ADVANCES IN BUILDING EDUCATION
INNOVACIÓN EDUCATIVA EN EDIFICACIÓN

Immersive UAV training through simulated environments as a cross-disciplinary educational methodology for architecture and engineering education

Entrenamiento inmersivo con UAV mediante entornos simulados como metodología educativa transversal para arquitectura e ingeniería

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Received: 31/03/2026 | Accepted: 20/04/2026 | Publication date: 12/06/2026
DOI:10.20868/abe.2026.1.5692

TITULARES

- Se plantea la metodología de aprendizaje inmersivo en UAV, que integra simuladores profesionales, controladores físicos y aprendizaje basado en retos.
- La metodología reduce la brecha entre la certificación normativa (A1/A3 and A2) y la competencia operativa en la educación de arquitectura e ingeniería.
- Se diseña un modelo de seis fases orientado a competencias que favorece la adquisición progresiva de habilidades antes de la práctica de vuelo real.
- En campos como la arquitectura y la edificación, la presente metodología facilita la formación en inspección de edificios, planificación de vuelo, fotogrametría y análisis térmico mediante UAV. La propuesta ofrece un modelo escalable y transferible para la innovación educativa en la educación superior.

HIGHLIGHTS

- An immersive UAV learning methodology is proposed, integrating professional simulators, physical controllers, and challenge-based learning.
- The methodology bridges the gap between regulatory certification (A1/A3 and A2) and operational competence in architecture and engineering education.
- A six-phase competency-oriented model is designed to support the progressive acquisition of skills prior to real-flight practice.
- In architecture and building engineering, the proposed methodology facilitates training in building inspection, flight planning, photogrammetry, and thermal analysis using UAVs. The framework provides a scalable and transferable model for educational innovation in higher education.

RESUMEN

La creciente integración de los UAV en arquitectura e ingeniería exige nuevas metodologías formativas adaptadas a contextos profesionales reales. Sin embargo, la enseñanza universitaria continúa limitada por restricciones normativas y condicionantes logísticos que reducen la práctica real de vuelo. Este trabajo presenta una metodología educativa inmersiva basada en simuladores profesionales combinados con controladores físicos, que permite desarrollar competencias técnicas, operativas y de toma de decisiones en un entorno seguro y repetible. La propuesta integra aprendizaje activo, misiones basadas en retos y evaluación por competencias, estructurándose en fases progresivas: selección de herramientas de simulación, aplicación de rúbricas iniciales y finales, análisis de resultados, transición a prácticas reales y mejora continua. Desde la perspectiva arquitectónica y de la edificación, la metodología facilita la formación en inspección de edificios, planificación de vuelos y captura de datos mediante fotogrametría y análisis térmico, ofreciendo un modelo escalable y transferible para la innovación educativa en educación superior.

Palabras clave: *Educación basada en UAV; Aprendizaje inmersivo; Simulación de vuelo; Arquitectura e ingeniería de la edificación; Fotogrametría*

ABSTRACT

The increasing integration of UAVs in architecture and engineering requires updated training methodologies aligned with real professional contexts. However, university education remains constrained by safety regulations and logistical limitations that restrict real-flight practice. This paper presents an immersive educational methodology based on professional flight simulators combined with physical controllers, enabling students to develop technical, operational, and decision-making competencies in a safe and repeatable environment. The approach integrates active learning, challenge-based missions, and competency-based assessment, structured into progressive phases: selection of simulation tools, implementation of initial and final evaluation rubrics, learning outcome analysis, transition to real-field practice, and continuous improvement. From an architectural and building engineering perspective, the framework supports training in building inspection, flight planning, and UAV-based data acquisition through photogrammetry and thermal analysis. The proposal offers a scalable and transferable model for educational innovation in higher education contexts.

Keywords: *UAV-based education; Immersive learning; Flight simulation; Architecture and building engineering; Photogrammetry*

1. INTRODUCTION

The accelerated integration of Unmanned Aerial Vehicles (UAVs) into professional practice has deeply reshaped technical workflows across architecture, building engineering, construction management, geomatics, territorial planning, and heritage conservation. Over the last decade, UAV platforms have evolved from experimental tools to consolidated professional instruments capable of acquiring high-resolution spatial, radiometric, and thermal data with unprecedented efficiency and accessibility (Colomina & Molina, 2014; Yao et al., 2019). Their applications now extend to façade inspection, structural monitoring, volumetric analysis, progress tracking in construction sites, energy performance assessment, risk evaluation in hazardous environments, and digital documentation of cultural heritage assets (Nex & Remondino, 2014; Rakha & Gorodetsky, 2018).

This rapid technological adoption has generated a structural transformation in professional competencies demanded by industry. Contemporary architects and engineers are increasingly expected not only to interpret UAV-derived data but also to understand flight planning, sensor configuration, regulatory compliance, data acquisition strategies, and operational risk management. In many professional contexts, UAV operation is no longer outsourced to specialised pilots but integrated into multidisciplinary technical workflows, requiring domain professionals to acquire at least intermediate operational competence (Bolick et al., 2022; Félix-Herrán et al, 2022).

Despite this profound transformation in professional practice, higher education curricula have not fully adapted to the operational dimension of UAV integration. In many architecture and engineering programs, UAV-related instruction remains predominantly theoretical, focused on regulatory frameworks, photogrammetric principles, or data processing methodologies, while practical flight training is either limited or absent. Even when real-flight sessions are included, they are frequently constrained by aviation regulations, safety protocols, insurance limitations, meteorological conditions, equipment availability, and institutional risk management policies. These structural constraints reduce students' opportunities for repeated practice, incremental skill development, and exposure to complex operational scenarios (Wilkerson et al., 2018; Mesas-Carrascosa et al., 2019; Bolick et al., 2022; Félix-Herrán et al, 2022).

This imbalance generates a pedagogical gap between academic preparation and professional expectations. Students may graduate with theoretical knowledge of UAV technology yet lack operational fluency, situational awareness, and real-time decision-making skills. From an educational perspective, this gap reflects a broader tension between technological innovation and curricular transformation, where rapid industry adoption outpaces pedagogical adaptation (Prince & Felder, 2006; Kolb, 2014; Graham, 2018; Bolick et al., 2022).

The challenge is therefore not merely technological but fundamentally educational. How can higher education institutions design structured, scalable, and safe training environments that allow students to develop operational competence without exposing them to unnecessary risk or logistical limitations? Addressing this question requires rethinking UAV education beyond sporadic practical sessions and toward systematic, progressive, and competency-oriented training models (Prince & Felder, 2006; Mulder, 2014; Biggs et al., 2022; Félix-Herrán et al, 2022).

Simulation-based learning offers a promising response to this challenge. In high-risk and technically demanding domains such as aviation, medicine, military training, and industrial engineering, immersive simulation environments have long been employed to replicate operational conditions in controlled settings. Simulation allows learners to rehearse procedures, experiment with decision-making strategies, confront unexpected scenarios, and develop procedural memory without material risk. Importantly, simulation environments enable repeated exposure to identical scenarios, facilitating iterative improvement and structured feedback mechanisms (Issenberg et al, 2005; Salas et al., 2009; Lateef, 2010; McGaghie et al., 2011).

Within engineering education, immersive learning approaches have demonstrated positive effects on skill acquisition, cognitive engagement, and professional readiness. By recreating authentic professional contexts, simulation fosters experiential learning processes in which students actively construct knowledge through interaction, experimentation, and reflection. Rather than passively receiving information, learners assume professional roles and engage in situated problem-solving. These approaches align with constructivist and experiential learning theories, which emphasise the centrality of action and reflection in competence development (Lave & Wenger, 1991; Prince & Felder, 2006; Kolb, 2014).

In the specific case of UAV training, professional flight simulators have been progressively incorporated into pilot certification programs and specialised technical training (Salas et al., 2009; Cardona-Reyes et al., 2021; Cook et al., 2011; Källström et al., 2022). However, their pedagogical integration into architecture and engineering education remains fragmented and often limited to isolated experiences rather than embedded within structured curricular frameworks. Existing studies have explored project-based learning using UAVs, challenge-based training models, and competency development approaches in engineering contexts. Nevertheless, there remains a lack of comprehensive methodological proposals that integrate immersive simulation, progressive skill development, transversal competence assessment, and transferability to multiple disciplines within a unified educational framework (Cook et al., 2011; Källström et al., 2022).

Moreover, much of the current literature focuses on UAV applications or project-based case studies rather than on the design of structured training architectures that precede real-field operations. The transition from theoretical instruction to real UAV flight remains pedagogically abrupt in many educational settings, increasing cognitive load, operational stress, and risk exposure for novice learners. A progressive intermediate stage (where students can rehearse operational scenarios in immersive, risk-free environments) may significantly improve learning efficiency, confidence, and safety (Sweller, 1988; Issenberg et al, 2005; McGaghie et al., 2011; Mesas-Carrascosa et al., 2019).

From an architectural and building engineering perspective, the relevance of such structured training becomes even more evident. UAV-based inspection of façades, roofs, and structural elements requires precise flight planning, stable manoeuvring near vertical surfaces, careful sensor configuration, and awareness of environmental constraints. Photogrammetric data acquisition demands control over overlap parameters, scale homogeneity, altitude settings, and trajectory optimization to ensure high-quality 3D reconstruction. Thermal inspection adds further complexity, requiring an understanding of emissivity, environmental conditions, and radiometric calibration. The integration of these technical dimensions within a single operational mission requires both technical knowledge and coordinated decision-making capacity (Remondino et al., 2012; Rakha & Gorodetsky, 2018; Russo et al., 2019; Melis et al., 2020).

In addition to technical proficiency, UAV operation in architectural and construction contexts involves transversal competencies. Team coordination, communication under time constraints, risk anticipation, ethical responsibility, and regulatory compliance are integral components of professional practice. Traditional lecture-based instruction is insufficient to develop these competencies effectively. Immersive, mission-based training environments offer a more appropriate context for fostering integrated technical and transversal skill development (Lave & Wenger, 1991; Prince & Felder, 2006; Salas et al., 2009; Félix-Herrán et al, 2022).

Consequently, there is a pressing need for pedagogically grounded, transferable, and scalable methodologies that integrate immersive UAV simulation into higher education curricula. Such methodologies should not be restricted to a single discipline but be adaptable across architecture, building engineering, geomatics, safety engineering, and construction management programs. Furthermore, they should incorporate structured assessment mechanisms capable of measuring both technical performance and transversal competence acquisition (Salas et al., 2009; Mulder, 2014; Biggs et al., 2022).

The present study addresses this need by proposing a comprehensive educational framework for immersive UAV training through simulated environments. The methodology is conceived as a progressive, competency-oriented model that integrates professional flight simulators, physical controllers, challenge-based missions, structured evaluation rubrics, and optional transition to real-field practice. Unlike isolated simulation exercises, the framework is designed as a complete pedagogical architecture aligned with professional workflows and educational innovation principles.

The objectives of this paper are threefold. First, to conceptualise and describe a structured immersive training model tailored to architecture and engineering education. Second, to define a progressive methodological sequence that enhances operational competence prior to real-flight exposure. Third, to establish an evaluation strategy capable of measuring technical improvement and transversal skill development within simulated environments.

By articulating simulation-based learning, challenge-based pedagogy, and competency-oriented assessment within a unified framework, this work seeks to contribute to the advancement of educational innovation in higher education. The proposed model aspires to reduce operational risk, increase learning efficiency, and enhance professional readiness, offering a scalable and transferable reference for institutions seeking to modernise UAV education.

2. METHODOLOGY

A. Educational Context and Pedagogical Rationale

The immersive training framework with UAVs is intended to be implemented within the teaching innovation project “Entrenamiento inmersivo en entornos simulados para el pilotaje profesional de UAV: mejora del aprendizaje práctico en aplicaciones geomáticas y de seguridad”

(ID2025/235), funded by the University of Salamanca for the 2025–2026 academic year.

The project is implemented within undergraduate and master's degree programs related to geomatics, civil engineering, safety applications, inspection in renewable energy plants, building engineering, architectural inspection, and construction supervision. Specifically, it is integrated into subjects within the following academic programs: (i) Civil Engineering; (ii) Energy and Mineral Resources Engineering; (iii) Geoinformation and Geomatics Engineering; (iv) Security Studies; and (v) the Master's Degree in Cartographic Geotechnologies in Engineering and Architecture. These degrees are taught at the Higher Polytechnic School of Ávila, belonging to the University of Salamanca.

Across several subjects within these programs, students receive comprehensive instruction on UAV technology and the European regulatory framework governing drone operations. Particular emphasis is placed on the European Union drone regulation, implemented in Spain through the Spanish Aviation Safety Agency (Agencia Estatal de Seguridad Aérea - AESA) (AESA, 2026). This regulatory framework classifies low-risk operations under the Open Category, which is subdivided into A1, A2, and A3 subcategories. These operational subcategories are defined according to factors such as drone class marking, weight, and associated operational risk.

In these subjects, students receive comprehensive instruction on the theoretical principles underlying the Open Category subcategories (A1, A2, and A3). This training includes detailed analysis of airspace restrictions, operational limitations, safety distances, drone class markings, technical components of UAS (Unmanned Aircraft System), risk mitigation strategies, and legal responsibilities associated with UAV operations. The theoretical content delivered in class is fully aligned with the official regulatory framework established by the AESA for obtaining Open Category certifications.

The A1/A3 certification primarily focuses on foundational theoretical knowledge, including aviation regulations, operational safety rules, privacy considerations, and general UAS technical concepts. It consists of an official 40-question multiple-choice examination conducted entirely online through the AESA Electronic Headquarters platform. This certification allows operators to fly lightweight drones over uninvolved persons under specific conditions (A1) or to operate drones in areas far from people and urban zones, maintaining a minimum distance of 150 meters from residential, commercial, industrial, or recreational areas (A3).

The A2 certification, which enables operations closer to people under controlled risk conditions, requires a higher level of operational understanding. A mandatory prerequisite is the successful completion of the A1/A3 examination. In addition, candidates must complete a practical self-training program following AESA guidelines, conducting independent flight exercises and formally declaring their completion prior to examination. The A2 theoretical assessment is more rigorous and focuses on meteorology, UAS flight performance, and technical ground-risk mitigation strategies.

This regulatory training is embedded within the academic curriculum not only as legal instruction but as a professional competency component, ensuring that students understand both the normative framework and its practical implications for real-world UAV operations.

Building upon this regulatory instruction, students are provided with direct access to official certification pathways. Since the theoretical components of the A1/A3 and A2 subcategories are fully addressed within the courses, students have the opportunity to obtain these certifications at no cost. The academic preparation delivered in class significantly facilitates this process, lowering the barrier to professional qualification and allowing students to obtain credentials that are directly applicable in their future careers.

Furthermore, this framework serves as a strategic precursor for advanced certifications under the Specific Category, specifically Standard Scenarios (STS-01 and STS-02). By simulating high-complexity environments and BVLOS (Beyond Visual Line of Sight) operations, students develop the rigorous operational discipline required for professional tasks in urban contexts and critical infrastructure monitoring

From an institutional perspective, the university makes a considerable effort to complement theoretical instruction with real-flight exposure. To support A2-level preparation and provide direct operational experience, a full-day field session is organised in a controlled flight environment, typically hosted at a certified aeroclub. This session is conducted under strict safety protocols, with professional supervision and compliance with all regulatory requirements.

However, the organisation of this practical activity entails significant logistical and financial investment. Transportation to the airfield requires chartered bus services; the controlled flight area must be rented; and insurance coverage must be ensured. These factors represent a substantial economic effort for the institution and limit field training to a single intensive session per academic year.

Furthermore, due to liability considerations and the need to minimise operational risk when working with undergraduate students, autonomous drone control cannot be granted without restrictions. Students participate in supervised manoeuvres and guided flight exercises, but opportunities for repeated independent practice are necessarily constrained. Consequently, while students gain valuable exposure to real operational environments, the limited duration and restricted hands-on repetition may not always be sufficient to consolidate motor coordination, situational awareness, and rapid decision-making skills.

This context reveals a critical pedagogical tension: although students can obtain official A1/A3 and A2 certifications (thereby becoming legally authorised to perform a wide range of open-category UAV operations) regulatory certification does not automatically guarantee deep operational proficiency. The difference between legal qualification and consolidated practical competence becomes particularly relevant in professional contexts involving façade inspection, renewable energy plant monitoring, construction supervision, or safety-related applications, where precision, stability, and rapid risk assessment are essential.

It is precisely within this gap between certification and operational mastery that the immersive simulation framework is positioned. Rather than replacing regulatory training or field sessions, simulation functions as an intermediate pedagogical layer. By enabling repeated, risk-free rehearsal of flight manoeuvres, mission planning procedures, obstacle management, and emergency response scenarios, immersive environments allow students to strengthen procedural fluency and build operational confidence before real-field exposure.

Through this complementary structure, the simulation stage enhances readiness for A2-level operational demands, optimises the educational value of the controlled flight session, and contributes to a stronger alignment between regulatory compliance and authentic professional competence.

B. From Regulatory Qualification to Operational Competence: Identified Training Gap

The integration of official UAV certification pathways within university curricula represents a significant step toward aligning academic training with professional regulatory standards. By enabling students to obtain A1/A3 and A2 certifications, higher education institutions provide formal recognition of regulatory knowledge and operational authorisation within the European Open Category framework. However, regulatory qualification and operational competence are not synonymous.

The A1/A3 and A2 certifications establish a minimum threshold of knowledge and declared practical preparation required to legally conduct UAV operations under specific risk conditions. These certifications confirm that the operator understands airspace restrictions, operational limitations, safety procedures, and risk mitigation principles. Nevertheless, the certification model (particularly within academic environments) does not inherently guarantee consolidated motor coordination, adaptive decision-making, or experiential familiarity with complex operational scenarios.

This distinction becomes particularly relevant in architecture, civil engineering, renewable energy inspection, and safety-related applications. Professional UAV operations in these contexts frequently involve flights near vertical structures, confined environments, reflective surfaces, or partially obstructed airspace. They require stable proximity control, precise trajectory planning, environmental awareness, and rapid response to unexpected disturbances such as wind gusts or signal interference. These competencies are developed through repetition, exposure, and iterative correction, conditions that are difficult to fully replicate within limited real-field academic sessions.

In traditional university training models, the transition from classroom-based theoretical instruction to real-flight practice is often abrupt. Students move directly from conceptual understanding of flight parameters and regulatory frameworks to operating real equipment in controlled but still authentic environments. This transition may increase cognitive load, operational stress, and error frequency, particularly for novice operators who have not yet internalised basic motor patterns and situational awareness skills.

Moreover, field sessions (while pedagogically valuable) are inherently constrained by time, cost, safety protocols, and environmental variability. Opportunities for deliberate practice, repeated manoeuvre rehearsal, and controlled exposure to emergency scenarios are limited. As a result, learning may remain episodic rather than progressive.

This situation reveals a structural training gap: students may achieve legal certification yet still lack the procedural fluency and operational confidence required for professional autonomy. The gap does not stem from deficiencies in regulatory instruction, but from the intrinsic limitations of combining theoretical preparation with infrequent, high-stakes real-flight exposure.

Educational research in skill acquisition and experiential learning suggests that competence develops most effectively through graduated exposure, immediate feedback, and low-risk iterative practice. In high-risk domains such as aviation and medical training, simulation-based environments are used precisely to bridge the gap between theoretical knowledge and real-world performance. By allowing repeated rehearsal of complex tasks without material consequences, simulation reduces performance anxiety, enhances procedural memory consolidation, and facilitates progressive skill mastery.

Transferring this pedagogical logic to UAV education within architecture and engineering programs addresses the identified training gap. Immersive simulation environments create an intermediate learning stage in which students can practice flight planning, manoeuvre execution, obstacle avoidance, and emergency management under controlled and repeatable conditions. This stage reduces cognitive overload during real-field exposure and strengthens alignment between regulatory qualification and authentic operational competence.

Thus, the immersive framework proposed in this study is not merely a technological enhancement, but a structural pedagogical response to a clearly identified competence gap. By positioning simulation as a preparatory and reinforcing layer between certification and real-flight practice, the methodology aims to transform certification from a formal requirement into a foundation for genuine professional proficiency.

C. Methodological Architecture of the Immersive Framework

The immersive UAV training framework is structured as a progressive six-phase methodological architecture designed to bridge the identified gap between regulatory certification and operational competence. Figure 1 illustrates the sequential and iterative structure of the model, integrating simulation-based learning, competency assessment, real-field validation, and continuous improvement.

Unlike isolated training sessions, the proposed architecture functions as a closed pedagogical loop, where each phase informs and strengthens subsequent stages.

- <u>Phase 1. Methodology Preparation and Simulation Tool Analysis</u>

The first phase focuses on the technical and pedagogical preparation of the training environment. This includes the evaluation and selection of professional flight simulation platforms (e.g., DJI Flight Simulator or equivalent systems), considering criteria such as flight physics realism, environmental configurability, compatibility with real controllers, scenario diversity, and performance tracking capabilities.

This phase ensures alignment between technological infrastructure and intended learning outcomes. The simulator must accurately reproduce UAV behaviour, including sensitivity to wind, inertia, obstacle interaction, and emergency conditions. By establishing a high-fidelity simulation environment, the methodological foundation for procedural skill development is secured.

- <u>Phase 2. Definition and Application of Assessment Rubrics</u>

Before immersive practice begins, structured evaluation instruments are defined and applied. This phase includes both an initial diagnostic assessment and a final competency evaluation.

The diagnostic assessment measures baseline knowledge, spatial awareness, manoeuvre control, and planning capacity. The final

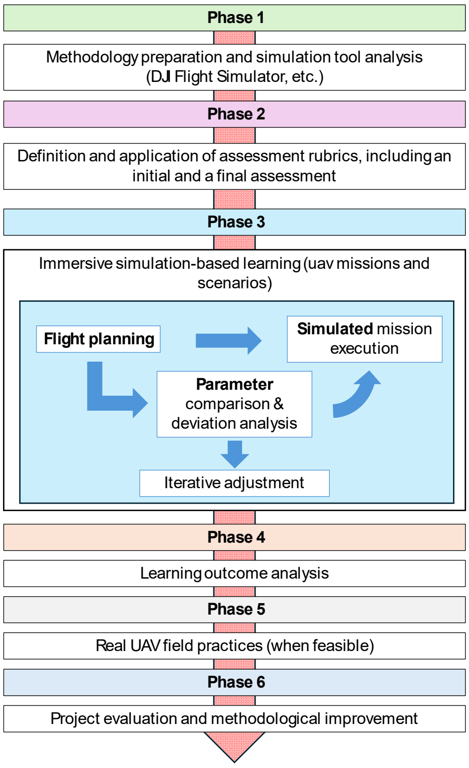

Fig. 1. Progressive methodological framework for immersive UAV training, integrating simulation-based learning, competency assessment, real-field practices, and continuous methodological improvement.

Fig. 2. Simulation workstation used during the immersive UAV training phase, including high-performance computer, professional flight simulation software, and real UAV remote controller. The system enables performance tracking and data collection for learning outcome analysis, supporting the evaluation of maneuver accuracy, mission execution time, and operational decision-making.

assessment evaluates improvements in flight precision, mission efficiency, risk management, and transversal competencies such as teamwork and decision-making.

The use of rubrics ensures alignment between learning objectives, training activities, and measurable outcomes. It also enables quantitative comparison of pre- and post-training performance indicators.

- <u>Phase 3. Immersive Simulation-Based Learning</u>

This phase constitutes the core of the framework. Students engage in structured mission-based scenarios that require prior flight planning and subsequent execution within the immersive simulation environment.

Scenarios include façade inspection flights, photogrammetric mapping missions, thermal analysis simulations, obstacle-rich environments, and emergency management exercises (Fig. 2.). Missions are progressively designed to increase cognitive load and operational complexity.

The immersive environment allows repeated manoeuvre rehearsal, iterative correction, and exposure to controlled failure scenarios without material risk. This repetition strengthens procedural memory consolidation, reduces anxiety during real operations, and enhances situational awareness.

In addition, the immersive methodology incorporates a structured flight planning stage prior to mission execution. Students are required to design and plan a complete UAV mission using an open-access professional flight planning tool provided within the project framework. This planning process includes the definition of trajectory geometry, flight altitude, distance to the inspected object, speed, camera orientation, and safety buffers according to operational constraints.

Once the planned mission is defined, students execute the operation within the simulated immersive environment. The system automatically compares the planned parameters with the executed flight data, enabling objective analysis of trajectory deviation, proximity control, stability, mission timing, and compliance with predefined safety distances.

This plan–execute–compare structure introduces a measurable control mechanism over key operational variables such as flight path accuracy and distance management, which are critical for professional UAV applications in inspection and geomatics. By explicitly linking planning decisions to execution outcomes, students develop deeper procedural awareness and reinforce the importance of precision in mission preparation.

- Phase 4. Learning Outcome Analysis

Following the immersive training phase, performance data are analyzed through a structured plan–execute–compare framework. The system contrasts the parameters defined during the flight planning stage with those recorded during simulated mission execution. This comparative analysis enables objective measurement of trajectory deviation, altitude stability, distance to inspected objects, speed consistency, and compliance with predefined safety buffers.

Key indicators include geometric accuracy of the flight path, variance between planned and executed distances, mission completion efficiency, response to environmental disturbances, and error correction capacity. The comparison between planned mission design and actual performance provides quantitative evidence of procedural coherence and operational precision.

In addition to these objective metrics, qualitative data are incorporated through instructor observation, debriefing sessions, and student self-assessment surveys. This mixed-method evaluation approach allows assessment not only of technical performance improvement, but also of confidence development, situational awareness, and decision-making maturity.

By integrating measurable deviation analysis with reflective feedback, Phase 4 consolidates the pedagogical value of the immersive framework and provides empirical validation of skill acquisition prior to real-field exposure.

- Phase 5. Real UAV Field Practices (When Feasible)

When institutional and regulatory conditions permit, students transition to real UAV operations in controlled environments. This stage serves as validation of skill transferability from simulation to real-world contexts.

The objective is not to replace field practice, but to optimise it. By entering the field with consolidated procedural fluency, students demonstrate reduced error rates, improved manoeuvre stability, and greater operational confidence.

- Phase 6. Project Evaluation and Methodological Improvement

The final phase closes the pedagogical loop. Results from assessments, field performance, and student feedback are analysed to refine simulation scenarios, adjust rubric criteria, and improve instructional design.

This continuous improvement component transforms the methodology from a static training protocol into an adaptive educational system capable of evolving alongside technological and regulatory changes.

Table I:
Competency-based assessment rubric and performance indicators applied in the immersive uav training framework.

	Competency Area	Performance Indicator	Measurement Method	Evaluation Scale (1–5)
Technical–Operational Performance	Flight Stability	Trajectory deviation from planned path (Planned vs. Executed)	Simulator flight log analysis	1 = Highly unstable / 5 = Highly stable
	Altitude & Distance Control	Precision in maintaining safety distances and altitude	Simulator telemetry + instructor observation	1 = Frequent deviations / 5 = Precise control
	Maneuver Execution	Smoothness of takeoff, landing, and proximity maneuvers	Structured observation protocol	1 = Abrupt/incorrect / 5 = Controlled and fluid
	Emergency Response	Reaction time and corrective action effectiveness	Simulated incident scenario analysis	1 = Delayed/ineffective / 5 = Immediate and appropriate
	Mission Efficiency	Time required to complete mission objectives	Time tracking within simulator	1 = Inefficient / 5 = Optimal execution
Cognitive & Planning Competence	Flight Planning Coherence	Alignment between objectives and selected flight parameters	Rubric-based planning assessment	1 = Incoherent / 5 = Fully coherent
	Risk Mitigation Strategy	Identification and mitigation of operational risks	Scenario-based evaluation	1 = Poor risk awareness / 5 = Proactive mitigation
	Regulatory Application	Correct integration of Open Category limitations (A1/A3/A2)	Case-based regulatory test	1 = Incorrect application / 5 = Accurate integration
	Sensor Configuration	Selection of camera parameters and mission settings	Planning documentation review	1 = Incorrect setup / 5 = Optimized configuration
Transversal Competencies	Team Coordination	Role distribution and collaborative execution	Instructor observation + peer assessment	1 = Disorganized / 5 = Highly coordinated
	Communication	Clarity and precision during mission execution	Observation protocol	1 = Confusing / 5 = Clear and effective
	Decision-Making Under Pressure	Adaptive response in unexpected scenarios	Simulated stress condition analysis with wearables	1 = Hesitant/inadequate / 5 = Confident and adaptive
	Self-Efficacy & Confidence	Perceived readiness before and after training	Pre/Post Likert-scale survey	1 = Low confidence / 5 = High confidence

3. RESULTS AND DISCUSSION

A. Evaluation Design and Performance Indicators

The validation of the immersive UAV training framework requires a structured evaluation design capable of measuring both technical performance improvements and transversal competency development. Given that the methodology is implemented progressively across simulation and real-field contexts, the evaluation strategy is conceived as a comparative and multi-dimensional assessment model.

The design follows a pre-test/post-test structure integrated within Phases 2 and 4 of the methodological architecture. An initial diagnostic assessment is conducted prior to immersive simulation training in order to establish baseline indicators of operational readiness. A final assessment is then applied after completion of the simulation-based missions and, when feasible, after real-field practice. This structure enables comparative analysis of performance evolution and learning consolidation.

The evaluation model integrates three complementary dimensions: (i) technical-operational performance, (ii) cognitive and decision-making capacity, and (iii) transversal competence development (TABLE I).

<u>1. Technical-Operational Performance Indicators</u>

Prior to simulation execution, students autonomously design their own flight plan using the open-access planning tool integrated within the framework, under instructional guidance but without relying on predefined mission templates. This planning stage is intentionally structured around core photogrammetric principles, requiring students to determine flight altitude based on the target Ground Sampling Distance (GSD), configure longitudinal and transversal overlap ratios, define camera orientation and trajectory geometry, and establish appropriate safety buffers for façade or proximity inspection missions.

Through this process, flight planning becomes an analytical task that integrates geometric reasoning, image acquisition strategy, and operational safety considerations rather than a purely procedural configuration step.

Once the mission is planned, the simulator records both the predefined parameters and the executed flight data. A structured plan–execute–compare mechanism enables automated comparison between the planned and executed missions across all operational variables, allowing systematic parameter-by-parameter deviation analysis of trajectory geometry, altitude stability, object distance control, velocity consistency, and compliance with predefined safety constraints.

Technical performance is assessed through objective, measurable variables obtained from simulator logs and structured observation protocols. These include:

- Trajectory stability and deviation from planned flight paths.
- Precision in altitude and distance maintenance during façade or proximity flights.
- Consistency between planned and executed photogrammetric parameters (e.g., altitude, overlap approximation, mission geometry).
- Time required to complete mission objectives.
- Error frequency (e.g., loss of stability, abrupt corrections, simulated collisions).
- Response time to unexpected, simulated events (e.g., wind disturbances, signal loss scenarios).

These indicators allow quantification of motor coordination improvement, procedural fluency, and risk management capacity. By systematically comparing planned mission design with executed flight performance across all defined parameters, it becomes possible to determine whether simulation-based repetition contributes to measurable operational refinement and photogrammetric coherence.

2. Cognitive and Decision-Making Indicators

Beyond motor control, UAV operations require planning coherence and adaptive decision-making. For this reason, scenario-based mission planning exercises are evaluated using structured rubrics that assess:

- Coherence between mission objectives and selected flight parameters.
- Risk anticipation strategies.
- Environmental constraint interpretation.
- Sensor configuration decisions.
- Emergency management planning.

These indicators measure the student's ability to integrate regulatory knowledge with operational execution.

The objective is to determine whether immersive simulation strengthens the alignment between theoretical understanding and applied decision-making.

3. Transversal Competency Development

Professional UAV operations in architecture and engineering contexts frequently involve teamwork, communication, and coordinated problem-solving. Consequently, the framework incorporates evaluation of transversal competencies through:

- Team coordination effectiveness.
- Role distribution clarity.
- Communication precision during mission execution.
- Stress management under simulated adverse conditions.
- Self-efficacy perception surveys administered before and after training.

The inclusion of self-perception instruments allows triangulation between objective performance data and subjective confidence development, providing a more holistic understanding of learning outcomes.

B. Expected Learning Outcomes and Pedagogical Impact

The immersive UAV training framework is designed to generate measurable improvements not only in technical-operational performance but also in cognitive readiness, professional confidence, and institutional efficiency. Although full empirical validation will be completed during the 2025–2026 academic implementation cycle, the expected learning outcomes are grounded in established principles of simulation-based training, experiential learning, and progressive skill acquisition (Ericsson, 2004; Issenberg et al, 2005; McGaghie et al., 2011; Kolb, 2014).

1. Enhancement of Operational Fluency

One of the primary expected outcomes is the consolidation of procedural fluency prior to real-field exposure. Repeated simulation-based manoeuvre practice allows students to internalise motor coordination patterns, stabilise flight trajectories, and refine proximity control near vertical surfaces or obstacles. By reducing the novelty factor associated with real UAV operation, immersive rehearsal is expected to lower cognitive overload during field sessions and decrease error frequency.

This improvement is particularly relevant for A2-level operational requirements, where precise distance control and risk mitigation strategies are critical. The simulation phase is therefore anticipated to function as a buffer stage that transforms regulatory knowledge into embodied operational competence.

2. Reduction of Performance Anxiety and Cognitive Load

Transitioning directly from classroom instruction to real-flight operation may generate stress and increased cognitive load, particularly for novice operators. Immersive simulation provides a low-risk environment in which students can experiment, fail, and repeat without material consequences. This iterative exposure is expected to reduce performance anxiety and strengthen self-efficacy perceptions.

Improved confidence is not merely a subjective benefit; it directly influences decision-making quality and situational awareness. Students who feel prepared are more likely to anticipate risks, apply mitigation strategies correctly, and maintain composure under unexpected conditions.

3. Improved Alignment Between Certification and Competence

A central pedagogical objective of the framework is to bridge the gap between regulatory certification and authentic operational proficiency. While A1/A3 and A2 certifications validate theoretical knowledge and declared practical preparation, simulation-based rehearsal provides structured opportunities for competence consolidation.

The expected outcome is a stronger alignment between legal qualification and practical readiness. Students entering real-field practice after immersive training are anticipated to demonstrate greater stability, more coherent mission planning, and faster adaptation to environmental variables.

4. Optimisation of Real-Field Training Sessions

From an institutional perspective, immersive preparation is expected to increase the pedagogical efficiency of the controlled aeroclub session. Given that field practice is limited to a single intensive day due to logistical and financial constraints, maximising its educational value is essential.

By arriving at the field session with rehearsed procedural familiarity, students can devote more time to refining advanced manoeuvres and contextual problem-solving rather than basic control familiarisation. This optimisation may contribute to better learning outcomes without increasing institutional costs or operational risk.

5. Development of Transversal Competencies

Beyond technical performance, the framework promotes transversal skill development. Mission-based simulation scenarios require teamwork coordination, communication clarity, role distribution, and adaptive problem-solving under time constraints. These competencies are directly transferable to professional contexts in architecture, engineering, and safety-related operations.

The integration of structured reflection and feedback mechanisms further strengthens metacognitive awareness, enabling students to critically assess their own performance and identify improvement strategies.

6. Transferability and Scalability

An additional expected impact lies in the methodological transferability of the framework. The six-phase architecture is not limited to UAV education but may be adapted to other technical domains requiring risk-controlled skill acquisition. Moreover, institutions with limited access to field infrastructure may use simulation-based training to compensate for logistical constraints while maintaining high pedagogical standards.

C. Limitations and Future Research Directions

While the proposed immersive UAV training framework offers a structured response to the identified gap between regulatory certification and operational competence, several limitations must be acknowledged.

First, simulation-based training, regardless of its technological fidelity, cannot fully replicate the complexity of real-world flight conditions. Environmental variables such as unpredictable wind turbulence, signal interference, lighting variability, and spatial depth perception differ in authentic operational contexts. Although high-fidelity simulators approximate flight dynamics with increasing realism, the transferability of skills from virtual to real environments requires empirical validation through longitudinal performance comparison.

Second, the effectiveness of immersive simulation depends significantly on the quality and configurability of the selected software platform. Not all simulation tools provide detailed performance logging, realistic aerodynamics, or customizable mission scenarios. Consequently, the pedagogical value of the framework may vary depending on technological infrastructure and institutional resources.

Third, the current implementation is embedded within a specific institutional and regulatory context governed by European Union drone legislation and AESA certification pathways. Although the conceptual model is transferable, adaptation to different national regulatory frameworks may require structural adjustments in training design and certification alignment.

Another limitation concerns assessment methodology. While the framework integrates pre- and post-training performance indicators, further research is needed to establish standardised benchmarking criteria for UAV operational competence in higher education contexts. The absence of widely accepted educational metrics for drone piloting performance presents a broader research challenge within emerging UAV pedagogy.

Future research should therefore focus on several complementary directions.

First, empirical validation through quantitative data collection across multiple academic cohorts is essential. Longitudinal studies comparing students who undergo immersive simulation training with those who receive traditional instruction would provide stronger evidence of impact.

Second, an investigation into cognitive load reduction and anxiety modulation during real-flight sessions would offer deeper insight into the psychological benefits of simulation-based preparation. Incorporating validated instruments for measuring self-efficacy, stress levels, and decision-making confidence could enrich the evaluation framework.

Third, exploration of advanced immersive technologies (such as virtual reality (VR) environments, augmented reality overlays, or AI-assisted adaptive training systems) may further enhance the realism and personalisation of UAV education. Integrating data analytics and machine learning into performance assessment could enable real-time feedback and individualized progression pathways.

Additionally, the incorporation of wearable biometric sensors (e.g., heart rate monitors or physiological stress indicators) may provide objective insight into students' psychophysiological responses during high-pressure or emergency simulation scenarios. Monitoring parameters such as heart rate variability, stress-related physiological activation, or response latency under simulated risk conditions could allow correlation between technical performance and stress regulation capacity.

Such integration would enable a more comprehensive evaluation model combining operational accuracy with cognitive-emotional response analysis, contributing to a deeper understanding of decision-making behavior under controlled stress conditions.

Finally, cross-institutional collaboration would allow broader validation of the six-phase methodological architecture, supporting its consolidation as a transferable model for UAV training in architecture, engineering, and safety-related higher education programs.

5. CONCLUSIONS

The accelerated integration of UAVs into architecture, engineering, safety, and infrastructure-related professions demands a transformation in higher education training models. While regulatory certification pathways such as A1/A3 and A2 provide legal authorisation for drone operations, certification alone does not guarantee consolidated operational competence. This study identifies and addresses the structural gap between formal qualification and authentic professional proficiency.

The proposed six-phase immersive training framework offers a structured pedagogical architecture that integrates simulation-based learning, competency-oriented assessment, real-field validation, and continuous methodological improvement. By positioning immersive simulation as an intermediate stage between theoretical instruction and real-flight practice, and through systematic comparison between planned and executed mission parameters, the model strengthens procedural fluency, reduces cognitive overload, and enhances alignment between regulatory knowledge and operational readiness.

Beyond technical skill acquisition, the framework promotes transversal competencies including teamwork, decision-making, and adaptive problem-solving in complex scenarios. It also contributes to institutional optimization by maximizing the educational value of limited and resource-intensive field sessions while maintaining high safety standards.

Furthermore, the consolidation of structured simulation-based training may encourage students to pursue advanced or scenario-specific operational certifications beyond the Open Category framework. By strengthening procedural confidence and planning competence, the proposed methodology can serve as preparatory groundwork for more specialized European certifications such as STS-01 and STS-02 scenarios, as well as complementary qualifications including aeronautical radio operator certification. In this sense, the framework not only bridges certification and competence within the academic environment but also fosters progressive professional development aligned with increasingly complex operational contexts.

Although further empirical validation is required, the methodological design presented herein provides a scalable and transferable model for UAV education in higher education contexts. By bridging certification and competence through immersive rehearsal, the framework contributes to educational innovation aligned with contemporary professional demands.

6. ACKNOWLEDGEMENTS

This work was supported by the University of Salamanca through the Teaching Innovation Project "*Entrenamiento inmersivo en entornos simulados para el pilotaje profesional de UAV: mejora del aprendizaje práctico en aplicaciones geomáticas y de seguridad*" (ID2025/235). The authors gratefully acknowledge the institutional funding provided for the development and implementation of the immersive UAV training framework.

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