

Beyond the Last Mile: A Systematic Review Exploring Indoor Delivery-UAV Requirements in the Last-Meter Context

Yutong Li ¹ , S. Thomas Ng ^{1,*}, Mingzhuo Ling ¹ and Qi Pan ^{1,2}

¹ Department of Architecture and Civil Engineering, City University of Hong Kong, Kowloon, Hong Kong; yli2376-c@my.cityu.edu.hk (Y.L.); mingzling2-c@my.cityu.edu.hk (M.L.); qipan28-c@my.cityu.edu.hk (Q.P.)

² Research Center for Underground Space & Department of Geotechnical Engineering, Tongji University, Shanghai 200000, China

* Correspondence: thomasng@cityu.edu.hk; Tel.: +852-3442-8028

Abstract

The final stage of urban logistics does not end at the building entrance but continues within complex, vertically structured indoor environments, where conventional ground-based delivery systems face limitations in efficiency, flexibility, and scalability. This study introduces the concept of last-meter delivery, defined as unmanned aerial vehicle (UAV)-enabled transport from the building envelope to the recipient within global navigation satellite system (GNSS)-denied, building-regulated indoor space, and systematically reviews the literature from two traditionally separate domains: indoor-UAV operation in GNSS-denied spaces, and outdoor-UAV-based logistics. Following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, 297 studies are synthesized through a two-stream thematic synthesis. The review makes three contributions. First, a unified analytical framework is developed across four dimensions (spatial mobility, logistical capability, social acceptance, and operational coordination) through which the two bodies of literature are shown to be largely complementary, with the gaps in one stream coinciding with the strengths of the other. Second, indoor aerial delivery is found to be subject to a distinct set of operational constraints, including micro-scale navigation accuracy, strict geometric safety envelopes, close human–UAV interaction, and privacy sensitivity, implying that indoor transport-UAVs cannot be realized through simple miniaturization of outdoor platforms but require precision-oriented, human-centric, and building-aware design. Third, the four dimensions are translated into a building-management-oriented indicator framework covering spatial compliance, handover standardization, building information modeling (BIM) integration, occupant consent, and liability allocation, reframing last-meter requirements in terms that are actionable for building planners and facility managers. By framing these challenges within the last-meter perspective, this review identifies the gap between current last-mile theories and emerging in-building aerial logistics and provides a structured foundation for future research.

Keywords: indoor-UAV; last-meter delivery; human–UAV interaction; GNSS-denied navigation; smart buildings; systematic review



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1. Introduction

The concept of last-mile delivery has been extensively discussed in logistics and transportation research for decades, referring to the final stage of goods movement from a distribution hub to the end-user. Unmanned aerial vehicles (UAVs) have increasingly

been proposed as an efficient solution to the last-mile delivery challenges, particularly in rural areas and low-density regions where ground transportation is constrained by long distances, limited infrastructure, or difficult terrain [1–4]. In such contexts, UAV-based delivery systems demonstrate clear advantages in terms of speed, accessibility, and operational flexibility [5,6]. However, current aerial delivery systems are mainly intended for professional logistics operations and are controlled through closed software platforms accessible only to trained operators [7]. In addition, their design's focus on medium- to long-range transport leads to large and heavy platforms that depend on dedicated landing zones, preventing safe and close-range handover to individual users [8]. In high-density urban environments, delivery tasks do not end at the building envelope. Instead, a substantial portion of logistical complexity arises after goods enter the buildings [9,10]. This shift necessitates extending the scope of last-mile delivery to what can be described as the last-meter, which is defined here as the UAV-enabled transport of goods from the building envelope (e.g., balcony, window, or lobby) to the point of final handover within a GNSS-denied, human-occupied building interior [11,12]. This last-meter scope should be distinguished from the last-centimeter personal drone delivery proposed by [7], which addresses short outdoor flights between individuals (typically under 5 km) and terminates at an open-air handover point. In contrast, last-meter delivery begins precisely where such outdoor handovers end, at the building envelope, and unfolds within enclosed, GNSS-denied, human-occupied interiors where spatial, technical, and governance conditions differ fundamentally from any outdoor segment. Despite the growing relevance of this problem, UAV-enabled indoor transportation remains underexplored compared to its outdoor counterpart, calling for a systematic review of its system-level requirements, constraints, and research gaps. Two concrete scenarios make this scope tangible. In a hospital, a UAV could move laboratory specimens or medications from a ward-level intake point to a laboratory or pharmacy on another floor, avoiding congested service lifts while remaining entirely within the building envelope. In a high-rise residential tower, a UAV could complete the final handover of a parcel from a ground-floor lobby or a balcony drop-point to a specific apartment, where corridor and elevator constraints make conventional ground-based delivery slow and labor-intensive.

Within high-density urban buildings, such as hospitals, hotels, residential towers, airports, office complexes, and mixed-use developments, indoor transportation is predominantly conducted through a combination of manual delivery, fixed building infrastructure, and ground-based automation. Manual portering and cart-based delivery remain common for flexible, ad hoc tasks but are labor-intensive and sensitive to workforce availability [13]. Fixed systems like elevators, service lifts, conveyors, and pneumatic tube systems are widely used for vertical and horizontal transport [14]. However, they require substantial upfront infrastructure investment, offering limited routing flexibility, and are often shared with passenger flows, leading to congestion and scheduling conflicts. More recently, automated guided vehicles (AGVs) and autonomous mobile robots (AMRs) have been deployed in structured indoor environments to improve efficiency and traceability [13], yet their operation is constrained by predefined paths, corridor availability, and reliance on elevators for vertical movement [15,16]. In contrast, indoor-UAV transportation introduces a three-dimensional mobility paradigm that is not bound to floor-based routes or elevator dependency [17]. By enabling direct point-to-point delivery across vertical and horizontal spaces, UAVs can potentially reduce transit time, bypass congested corridors, and operate independently of human traffic patterns [8,10]. These advantages are particularly pronounced in complex, vertically dense buildings where existing indoor transport methods face scalability and flexibility limitations [8], highlighting the potential

of UAVs as a complementary solution rather than a replacement for conventional indoor logistics systems.

A substantial body of literature has investigated indoor-UAV applications. However, this research has predominantly focused on inspection, surveying, mapping, and environmental monitoring tasks [18–21]. These studies emphasize sensing accuracy, localization, and navigation performance, while largely overlooking transportation-oriented questions such as system deployment, fleet coordination, operational scheduling, and governance within indoor environments. In contrast, research on UAV-based transportation has mainly evolved within the context of last-mile logistics, where the primary focus remains on outdoor operations, including routing optimization, infrastructure planning, and regulatory compliance in open-air urban settings [5,6,22]. As a result, limited guidance exists on how transportation-oriented UAV concepts can be translated into indoor contexts, particularly within complex, high-density buildings. This disconnection highlights the need to examine the intersection between indoor-UAV research and outdoor-UAV logistics studies, in order to establish a structured framework that captures the system-level requirements of indoor-UAV transportation, encompassing operational design, management strategies, and regulatory considerations.

Against this background, the objective of this review is twofold: to systematically synthesize the two largely disconnected literatures, indoor-UAV operation in GNSS-denied spaces and outdoor-UAV-based logistics, and, from that synthesis, to derive a unified, building-management-oriented framework that specifies the system-level requirements of last-meter delivery. This focus also defines the research gap the review fills. Existing last-mile frameworks terminate at the building envelope and offer no account of how aerial transport should operate within enclosed, human-occupied, building-regulated interiors; indoor-UAV research, in turn, concentrates on enabling flight rather than on transport, coordination, and governance. Bridging these two bodies of work, and reframing their combined requirements from the last-meter perspective, is the central contribution of this study.

2. Theoretical Framework

2.1. Last-Mile Delivery as a Socio-Technical System

Across these theoretical frameworks, last-mile delivery is generally understood as a boundary layer between urban logistics networks and end users, in which physical distribution processes intersect with service design, policy environments, and user behavior [23,24]. The literature treats this stage as a tightly coupled socio-technical system, where operational decisions (e.g., routing, consolidation, and delivery location choice) are embedded within broader economic, environmental, and regulatory contexts, and where customer preferences and service expectations play a central role in shaping system performance [25]. Spatially, last-mile logistics is conceptualized as an urban interface problem, in which public infrastructure, access control, and stakeholder coordination determine how goods are transferred from transportation networks to recipients. This perspective implicitly defines completion of delivery at the point of urban or building access, providing a coherent system boundary for city-scale analysis [26]. Building upon this shared conceptualization, the notion of a subsequent last-meter stage extends the analytical scope beyond this interface to consider how logistics processes continue within the three-dimensional, indoor environments of dense urban buildings, where different spatial, operational, and regulatory logics may apply. To illustrate the heterogeneity of existing conceptualizations, Table 1 compares six representative last-mile delivery frameworks in terms of their core conceptual lens, operational scope, cargo focus, and supported transport modes.

Table 1. Conceptual frameworks and operational scope of selected last-mile delivery studies.

Reference	Core Concept/Framework	Transportation Scope	Cargo Type	Transport Modes
[25]	Conceptualizes last-mile delivery as a structured process chain (storage–transport–handover) and analyzes delivery concepts through infrastructure design, fleet sizing, and routing/scheduling from an operations research perspective	Urban scale, from city depots or micro-hubs to end users	Small- to medium-sized parcels	Vans; bikes; drones; autonomous ground delivery robots
[26]	A multi-layered system encompassing planning, execution, and control of goods flows, structured around fulfillment, transport, and final delivery activities within urban logistics systems	Urban, depot-to-destination	Parcels; retail goods; groceries	Vans; bikes; EVs; drones
[27]	A customer-facing urban delivery system emphasizing alternative delivery locations to improve flexibility, efficiency, and sustainability	Urban, hub-to-receiver	Parcels; retail goods	Vans; lockers; pickup points; drones
[24]	Frames last-mile logistics as an urban delivery system shaped by economic, environmental, and policy dimensions, emphasizing sustainability and stakeholder interactions	Urban, city-to-recipient	Parcels; groceries; retail goods	Vans; cargo bikes; EVs; drones
[23]	A city-scale delivery system influenced by customer choices, demand patterns, and sustainability performance, linking logistics operations with urban policy and data-driven decision-making	Urban, city-to-recipient	Parcels; retail goods; groceries	Vans; cargo bikes; EVs; drones
[28]	A component of urban supply chain management, shaped by interactions among public authorities, logistics operators, and end users, with strong emphasis on sustainability and policy context	Urban, hub-to-city	Parcels; retail goods; groceries	Trucks; vans; cargo bikes; drones

As summarized in Table 1, the six frameworks are compared across four attributes: their core conceptual lens, operational scope, cargo focus, and supported transport modes. Read across these columns, two patterns emerge. First, although the conceptual lenses differ, ranging from network optimization and service design to spatial and policy perspectives, the operational scope of every framework terminates at an outdoor interface (curbside, locker, or building entrance), and none extends inside the building. Second, the cargo focus and transport modes are oriented toward ground-based or outdoor-aerial movement, so that vertical, in-building distribution falls outside the supported modes of all six. The comparison thus shows that existing last-mile frameworks are mutually consistent in where they stop, and it is precisely this shared terminus at the building envelope that the last-meter concept is introduced to address.

Despite differences in emphasis, these frameworks converge on a shared spatial logic. The delivery chain is organized as a multi-tier, hub-to-customer pipeline in which goods

flow sequentially from a central warehouse through long-haul transportation to regional logistics transfer stations, are redistributed via mid-tier modes (trucks, vans), and are finally handed over through last-mile delivery to end customers (Figure 1). Across this chain, each tier operates within its own outdoor transport regime, and the entire pipeline terminates at an outdoor interface, viz. the customer's building envelope or curbside. This shared terminus exposes the unaddressed segment that motivates the present review, i.e., what happens after the parcel reaches the building.

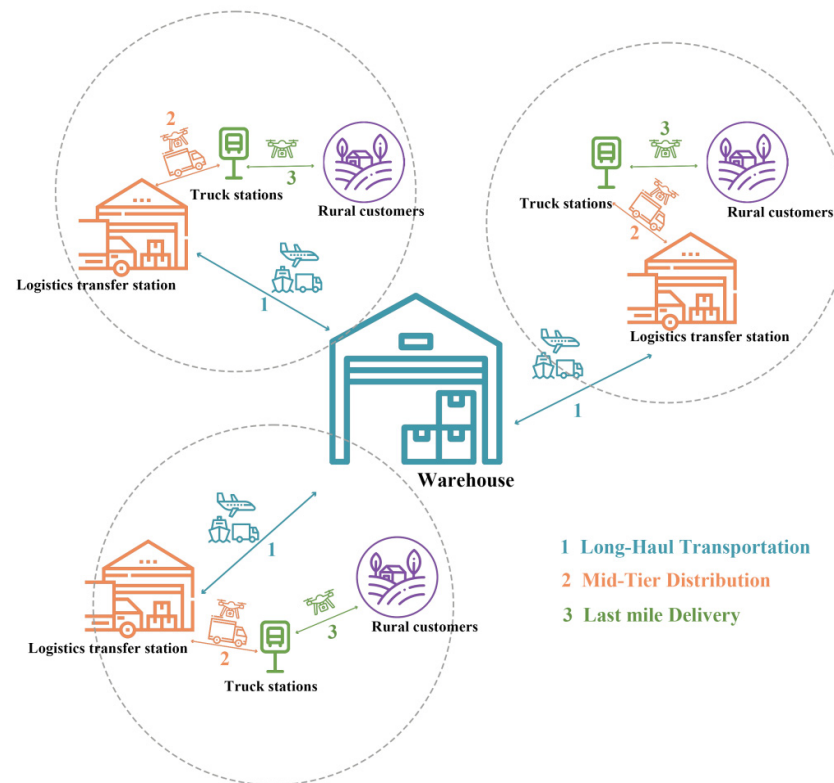


Figure 1. Schematic of the conventional last-mile delivery pipeline, in which goods move from urban hubs through long-haul, mid-tier, and last-mile stages, terminating at the building envelope.

2.2. Multi-Dimensional Frameworks for UAV Last-Mile Delivery

Recent studies have developed multi-dimensional theoretical frameworks to conceptualize UAV-based last-mile delivery as an integrated socio-technical system rather than a single transport mode. From an operational-technical perspective, models of truck–drone coordination and aerial logistics networks describe drone delivery as a system constrained by coupled relationships between vehicle performance, energy availability, and routing structure, in which payload-range trade-offs, endurance limits, and launch-recovery coordination fundamentally shape feasible service patterns [1,5]. Complementary operations-research frameworks further embed drone flights into routing and scheduling problems, treating aerial vehicles as synchronized components of hybrid delivery chains whose effectiveness depends on spatio-temporal coordination, energy-aware dispatching, and infrastructure support [6,22].

At the system and economic level, UAV delivery is framed as a cost-service trade-off structure in which time savings, accessibility gains, and labor substitution must be balanced against capital investment, operating cost sensitivity, and fleet scalability [1]. Sustainability-oriented studies extend this perspective by embedding drone logistics within energy and environmental systems, interpreting performance through life-cycle impacts, emissions intensity, and dependence on electricity mix and charging infrastructure [29]. In parallel,

governance-focused frameworks conceptualize drone delivery as a regulated air-ground interface shaped by safety assurance, noise exposure, public acceptance, privacy protection, and institutional readiness, emphasizing that operational feasibility is co-determined by technological capability and regulatory legitimacy [6,22].

Across these contributions, a convergent indicator space can be identified in which UAV last-mile delivery is evaluated along five interrelated dimensions: (i) aerial vehicle and energy-mobility coupling; (ii) network coordination and routing logic; (iii) infrastructure and platform integration; (iv) economic and scalability performance; and (v) regulatory, social, and environmental embedding. Together, these dimensions define drone delivery as a three-dimensional, cyber-physical urban interface system linking distribution networks to recipients through aerial accessibility, digital control, and institutional governance. Table 2 consolidates these five dimensions and their sub-indicators across the reviewed frameworks.

Table 2. Multi-dimensional evaluation criteria for UAV-based last-mile delivery systems.

Dimension	Evaluation Criteria	Reference
Operational and Technical	Payload capacity, battery capacity, MTOW, cargo distribution and payload allocation	[1,5,6,22,29]
	Flight range or endurance	[1,6,22,29]
	Routing and scheduling complexity	[1,5,6,22]
	Speed, delivery time	[1,6,22,29]
	Reach accessibility	[22]
	Energy infrastructure, charging time and station capacity, launch pads, docking stations, charging networks, depots	[1,6,22,29]
	Energy consumption, energy–speed–weight relationship	[1,5,6,29]
	Delivery models (PD/SM)	[1,5,6,29]
Economic and System	Cost efficiency, truck–drone coordination savings, operating cost sensitivity	[1,5,6,22,29]
	Scalability, fleet size	[6,22]
Safety, Regulation	Airspace safety	[1,22,29]
	Public acceptance	[5,6,22]
	Noise	[6,29]
	Policy and infrastructure readiness	[5,6,22]
	Data security and privacy	[1]
Cargo Characteristics	Item condition sensitivity	[22]
	Barrier avoidance	[6]
	Service coverage	[6,29]
	Data communication reliability	[1,5]
	Navigation accuracy	[5]
Environmental Performance	Life-cycle impacts	[5,29]
	GHG emissions	[1,5,29]
	Electricity mix, renewable integration	[29]

As Table 2 shows, current frameworks articulate UAV delivery through outdoor-oriented indicators and terminate analytically at the building envelope. Figure 2 reframes this boundary, identifying the last-meter segment as a distinct operational stage that

begins where conventional last-mile delivery ends. Within high-density urban buildings, the segment unfolds through three sub-stages: (i) envelope handover at building-access interfaces such as terraces or windows; (ii) vertical and horizontal in-building transit via lifts and corridors; and (iii) unit-node delivery to the final recipient at the room level (RoomA, RoomB, RoomC). Across this segment, UAVs operate in GNSS-denied space, navigate strict geometric clearances, and interact directly with building infrastructure and occupants, viz., conditions that lie outside the analytical scope of existing last-mile frameworks.

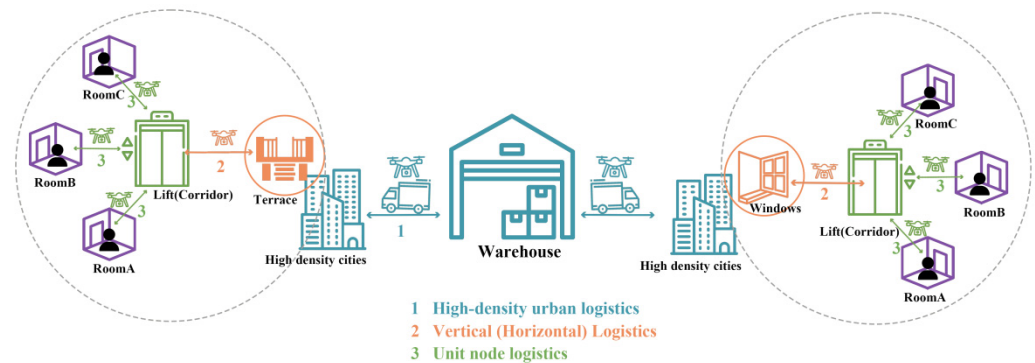


Figure 2. The last-meter segment, extending the delivery chain beyond the building envelope through high-density urban logistics, vertical/horizontal in-building transit, and unit-node delivery to the recipient.

Notably, however, the spatial and conceptual scope of these frameworks remains largely confined to outdoor urban environments and terminates at the building envelope, where delivery is assumed to be completed at curbside, rooftop, or designated landing interfaces [5,22]. While extensive theoretical attention has been devoted to airspace routing, truck–drone synchronization, infrastructure deployment, and regulatory compliance, comparatively little work addresses how UAV-enabled logistics should be organized, managed, and regulated once the delivery process enters enclosed, vertically structured, and human-occupied indoor spaces. The absence of a dedicated framework for in-building aerial logistics therefore points to a gap between outdoor last-mile theory and the emerging need for indoor, three-dimensional distribution systems.

2.3. Deriving the Last-Meter Framework from Two Literature Streams

Defining last-meter delivery. To avoid ambiguity with adjacent terms in the literature, such as last-mile, last-100-feet, last-centimeter [7], and indoor last-mile, this review adopts a tightly scoped definition. Last-meter delivery is defined here as the UAV-enabled transport of goods that simultaneously satisfies three conditions:

- Spatial boundary:** The delivery segment begins at the outdoor–indoor transition interface of a building (e.g., balcony, window, rooftop access, or ground-floor lobby) and terminates at the point of final handover to the recipient inside the building. Typical travel distances fall within the order of 10^0 – 10^2 m, distinguishing this stage from last-mile delivery (10^3 – 10^4 m, outdoor, hub-to-building) and from the last-centimeter concept (<5 km, outdoor person-to-person).
- Technical boundary:** the operational environment is GNSS-denied and requires sub-meter navigation precision under strict geometric clearances, relying on onboard SLAM, UWB, visual-inertial, or infrastructure-assisted localization rather than satellite positioning.
- Governance boundary:** While such operations remain subject to the oversight of national civil aviation authorities, particularly rules governing flights near people, beyond visual line of sight (BVLOS), and for commercial purposes, the indoor airspace

is, in practical terms, primarily administered by building owners and facility managers as the site-access and operational authority, rather than being managed solely through the public-airspace unmanned traffic management (UTM) or equivalent traffic-management frameworks that govern outdoor delivery. Last-meter delivery therefore sits at the interface between aviation regulation and building-level governance.

These three boundaries jointly distinguish last-meter delivery from other terms in use and directly motivate the analytical framework developed in this section: the spatial boundary requires integrating indoor and outdoor mobility research; the technical boundary requires drawing on indoor-UAV literature for GNSS-denied navigation; and the governance boundary requires reframing operational coordination through building management rather than civil aviation governance. To bridge this discontinuity, this review does not import a generic adoption framework (e.g., the Technology–Organization–Environment [TOE]; Political, Economic, Social, Technological, Legal and Environmental [PESTLE]; or Unified Theory of Acceptance and Use of Technology [UTAUT] frameworks); such models operate at the level of whether an organization adopts a technology, whereas last-meter delivery first requires a framework that specifies how a UAV system must function inside a building. Instead, the analytical framework is derived inductively from the two literature streams that already address the operational requirements of UAV movement and UAV logistics, respectively: indoor-UAV research and delivery-UAV research (Figure 3).

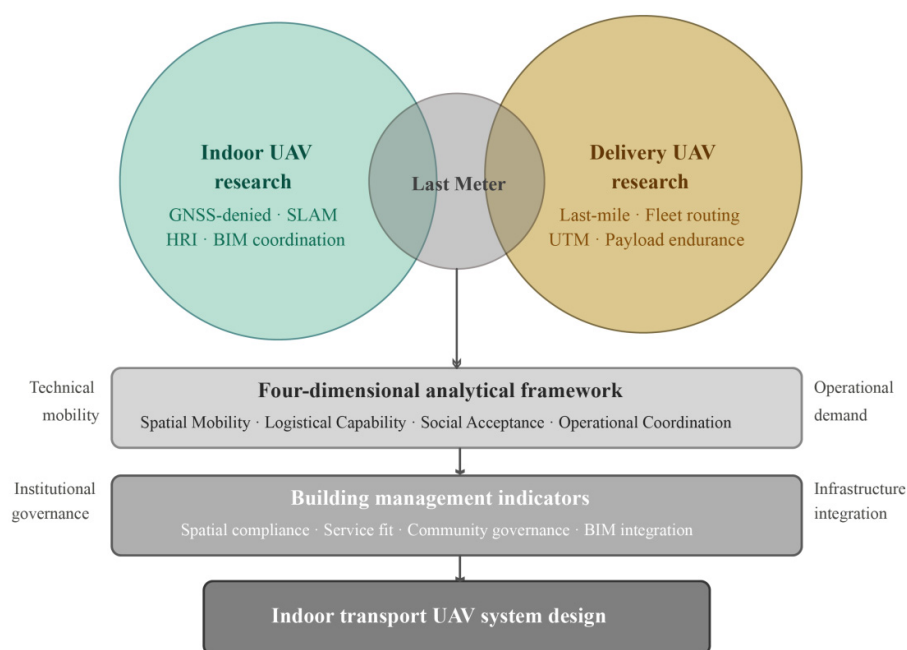


Figure 3. Conceptual intersection of indoor-UAV research and delivery-UAV research, from which the four last-meter dimensions are derived.

Each stream offers a partial but complementary account of what a last-meter system must achieve. The indoor-UAV literature specifies technical mobility requirements, i.e., how a vehicle localizes, navigates, and remains stable in GNSS-denied, confined, human-occupied space [8,30]. The delivery-UAV literature specifies operational demand requirements, i.e., how a vehicle carries useful payload, integrates into scheduling and routing systems, satisfies regulatory and social constraints, and coordinates with supporting infrastructure [1,22,29]. Neither body of literature alone is sufficient: indoor-UAV work is largely silent on delivery as a logistics function, while delivery-UAV work terminates at the building envelope. Last-meter delivery sits at their intersection, and the framework must therefore integrate, rather than choose between, the two sides.

Comparing the two bodies of literature along their shared concern with system-level UAV operation, four dimensions emerge as jointly necessary for last-meter delivery. Each dimension integrates one requirement articulated in the indoor-UAV stream with a counterpart articulated in the delivery-UAV stream:

Spatial mobility integrates indoor “precision and micro-navigation” with outdoor “efficiency and coverage”. Both concern the UAV’s capability to traverse its operating environment, and both resolve, at the interface, into the problem of continuous, seamless navigation across outdoor–indoor transitions, a requirement neither stream addresses alone.

Logistical capability integrates indoor “compactness and agility” with outdoor “payload and endurance”. These appear opposed on the surface but jointly define the payload–size–clearance trade-off that governs whether a platform designed for delivery can physically access human-centric architecture.

Social acceptance integrates indoor human–UAV interaction with outdoor privacy and public safety. The indoor literature frames the issue at close range (psychological and physical safety in shared space); the outdoor literature frames it at community scale (noise, privacy, perceived legitimacy). Last-meter delivery inherits both simultaneously, because it operates at close range within a shared community space.

Operational Coordination integrates indoor decentralized autonomy and building integration with outdoor hierarchical management and network optimization. Last-meter systems must interoperate with building-level digital infrastructure (building information modeling [BIM], building automation systems [BAS], and the Internet of Things [IoT]) while remaining compatible with upstream UTM and fleet-scheduling regimes.

These four dimensions were selected on two grounds: (i) each is addressed as a central concern in both bodies of literature, rather than dominating only one side; and (ii) each describes an operational condition, a capability the system must exhibit to function within a building, rather than an adoption or evaluation condition external to operation. Dimensions that appeared strongly in only one stream (e.g., environmental performance, dominant in outdoor sustainability studies but largely absent in indoor-UAV work) or that govern whether the system is adopted rather than how it operates (e.g., economic viability, regulatory compliance) were excluded from the core framework and are treated as adjacent research agenda items in Section 5.2. The four dimensions are interdependent rather than parallel: spatial mobility is the entry condition that lets the UAV physically reach the recipient; logistical capability is the service condition that determines what can actually be carried and handed over; social acceptance is the permission condition under which occupants, operators, and regulators tolerate the system; and operational coordination is the organizational condition that integrates the other three into building workflows. A deployment is viable only when all four hold together, and a deficiency in any one constrains the others; precise navigation without occupant acceptance and a capable platform without coordinated building integration both fail in practice.

Table 3 summarizes how each dimension is articulated in the two literature streams and how the two articulations together specify the requirements of last-meter delivery. Figure 3 visualizes the same derivation: the intersection of the indoor-UAV and delivery-UAV research fields yields the four-dimensional analytical framework, which in turn grounds the building-management indicators presented in Section 5 and, ultimately, indoor transport-UAV system design. Specifically, the table is read row by row across the four dimensions: for each dimension it contrasts how the indoor-UAV literature and the delivery-UAV literature articulate the requirement, and then states the combined last-meter requirement that neither stream addresses on its own. This structure makes the complementarity identified in Section 4 explicit: the strengths of one stream coincide with the gaps of the

other, and provides the direct basis for the building-management indicators developed in Section 5.

Table 3. Integration of indoor-UAV and delivery-UAV literature streams across the four last-meter dimensions.

Dimension	Indoor-UAV	Delivery-UAVs
Spatial Mobility	Precision and Micro-Navigation: The capability of the UAV to operate in GNSS-denied environments. The focus is on localization accuracy and stability within confined spaces using visual or sensor-based SLAM methods.	Efficiency and Coverage: The ability to traverse distances effectively to reach the destination. The focus is on barrier avoidance and maintaining navigation accuracy over longer ranges, typically utilizing GPS or hybrid systems outdoors.
Logistical Capability	Compactness and Agility: The physical constraints required to navigate human-centric architecture (e.g., doors, corridors). While current indoor research focuses on mobility, last-meter delivery requires adapting these platforms to carry loads without compromising agility.	Payload and Endurance: The capacity to transport goods efficiently. Critical metrics include payload capacity, battery endurance, and the trade-off between cargo weight and flight range (energy–speed–weight relationship).
Social Acceptance	Interaction: The immediate human–robot interaction (HRI) within shared spaces. It involves human reaction to the drone’s presence, requiring sophisticated interaction technologies to ensure psychological safety and physical safety in close proximity.	Privacy and Public Safety: The broader impact on the community and customer. Key concerns include noise pollution, data privacy protection, and general public acceptance of drones operating in residential or commercial areas.
Operational Coordination	Decentralized autonomy and building integration: The system’s ability to function in communication-denied environments through edge computing and semantic interaction. The focus is on multi-agent swarm coordination (without a central server) and utilizing building information modeling (BIM) or digital twins to navigate logical spaces (rooms, corridors) and interact with IoT infrastructure (e.g., automatic doors/windows).	Hierarchical management and network optimization: The governance structure required to manage large-scale fleets in public airspace. The focus is on centralized UTM (unmanned traffic management) for safety and conflict avoidance, supported by cloud-based algorithms to optimize global path planning (VRP) and the strategic deployment of physical infrastructure (hubs, lockers, charging stations).

3. Methods

3.1. Systematic Review and Inclusion Criteria

During the literature review, the identification, screening, eligibility assessment, and final inclusion of studies were documented in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, and the number of records retained at each stage was reported in a flow diagram [31]. Peer-reviewed journal articles published in English were retrieved from the Web of Science Core Collection (Figure 4). Given the limited number of studies explicitly addressing indoor-UAV transportation, the search was conducted in two parallel streams: (i) indoor-UAV research; and (ii) UAV-based transportation and last-mile delivery studies. For the indoor-UAV stream, the search focused on literature related to UAV operation in enclosed environments, including indoor navigation, localization, collision avoidance, infrastructure interaction, and safety management, with particular attention to spatial constraints, building topology, and human–UAV coexistence. Keywords and subject terms emphasized indoor flight environments, building interiors, vertical circulation spaces, and indoor airspace control, while

studies purely concerned with outdoor flight dynamics or hardware-level aerodynamics were excluded. For the transportation-UAV stream, the search targeted studies addressing drone-based logistics, last-mile delivery, fleet coordination, routing and scheduling, infrastructure deployment, and regulatory frameworks, with an emphasis on system-level operation and management rather than low-level vehicle design. Search terms were constructed around concepts such as last-mile delivery, urban logistics, truck–drone cooperation, airspace governance, and delivery platform architecture. Only studies that provided explicit discussion of operational structures, spatial interfaces, or system-level requirements were retained. Publications focusing solely on component-level control algorithms, sensor design, or abstract performance simulation without reference to deployment environments or logistics processes were excluded. The two literature streams were then synthesized through a comparative analysis, aiming to identify the intersection between indoor-UAV operation and outdoor-UAV logistics, and to extract common and missing system dimensions that motivate the formulation of the last-meter framework for indoor drone-based transportation. The full screening pathway and record counts retained at each stage are shown in Figure 4.

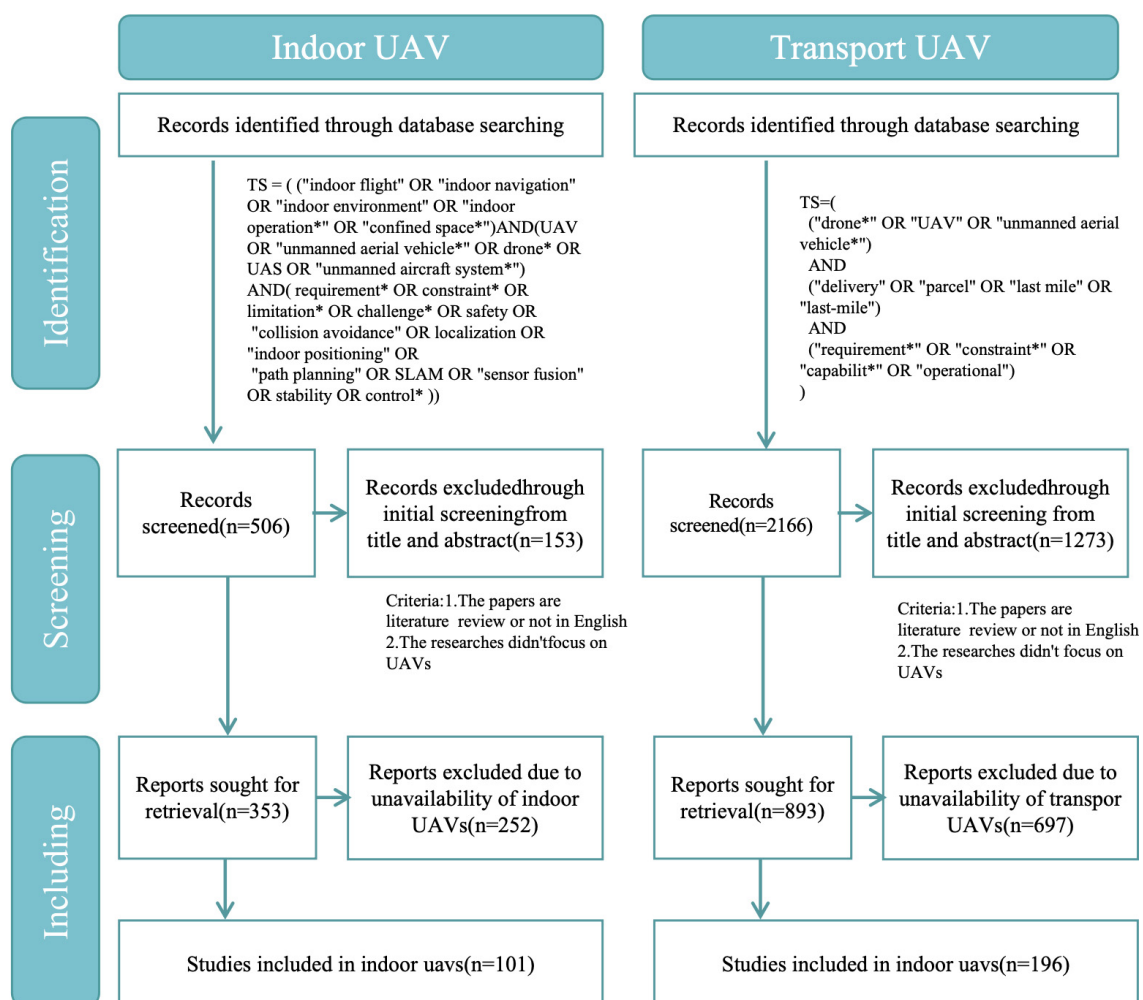


Figure 4. PRISMA literature screening workflow for the two parallel review streams.

To make explicit how the final corpus was retained, the screening followed the four PRISMA stages against pre-specified criteria. Records were identified from the Web of Science Core Collection (indoor-UAV stream: 506 records; delivery-UAV stream: 2166 records). Titles and abstracts were screened against the inclusion criteria—peer-reviewed journal

articles, written in English, addressing system-level UAV operation, spatial interfaces, or logistics requirements—and 1426 records were excluded as off-topic. The remaining 1246 full texts were assessed for eligibility, of which 949 were excluded for the reasons specified above (e.g., component-level control or sensor design without an operational or deployment context, or studies not reporting operational structures or system-level requirements). This screening retained the final 297 studies (101 indoor-UAV and 196 delivery-UAV studies) synthesized in this review, consistent with the counts reported at each stage of the flow diagram in Figure 4.

The Web of Science Core Collection was selected as the single source database for three reasons: its curated, selective indexing and consistent metadata quality; its adequate cross-disciplinary journal coverage across the engineering, robotics, transportation, and management fields relevant to the two streams; and the reproducibility of its field-tagged search syntax, which allows the search to be re-executed and independently audited. The trade-offs of relying on a single database and on English-language journal articles are acknowledged in Section 5.2.

3.2. Screening Criteria and Study Selection

A systematic literature search was conducted using the Web of Science Core Collection across two parallel streams. The indoor-UAV stream yielded 506 records, while the transport-UAV stream yielded 2166 records. Each stream underwent an independent screening process designed to retain studies directly relevant to their respective domains.

For the indoor-UAV stream, 153 records were excluded at the title and abstract screening stage based on the following criteria: studies that only mentioned GNSS-denied environments without specifying an indoor operational setting; research conducted in outdoor or semi-natural confined spaces, including mines, caves, forests, or open construction sites; studies focused solely on low-level flight dynamics, aerodynamic modeling, or attitude stabilization without addressing navigation, planning, or system-level operation; and studies limited to sensing or inspection tasks with no relevance to UAV movement or route management. The remaining 353 records were sought for full-text retrieval, of which a further 252 were excluded due to the unavailability of indoor-UAV content, yielding 101 studies for qualitative analysis.

For the transport-UAV stream, 1273 records were excluded at the title and abstract stage on the grounds that papers were either literature reviews, not published in English, or did not focus on UAV-based transportation. The remaining 893 records were sought for full-text retrieval, of which 697 were excluded due to the unavailability of transport-UAV content, yielding 196 studies for qualitative analysis.

Although only a small number of the indoor-UAV studies explicitly addressed indoor-UAV transportation, a broader set was preserved to capture enabling technologies and operational constraints transferable to transport-oriented applications. Together, the two streams provided a combined corpus of 297 studies for the subsequent synthesis.

3.3. PRISMA-Based Classification and Analysis

The retained studies were analyzed following the PRISMA framework and classified according to their primary research focus. The 101 indoor-UAV studies were categorized based on core functional dimensions of indoor-UAV operation, while the 196 transport-UAV studies were organized around key themes in last-mile logistics and drone-based delivery systems. This classification provides a structured foundation for Section 4, where each category is examined to assess its implications for indoor-UAV transportation and to identify remaining research gaps. To derive the higher-order analytical dimensions presented, a thematic synthesis was conducted across the two streams. Each study was first

coded for the system-level requirements and operational constraints it explicitly addressed. Codes from the indoor-UAV and transport-UAV streams were then compared through constant comparison, grouping categories that referred to the same underlying capability even when articulated in different terms (e.g., precision localization and delivery accuracy). The process continued until no new cross-stream groupings emerged, yielding the four dimensions (spatial mobility, logistical capability, social acceptance, and operational coordination) used to structure the analysis in Sections 4 and 5.

The coding and classification were carried out by a single researcher, which introduces a degree of subjectivity into the thematic synthesis. To support consistency, coding followed a predefined codebook that combined a deductive scheme, anchored in the four analytical dimensions of Section 2.3, with inductively derived sub-categories that emerged during reading. Category definitions were refined iteratively through repeated passes over the corpus; borderline studies were re-examined and reconciled against the codebook; and an audit trail linking each study to its assigned sub-category was maintained in the Supplementary List of included studies, allowing the classification to be independently inspected. The reliance on a single coder, and the potential subjectivity of the categorization, are recognized as limitations in Section 5.2.

Consistent with the configurative (interpretive) nature of this review, whose aim is to organize and synthesize heterogeneous evidence across two engineering domains rather than to statistically pool comparable outcomes, methodological quality was managed primarily at the eligibility stage rather than through a standardized study-level risk-of-bias instrument. Because the corpus spans diverse study types—experimental, simulation-based, field-deployment, and conceptual—no single appraisal tool is applicable across all of them. Quality was therefore controlled by restricting inclusion to peer-reviewed journal articles indexed in the Web of Science Core Collection, by applying the pre-specified eligibility criteria described above, and by requiring that each retained study report system-level operational content; the full list of the 297 included studies is summarized in Tables S2 and S3 (Supplementary Materials), in which each study is matched to its corresponding reference number, to allow independent verification. The absence of a formal study-level quality scoring is noted as a limitation in Section 5.2.

4. Results

4.1. Overview of the Reviewed Literature

A total of 297 articles were reviewed in this study to explore the feasibility of last-meter delivery. These studies broadly fall into two thematic categories: indoor general UAV technologies and outdoor delivery logistics. The former (101 articles) primarily focuses on the technical enablers required for flight in GNSS-denied environments, emphasizing localization accuracy, stability, and obstacle avoidance. The latter (196 articles) concentrates on the operational strategies of last-mile logistics, employing mathematical modeling, routing optimization, and cost-benefit analysis to assess the efficiency of drone-based transport systems. This dichotomy reflects a fundamental distinction in how drone operations are conceptualized, i.e., either as a robotic control problem within confined spaces or as a logistical node within a supply chain network. While distinct in emphasis, both domains contribute essential prerequisites for the realization of indoor aerial delivery, with technical mobility and operational demand. To identify the dominant research focuses, a frequency analysis of sub-topics was performed based on the classification of the selected literature.

For the indoor-UAV subset, the 101 retained studies were classified into seven sub-categories mapped onto the four-dimensional framework of Section 2.3 (Figure 5). Research is heavily concentrated along spatial mobility, which accounts for 67 studies (64.4%), split across localization and state estimation ($n = 40$, 38.5%), path planning and obstacle

avoidance ($n = 17$, 16.3%), and mapping and SLAM ($n = 10$, 9.6%). Within localization, visual and visual-inertial methods dominate ($n = 20$), followed by ultra-wideband ($n = 8$), LiDAR ($n = 7$), radar ($n = 6$), and acoustic positioning ($n = 3$), indicating that indoor positioning is pursued through multiple substitute modalities rather than a converged solution. The remaining dimensions are thinly represented: operational coordination contributes 21 studies (20.2%) through building and infrastructure integration ($n = 11$) and Fleet Coordination & Management ($n = 10$); logistical capability is limited to 10 studies on platform design and aerodynamics; and social acceptance is the smallest dimension, with only 6 studies (5.8%) on human–UAV interaction. The overlap pattern reinforces this asymmetry. The strongest cross-category links cluster around localization, with mapping and SLAM ($n = 10$), path planning ($n = 8$), and platform design ($n = 4$), showing that positioning, environment reconstruction, and vehicle design are treated as a coupled technical problem. In contrast, human–UAV interaction exhibits no cross-dimensional chords, meaning that social-acceptance research in the indoor corpus is pursued in isolation from the mainstream technical agenda. This distribution indicates that indoor-UAV research remains oriented primarily toward enabling the vehicle to move through space, with comparatively little attention to building-level coordination, payload handling, or occupant coexistence, precisely the capabilities that last-meter delivery would require.

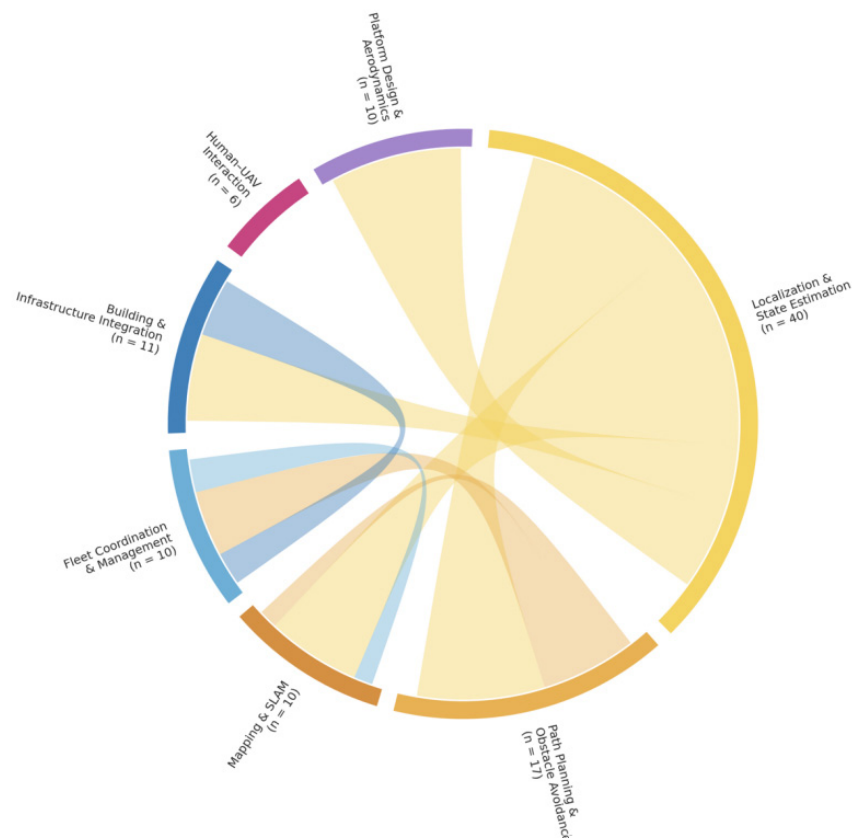


Figure 5. Chord diagrams of research-dimension co-occurrence across the reviewed indoor-UAV literature.

For the transport-UAV subset, the 196 retained studies were classified into twelve sub-categories mapped onto the same four-dimensional framework (Figure 6). The distribution is markedly more balanced than in the indoor corpus: spatial mobility accounts for 81 studies (44.0%), operational coordination for 50 (27.2%), social acceptance for 35 (19.0%), and logistical capability for 18 (9.8%). Spatial mobility is dominated by truck–drone cooperative routing ($n = 45$, 24.5%) and route planning and trajectory optimization ($n = 32$, 17.4%),

reflecting a decade of work on two-echelon vehicle-routing and multimodal pairings; airspace obstacle avoidance ($n = 4$) is notably under-represented. Operational coordination is split across dispatching ($n = 19$), traffic management ($n = 19$), and hub location ($n = 12$), while logistical capability covers platform design ($n = 12$) and endurance and charging ($n = 6$). The defining feature of this corpus is social acceptance, led by customer willingness and adoption ($n = 19$, 10.3%) and complemented by environmental impact ($n = 6$), human–UAV interaction ($n = 6$), and privacy and security ($n = 4$), together forming a substantial non-technical research track that is almost entirely absent in the indoor literature. Cross-category overlaps form three clusters: a logistical infrastructure cluster (END-HUB = 6, END-TDR = 5, HUB-TDR = 5) where battery limits, depot siting, and truck–drone tandem design are co-optimized; a routing-coordination cluster (DSP-RTE = 5, DSP-MGT = 3, MGT-RTE = 3) integrating optimization with airspace orchestration; and an isolated customer willingness arc, which, despite its volume, exhibits almost no overlap with technical categories, indicating that social-acceptance research in the outdoor stream is similarly siloed from its technical core. Read together with Figure 5, the two corpora are most strongly complementary along social acceptance (19.0% vs. 5.8%), while both remain equally weak in logistical capability (9.8% vs. 9.6%), a pattern that motivates the integrative framing adopted in Section 5.

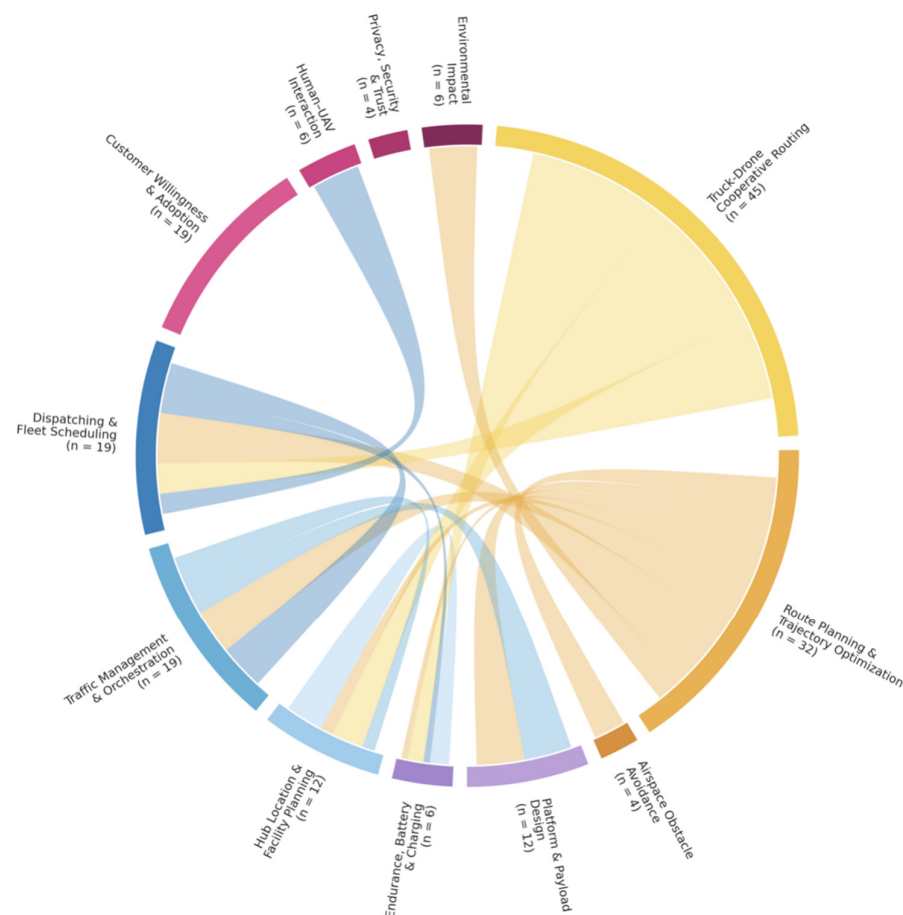


Figure 6. Chord diagrams of research-dimension co-occurrence across the reviewed transport-UAV literature.

At the same time, the near-absence of studies on vertical transport in buildings, combined with the scarcity of privacy/security and obstacle-avoidance research, suggests that while the logistical demand for drone delivery is well established, the specific operational challenges of entering and navigating vertical indoor spaces associated with the

last meter have not yet been adequately integrated into mainstream delivery frameworks. Figures 7 and 8 visualize this asymmetry from two complementary angles. Figure 7 reports the within-corpus share of each sub-topic, placing the two bodies of literature side by side on a common axis. The indoor-UAV corpus is strongly concentrated on enabling technologies: localization and navigation alone account for 54.8% of its studies, followed by sensor scanning (23.1%) and path planning (20.2%), while stability improvement (5.8%) and human interaction (2.9%) remain marginal. The delivery-UAV corpus, in contrast, is distributed across operational concerns, last-mile delivery (25.1%), truck–drone coordination (20.4%), routing (11.0%), and fleet scheduling (10.5%), with privacy and security (2.1%) and vertical transport (1.6%) receiving negligible attention. The two distributions are not simply different in volume; they are organized around different problems. Figure 8 re-projects the same data onto the four-dimensional framework developed in Section 2.3, making the asymmetry visible as a shape rather than a ranking. The indoor-UAV literature extends along spatial mobility and logistical capability but contracts sharply on social acceptance and operational coordination; the delivery-UAV literature traces the opposite profile, strong on operational coordination and social acceptance but weak on precision-oriented spatial mobility. Neither profile envelops the last-meter target (dashed) that last-meter delivery would require, and the two profiles are largely complementary rather than overlapping: the gaps in one corpus coincide with the strengths of the other. This justifies the dimension-by-dimension synthesis that follows, which treats last-meter delivery not as an extension of either literature but as the systematic integration of the capabilities each has developed in isolation.

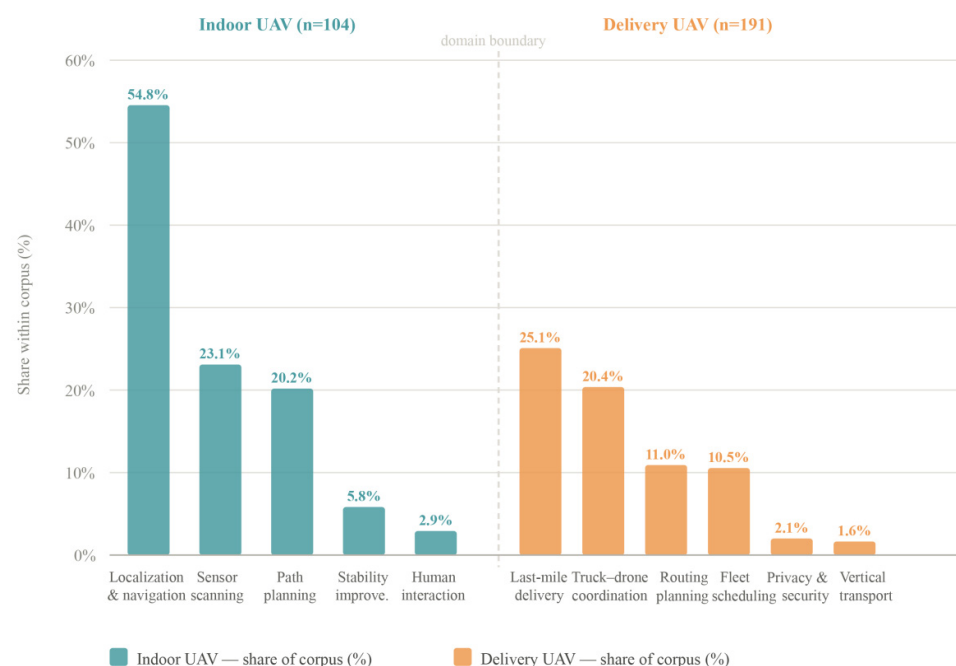


Figure 7. Topic frequency distribution across the indoor-UAV and delivery-UAV corpora.

4.2. Analyzing Indoor-UAV and Delivery-UAV Characteristics in Four Dimensions

4.2.1. Spatial Mobility

In the domain of delivery-UAVs, spatial mobility research is predominantly driven by the dual objectives of maximizing logistical efficiency and ensuring operational safety in non-segregated airspace. Regarding path planning, a substantial volume of literature approaches the problem through the lens of the vehicle routing problem with drones (VRP-D), specifically emphasizing the ‘truck-drone’ tandem model to overcome battery constraints and extend service range. Studies in this cluster have extensively modeled

the synchronization between mobile launch hubs (trucks) and aerial units, demonstrating that such collaborative routing strategies can significantly reduce total delivery time and operational costs compared to standalone drone fleets. Research has also expanded into fleet management, proposing heuristic algorithms to optimize flight sequences and minimize waiting times at rendezvous points, thereby enhancing the overall throughput of the logistics network [32–34]. In terms of localization and safety, the focus shifts from route efficiency to terminal precision and dynamic responsiveness. While global navigation satellite systems (GNSS) serve as the backbone for waypoint tracking during the cruise phase, recent works have concentrated on improving delivery location accuracy to ensure precise parcel dropping at designated coordinates, addressing errors caused by environmental factors [35]. Concurrently, to mitigate collision risks, scholars have developed robust ‘sense-and-avoid’ mechanisms utilizing LiDAR, radar, or visual sensors, enabling UAVs to autonomously detect and bypass static urban structures (e.g., buildings, power lines) and dynamic obstacles during long-range transit [36,37].

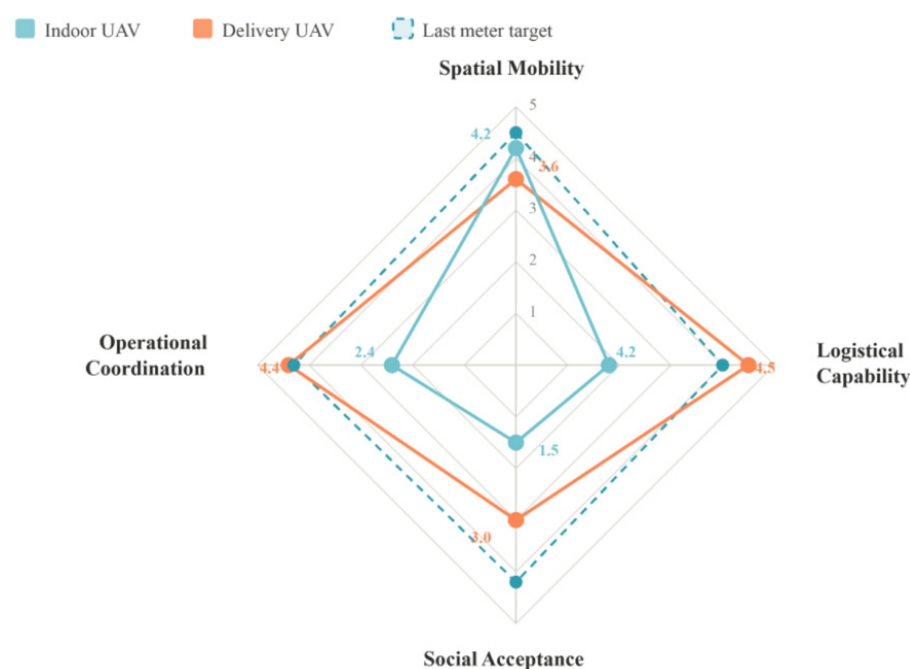


Figure 8. Research maturity radar comparing the two corpora across the four analytical dimensions.

In the context of last-meter delivery, spatial mobility extends beyond simple movement to represent the seamless continuity of navigation between external and internal environments. A critical breakthrough in this transitional mobility established a handover mechanism for balcony delivery that allows drones to autonomously switch from global GNSS guidance to local visual-inertial tracking upon approaching the building interface, thereby physically connecting the outdoor logistics network with indoor reception points [9]. For indoor-UAVs, spatial mobility is generally expressed through a high degree of local autonomy, measured by the system’s ability to integrate continuous positioning with reactive obstacle avoidance in GNSS-denied spaces [38]. Within the interior domain, this mobility is primarily characterized by the capability to maintain precise localization under strict payload constraints; for instance, visual SLAM is widely regarded as a key component for micro-drones due to its lightweight nature, enabling self-positioning in texture-rich environments [30,39]. In scenarios requiring robustness against varying illumination, LiDAR-based solutions are often prioritized to ensure navigational reliability despite the additional weight penalty [40–42]. Furthermore, the operational definition of indoor mobility encompasses the agility to negotiate complex topologies, where path

planning research focuses on utilizing algorithms to generate collision-free trajectories through static clutter [8], while emerging control strategies address the aerodynamic stability required to counteract ground effects in confined corridors [43].

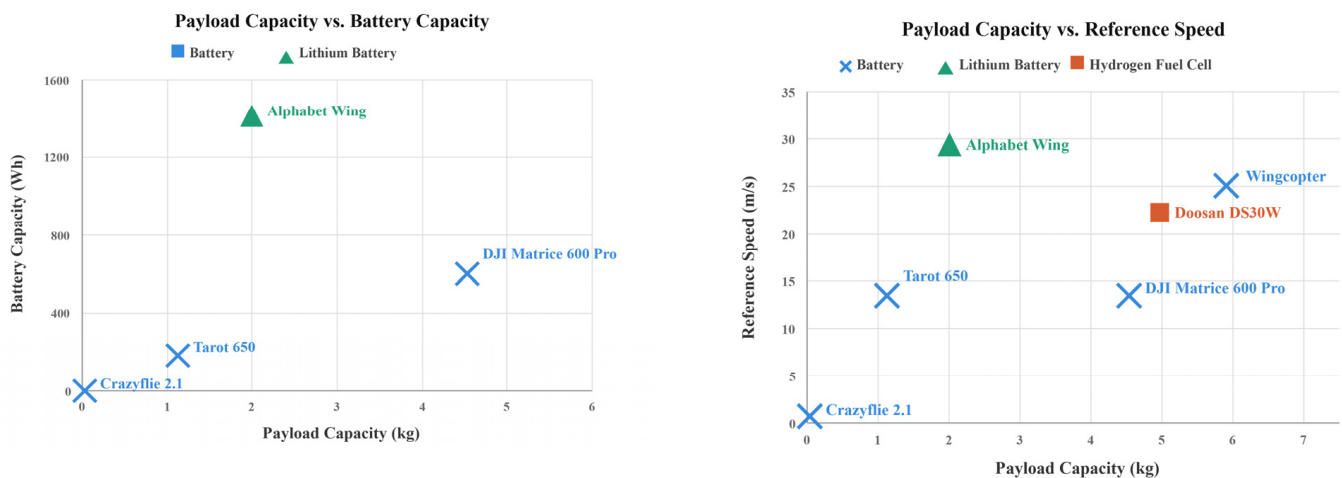
4.2.2. Logistical Capability

In the domain of outdoor logistics, research efforts are heavily concentrated on maximizing operational range and payload efficiency through platform optimization and energy innovation. Comparative studies on different UAV models have established performance baselines for commercial delivery, analyzing the trade-offs between multi-rotor stability and fixed-wing endurance under varying load conditions [44]. To address the critical bottleneck of flight duration, specific investigations have contrasted traditional lithium-polymer batteries with emerging hydrogen fuel cell technologies, demonstrating the latter's potential to significantly extend service radius for long-haul transport [45]. Furthermore, to mitigate “range anxiety” in continuous operations, diverse energy replenishment infrastructures have been proposed, including automated battery swapping stations for rapid turnaround [46], wireless charging pads for contactless maintenance [47], and tethered power systems for sustained localized operations [48]. Regarding the delivery, Amazon Project Wing and Wingcopter have proposed a tether-based delivery technique in which the package is lowered from a hovering UAV to the ground or a designated drop-off point using a winch or cable, allowing the aircraft to remain airborne without landing. Zipline has developed an aerial drop system for medical logistics, where the UAV releases the parcel over the target area and a parachute or similar deceleration device enables it to descend safely without physical contact with the aircraft. In addition, Wingcopter and other commercial platforms have implemented a landing-based delivery mode, in which the UAV performs a full autonomous touchdown at a prepared site and the parcel is subsequently retrieved by the recipient or a ground robot.

The logistical capability of indoor-UAVs is defined less by range and more by the strict geometric constraints required for safe access. While literature specifically addressing indoor charging infrastructure remains scarce, distinct delivery mechanisms adapted for building interiors have emerged: hovering handover protocols allow the drone to maintain a stable position while a human recipient manually retrieves the package, requiring robust safety guards and human–robot interaction design [8]; docking with smart furniture enables the UAV to land on specialized surfaces, such as automated tables or window ledges, facilitating payload detachment through magnetic or mechanical releases [49,50]; and robotic arm manipulation involves active grasping systems where either the drone or the receiving station mechanically secures the cargo, ensuring stability during the complex transfer process [49]. However, the capacity to implement these methods is fundamentally limited by the payload-to-size paradox dictated by confined spaces. Experimental data indicates that reliable navigation in narrow corridors (e.g., >0.65 m) necessitates the use of nano-UAVs (rotor span < 0.1 m), as safety margins dictate a lateral clearance of at least four times the vehicle's characteristic diameter ($4d$) to preserve dynamic maneuverability [51]. This geometric scaling law implies that for last-meter delivery, the logistical volume must be drastically miniaturized to fit within the safety envelopes of human-centric architecture. Table 4 lists the specifications of representative platforms from both bodies of literature, and Figure 9 plots payload against battery capacity and reference speed. The two-to-three-order-of-magnitude gap between outdoor delivery drones and indoor-capable nano-UAVs exposes a design trade-off that cannot be resolved by scaling alone.

Table 4. Performance comparison of representative outdoor- and indoor-UAV platforms.

Article	Model	Type	Power Source	Battery Capacity	Payload	Reference Speed	Cost
[44]	DJI Matrice 600 Pro	Rotary hexacopter	Battery	600 Wh	4.54 kg (experimental max)	13.41 m/s	\$8000
	Tarot 650	Quadcopter	Battery	177.6 Wh	1.13 kg	13.41 m/s	\$4000
	Wingcopter	Fixed-wing VTOL	Battery		5.9 kg	25 m/s	
[45]	Alphabet Wing	Electric multi-rotor	Lithium Battery	1400 Wh	2 kg (actual)	29 m/s	\$147/h
	Doosan DS30W	Hydrogen multi-rotor	Hydrogen Fuel Cell	250 g	5 kg (actual)	22 m/s	\$122/h
[51]	Crazyflie 2.1	Nano-UAV (Nano Drone)	Battery	250 mAh	35 g (effective payload < 10 g)	0.5–1.0 m/s (indoor test)	

**Figure 9.** Payload capacity versus battery capacity and reference speed for representative UAV models, revealing the gap between outdoor delivery platforms and indoor-capable nano-UAVs.

4.2.3. Social Acceptance

For outdoor delivery-UAVs, social acceptance is primarily framed as a macro-level issue of “public nuisance” and community trust, dominated by concerns over noise pollution, privacy infringement, and airspace safety. Extensive surveys indicate that public willingness to adopt drone delivery is negatively correlated with the acoustic signature of the aircraft; specifically, the high-frequency buzzing noise generated by rotors is perceived as significantly more annoying than traffic noise of similar decibel levels, raising concerns about the degradation of residential acoustic environments [52–54]. Furthermore, privacy remains a contentious barrier, as the deployment of camera-equipped drones for navigation is frequently interpreted by the public as a tool for aerial surveillance, triggering legal and ethical debates regarding data collection in private residential zones [55,56]. In terms of safety, the literature emphasizes “third-party risk”, i.e., the fear of mechanical failure leading to uncontrolled falls or collisions with pedestrians, which dictates that route planning must prioritize low-risk ground paths (e.g., flying over rivers or roads) to maintain public confidence [29,52]. Consequently, regulatory frameworks have evolved to enforce strict “geofencing” and remote identification standards to mitigate these societal risks before large-scale operations can be authorized [5,6].

The social acceptance of indoor-UAVs shifts the focus from “public disturbance” to “immediate personal intrusion”, necessitating a rigorous examination of human–robot interaction (HRI) and co-habitation comfort. In confined spaces, the acoustic impact is amplified; research on psychoacoustics suggests that even low-level drone noise can dis-

rupt cognitive concentration and cause stress in office or home environments, making acoustic stealth a critical design requirement [57]. Regarding physical safety, the concern transitions to proxemics, i.e., the psychological and physical distance between the drone and the human. Studies indicate that drones operating within a user's intimate social zone (<1.2 m) evoke strong feelings of intimidation, requiring flight algorithms to respect dynamic personal safety bubbles and the integration of protective cages to prevent laceration injuries [58]. Moreover, the privacy paradox is intensified indoors: unlike outdoor flyovers, indoor drones operating in high-density buildings risk capturing sensitive visual data (e.g., documents on a desk, domestic activities), prompting scholars to propose "privacy-by-design" solutions [59,60].

Read together, these findings indicate that "acceptance" in the last-meter context is not a single construct but operates across three interdependent layers, following the established distinction between socio-political, community, and market acceptance. Socio-political acceptance concerns the broad stance of the public, key stakeholders, and policymakers or regulators toward in-building aerial logistics and is shaped by prevailing attitudes to surveillance, aviation safety, and the legitimacy of automating tasks within private premises. Community acceptance concerns how specific building occupants, users, and local authorities perceive and respond to UAVs operating in their immediate environment, and is governed by the proxemic, acoustic, and privacy factors discussed above, together with procedural fairness in how occupant consent is sought and how grievances are handled. Market acceptance concerns whether building owners, service providers, and end-users are willing to adopt and pay for such services in practice, and depends on perceived reliability, cost, liability arrangements, and the availability of clear handover and opt-out mechanisms. Distinguishing these layers clarifies that an indoor delivery-UAV may be technically capable and even socio-politically tolerated yet still fail at the community or market level [61].

4.2.4. Operational Coordination

In the realm of delivery-UAVs, operational coordination is established through a hierarchical governance structure that synchronizes regulatory oversight with physical network optimization. At the macro level, coordination relies on centralized unmanned traffic management (UTM) systems; for instance, the PansaUTM deployed in Poland demonstrates how digitizing flight authorizations enables the safe integration of complex operations like medical transport even as flight volumes double [62]. In infrastructure-sparse regions, such as mountainous terrains, this coordination is maintained via self-fly autonomy supported by ground-based surveillance nodes (4G/Solar), which continuously broadcast telemetry for real-time risk assessment [3]. Beneath this governance layer, physical coordination is achieved through the strategic deployment of logistical nodes. Research advocates for an air-ground cooperative model, utilizing "parcel-receiving stations" and shared public transit routes to replace risky point-to-point flights, thereby minimizing collision probability through bi-layer optimization [63]. Empirical studies emphasize that the optimal configuration of infrastructure is the primary determinant of viability; for example, in the London NHS network, hub location was found to impact economic feasibility more than aircraft range or payload [10]. To adapt to diverse geographies, scholars have developed specific location strategies: minimizing distances in mixed Euclidean-Manhattan grids [64], applying compact cuckoo search algorithms for rural hub selection [65], and utilizing two-stage continuum approximation (CA) models to optimize urban micro-fulfillment centers (MFCs) [66]. At the execution level, dynamic fleet coordination is managed by advanced computational algorithms. To ensure network stability, researchers have designed impedance functions to evaluate air route capacity based on safety separations [67],

while others have utilized simulated annealing algorithms to optimize demand-based scheduling within the constraints of urban road and building data, as validated in Shanghai [68]. Supporting these operations, immersive 3D frameworks have been proposed to simulate realistic energy consumption physics [69], alongside specialized solvers such as the order-aware adaptive iterative local search (OAILS) for multi-depot tasks, conflict-free scheduling schemes (MDSP) for battery-constrained fleets [70], and the MID algorithm which combines dispatching rules to significantly minimize total delivery time [71].

Indoor operational coordination shifts the focus from centralized supervision to decentralized, semantic interaction within communication-denied environments. To navigate confined spaces without global traffic management, fleets rely on bio-inspired algorithms, such as the self-organized Reynolds model, to enable autonomous flocking behaviors in dense environments [72]. Collision-free operations are further supported by game-theoretic formulations and winning strategy synthesis, which manage fleet dynamics in restricted areas [73]. For exploration tasks in unknown terrains, multi-UAV systems employ collaborative logic like the Tracking-D*Lite algorithm to autonomously map boundaries and track targets without GPS [74]. Human-machine interaction is enhanced through augmented reality (AR) interfaces, allowing engineers to visualize drone paths and define waypoints directly within the physical environment [75].

Realizing this coordination in practice requires indoor-UAVs to interoperate with the building's existing digital infrastructure rather than to act as standalone agents. Three interfaces are particularly relevant. First, BIM and digital-twin models can serve as a shared spatial and semantic substrate: a continuously updated digital twin supplies the UAV with as-built geometry, room and corridor semantics, and the location of docking and charging interfaces, while the UAV in turn feeds back occupancy and as-operated data, enabling pre-flight path validation against the current building state [76]. Second, integration with IoT-enabled building automation systems allows the UAV to query and actuate building components along its route, requesting automatic doors, elevators, or access-controlled thresholds, and reserving airspace segments, provided these exchanges follow open, standardized interface protocols that ensure cross-vendor interoperability and prevent vendor lock-in [77]. Third, coupling to facility-management and security platforms embeds UAV missions within the building's scheduling, incident-response, and audit workflows, so that flights are authorized, logged, and supervised through the same operational governance used for other building services. Treating BIM, digital twins, IoT/BAS, and facility-management platforms as a single coordinated stack, rather than as separate technologies, is therefore a precondition for seamless and accountable last-meter operation [76,77].

5. Discussion

5.1. Proposed Challenges and Indicators for Last-Meter Delivery

The four-dimensional framework developed in Section 2.3 and the comparative synthesis in Section 4 together establish a clear premise: last-meter delivery requires capabilities that neither the indoor-UAV literature nor the outdoor delivery-UAV literature currently addresses in isolation, and in particular, neither stream connects technical spatial capabilities with the human-centered and governance-oriented concerns that in-building operation demands.

How this gap is interpreted, however, matters as much as its identification. Engineering literature has predominantly framed indoor-UAV delivery as a robotics problem: one to be solved through higher localization accuracy, lighter payloads, and quieter propulsion. This framing implicitly treats the building as a passive container in which, once the vehicle performs well enough, delivery simply occurs. Yet buildings are not passive: they are

planned, managed, and governed environments, with their own circulation logics, service agreements, occupant communities, and digital management infrastructures. Whether a UAV can navigate a corridor is a robotics question; whether it is allowed to operate, scheduled to operate, and accepted by occupants is a building-management question. The realization of last-meter delivery therefore depends as much on institutional integration as on technical capability. As shown in Figure 10, this section re-reads the four dimensions of the framework through a building-management lens, translating each into a set of institutional, spatial, and procedural indicators that govern whether indoor aerial logistics can be integrated into the daily life of a building.

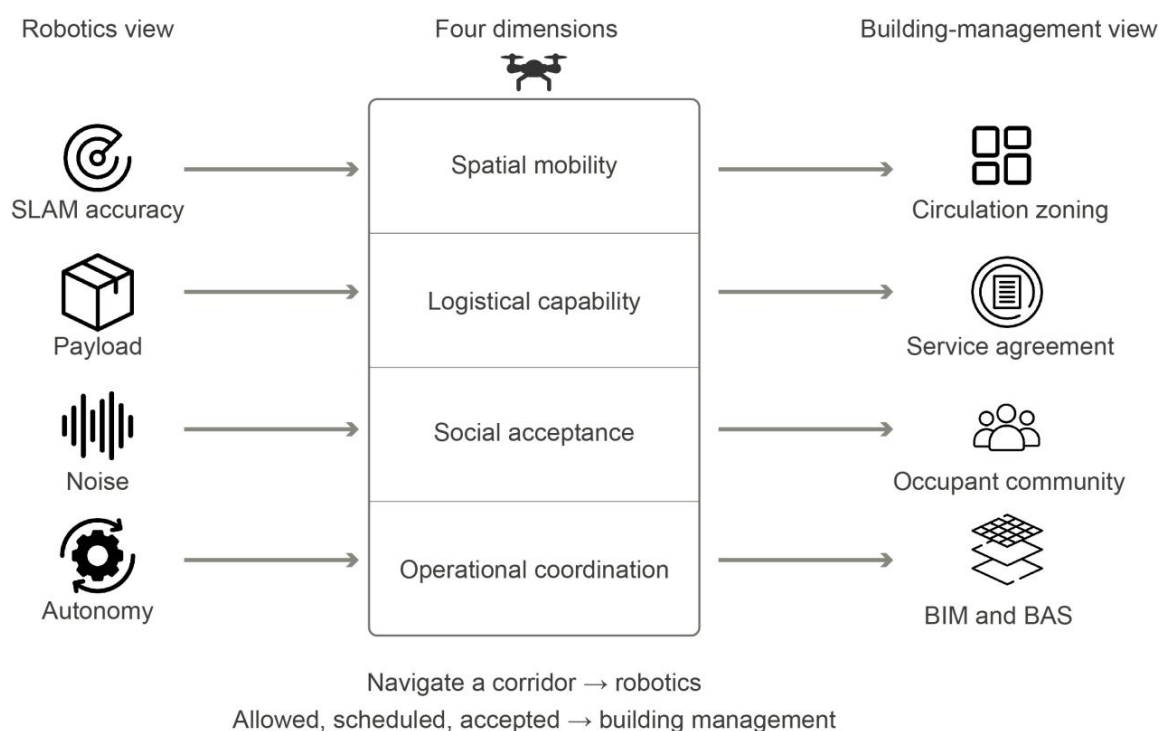


Figure 10. From robotics to building management: four dimensions as translation bridges.

In the dimension of spatial mobility, the critical managerial challenge is not algorithmic navigation per se, but the spatial designation and standardization of UAV-accessible zones within a building's circulation hierarchy. Buildings operate according to layered circulation logics, i.e., separating passenger flows from service flows, public zones from private ones; indoor-UAV routes must be embedded within these existing spatial hierarchies rather than superimposed upon them. This requires building managers and architects to define dedicated UAV corridors, transition interfaces at building envelopes (e.g., designated balcony or window handover points), and vertical mobility strategies that are coordinated with elevator scheduling and fire egress protocols. The relevant management indicator is therefore not navigation accuracy in meters, but spatial compliance: the degree to which UAV flight paths conform to the building's spatial governance framework, including access zoning, height stratification, and circulation priority rules. Figure 11 schematizes this zoning logic, showing how UAV corridors can be layered within the building's existing circulation hierarchy rather than competing with it.

Regarding logistical capability, building management literature has long distinguished between fixed infrastructure logistics (elevators, pneumatic systems) and flexible service logistics (portering, AMRs), evaluating them through operational metrics such as turnaround time, service frequency, and load balancing across the building day. For indoor-UAV transport to be institutionally viable, it must be evaluated on the same operational terms. Key

indicators include mission cycle efficiency, i.e., the total time from task initiation to confirmed delivery and UAV recovery, as well as service fit, defined as the alignment between cargo type, packaging standards, and the UAV's physical access constraints. Building operators need to define which item categories (e.g., pharmaceutical samples, confidential documents, small food orders) are appropriate for aerial handover, and establish standardized handover protocols, i.e., specifying where, when, how, and with what proof of receipt, that can be incorporated into facility service agreements. In the dimension of social acceptance, the building management perspective reframes occupant response not as individual psychological reaction, but as a building community governance issue. Buildings are shared environments subject to collective norms, and the introduction of UAV operations affects the acoustic environment, visual privacy, and perceived safety of all occupants, not just delivery recipients. The relevant indicators are therefore managerial rather than purely psychophysical: occupant policy literacy (the extent to which building residents understand UAV operating rules and their rights), complaint and redress mechanisms (whether building management has established formal channels for noise, privacy, or safety grievances), and consent and opt-out procedures for occupants in proximity to UAV corridors. These governance instruments are prerequisites for the social license to operate, and their absence would undermine deployment regardless of technical performance. Figure 12 summarizes how the four last-meter dimensions map onto the building's management structure.

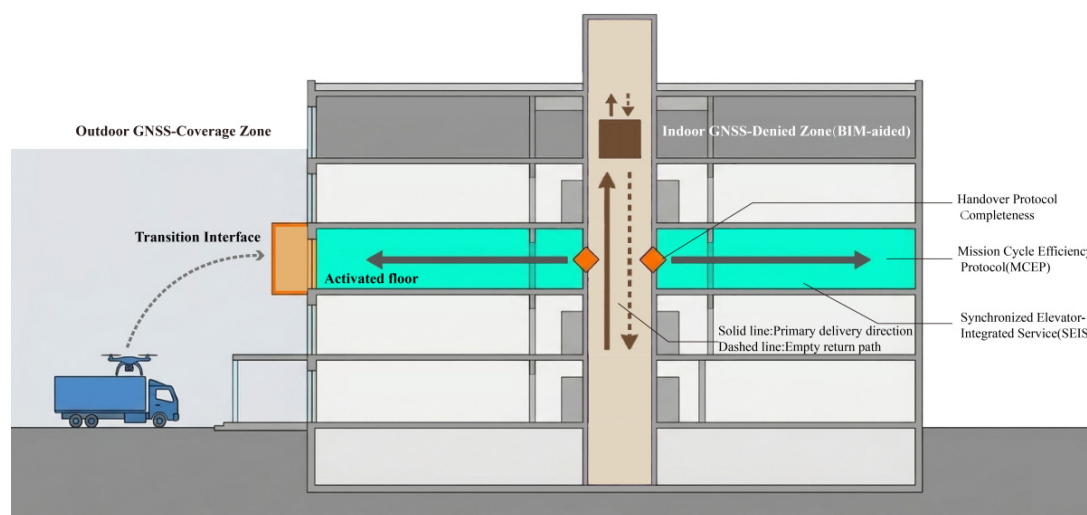


Figure 11. Building cross-section illustrating spatial zoning and UAV corridors within the existing circulation hierarchy.

In operational coordination, the building management dimension centers on institutional interoperability: the integration of UAV operations into the existing management structures of the building, including facility management systems, building automation systems (BAS), security protocols, and smart-building platforms. Buildings in high-density urban contexts increasingly operate through digital management frameworks, i.e., building information modeling (BIM), IoT-enabled infrastructure, and digital twins, and indoor-UAVs must function as coordinated actors within these systems rather than independent agents. Management indicators include infrastructure integration completeness (the degree to which UAV docking, charging, and routing are embedded into the building's BIM and operational database), protocol standardization (whether UAV-building interface commands follow open IoT standards enabling cross-vendor interoperability), and liability and incident governance (the clarity of responsibility allocation between building operators,

UAV service providers, and occupants in the event of operational failure). Based on this building-management-oriented analysis, Table 5 presents a consolidated indicator framework that reframes last-meter UAV delivery requirements in terms that are actionable for building planners, facility managers, logistics providers, and urban governance bodies. The indicators were extracted through the same thematic synthesis used to derive the four dimensions (Section 3.3). Specifically, where studies identified operational requirements, performance criteria, or evaluation metrics for UAV operation in structured environments, these were coded and clustered into the indicators listed below. Each indicator is traceable to at least one reviewed study, as shown in the rightmost column.

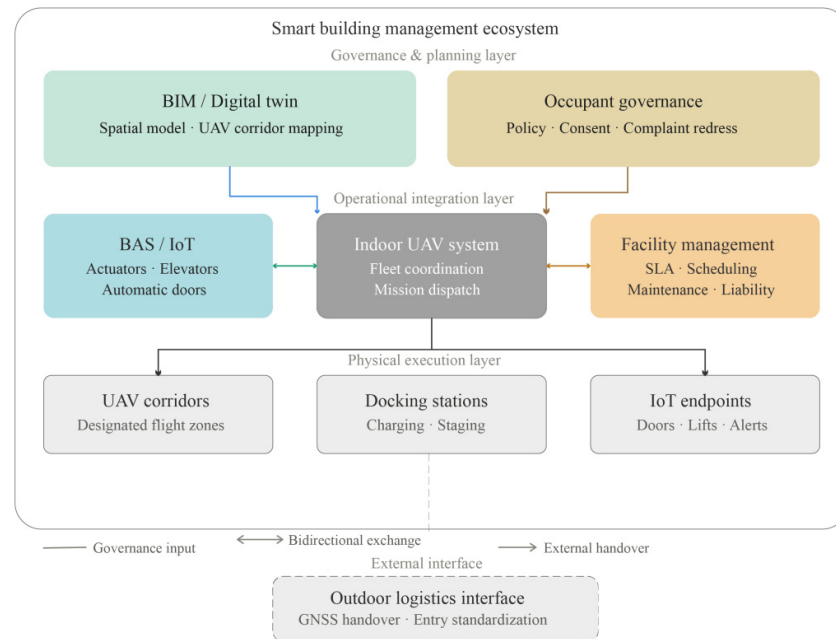


Figure 12. Building management integration structure linking the four last-meter dimensions to operational governance indicators.

Cutting across these indicators is a regulatory and data-governance challenge that the building-management lens alone does not resolve. Although indoor space is administered by building owners and facility managers, last-meter operations are not exempt from aviation oversight: national civil aviation authorities retain jurisdiction over remotely piloted aircraft, and rules addressing flights near or over people, beyond visual line of sight (BVLOS), and commercial operation remain applicable even in enclosed or semi-enclosed, near-building settings, as reflected, for example, in recent Australian remotely piloted aircraft regulations [78,79]. The last-meter framework must therefore be read as a two-tier governance arrangement in which building-level site-access and operational rules are layered beneath, and must remain consistent with, civil-aviation requirements; standardized handover and liability provisions are the practical mechanism through which responsibilities are allocated across the aviation operator, the service provider, and the building, and through which the current regulatory gap for indoor commercial UAV operation can be addressed rather than assumed away.

A second cross-cutting concern is privacy, data governance, and cybersecurity, which is heightened in indoor, human-occupied environments. Unlike outdoor flyovers, an indoor-UAV navigates continuously among occupants and may capture sensitive visual and spatial data, faces, documents, and the internal layout of private or secured areas, so that the navigation sensing required for flight is simultaneously a surveillance capability. This raises three coupled requirements. First, data minimization and privacy-by-design: on-

board processing, low-resolution or event-based sensing, and edge computing that derives navigation cues locally without retaining or transmitting identifiable imagery, together with explicit occupant consent and clearly demarcated no-capture zones. Second, secure-by-design operation: because indoor-UAVs are networked actuators that interact with doors, elevators, and building systems, the command, telemetry, and building-interface links constitute an attack surface whose compromise has physical-safety consequences, motivating authenticated and encrypted control channels, integrity protection for BIM and digital-twin exchanges, and resilient fail-safe behavior under link loss or spoofing. Third, accountable data governance: clear ownership, retention, access-control, and auditing rules for any data the UAV does collect, aligned with applicable data-protection regimes and with the building's own security policies. These requirements are reflected in the occupant-consent and liability indicators of the framework and should be treated as first-order design constraints rather than after-the-fact compliance steps [80,81].

Table 5. Indicator framework for last-meter indoor-UAV transportation.

Dimension	Critical Gap/Challenge	Specific Requirements for Indoor Delivery	Article
Spatial Mobility	Spatial designation gap: UAV routes have no standing within existing building circulation hierarchies (passenger, service, emergency flows).	Spatial compliance rate: % of UAV flight path conforming to designated zones, access rules, and egress clearances.	[82–84]
		Handover interface standardization: existence of formally designated outdoor-to-indoor transition points (balconies, windows, lobbies) with defined entry protocols.	[8,9,50,85]
		Vertical mobility coordination protocol: defined procedure for multi-floor delivery that avoids conflict with elevator scheduling and stairwell evacuation routes.	[49,85,86]
		Dynamic occupancy sensitivity: capacity to adjust routing in response to real-time building occupancy data (event scheduling, peak hours).	[32,87,88]
Logistical Capability	Service integration gap: no standardized framework exists to embed UAV delivery into building service agreements, maintenance schedules, or cargo classification systems.	Mission cycle efficiency: total time from task dispatch to completed delivery and UAV return to staging station, benchmarked against existing building logistics alternatives.	[12,33,89,90]
		Service fit index: formal classification of cargo types (documents, pharmaceuticals, consumables) eligible for aerial delivery, with packaging and labelling standards.	[91–93]
		Handover protocol completeness: existence of standardized procedures for recipient interaction, proof-of-delivery recording, and failed-delivery contingency.	[7,8,52]
		Operational turnaround capacity: defined staging, charging, and resetting workflow per building, with capacity benchmarks per building typology (hospital, residential tower, office).	[10,94]
Social Acceptance	Community governance gap: UAV introduction affects shared acoustic, visual, and safety environments of all occupants, yet current frameworks address only individual user consent.	Occupant policy literacy score: % of building occupants who are aware of UAV operating rules, corridor locations, and their rights regarding noise and privacy.	[52,54,95]
		Consent and opt-out coverage: proportion of occupants in proximity to UAV corridors who have been offered formal opt-out or scheduling preference options.	[55,56,96,97]
		Acoustic environment compliance: UAV noise impact assessed against building-type acoustic standards rather than generic dB limits.	[57,98]

Table 5. *Cont.*

Dimension	Critical Gap/Challenge	Specific Requirements for Indoor Delivery	Article
Operational Coordination	Institutional interoperability gap: UAV systems lack formal integration with building management infrastructure (BMS, BAS, BIM, security), creating coordination voids and liability ambiguities.	BIM/digital twin integration completeness: degree to which UAV docking stations, corridors, and handover points are represented and schedulable within the building's digital management platform.	[20,75,99]
		Facility management service level agreement (SLA) coverage: existence of contractual obligations defining UAV uptime, incident response time, maintenance responsibilities, and performance benchmarks.	[100–102]
		Liability and incident governance clarity: defined allocation of responsibility among building operator, UAV service provider, and recipient in cases of delivery failure, property damage, or data breach.	[36,56,103]

Although Table 5 frames each requirement as a measurable indicator, these indicators remain to be operationalized in future empirical work. In practice, spatial compliance could be measured by checking logged flight paths against the building BIM geometry and designated-zone rules; handover standardization by handover success rate and handover time per delivery; service performance by mission-cycle efficiency and energy consumption per delivery; and occupant-related acceptance by consent coverage and occupant survey or complaint rates. Rather than imposing a universal ranking, the indicators are intended to be applied in a deployment-stage order that mirrors how an installation would be approved and scaled: first spatial and legal feasibility (spatial compliance and regulatory alignment), then safety and privacy (geometric safety envelopes, occupant consent, and data governance), then service performance (handover reliability and mission-cycle efficiency), and finally optimization (fleet coordination and energy efficiency). This staged use makes the framework actionable for building operators, facility managers, and logistics providers, who can apply the relevant indicators at the corresponding decision gate.

The environmental and energy implications of last-meter operation also warrant explicit attention, particularly given the sustainability focus of in-building logistics. Whereas outdoor-UAV logistics has been assessed through life-cycle impacts, emissions intensity, and dependence on the electricity mix [29], the indoor last-meter segment introduces distinct considerations: the energy consumed per delivery over short but frequent vertical trips, the charging and docking infrastructure that must be embedded within the building, the trade-off between low-noise and low-energy operation and payload or speed, and the life-cycle and end-of-life impacts of dense indoor-UAV fleets. These factors are not yet quantified in the reviewed literature and represent a priority for future evaluation, so that last-meter systems can be assessed not only on operational performance but also on their net environmental contribution relative to incumbent indoor transport such as service lifts and ground-based robots.

5.2. Limitations and Recommendations

Despite the comprehensive synthesis of indoor-UAV and outdoor-delivery-UAV literature, several limitations remain. First, the number of studies that explicitly address UAVs as indoor transportation agents is still extremely limited; consequently, the system-level conclusions in this review are derived from conceptual integration and cross-domain analogy rather than from direct empirical evidence. This restricts the extent to which the proposed last-meter framework can be quantitatively validated. Second, most indoor-UAV studies concentrate on localization, obstacle avoidance, and flight stability, while long-term operational aspects, such as continuous mission endurance, cumulative energy consumption, maintenance requirements, and high-density task scheduling, are rarely

investigated with real-world data. As a result, the lifecycle performance and scalability of indoor delivery-UAV systems remain insufficiently understood. Third, the proposed indicator framework has not yet been systematically tested across heterogeneous building typologies. The spatial configuration, occupancy density, and management regimes of hospitals, residential towers, airports, and office buildings differ substantially, and these differences may significantly affect navigation feasibility, social acceptance, and operational coordination, thereby limiting the current generalizability of the framework.

Fourth, this review draws exclusively on peer-reviewed, English-language journal articles indexed in the Web of Science Core Collection. While this choice favors source consistency and reproducibility, it introduces potential coverage and selection biases: relevant work indexed only in other databases (e.g., Scopus, IEEE Xplore, or ScienceDirect), peer-reviewed conference proceedings, which are a primary publication venue for indoor-UAV and robotics research, and non-English studies were not captured, which may under-represent applied engineering results and regional deployment cases. Fifth, the thematic classification was performed by a single coder and was not subjected to a formal study-level quality or risk-of-bias appraisal; although a predefined codebook, iterative reconciliation of borderline cases, and an auditable list of included studies were used to limit subjectivity, residual classification bias cannot be excluded. Future reviews could extend the search across multiple databases and grey literature and adopt independent double-coding with formal inter-coder agreement to further strengthen methodological robustness.

Based on these limitations, several directions for future research are recommended. First, prototype-based and field-deployment studies in representative indoor environments, such as hospital campuses or high-rise residential buildings, should be conducted to obtain longitudinal measurements of energy efficiency, reliability, safety, and human-UAV interaction under realistic operational conditions. Such empirical evidence is essential for validating and refining system-level performance models. Second, at the technological level, coordinated advances are required in high-energy-density micro power sources, low-noise propulsion systems, and sub-centimeter-accuracy docking and handover mechanisms, in order to alleviate the fundamental trade-off between vehicle miniaturization, payload capability, and safety margins in confined spaces. Third, from a planning and governance perspective, indoor-UAV transportation should be integrated into building design and facility management frameworks, particularly through the early incorporation of UAV corridors, docking interfaces, and traffic coordination rules into BIM and smart-building platforms. The establishment of standardized spatial, technical, and operational guidelines will be crucial for enabling scalable and socially acceptable last-meter UAV delivery systems.

6. Conclusions

This study investigated the concept of last-meter delivery by synthesizing research on indoor-UAV operation and transport-UAV-based logistics, and proposed a unified framework covering spatial mobility, logistical capability, social acceptance, and operational coordination. The analysis indicates that indoor transport-UAVs are subject to a distinct set of operational constraints compared with conventional last-mile delivery drones, including GNSS-denied environments, confined three-dimensional spaces, close human-UAV interaction, and the need for integration with building infrastructure and management systems. These conditions suggest that the design focus for indoor transport-UAVs should shift from range and payload maximization toward high-precision navigation, safety within strict geometric envelopes, low-noise and privacy-aware operation, and decentralized, building-aware coordination. The review further highlights that indoor aerial delivery is unlikely to be achieved through simple miniaturization of outdoor platforms, and that

progress will depend on coordinated advances in outdoor–indoor localization handover, micro-scale payload handling, and semantic interaction with indoor environments. By identifying under-researched dimensions and proposing an analytical framework together with a set of building-management indicators, this review provides a structured foundation for future empirical research on indoor-UAV transportation in smart buildings and urban logistics systems. By framing these requirements within the last-meter perspective, this review clarifies the key technical and organizational gaps that must be addressed before indoor-UAV transportation can become a viable component of smart building and urban logistics systems.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/su18136728/s1>. Table S1: PRISMA checklist; Table S2: The 196 outdoor-UAV logistics studies included in this review [1–10,17,22–29,32–34,37,44–49,52,54–56,62–71,82–97,100–236]; Table S3: The 101 indoor-UAV studies included in this review [11,12,18–21,30,35,38–43,50,57,59,60,72–75,99,237–314]. Each included study is listed with its corresponding reference number in the table.

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Nomenclature

AR	Augmented reality
BAS	Building automation system
BIM	Building information modeling
BVLOS	Beyond visual line of sight
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HRI	Human–robot interaction
IoT	Internet of things
LiDAR	Light Detection and Ranging
PESTLE	Political, Economic, Social, Technological, Legal, and Environmental (analysis)
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
RPA	Remotely piloted aircraft
SLAM	Simultaneous Localization and Mapping
TOE	Technology–Organization–Environment (framework)
UAV	Unmanned aerial vehicle
UTAUT	Unified Theory of Acceptance and Use of Technology
UTM	Unmanned traffic management
VRP(-D)	Vehicle routing problem (with drones)

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