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Advanced drone applications for efficiency and sustainability in construction safety

Nyaribari Momanyi Kepha *

Department of Construction Management, College of Engineering and Innovation, Bowling Green, Ohio, United State.

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Abstract

This paper examines advanced applications of drone, or unmanned aerial vehicle (UAV), technology, in U.S. construction beyond traditional safety roles. The focus was on analyzing project cost optimization, logistics and workflow coordination, environmental monitoring, supply chain tracking, and subcontractor oversight. Drones are shown to enhance surveying, progress tracking, and reduce time and labor costs, improve site logistics and material deliveries, enable real-time inventory and asset tracking, and systematically document environmental compliance. A Technology Acceptance perspective suggests that perceived usefulness drives adoption, while Systems Theory highlights how drones integrate information flows across project subsystems. This paper proposed a simplified cost–benefit model, like labor-cost savings from drones compared to manual surveys, to illustrate quantitative gains. A summary table compares drone-enabled benefits across applications, and example calculations demonstrate potential savings. Findings indicate that drones, treated as strategic resources, significantly compress schedules and costs while supporting sustainability goals. The paper recommends different ways to improve the return on investment beyond five years while saving on costs by increasing drone fleets and using them for high-frequency tasks. This review contributes a comprehensive, theory-informed analysis of non-safety UAV uses in construction operations.

Keywords: UAV; Drone; Cost; Saving; Survey

1. Introduction

Construction project managers face mounting pressures to cut costs, accelerate schedules, and comply with environmental regulations while coordinating complex workflows. Traditional survey and monitoring methods, such as manual site walks and ground teams, are labor-intensive and error-prone, leading to cost overruns and delays. Riddell (2022) industry studies report shows that nearly 14% of construction rework costs, totaling approximately $1.84 trillion globally, stem from inadequate site data and coordination. Drones have emerged as transformative tools that reduce such errors by providing rapid, accurate aerial data. Whereas early drone use in construction focused on safety inspections and hazard detection, recent innovations emphasize operational optimization. In the U.S, up to 55% of contractors adopted drones by 2023 compared to 48% and 36% in 2021 and 2022 respectively. This indicates growing acceptance as shown in Figure 1.

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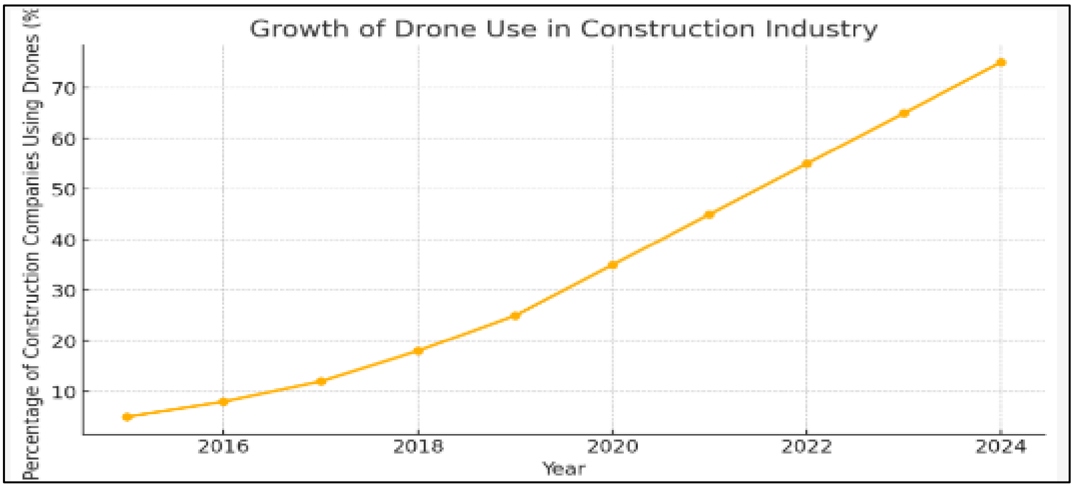
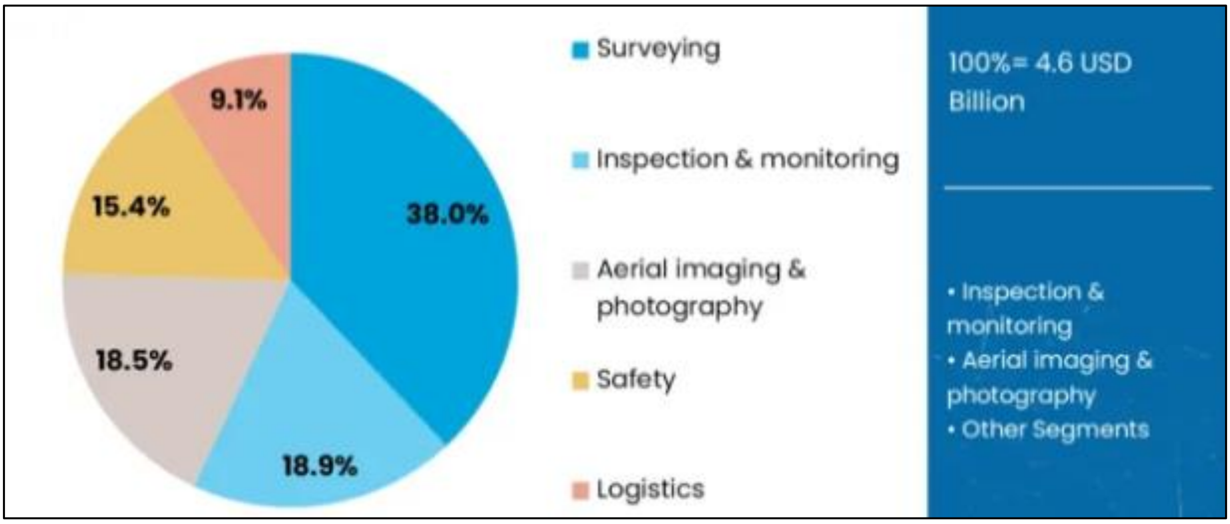
* Corresponding author: Nyaribari Momanyi Kepha



Source: https://etraintoday.com/blog/how-drones-are-making-construction-sites-safer/

Figure 1 Growth in Construction usage

Drones now enable high-precision topographic surveys, frequent progress tracking, material logistics and automated volume calculations, all of which compress project timelines and reduce labor costs. These drone application areas have been summarized in figure 2. They also support logistics by tracking material deliveries and inventory locations, effectively acting as flying sensors in the supply chain. environmental side, drones continuously monitor dust levels, erosion control, water runoff, and habitat impact across the site. These non-safety applications promise not only operational efficiencies but also enhanced sustainability compliance. For instance, drones document erosion control measures and wildlife protection in real time, helping firms meet strict regulatory requirements.



Source: https://www.futuremarketinsights.com/reports/construction-drone-market

Figure 2 Drone application areas in construction

This paper reviews the literature on these advanced drone functions, with a specific focus on the U.S. construction environment, and employs a systems perspective to link drone data flows to project control. The paper also presents a simple analytical model to quantify cost and time savings from UAV integration.

The objectives of this study are:

- To examine how drone technology contributes to operational efficiency in the U.S. construction industry.
- To evaluate drone benefits, demonstrating how drone adoption can influence labor efficiency, material usage, and schedule control in practical construction scenarios.

The scope of the research is limited to secondary data, with a primary focus on construction practices within the United States. The study concentrates on medium-to-large commercial construction projects where drone integration is most visible. The analysis centers on operational, environmental, and managerial functions of drones across the project lifecycle, from pre-construction planning to execution and monitoring. The research applies a simplified quantitative model to illustrate cost and productivity impacts.

2. Literature Review

2.1. Theoretical Perspectives

2.1.1. Systems theory

Systems theory, according to Von Bertalanffy (1972) is relations and interdependencies that shape how work is conducted and managed. From a construction environment perspective, the theory views a construction project as an interdependent network of activities and information flows. Drones act as nodes that gather data across the system, improving feedback and coordination. Feeding timely aerial data into building information modelling (BIM) and project-control systems helps UAVs help synchronize schedules, resources, and site conditions.

2.1.2. Resource-based view (RBV)

Barney (2001) RBV theory posits that it is a strategic management framework asserting that firms achieve sustainable competitive advantage and superior performance by leveraging internal resources that are Valuable, Rare, Inimitable, and Non-substitutable (VRIN). An organization’s drone program becomes a strategic capability in which firms that effectively harness UAVs for recurring tasks create valuable and inimitable competencies.

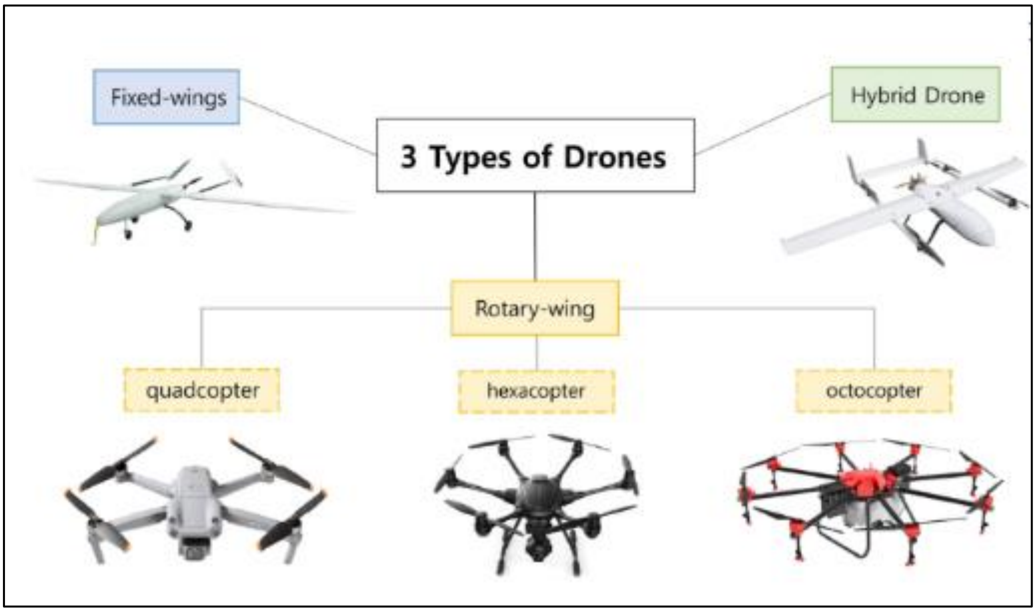
2.1.3. Technology Acceptance Model (TAM)

TAM suggests that technology usage is influenced by performance expectancy, effort expectancy, social influence, and facilitating conditions. This implies that increase in drone application in construction trend is driven by perceived usefulness and ease-of-use where stakeholders recognize drones’ ability to deliver real-time site intelligence and streamline tasks, adoption increases.

2.2. Project Cost Optimization and Productivity

2.2.1. Site Surveying and Mapping

One of the most mature drone uses is high-resolution aerial mapping. Dlamini and Ouma (2025) research on large-scale topographic aping show that a single drone flight with RTK GPS cover a 100-acre site in under an hour, generating maps and 3D terrain models with centimeter accuracy. These rapid scans support precise cut/fill analyses and grading verification. For example, earthwork volume calculations from drone photogrammetry reduce material over-ordering and change orders by catching site deviations early. The type of drone used depends on the project context (Choi et al., 2023). Fixed-wing drones are ideal for covering large areas quickly, making them suitable for large infrastructure or highway projects. Rotary-wing drones, such as quadcopters, are more effective for close-range mapping and operations in confined or complex environments, such as dense urban construction sites. Hybrid drones combine features of both systems, offering greater versatility across different site conditions, although they tend to be more complex and costly.



Source: https://www.mdpi.com/2504-446X/7/8/515

Figure 3 Different drone types used in construction

2.2.2. Progress Tracking and Documentation

Drones provide transparent 3D meshes that create a visual timeline of construction. In Choi et al. (2023), managers overlay design plans on drone images to verify that earthworks and structures align with the schedule. This capability improves cost control by preventing rework. This automated mapping cuts documentation time dramatically: one case study noted replacing a full day of manual inspection with a 15-minute drone flight saved five man-hours per visit For instance, Ahmad et al. (2025) reports that accurate aerial data minimizes over-ordering of materials, reduces errors and simplifies subcontractor billing, which in turn prevents change orders. Similarly, time-stamped georeferenced photos are strong evidence in payment disputes (Francis et al., 2022). The authors claim that they clearly show completed scope versus claimed progress.

2.2.3. Labor and Inspection Cost Savings

Asim (2025) notes that many construction companies have shifted from external surveyors to in-house drone operations. Drones convert fixed inspection costs into scalable data collection, where a single pilot capture used to require multiple teams. Drone aerial data also improves the accuracy of resource forecasts. In a study that focused on dm construction, Yin et al. (2023) painted a picture of how drone-derived volumetric measurements of construction materials using the digital elevation model (DEM) to eliminate much of the uncertainty in material usage. This allows construction managers to update cost forecasts based on actual volumes rather than estimates, which tightly bounds contingency budgets.

2.2.4. Supply Chain Tracking

Drones expedite on-site logistics. Studies have shown that small UAVs have been tested to carry urgent tool deliveries or sensor units across large yards, bypassing traffic and terrain constraints (Jeelani & Gheisari, 2021; Singh et al., 2025). UAVs real-time aerial imagery also aids scouting clear routes for hauling materials, monitor crane operations, or verify site layout before delivery trucks arrive. In Jiang et al. (2021) case study of a petrochemical plant construction, a drone assisted in crane placement planning by mapping building models and overlaying scans to ensure clearances. Drones thus act as site-scale logistics scouts, often saving hours in coordination each week.

Drones, combined with IoT, also provide a flying eye for inventory control. In a drone-based supply-chain model, UAVs perform periodic flies over stockpiles and material yards, scanning RFID tags or barcodes and updating inventories in real time. Yıldız et al. (2024) study explores inventory management on large sites where the results show that feeding location and quantity data to project managers gives drones the ability to eliminate the ground delays typical of manual inventory checks. If a remote drone scan shows a shortage of piping material, this allows procurement to be triggered before crews idle waiting.

2.3. Environmental Impact Monitoring

Construction projects must comply with strict environmental regulations such as erosion control, and air quality. Drones` aerial surveillance provides comprehensive views of erosion and sediment barriers, quickly identifying breaches that ground inspectors might miss. While modelling streamflow and sediment load during a fluvial excavation operation Hupy & Wilson (2021) demonstrate how a drone scan on the drainage and sediment basins immediately to ensure systems function as designed. Similarly, dust-control measurescan be verified via drone imagery. In urban projects with tight particulate limits, UAVs fly swaths of the site to check that water sprays or cover systems are in place (Muhmad Kamarulzaman et al., 2023). This further confirms how drones are used to inspect material stockpiles, confirming their importance in environmental impact monitoring.

Water quality is another area where drones monitor dewatering discharge and chemical storage sites, ensuring buffers are maintained (Whitman et al., 2023). They fly over wetlands or streams adjacent to work zones to document that setback requirements are respected. Wildlife protection e.g. bird nesting also benefits from seasonal drone surveys that map habitat buffers without human intrusion. In this way, environmental compliance becomes a continuous, documented process rather than a series of intermittent audits.

Drones further extend monitoring beyond construction safety into sustainability. Kim et al. (2021) were keen to report that integrating onboard sensors, including gas and particulate matter, etc. allow UAVs to measure fugitive emissions or noise. In summary, drone-based environmental monitoring represents a shift from reactive checks to proactive oversight, moving from elevating compliance to a continuous oversight function.

2.4. Subcontractor Oversight and Accountability

Multi-contractor sites require robust progress documentation as discussed earlier in this chapter. Frequent aerial scans create a third-party record, for instance, weekly flight logs verify that concrete slabs have been poured to plan or that utility trenches are completed before backfill. This transparency has benefits where it first it holds managers nd contractors as accountable to scope and schedule, and it streamlines billing and dispute resolution. Choi et al. (2024) digital construction study notes that drone imagery supports construction progress verification, compliance checks, and scope confirmation, which in turn facilitates audits and invoice reviews. Because images are geotagged and timestamped, any change order or dispute can be investigated with objective evidence rather than conflicting reports.

Moreover, routine drone monitoring reduces subcontractor labor. As Asim (2025) highlighted, in-house UAV use reduces subcontractor expenses, shortens lead times, and enables more frequent data collection without increasing staff. In effect, drones automate progress reporting tasks that used to be passed down to specialized subcontractors. This also applies in subcontractor coordination, where clear data ownership policies ensure that when subcontractors contribute to drone flights, their roles and rights are predefined. This contractual clarity is crucial when sharing drone outputs with partners.

3. Methodology

This study is a desk-based review synthesizing secondary sources. To illustrate quantitative aspects of drone impact, we formulate simplified models. For cost optimization, this research considered a survey labor model as outlined below

labor savings $S = N(T_m - T_d)C_L$, where Nis number of survey units (e.g. acres or grid points), $T_m$and $T_d$are manual and drone times per unit, and $C_L$is labor cost per hour. This linear model can be extended to other tasks such as inspections and deliveries.

Similarly, a simple Return on Investment (ROI) metric was used: $\mathrm{ROI} = (S - C_{\text{drone assets}})/C_{\text{drone assets}}$, guiding decisions on fleet purchase. These elementary models show that when a drone's efficiency gain (T_m/T_d) is high, even a few flights justify the investment.

This research also considered an ROI framework for a drone program:

$$\mathrm{ROI} = \frac{\text{Total Benefits} - \text{Drone Investment Cost}}{\text{Drone Investment Cost}}.$$

Here, Total Benefits include labor-cost savings and avoided rework, while Investment Cost covers drone hardware, software, and training amortized over the project. Results from this modeling (below) are combined with qualitative insights from sources.

4. Results

Table 1 Comparison of Traditional Surveying Methods and UAS (Drone-Based) Methods Showing Time Reduction and Labor Cost Savings for a10 – Acre Grading Survey

Test	Traditional time (Tm)	UAS time (Td)	Time saved per unit	Labor cost
Volumetric calculation	11 h	5 h	6 h	2,235
Topographic mapping (LIDAR)	10 h	7 h	3 h	4,600
Topographic mapping (Cross-section)	16 h	8 h	8 h	3,200

Adapted from: https://doi.org/10.3389/fbuil.2022.1037487

4.1. Survey labor model

savings $S = N(T_m - T_d)C_L$

The table above represents a 10-acre grading survey. For volumetric calculation for instance:

$T_m = 11$ hours, whereas a drone flight cover the same area in $T_d = 5$ hours. If labor costs C_L2,235, then the labor cost drops from $10 \times 11 \times \$2{,}235 = \$245{,}850$ manually to $10 \times 5 \times \$2{,}235 = \$111,750$ by drone, saving $34,100.

For the productivity ratio, this paper calculated efficiency gain using the following formula, which still used information from Table 1:

Formula

$$Efficiency = \frac{T_m}{T_d}$$

Volumetric calculation

$$= \frac{11}{5} = 2.2$$

LiDAR mapping

$$= \frac{10}{7} = 1.43$$

Cross-section mapping

$$= \frac{16}{8} = 2.0$$

Average efficiency gain

$$= \frac{2.2 + 1.43 + 2.0}{3} = 1.88$$

Therefore, drone methods are 1.88 times faster on average.

Table 2 Five- Year Cost breakdown and Total Outflow for Robot Implementation

Per Robot Cost	Year 1	Year 2	Year 3	Year 4	Year 5	Total
Hardware	600,000					600,000
Software						
Network and utility	3,000	3,000	3,000	3,000	3,000	15,000
Training	21,900					21,900
Transport	5,000	5,000	5,000	5,000	5,000	25,000
Installation	35,735.70	36,807.77	37,912	38,049.36	40,220.85	189,725.68
Operation	16,893.24	17,400.04	17,922.04	18,459.70	19,013.49	89,668.51

Disassembly	5,197.92	5,353.86	5,514.47	5,679.91	5,850.30	27,596.46
Maintenance	60,000	60,000	60,000	60,000	60,000	300,000
Total Outflow	747,726.86	127,561.67	129,348.52	131,188.97	133,084.64	1,268,910.65

Adapted from:

Table 2:

From the Per Robot Cost table:

Total investment = 1,268,910.65 in 5 years

Table 3 Five – Year Savings Analysis Showing Annual Savings, Net Cash Flow, and Cumulative Cash Position for UAS (Drone) Implementation

Savings	Year 1	Year 2	Year 3	Year 4	Year 5	5-Year Total
Equipment-related	50,000.00	50,000.00	50,000.00	50,000.00	50,000.00	250,000.00
Labor efficiency savings	159,390.50	164,172.22	169,097.39	174,170.31	179,395.42	846,225.83
Utility consumption	1,000.00	1,000.00	1,000.00	1,000.00	1,000.00	5,000.00
Maintenance	5,000.00	5,000.00	5,000.00	5,000.00	5,000.00	25,000.00
Total annual savings	215,390.50	220,172.22	225,097.39	230,170.31	235,395.42	1,126,225.83
Net annual cashflow	-273,867.75	356,817.22	365,865.73	375,185.70	384,785.28	1,208,786.18
Cumulative cash position	-273,867.75	82,949.47	448,815.20	824,000.90	1,208,786.18	1,208,786.18

From the **Savings** table:

Total benefits = 1,126,225

To calculate the net benefit:

Formula

Net Benefit = Total Benefits-Total Investment

=1,126,225.83 – 1,268,910.65

= -142,684.82

To calculate overall 5-year ROI

ROI formula:

$$\textbf{ROI} = \frac{\text{Net Benefit}}{\text{Total Investment}}$$

$$\text{ROI} = -\frac{142{,}684.82}{1{,}268910.65}$$

ROI = -0.1125

ROI = -11.25%Final result

Comprehensive 5-year ROI:

-11.25%

This indicates that, based strictly on the provided tables, the total savings over five years fall short of the total investment by approximately 11.25%.

5. Discussion

This review indicates that advanced drone functions markedly improve construction project operations. Drones shorten many traditional processes: surveys that once took days are now hours, and progress checks that required dozens of field staff are now done with a single flight. These efficiency gains translate directly into cost savings and schedule compression, validating the RBV perspective that drones act as value-creating resources. From a TAM viewpoint, firms see these improvements as tangible benefits, boosting managerial support for UAV programs. Indeed, as practitioners have noted, drones shift from experimental to tools when applied consistently.

The consolidated evidence also shows systemic benefits. Through the lens of systems theory, drones become part of an integrated information feedback loop. Aerial data flow into BIM and scheduling software, enabling more agile resource allocation. For example, instant drone updates trigger just-in-time ordering of materials or re-sequencing of tasks, reducing slack and variability. Teams that treat drone programs with the same rigor as other processes like estimating and quality control reap the most reward.

The results demonstrate that drone integration produces clear operational efficiency gains, yet the financial outcomes depend strongly on investment scale and cost structure. The survey labor model indicates substantial time reductions across all three tested activities. Efficiency ratios ranged from 1.43 for LiDAR mapping to 2.2 for volumetric calculations, with an overall average of 1.88. This suggests that drone-based workflows nearly double productivity in core surveying functions. When applied to a 10-acre scenario, the labor model showed notable reductions in working hours and associated costs, confirming that time-based efficiency translates directly into measurable savings.

However, the five-year ROI analysis presents a more complex economic picture. Although cumulative benefits reached $1,126,225.83, total investment costs amounted to $1,268,910.65, producing a net loss of $142,684.82 and an overall ROI of −11.25%. This indicates that high upfront capital expenses, particularly hardware and maintenance, can offset operational savings in the early years of deployment. The negative ROI does not necessarily imply inefficiency; rather, it highlights the importance of utilization rates, project scale, and amortization periods. If the same system were deployed across multiple projects or operated beyond the five-year window, the cumulative efficiency gains would likely surpass the initial investment, shifting the ROI into positive territory.

6. Conclusion

This review finds that advanced drone applications are revolutionizing U.S. construction project operations across multiple dimensions. By shifting beyond safety monitoring, drones now drive cost optimization through rapid surveys and progress tracking, logistics efficiency via real-time inventory and delivery support, and sustainability oversight through continuous environmental monitoring. The theoretical lenses of Systems Theory and RBV reinforce that UAV integration yields strategic and systemic gains, provided that organizations manage acceptance and technical challenges. We presented a simple cost–benefit model to quantify these advantages, illustrating how even basic calculations show substantial labor and schedule savings.

Construction firms deploying drones benefit from improved accuracy and transparency, tighter schedule control, and reduced waste which are outcomes vividly supported by this narrative review. Evidence strongly indicates that UAVs are poised to transform project delivery models. As drone technology continues to mature, it is likely to become an indispensable part of the construction toolkit as an eye in the sky that drives efficiency, coordination, and sustainability in U.S. construction projects. Therefore, organizations should begin with high-frequency tasks such as volumetric surveys and progress mapping, where efficiency gains are highest and utilization rates justify the investment. Shared drone fleets across multiple projects or divisions can further improve asset utilization and accelerate cost recovery.

Firms should also prioritize scalable platforms and modular software subscriptions to reduce long-term maintenance and upgrade expenses. From a managerial perspective, integrating drone data into existing project management and BIM systems will maximize the value of collected information. Finally, extending the operational life of drone assets beyond five years or increasing project volume will significantly improve overall return on investment.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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