

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with ground transportation systems, and hub-and-spoke network design, which are critical to operational viability but have been underrepresented in path planning-oriented studies (Jones et al., 2023). Moreover, environmental uncertainty, weather variability, acoustic effects, and privacy-aware routing also present multi-objective trade-offs that go beyond traditional geometric optimization. These aspects are therefore considered within the analytical framework of this survey to offer a comprehensive and system-level view of UAV medical delivery planning (Ajakwe & Kim, 2024).

The main contributions of this paper are as follows:

- This survey presents a multi-layer decision framework that systematically structures the UAV medical delivery literature from trajectory planning to dynamic resilient operations, identifying the trade-offs between optimality, scalability, and deployability.
- Aside from vehicle-level path planning, this survey review also considers network-level design considerations such as launch site location, charging station allocation, and intermodal connectivity, as well as reliability, weather uncertainty, privacy, and acoustic constraints. By doing so, the survey places UAV routing within a system-level and socio-technical planning framework.
- It points out the regulatory-algorithmic interface through cross-national airspace regulation analysis and the formulation of UAV medical delivery as a cyber-physical-legal co-design problem.

The remaining part of the paper is structured as follows: Section 2 presents the review process, Section 3 presents the methodological taxonomy, Section 4 presents challenges and opportunities, Section 5 presents regulatory frameworks, and Section 6 concludes the paper.

2 Review Process

This section describes the systematic review methodology, from the definition of scope to the search, screening, and analysis framework, to make the process clear and traceable.

2.1 Study Scope and Literature Selection

This review studies UAV-assisted medical delivery systems. It focuses on path planning, routing optimization, trajectory calculation, and multi-UAV coordination. The goal is to study algorithms and system methods that support safe, efficient, and legal medical logistics. To reach this goal, we reviewed journal and review articles written in English and published between 2021 and 2026. We only selected studies that focus mainly on planning or routing. We removed papers where UAV use was not the main topic. We also removed studies that mainly focused on hardware, sensing, communication, or general logistics management without clear planning methods. In addition, we excluded studies that did not focus on medical delivery. We searched the Web of Science database using the keywords listed in Table 1. The search returned 52 papers. We then screened these papers manually. After screening, we selected 27 papers for detailed analysis.

Table 1. Criteria for data collection and results.

Description	Conditions/Results
Target Database for Search	Web of Science
Search Expression	TS = (UAV OR UAS OR drone OR unmanned aerial vehicle OR unmanned aircraft system) AND TS = (medical OR healthcare OR health-care OR hospital OR pharmaceutical OR drug OR vaccine OR blood) AND TS = (deliver OR logistics OR transport OR distribution) AND TS = (path planning OR trajectory planning OR route planning OR motion planning OR navigation)
Types	Journey, Conference
Fields Searched	Title, Keywords, Abstract
Search Period	2021 - 2026
Total Number of Retrieved Documents	52

2.2 Analysis of Publication Trends and Research Clusters

Fig. 1 depicts the annual distribution of the 52 identified studies. Although there was a slight drop in 2023, the overall trend of publication is still on the rise, with conference papers remaining stable and journal papers slowly increasing, which indicates that UAV medical delivery research is still of great interest.

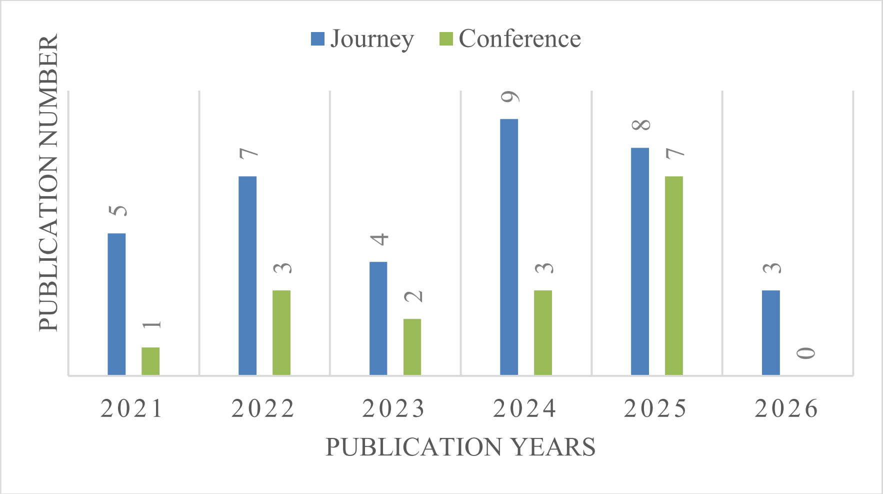

Fig. 1. Publication trends of literature.

Figure 2 is the co-occurrence network of keywords created by VOSviewer. The distance between nodes represents the strength of co-occurrence, and the size of the nodes represents the frequency of the keywords, with larger nodes and smaller distances between them indicating more prominent and closely related topics.

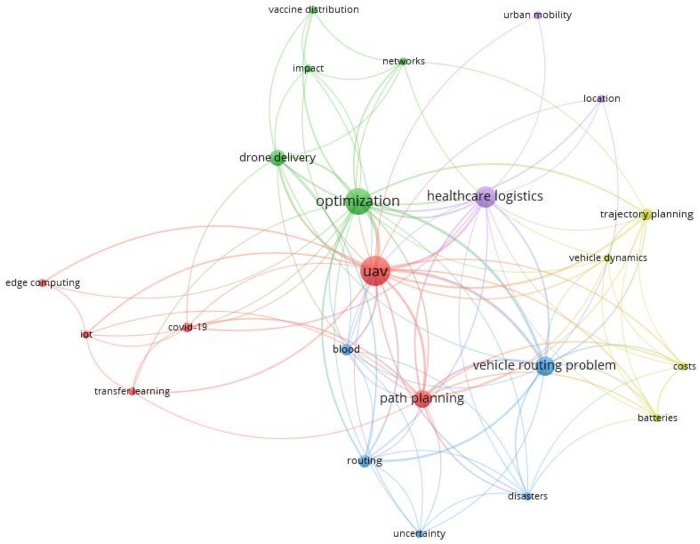

Fig. 2. Network visualization of keywords.

3 Methodological Taxonomy of UAV Medical Delivery Planning

This section provides a systematic taxonomy of UAV medical delivery planning approaches based on the decision level, including deterministic optimization, approximate search, data-driven adaptation, and logistics coordination.

3.1 Classical Graph-Based Methods

The seven papers reviewed in Table 2 above form a systematic sequence of optimization-based UAV medical logistics planning from low-level trajectory planning to large-scale logistics coordination. While all approaches use mathematical optimization, they are at different decision levels. The decision level of the trajectory deals with the feasibility of continuous motion and avoidance of obstacles for individual UAVs. The routing level involves visit ordering and scheduling over multiple locations. The logistics system level coordinates the UAV fleet, depots, and charging. Finally, dynamic resilient operations consider uncertainty and real-time adaptation to ensure reliable service.

Table 2. Integrated Comparison of Classical Graph-Based UAV Medical Delivery Planning.

Article	Algorithm	Scenario	Data	Key result
Chen et al. (2025)	Convex opt + STL + CFS	Multi-hospital urban delivery with time windows + static obstacles	Synthetic (3 hospitals, 3 AABBs)	Fast convergence (~5 iters, <0.3 s) with STL satisfaction + collision-free 3D trajectory (sim).
Li et al. (2025)	MILP + ALNS	Real-time blood delivery (scheduled + emergency), multi-depot/multi-trip	HK-inspired sim (9 depots, 42 hospitals, dynamic demands)	ALNS scales to large instances; outputs feasible joint routing/scheduling beyond exact MILP (sim).
Rave et al. (2025)	Two-stage stochastic IRP + ALNS	Cyclic van replenishment + drone emergency recourse under uncertainty	MEDinTime-inspired (10 clinics, 7 products, 100 scenarios)	Jointly optimizes routes + reorder points; improves robustness and expected cost (sim/benchmarks).
Campbell et al. (2023)	Branch-and-Cut + matheuristic	Multi-drone routing on graphs for delivery + sensing tasks	Public synthetic grid benchmarks	Optimal for small/medium; matheuristic provides high-quality scalable solutions (sim).
Wang et al. (2025)	MILP + rolling horizon	ET–UAV emergency logistics with disruptions + charging decisions	SF–Oakland-inspired (14–42 nodes, disruption scenarios)	85.5–96.4% on-time; delay cost ↓ 35.6–66.5%; runtime 225–295 s (sim).
Molinari et al. (2024)	Risk-minimizing grid heuristic + SORA	Urban blood-sample flights with regulatory ground-risk constraints	Helsinki population grid + no-fly + buildings	Produces lower-risk trajectories and SORA feasibility metrics (e.g., GRC reduction; SAIL V–VI) (sim).
Thomas et al. (2025)	Waypoint navigation + reactive avoidance	Practical autonomous medical delivery in crisis/remote areas	Real-time onboard sensors + mission waypoints	Demonstrates deployable autonomy (mission execution + failsafes) rather than provable optimality (field/system tests).

At the trajectory level, Chen et al. (2025) ensure kinematic feasibility and time-window compliance through constrained convex optimization. At the routing and logistics level, Li et al. (2025), Rave et al. (2025), Campbell et al. (2023), and Wang et al. (2025) formulate delivery as graph-based scheduling and supply-chain optimization, where exact models provide optimal solutions for small instances and heuristics improve scalability under uncertainty and operational constraints. At the deployment level, Molinari et al. (2024) and Thomas et al. (2025) focus on safety compliance and operational effectiveness, integrating risk measures and autonomy at the operational level.

3.2 Heuristic and Metaheuristic Optimization

The papers listed in Table 3 above are examples of heuristic and metaheuristic planning methods for complex medical logistics problems that are infeasible to solve by exact optimization. Traditional graph search methods try to find a fixed best solution. These new methods focus on fast computation and flexible use. They also respond better to changes in real operations.

Table 3. Integrated Comparison of Heuristic and Metaheuristic Optimization-Based UAV Medical Delivery Planning.

Article	Algorithm	Scenario	Data	Key result
Sharma and Lin (2024)	Transfer-learning + Deep-Q + MST	Secure medical-waste transport (UAV-UGV)	Hospital waste samples + synthetic map	Adaptive collision-free routes; reward ≈0.7–0.9
Meng et al. (2024)	k-means + Genetic Algorithm	Urban blood distribution (vehicle-UAV)	Shanghai hospitals (251 nodes)	Reduced delivery time/cost vs vehicle-only
Al-Fowaih et al. (2025)	GA–Simulated Annealing hybrid	Medical delivery with obstacles/weather	TSPLIB + Riyadh case	Feasible routes with lower logistics cost
Han et al. (2023)	Differential Evolution + Whale Optimization	Pandemic supply & waste collection	Shanghai communities (real map)	Better cost/time than PSO/GWO/DE baselines
Munawar et al. (2021)	Greedy + Tabu Search	COVID test-kit delivery	Simulated Islamabad patients	Shortest routes; fast computation
Munawar et al. (2023)	Artificial Bee Colony	Home medical delivery	Geelong + CVRP benchmarks	Near-optimal routes (≈2–25% gap)
Amirsahami et al. (2023)	Robust optimization + MILP	Blood supply chain planning	Tehran network scenarios	Balanced cost vs coverage trade-off
Lin et al. (2025)	Risk-minimization heuristic	Urban blood sample transfer	Helsinki population dataset	Reduced ground risk; regulatory feasible
Sengupta et al. (2025)	DUVA heuristic	Organ transport (deadline-critical)	Synthetic hospital network	Higher on-time delivery rate

Heuristic and metaheuristic approaches in UAV medical delivery can be grouped into three objectives. First, safety-constrained planning prioritizes feasibility and regulatory compliance, as demonstrated by learning-assisted and risk-aware routing strategies (Sharma & Lin, 2024; Al-Fowaih et al., 2025; Lin et al., 2025). Second, large-scale distribution efficiency is addressed through clustering and population-based search methods that enhance scalability under capacity and operational constraints (Meng et al., 2024; Munawar et al., 2021, 2023). Third, reliability- and urgency-driven models incorporate robust and deadline-aware optimization to maintain service performance under uncertainty (Han et al., 2023; Amirsahami et al., 2023; Sengupta et al., 2025).

3.3 Learning-Based Strategies

The studies summarized in Table 4 represent learning-driven decision frameworks that extend traditional routing optimization toward adaptive, context-aware autonomy.

Table 4. Integrated Comparison of Learning-Based UAV Medical Delivery Planning.

Article	Algorithm	Scenario	Data	Key result
Sharma and Lin (2024)	Transfer learning + Deep Q-learning	Medical-waste UAV–UGV delivery	Hospital waste data + synthetic 3D environment	Learns adaptive collision-free routes (high reward, low error)
Su et al. (2022)	Edge-AI + PID control	Emergency AED dispatch	Simulated operational parameters	Real-time trajectory adjustment within strict response time
Sayarshad (2025)	SVIR + MIP optimization	Equity-aware vaccine distribution	Real COVID-19 regional data	Cost–equity balanced routing prioritizing high-risk areas
Borges et al. (2024)	RRT + A + GA	Humanitarian supply delivery in risky zones	Synthetic risk-map simulations	Safe multi-UAV routing minimizing exposure risk

Learning-based planning enhances UAV medical delivery through adaptive and context-aware decision making. The Secure framework integrates transfer learning and Deep Q-learning for cooperative UAV–UGV routing under uncertainty (Sharma & Lin, 2024). Real-time autonomy is demonstrated through edge-assisted trajectory updates with stable control for emergency response (Su et al., 2022). Equity-aware routing combines demand prediction with optimization to balance cost and fairness (Sayarshad, 2025), while risk-aware exploration improves safety in hazardous environments (Borges et al., 2024).

3.4 Hybrid Multi-Modal Delivery Models

The hybrid multi-modal delivery studies address different layers of the medical UAV logistics system, ranging from fleet coordination, to navigation reliability, and finally to decision-aware routing as Table 5 shows.

Table 5. Integrated Comparison of Hybrid Multi-Modal-Based UAV Medical Delivery Planning.

Article	Algorithm	Scenario	Data	Key result
Patchou et al. (2021)	Truck–UAV coordinated medical delivery	OSM map + synthetic tasks	Prioritized medical tasks and reduced waiting time; improved throughput	Truck–UAV coordinated medical delivery
Ghaffar et al. (2024)	Emergency vehicle–UAV distribution	Solomon-based 60-node dataset	Better routing quality than GA baseline	Emergency vehicle–UAV distribution
Shao et al. (2022)	Mountain medical supply transport	Real GIS + flight logs	Demonstrated safe real-world delivery (~5.5 km mission)	Mountain medical supply transport
Taib et al. (2024)	Smart-city healthcare delivery	Prototype field tests	Reliable semi-autonomous operation and safety recovery	Smart-city healthcare delivery
Barnawi et al. (2023)	COVID medical kit logistics	Synthetic network + X-ray dataset	Feasible routing maximizing coverage under capacity limits	COVID medical kit logistics
Nacu et al. (2025)	Urban delivery with weak GPS	Sensor logs + waypoint tests	Stable navigation (~meter-level accuracy)	Urban delivery with weak GPS
Dujari et al. (2024)	Indoor medical delivery	Simulation + indoor trials	Shorter path/time vs classical baselines	Indoor medical delivery
Benayad et al. (2022)	Vaccine distribution planning	Theoretical modeling	Closed-form optimal fleet size and path length	Vaccine distribution planning

Hybrid multi-modal research projects fall under three categories. First, vehicle-UAV coordination strategies enhance efficiency by allocating ground and aerial resources simultaneously (Patchou et al., 2021; Ghaffar et al., 2024), but mostly in simulation studies. Second, autonomy and navigation performance are improved using terrain-aware routing, semi-autonomous control, sensor fusion, and indoor planning in complex or GPS-denied settings (Shao et al., 2022; Taib et al., 2024; Nacu et al., 2025; Dujari et al., 2024). Third, decision-integrated models integrate medical demand with logistics optimization and fleet sizing (Barnawi et al., 2023; Benayad et al., 2022).

4 Challenges and Opportunities

Planning for UAV medical transport has shifted from deterministic optimization to heuristic, learning-based, and logistics-integrated planning, focusing on feasibility rather than optimality (Li et al., 2022). While traditional graph models are explainable (Thomas et al., 2025), they are challenged by scalability, uncertainty, and logistics integration, requiring hierarchical models with digital twins, predictive analytics, and robust optimization.

Heuristic methods can handle large problems. They do not always find the best solution (Lin et al., 2025). Learning-based methods are flexible. They depend on data and system delay (Sharma & Lin, 2024). Researchers need to combine heuristic search and exact optimization. They also need to use adaptive learning and UTM-based planning. They need to test systems in real conditions (Shao et al., 2022).

Researchers also study multi-modal systems and large networks. These systems improve overall ability. They also increase system complexity (Nacu et al., 2025). Teams must manage timing, energy limits, and rules. They must also improve system awareness. To build safe and reliable systems, teams need strong vehicle-UAV coordination. They need sensor-based routing and good sensor fusion. They also need to link diagnosis, inventory, and routing management.

UAV medical delivery has special limits. It differs from general logistics. Medical delivery often includes temperature-sensitive and time-critical items. It must follow strict tracking rules. It must provide high service reliability. It often works in crowded or resource-limited areas. Emergency tasks need fast dispatch and fixed arrival times. They also need safe operation in bad weather. These needs require planning models that focus on mission importance, service rules, and backup plans.

Many studies do not fully address reliability. Weather changes affect flight safety and energy use. Wind, rain, and low visibility change flight paths and safety margins. Many simulation models ignore these factors. They need robust trajectory planning to support safe medical delivery.

Urban area deployment adds socio-technical constraints regarding privacy and acoustic effects. Noise-aware routing and population exposure-aware optimization may compete with distance-minimizing objectives, and privacy-preserving corridor selection may limit the feasible airspace area. These issues make UAV medical delivery a multi-objective optimization problem that needs to address efficiency, safety, environmental sustainability, and social acceptability.

5 Regulatory Frameworks for UAV Medical Delivery Planning

The implementation of UAV medical delivery systems is not only reliant on the algorithmic capability but also on airspace regulation (Li et al., 2022). Airspace regulations are determined by aviation regulatory bodies, which determine the limits of operation based on altitude restrictions, certification, risk assessment, and approvals (Buzzo et al., 2024). This implies that the routes are determined by the operational categories that are permissible, and not three-dimensional space, and therefore routing is an optimization and compliance problem.

The airspace regulations differ significantly from one country to another. In the United States, there is a case-by-case approval system, where the UAV operators must demonstrate the safety equivalence of complex routes such as beyond the line of sight (Federal Aviation Administration, 2025). This means that the planning process is centered on predictable paths, contingency planning, detect-and-avoid systems, and safety assurance. The European Union has a risk-based framework, whereby route feasibility is dependent on the quantified ground and air risk exposure (Becker, 2025). This means that path planning is a multi-objective optimization problem that balances efficiency and safety. China has a geofenced airspace control system, whereby the UAVs have to be registered and operate within designated corridors (McNabb, 2025). This means that the routing problem is a graph search problem within the geofenced zones. Australia has a safety assurance certification process, whereby the UAVs have to operate within safety-assured patterns, which are repeatable and validated (Civil Aviation Safety Authority, n.d.).

The above regulatory frameworks mean that the UAV medical delivery planning problem is a cyber-physical-legal co-design problem. The systems are dependent on authorization, which requires trajectories that are certifiable, risk-based frameworks that require safety optimization, controlled airspace that requires corridor-constrained routing, and certification-oriented environments that require stable operational patterns. Future planning systems will, therefore, have to include regulatory reasoning in the decision-making process, whereby the path planning process becomes an optimization-compliance problem.

6 Conclusion

This paper conducted a systematic review of the literature on UAV medical delivery planning research published between 2021 and 2026, and the literature was categorized using a multi-layer decision framework that covers trajectory feasibility, routing and scheduling, logistics system coordination, and dynamic resilient operations. It is clear from the analysis that UAV medical delivery is more than a single routing problem and involves a hierarchical decision-making process that considers motion-level feasibility, fleet-level optimization, and system-level reliability simultaneously. Different planning methods serve different needs. Deterministic optimization tries to find the best solution. Heuristic search focuses on speed and scale. Learning methods focus on adaptation. Multi-modal coordination focuses on system-level cooperation. Each method has its own strengths and limits in optimality, scalability, adaptability, and certification.

Medical UAV deployment involves more than algorithms. Network design also affects performance. Teams must choose depot locations. They must plan charging stations. They must manage intermodal coordination. These factors affect routing and system efficiency. The environment also creates limits. Weather patterns affect flight safety. Noise exposure and privacy concerns affect public acceptance. These issues make medical UAV delivery a multi-objective problem. Planners must balance efficiency, safety, resilience, and social acceptance. Many path planning studies do not fully address these issues.

Regulations also shape routing decisions. Authorization rules limit where UAVs can fly. Risk evaluation standards affect route choice. Air corridors restrict flight paths. Certification rules define safety requirements. Planning must follow these legal rules. Teams must design algorithms together with safety and regulatory limits. They must include risk measures and certification rules in trajectory planning. They must use compliance-based decision logic.

Future research should develop regulation-aware planning methods. Researchers should combine optimization and learning methods. They should use digital twin airspace models and stochastic design. They should also connect trajectory control, fleet management, and healthcare demand models in one decision-support system.

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