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Research Article

Feasibility and Design of a Multi-Mode Fuel Delivery System for Aircraft Engine Test Cells in the Philippines

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Abstract

This case study evaluates innovation management in aviation training by assessing a multimodal fuel-delivery system for aircraft reciprocating-engine test cells in the Philippines. The modular platform is designed to support carbureted, electronic fuel injection (EFI), and direct injection (DI) configurations, addressing capability gaps in Maintenance, Repair, and Overhaul (MRO) and academic laboratories while advancing sustainability. A design-based strategy is developed to integrate three analytical lenses: TELOS (technical, economic, legal, operational, and schedule) for feasibility; Technology–Organization–Environment (TOE) for adoption readiness; and Triple Bottom Line (TBL) for economic, environmental, and social value. Evidence is obtained from regulatory documents, international benchmarks, and semi-structured interviews with practitioners. Findings show that the system is technically viable, cost-advantageous over multiple single-purpose rigs, and compliant with CAAP and ICAO requirements. The TOE analysis reveals strong regulatory drivers, although organizational capacity, funding, and upskilling remain uneven. The TBL findings confirm cost efficiencies, compatibility with Sustainable Aviation Fuels (SAF), and contributions to human capital development. A five-phase roadmap is proposed: alignment, pilot validation, institutional rollout, regional scaling, and national integration. Test-cell modernization is reframed as a technological and organizational innovation that enhances competitiveness and supports sustainability. Identified limitations motivate prototype development to quantify technical and economic performance.

1. Introduction

Aircraft reciprocating engines remain vital in general aviation and training, particularly in the Philippines, where piston-engine aircraft dominate educational and light commercial operations. Traditionally, these engines have relied on carbureted fuel systems valued for their mechanical simplicity and cost-effectiveness. However, their limitations—such as uneven fuel-air distribution and vulnerability to icing—pose operational and safety risks (Martin, 2017). Technological advancements have led to the widespread adoption of fuel injection systems, particularly electronic fuel injection (EFI), which enhances combustion efficiency, improves fuel economy, and increases reliability at higher altitudes (Aeronautics Guide, n.d.; Ilyas et al., 2020; Reddy et al., 2021). More recently, direct injection (DI) technologies, though promising in terms of precision and performance, introduce new challenges related to system complexity, carbon buildup, and particulate emissions (Chen et al., 2022). Emerging research also explores exhaust gas recirculation (EGR) and integration of artificial intelligence for fault detection, underscoring the transition toward more sophisticated and sustainable fuel delivery systems (Elkelawy et al., 2022; Li et al., 2023).

Recent industry discussions highlight the growing importance of modern test-cell infrastructure equipped with computerized data-acquisition and control systems to meet the increasing demands for MRO and education (Sweeney & Guise, 2023; Sweeney & Thiel, 2022). However, in the Philippine context, such infrastructure remains sparse, with most aviation institutions relying on partial or component-based training setups, which limit practical readiness. Globally, the aircraft engine test cell market is substantial—valued at approximately USD 3.5 billion in 2023 and projected to exceed USD 4.2 billion by 2032—highlighting significant growth in modern testing capabilities (Market Research Future, 2025; Polaris Market Research, n.d.).

Understanding the adoption of such innovations requires structured frameworks. The Technology–Organization–Environment (TOE) framework explains technology adoption by considering technological readiness, organizational capacity, and environmental pressures such as regulation and market competition (Bryan & Zuva, 2021; Li, 2020). Within aviation, TOE has been applied to predictive maintenance and digital transformation, demonstrating its value in identifying adoption barriers and enablers (Tan & Masood, 2022). Complementing TOE, the TELOS feasibility framework provides a holistic assessment of technical, economic, legal, operational, and schedule viability, ensuring balanced decision-making in complex projects (McLeod, 2021; Thom, 2025). Applying these frameworks to test cell development can highlight both the readiness of Philippine institutions and the adjustments needed for successful implementation.

Sustainability further adds a crucial layer to this discourse. Guided by the Triple Bottom Line (TBL), sustainable aviation facilities must demonstrate not only economic efficiency but also environmental responsibility and social value (Gupta et al., 2020; Goh et al., 2020). International precedents show that sustainable infrastructure—whether in hangar design or runway redevelopment—yields measurable gains in cost savings, energy efficiency, and workforce safety (Dubey, 2017; Plastropoulos et al., 2024). However, sustainability practices remain underexplored in aviation training facilities, particularly in Southeast Asia, where resource constraints often hinder their adoption (Sandanayake et al., 2022). This suggests a pressing need to integrate sustainability principles into the design of multipurpose test cells to future-proof aviation education and local MRO capabilities.

Given these considerations, the present study evaluates the feasibility of a multi-purpose fuel delivery system for reciprocating engine test cells that can accommodate carbureted, EFI, and DI systems. By applying the TELOS feasibility model, TOE adoption readiness, and TBL sustainability analysis, this research addresses the dual challenges of modernization and sustainability in Philippine aviation training and MRO. The findings aim to close infrastructure readiness gaps, inform regulatory and institutional strategies, and support workforce development, thereby helping position the Philippines as a regional contributor to aviation modernization.

2. Literature Review

2.1. Aircraft Reciprocating Engine Fuel System

Aircraft reciprocating engine fuel systems have evolved from simple carburetion to electronic and direct injection to meet rising demands for efficiency, performance, and emission control. Carbureted systems, once the general aviation standard, remain valued for their simplicity and low cost but are limited by uneven fuel-air distribution, icing susceptibility, and reduced high-altitude performance (Martin, 2017; Monroe Aerospace, 2024; Wood, 2022). Electronic Fuel Injection (EFI) addresses these issues by precisely metering fuel, improving combustion stability, efficiency, and altitude performance, though it requires stable power and specialized maintenance (Reddy et al., 2021; Ilyas et al., 2020). Direct Injection (DI) further advances efficiency by delivering high-pressure fuel directly to the combustion chamber, enhancing atomization and power density but increasing system complexity and cost (Zhao, 2010; Moore, 2021).

Emerging technologies—such as EGR for emissions reduction, AI-based diagnostics, and electric pumps for More-Electric Aircraft—are reshaping fuel system design toward smarter, cleaner operations (Elkelawy et al., 2022; Nguyen, 2025). Modern systems also integrate FADEC, advanced gauging, and thermal management, improving efficiency and reliability (Li, 2020). This technological shift underscores the need for test cells that support carbureted, EFI, and DI systems, enabling training and MRO facilities to bridge legacy technologies with future-ready propulsion (Glazer, 2023; Reddy et al., 2021).

2.2. Engine Test Cell Applications in Aviation Training and MRO

Engine test cells are critical to aviation training and MRO, providing controlled environments for diagnosing, tuning, and validating aircraft powerplants. They enable students and technicians to build practical competencies with reciprocating engines while minimizing operational risks. Worldwide, training centers and MRO facilities are upgrading to computerized rigs with integrated data-acquisition and control systems, enabling more accurate performance evaluation and predictive maintenance (Safran Test Cells' DACS, 2019). These advancements align with Maintenance 4.0, where digitalization, health monitoring, and analytics drive more efficient maintenance practices (Metso & Thenent, 2020).

Complementary technologies are also transforming training. VR and 3D simulation enhance engagement and offset equipment shortages (Dela Peña, 2025; Miranda et al., 2020). Blockchain enhances record security (Dela Peña et al., 2024), while alternative propulsion systems, such as fuel cells, create new maintenance and training demands (Hoff et al., 2022). Competency-based and simulation-driven instruction is gaining global traction (Patel, 2025), yet skill shortages and certification gaps persist across Southeast Asia (Fahriza et al., 2021).

In the Philippines, however, dedicated test cell infrastructure remains limited. Most schools and MROs rely on component-level training or integrated airframes, reducing exposure to modern diagnostic tools. This gap undermines workforce readiness and increases reliance on overseas training for advanced maintenance capabilities. As general aviation and piston-engine operations expand in the region, the absence of scalable test cell infrastructure risks widening skill gaps and constraining industry competitiveness (Market Research Future, 2025).

2.3. Technology Adoption in Aviation

Technology adoption in aviation training and maintenance is increasingly analyzed through the Technology–Organization–Environment (TOE) framework, which emphasizes technological readiness, organizational capacity, and environmental pressures as key determinants. Advances such as VR, AI, and cloud computing have enhanced training quality and reduced maintenance errors (Gonzalo, 2024; Karunakaran, 2021). Combined with the Technology Acceptance Model (TAM), TOE offers a structured lens for assessing benefits, compatibility, and potential adoption barriers (Bryan & Zuva, 2021; Li, 2020).

TOE has informed studies on predictive maintenance, blockchain logistics, and cloud adoption, particularly in Southeast Asian MROs, where technological viability contrasts with uneven organizational readiness and regulatory alignment (Ganguly, 2022; Gui et al., 2020; Triandini et al., 2022). In airport operations, TOE assessments further highlight workforce capability and digital infrastructure as critical to successful digital transformation (Tan & Masood, 2022).

Overall, TOE provides a versatile framework for examining innovation uptake in aviation. Persistent barriers—especially in under-resourced facilities and aging workforces—underline the need to align technology, organizational capacity, and environmental support to ensure effective and sustainable adoption (Goritiyal et al., 2021).

2.4. Feasibility Assessment Models

Feasibility assessment models offer structured methods for evaluating a project's implementation potential. The TELOS framework, which examines Technical, Economic, Legal, Operational, and Schedule factors, remains one of the most widely used tools for assessing the feasibility of project and technology adoption. It provides a holistic view of viability and has been applied across domains such as e-government, academic information systems, and augmented reality (Lestari et al., 2021; Ningsi & Nuzul, 2023; Perdana et al., 2022; Gunawan et al., 2024). Through scoring systems, TELOS helps organizations assess readiness, identify risks, and minimize failure, financial loss, and reputational damage (Restyandito et al., 2023; Afilla et al., 2024; McLeod, 2021).

For complex or emerging technologies, design-based feasibility methods complement TELOS by emphasizing iterative development, stakeholder engagement, and uncertainty management (McLeod, 2021). In education, models such as TAM highlight the roles of perceived usefulness, self-efficacy, and social factors in adoption (Granić, 2022), while frameworks such as ETADC integrate TPACK with local constraints to support context-sensitive assessments (Sabiteka et al., 2025).

These approaches demonstrate that feasibility extends beyond technical and financial considerations, encompassing organizational capacity, stakeholder readiness, and contextual adaptability—essential factors for sustainable adoption in aviation training and maintenance.

2.5. Sustainability in Aviation Training Facilities

The integration of sustainability in aviation training facilities is increasingly guided by the Triple Bottom Line (TBL) framework, which balances economic, environmental, and social dimensions (Gupta et al., 2020; Goh et al., 2020). In facility management, energy-efficient systems, waste reduction, and environmentally conscious design are recognized as essential for long-term operational viability (Charytonowicz & Falcão, 2019; Opoku & Lee, 2022). Within higher education, sustainability has evolved further, with some institutions adopting a quadruple bottom line that adds educational value, reinforcing the importance of environmental education and structured waste management (Michael & Elser, 2019; Sandanayake et al., 2022).

Practical applications illustrate these principles. The “hangar of the future” at Cranfield University demonstrates how digital technologies, robotics, and sustainable materials can reduce costs, increase efficiency, and enhance safety (Plastropoulos et al., 2024). Similarly, TBL-based runway redesign at John Glenn Columbus International Airport leveraged material reuse and LED lighting to lower costs and environmental impact (Dubey, 2017). Although research directly focused on aviation training facilities remains limited, these examples indicate that embedding TBL strategies into test cell and training facility design can yield economic savings, greener operations, and stronger training outcomes—advancing both industry sustainability goals and workforce development.

2.6. Theoretical Framework

This study is anchored on three interrelated frameworks—the TELOS Feasibility Model, the Technology–Organization–Environment (TOE) Framework, and the Triple Bottom Line (TBL) approach—to assess the adoption feasibility of a modular multi-mode fuel delivery system for aircraft reciprocating engine test cells in the Philippine aviation context. The TELOS Feasibility Model evaluates project viability across five key dimensions: Technical, Economic, Legal, Operational, and Schedule (McLeod, 2021). Its application ensures that the proposed system is technically sound, cost-efficient, compliant with regulatory standards, operationally practical for aviation schools and MROs, and achievable within time and resource constraints.

The Technology–Organization–Environment (TOE) Framework (Tornatzky & Fleischer, 1990) analyzes adoption drivers at the organizational level. TOE considers technological performance and compatibility, organizational readiness and workforce capacity, and environmental factors such as regulatory frameworks and global benchmarks. In this study, TOE clarifies how aviation schools, MROs, and regulatory bodies like CAAP and ICAO shape readiness and adoption pathways. Finally, the Triple Bottom Line (TBL) framework extends the analysis by integrating economic, environmental, and social dimensions. Economically, the modular test cell reduces costs through shared infrastructure. Environmentally, it minimizes equipment redundancy and supports the use of alternative fuels. Socially, it enhances training quality, workforce preparedness, and safety culture. Together, TELOS, TOE, and TBL provide a holistic lens that captures both short-term feasibility and long-term sustainability, supporting the modernization of aviation training infrastructure and informing policy and industry practice in the Philippine context.

2.7. Conceptual Framework

Fig. 1 illustrates the conceptual framework guiding this study. The framework integrates three analytical perspectives: TELOS feasibility dimensions, TOE adoption drivers, and TBL sustainability impacts. The TELOS framework assesses feasibility across technical, economic, legal, operational, and scheduling considerations. The

TOE framework identifies adoption drivers shaped by technological performance, organizational readiness, and environmental regulations. The TBL framework highlights sustainability outcomes across the economic, environmental, and social domains. Collectively, these dimensions converge on evaluating the adoption feasibility of a multi-mode fuel delivery system for aircraft reciprocating engine test cells in the Philippine context, ensuring that both practical viability and sustainability impacts are systematically addressed.

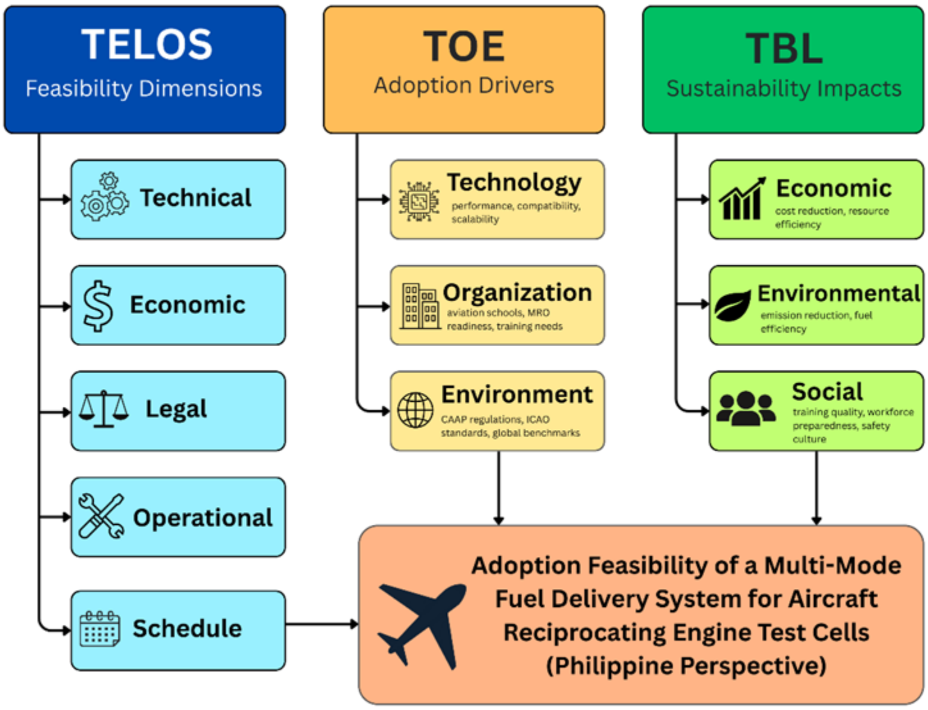


Fig. 1. Conceptual framework integrating TELOS feasibility dimensions, TOE adoption drivers, and TBL sustainability impacts for assessing the adoption feasibility of a multi-mode fuel delivery system in Philippine aircraft engine test cells (Source: Authors' own work)

3. Method

3.1. Research Design

This study uses a qualitative multimethod approach that integrates document analysis and semi-structured interviews to ensure conceptual rigor and contextual relevance. The core of the research is a document-based feasibility assessment that examines technical manuals, regulatory guidelines, and scholarly literature to conceptualize a multimodal fuel-delivery system for aircraft reciprocating-engine test cells. To enrich this foundation, semi-structured interviews are conducted with purposively selected stakeholders—maintenance trainers, regulators, and industry practitioners—who provide operational, regulatory, and pedagogical perspectives relevant to the Philippine aviation sector.

This combination allows cross-validation of technical evidence with practitioner insights. Findings are synthesized narratively and translated into visual representations, including a schematic diagram of the proposed system (Fig. 2) and a data collection flowchart (Fig. 3), which enhance clarity and practical applicability. This integrated qualitative approach ensures a credible, contextually grounded feasibility assessment that aligns technical design with regulatory requirements and educational objectives.

3.2. Data Sources and Participants

This study draws on two primary data sources: documentary materials and stakeholder interviews. Documentary data—including regulatory frameworks, technical manuals, and institutional policies—are purposively selected to establish baseline technical, regulatory, and operational criteria → are purposively selected to define baseline technical, regulatory, and operational criteria for assessing the feasibility of a multimodal fuel-delivery system.

Semi-structured interviews are conducted with key stakeholders from aviation schools, MRO organizations, and regulatory bodies. Inclusion criteria require at least five years of relevant experience in aircraft maintenance, training, or regulatory oversight, while those without direct technical or supervisory roles are excluded. A total of eight participants are engaged, representing instructors, maintenance supervisors, and regulatory officers with 5–18 years of experience → representing instructors, maintenance supervisors, and regulatory officers with 5–18 years of experience.

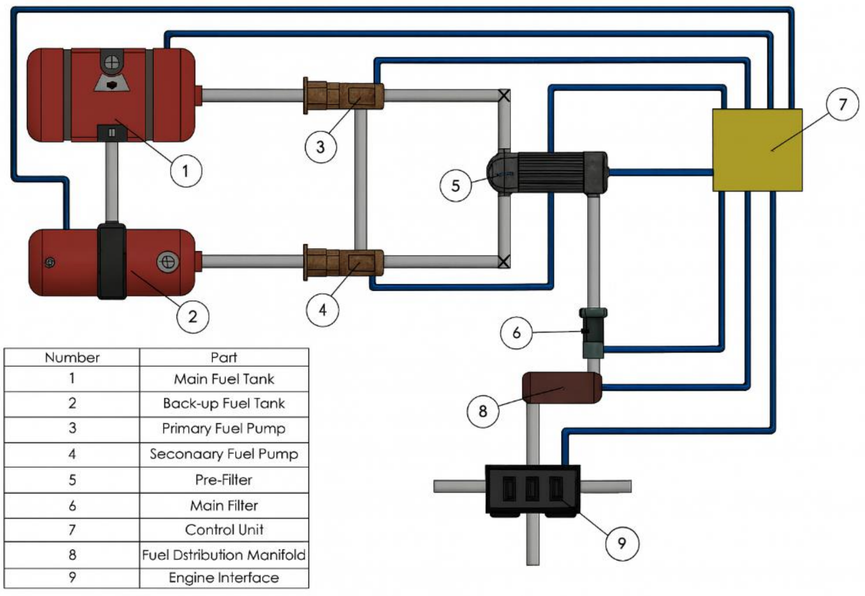
Recruitment continues until thematic saturation is achieved, reinforcing the credibility and robustness of findings → is achieved to ensure data adequacy and credibility. Participant details—role, experience, and affiliation—are summarized in a coding sheet to maintain transparency and anonymity.

The integration of documentary evidence and practitioner perspectives enables methodological triangulation, thus strengthening validity and informing the schematic design of the proposed system → supports methodological triangulation, strengthening validity and directly informing the framework synthesis in Section 3.4.

3.3. Data Collection Procedures

Data collection employs a dual strategy—document analysis and semi-structured interviews—to comprehensively assess the feasibility of a multimodal fuel delivery system for aircraft engine test cells. This multimethod design enables triangulation, ensuring that both technical evidence and practitioner perspectives are systematically captured. Relevant materials from regulatory agencies, academic literature, technical manuals, and industry reports are purposively selected and screened for credibility, recency, and relevance. Priority is given to sources on reciprocating engine test cells, fuel delivery technologies, and maintenance requirements. Findings establish the technical foundation for interview protocols and preliminary schematic design.

Aviation practitioners and instructors—including maintenance engineers, faculty, and technical personnel from test cell facilities—are purposively selected to align operational, regulatory, and instructional perspectives. A semi-structured guide ensures consistent thematic coverage while allowing in-depth exploration. Ethical protocols, including informed consent and confidentiality, are strictly followed. Document analysis precedes interviews to establish baseline knowledge. Interviews are conducted individually, either in person or online, and are audio-recorded with participant consent, supplemented by field notes. Insights from both sources are synthesized into a schematic diagram of the proposed system (Fig. 2) and a flowchart outlining the data collection sequence (Fig. 3), integrating both technical evidence and stakeholder validation. This combined approach strengthens validity through methodological triangulation, producing a robust feasibility assessment for aircraft engine test cell applications.



Number	Part
1	Main Fuel Tank
2	Back-up Fuel Tank
3	Primary Fuel Pump
4	Seconaary Fuel Pump
5	Pre-Filter
6	Main Filter
7	Control Unit
8	Fuel Dstribution Manifold
9	Engine Interface

Fig. 2. Conceptual schematic of the proposed multimodal fuel-delivery system integrating carbureted, EFI, and DI configurations. The figure illustrates the component interconnectivity and pressure-regulation pathways that enhance fuel stability and training adaptability, supporting the TELOS technical feasibility analysis (Source: Authors' own work)

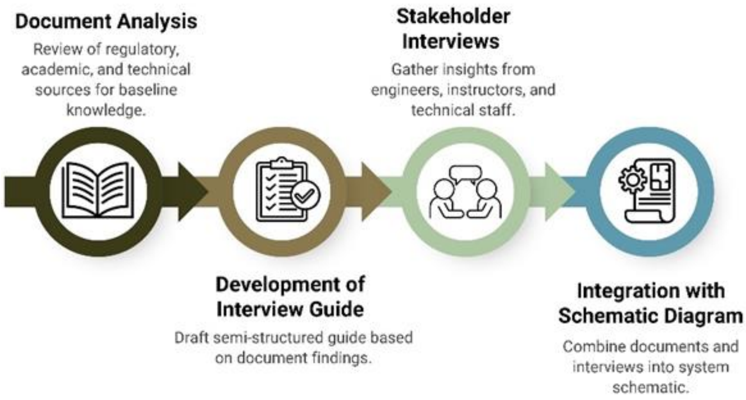


Fig. 3. Flowchart of data-collection procedures from document analysis to schematic integration. The figure is included to clarify methodological triangulation and to show how evidence from documents and interviews is systematically funneled into the design, ensuring analytic rigor (Source: Authors' own work)

3.4. Analytical Application of Frameworks

To structure the analysis and ensure rigor, this study operationalizes three established frameworks—TELOS, TOE, and TBL—to evaluate the feasibility and readiness of a multimodal fuel-delivery system for aircraft reciprocating-engine test cells. The TELOS Feasibility Model → TELOS model is applied through a structured scoring matrix → structured scoring matrix assessing five dimensions: technical, economic, legal, operational, and schedule feasibility.

The Technology–Organization–Environment (TOE) framework guides the assessment of adoption readiness by examining technological performance and scalability, organizational capability and workforce preparedness, and environmental or regulatory drivers.

The Triple Bottom Line (TBL) approach addresses sustainability by linking economic efficiency, environmental optimization, and social benefits → economic efficiency, environmental gains, and social value through improved training quality and workforce development.

A linkage matrix aligns TELOS, TOE, and TBL dimensions to ensure analytical coherence. This matrix ensures analytical coherence, with feasibility scores informing adoption readiness and sustainability dimensions validating long-term applicability. The process strengthens reproducibility and provides a unified basis for interpreting results.

3.5. Data Analysis Procedures

Data analysis follows a qualitative interpretive approach, integrating evidence from documents, stakeholder interviews, and the schematic diagram of the proposed multimodal fuel-delivery system. Documentary sources are analyzed through thematic content analysis, focusing on feasibility indicators—technical, economic, legal, operational, and sustainability—and broader modernization themes.

Interview data are transcribed verbatim and coded using an inductive–deductive strategy by two independent researchers to ensure coding consistency. Theme prevalence is indicated by brief frequency indicators (e.g., mentioned by 5 of 8 participants) to reflect the relative importance of emerging categories. Open coding captures → captures participants' raw insights, which are clustered into axial codes and consolidated into four major themes → are clustered into axial codes and synthesized into four main themes: (1) challenges (e.g., funding gaps, limited expertise, regulatory ambiguity), (2) benefits (e.g., enhanced training, cost efficiency, sustainability alignment), (3) recommendations (e.g., faculty upskilling, phased rollout, policy support), and (4) validation points confirming the accuracy and applicability of the proposed schematic design. Selected quotations are included to support interpretive depth and transparency.

Credibility is strengthened through methodological triangulation—cross-validating interview data with documentary evidence and the schematic design—along with peer debriefing and member checking with two participants to confirm the accuracy of the interpretation. Analytical rigor is further enhanced by the TELOS model (feasibility assessment), the TOE framework (adoption readiness), and the TBL framework (sustainability mapping). A coding matrix (Table 1) aligns analytical dimensions, codes, data sources, and framework components, ensuring consistency, transparency, and a holistic evaluation of feasibility and adoption potential.

Table 1. Coding Matrix for Data Analysis

Framework Dimension	Sample Codes	Data Source	Analytical Focus
Challenges	"Lack of funding," "Limited faculty expertise," "Unclear CAAP guidelines," "Maintenance complexity"	Semi-structured interviews	Barriers to adoption, resource constraints, and regulatory gaps
Benefits	"Enhanced training realism," "Sustainability readiness," "Cost efficiency," "SAF compatibility"	Semi-structured interviews, documents	Advantages of multimodal system, alignment with modernization goals
Recommendations	"Faculty upskilling," "Phased implementation," "Industry–academe collaboration," "Policy support"	Semi-structured interviews, stakeholder consultations	Practical strategies for adoption and sustainability
Validation Points	"Schematic reflects test cell reality," "Design is technically sound," "Operationally adaptable"	Semi-structured interviews, schematic diagram feedback	Practitioner confirmation of design feasibility and accuracy
Feasibility (TELOS)	Technical adequacy, cost-effectiveness, legal compliance, operational readiness, sustainability	Documents, schematic diagram, interviews	Structured feasibility assessment across TELOS domains
Adoption Enablers/Barriers (TOE)	Technological readiness, leadership support, regulatory environment, and environmental demand	Documents, interviews	Adoption potential in organizational and environmental contexts
Sustainability (TBL)	Cost savings, SAF integration, workforce development, and emission reduction	Documents, interviews	Mapping economic, environmental, and social benefits

4. Results and Discussion

The findings are examined through three complementary lenses—TELOS, TOE, and TBL. TELOS evaluates feasibility across technical, economic, legal, operational, and schedule dimensions. TOE assesses adoption readiness by linking technological capacity, organizational resources, and environmental drivers. TBL situates the design within sustainability goals, emphasizing economic efficiency, environmental responsibility, and social value. Together, these frameworks provide a comprehensive basis for interpreting feasibility, readiness, and long-term impact.

4.1. TELOS Feasibility

The feasibility of the proposed multimodal fuel-delivery system was assessed using the TELOS framework, which evaluates technical, economic, legal, operational, and schedule considerations. A synthesis of these findings is presented in Table 2.

Technical. The modular design effectively integrates carbureted, EFI, and DI systems into a single rig, increasing versatility while introducing manageable complexity. Shared manifolds and adjustable pressure regulators stabilize fuel distribution and allow rapid reconfiguration—features consistent with modern multi-mode test benches used in engine research and training (Zhao, 2010; Ilyas et al., 2020). These attributes support high technical feasibility and long-term instructional adaptability.

Economic. Although the initial investment is higher than constructing separate single-purpose rigs, consolidating three systems into one platform reduces equipment redundancy, maintenance cycles, and spare parts inventory. This leads to lower lifecycle costs and a reduced cost-per-training-hour, mirroring the efficiencies documented in modular and hybrid engine-training infrastructures (Gupta et al., 2020). The system is therefore economically viable over its operational lifespan.

Legal. The design aligns with CAAP fuel-handling requirements and ICAO Annexes 8 and 14. Integrated safety components—such as pressure-relief valves, spill-containment features, and grounding systems—support compliance with aviation fuel-safety standards and minimize electrostatic discharge and fire risks (CAAP, 2022; ICAO, 2018). Legal feasibility is strong, contingent on adherence to established occupational safety protocols.

Operational. Operational feasibility is supported by the system's modular control layout and use of standard couplings, which reduce setup time and enable smooth transitions between fuel-delivery configurations. Effective utilization, however, depends on instructor and technician upskilling, particularly for EFI and DI systems, to maximize technical accuracy and pedagogical value. The system is well-suited for both aviation schools and MRO environments, provided that capacity-building measures are in place.

Schedule. Implementation within one to two years is realistic, reflecting expected procurement timelines, training requirements, and regulatory coordination. A phased rollout—beginning with familiar carbureted systems and progressing to EFI and DI—can manage integration risks while allowing institutions to adapt gradually. Similar timelines have been reported in ASEAN aviation modernization initiatives (Tan & Masood, 2022). Overall, the TELOS assessment confirms that the multimodal fuel-delivery system is technically sound, economically advantageous, legally compliant, operationally viable, and achievable within a reasonable timeframe.

Table 2. TELOS feasibility assessment synthesizing technical, economic, legal, operational, and schedule dimensions. The table is included to show where feasibility is strongest (technical/economic) and where enabling actions (instructor capacity, phased rollout) are most needed

Dimension	Findings	Interpretation
Technical	Modular design accommodates carbureted, EFI, and DI systems within one rig.	Feasible; increases adaptability, though integration adds complexity.
Economic	Higher upfront cost vs. single rigs, but shared infrastructure reduces long-term expenses.	Economically viable on a lifecycle cost basis.
Legal	Aligned with CAAP standards and ICAO Annex 8/14, it requires strict safety protocols for fuel handling.	Legally compliant if occupational safety is ensured.
Operational	Suitable for aviation schools and MRO facilities; enhances training flexibility.	Operationally advantageous but requires specialized instructor preparation.
Schedule	Realistic adoption in 1–2 years, contingent on procurement, training, and approval.	Timeline feasible with phased implementation.

4.2. TOE Adoption Readiness

The Technology–Organization–Environment (TOE) framework was applied to assess the readiness of aviation training and MRO facilities to adopt the proposed multimodal fuel-delivery system, examining technological capacity, organizational preparedness, and environmental drivers.

Technological. Most facilities have compatible infrastructure and utilities, requiring only incremental upgrades for integration. However, gaps in advanced instrumentation and sensor systems may limit the system's full diagnostic capability. This limitation arises from legacy analog configurations that lack data-acquisition capacity, similar to barriers observed in predictive maintenance and digital retrofit studies (Tan & Masood, 2022; Gonzalo, 2024).

Organizational. While faculty and MRO personnel are well-versed in conventional fuel delivery, many require upskilling to handle EFI and DI technologies. Successful adoption depends on structured training and sustained institutional commitment to capacity building. This trend reflects earlier TOE-based aviation research indicating that workforce capability is a decisive factor in technology diffusion across Southeast Asian MROs (Ganguly, 2022).

Environmental. Regulatory alignment with ICAO standards and global trends toward sustainable fuels and hybrid systems create intense external pressure to modernize. [These regulatory incentives and market expectations act as environmental catalysts that accelerate adoption, consistent with findings by Bryan & Zuva (2021), who highlight policy-driven diffusion in aviation innovation.] These factors position multipurpose test rigs as essential for compliance and competitiveness.

Overall, the TOE assessment shows that although technological and organizational gaps persist, favorable baseline infrastructure and strong environmental drivers support adoption readiness. This alignment reinforces earlier

TOE applications in aviation, confirming that readiness improves when technological feasibility and regulatory support converge (Tan & Masood, 2022). A structured summary of these findings is presented in Table 3.

Table 3. TOE adoption-readiness matrix across technological, organizational, and environmental contexts. The table is included to reveal that baseline infrastructure is sufficient, but diagnostic instrumentation and workforce upskilling determine the pace of integration under strong external regulatory drivers

Dimension	Findings	Implications for Adoption
Technological	Facilities have basic infrastructure, but there are gaps in advanced instrumentation.	Incremental upgrades are needed; this may limit the diagnostic scope.
Organizational	Skilled in carbureted systems; limited expertise in EFI/DI.	Upskilling and training are essential for effective integration.
Environmental	Strong regulatory alignment (CAAP/ICAO); modernization pressures.	External drivers create urgency for adoption.

4.3. TBL Sustainability Analysis

The Triple Bottom Line (TBL) framework is applied to assess the economic, environmental, and social sustainability of adopting the multimodal fuel-delivery system, with emphasis on long-term institutional and industry value.

Economic. Consolidating carbureted, EFI, and DI configurations into a single modular rig reduces capital and maintenance costs compared to multiple standalone systems. This cost reduction results from shared instrumentation, fewer calibration cycles, and optimized utilization rates—mechanisms also reported in TBL-based analyses of hybrid training facilities (Tan & Masood, 2022). This resource optimization [supports → supports] financially sustainable training and MRO operations.

Environmental. The system minimizes equipment redundancy, lowering energy and material consumption. Its compatibility with Sustainable Aviation Fuel (SAF) and blended fuels aligns with ICAO's decarbonization goals, enhancing future sustainability readiness. The environmental gains arise from reduced embodied energy in manufacturing and lower emissions during test operations, comparable to efficiency improvements documented in sustainable hangar retrofits and engine test-cell decarbonization studies (Gupta et al., 2020; Bryan & Zuva, 2021).

Social. By exposing learners to multiple fuel-delivery technologies on a single platform, the system broadens technical competencies, strengthens workforce readiness, and improves graduate employability in an evolving aviation sector. This pedagogical impact mirrors findings from TBL-oriented aviation education research, which emphasize skill diversification and employability as social sustainability indicators (Ganguly, 2022).

Overall, the TBL assessment shows that the proposed system delivers clear economic and environmental advantages while advancing social objectives. These results are consistent with prior TBL-based facility assessments, confirming that integrated design and workforce-centered innovation jointly enhance institutional sustainability (Tan & Masood, 2022). A synthesis of these findings is presented in Table 4.

Table 4. TBL sustainability synthesis covering economic, environmental, and social outcomes. The table is included to show that a single modular rig concentrates capital/maintenance savings, reduces embodied and operational resource use, and broadens students' employability skills

Dimension	Findings	Implications for Sustainability
Economic	Single modular rig reduces capital and maintenance costs.	Financially efficient and resource-optimized solution.
Environmental	Reduced redundancy; compatible with SAF and blended fuels.	Aligns with global decarbonization and efficiency goals.
Social	Broader skill development in carb/EFI/DI systems.	Enhances employability and workforce adaptability.

4.4. Qualitative Results

4.4.1. Emerging Themes

Three key themes emerge from the interviews: integration challenges, perceived benefits, and recommendations for refinement and adoption. Integration challenges center on the technical complexity of combining carbureted, EFI, and DI systems into a single schematic. Participants emphasize the need for precise calibration and stable fuel pressure and flow control to ensure seamless switching between systems. They also note the constraints of educational settings, where advanced monitoring tools are often limited, stressing the importance of maintaining practicality in design. These insights highlight the trade-off between realism and resource availability, a trade-off often observed in aviation training facilities, and align with findings from hybrid-engine instructional models (Ganguly, 2022).

Perceived benefits highlight the schematic's value as both a cost-efficient and pedagogically powerful training tool. Participants view the integrated design as a practical way to expose students to multiple fuel-delivery technologies without the cost of multiple rigs. Broader system exposure is perceived as enhancing student adaptability and industry readiness. This perception mirrors broader trends in aviation education, which emphasize experiential learning and competency-based exposure to diverse systems.

Recommendations focus on improving usability, safety, and alignment with real-world practices. Participants suggest modular fittings, color-coded lines, built-in safety redundancies, and the integration of digital monitoring tools to support hands-on learning and operational accuracy. These suggestions align with global shifts toward digital instrumentation and standardized configurations in MRO education (Tan & Masood, 2022). Collectively, these insights reflect a balanced perspective: while technical integration poses real challenges, the schematic is widely viewed as a promising innovation for strengthening both aviation training and industry preparedness.

4.4.2. Validation of the Proposed Schematic Diagram

Participants broadly affirm the practicality and educational value of the proposed schematic diagram, recognizing its technical feasibility and pedagogical relevance. They agree that integrating carbureted, EFI, and DI systems is achievable with proper calibration and safety protocols. One participant notes that "the schematic captures the essential flow paths and components without overcomplicating the design." At the same time, another emphasizes the importance of "accurate fuel pressure regulation across systems" to ensure functionality.

From an educational standpoint, the schematic is validated as an effective bridge between theory and practice. Its multi-system design allows students to simulate and compare different fuel-delivery technologies on a single platform—an opportunity rarely available in typical training environments. This alignment with simulation-based pedagogy reinforces international findings on the value of integrated systems in technical education (Bryan & Zuva, 2021).

Participants also propose refinements to improve usability and alignment with industry standards. These include more transparent labeling of components, integration of digital monitoring, and the use of visual cues to minimize operational errors. As one remarks, "adding standardized labels and digital readouts will enhance both ease of use and relevance to MRO practices." Overall, the validation results indicate that the schematic is technically sound and pedagogically valuable, requiring only minor enhancements for optimal implementation and alignment with emerging aviation training frameworks. The integrated interview results are presented in Table 5.

Table 5. Consolidated Interview Results: Emerging Themes and Validation of the Proposed Schematic Diagram

Theme / Aspect	Participant Insight (Quote/Paraphrase)	Recommendation / Suggested Improvement
Challenges	"*Integrating three fuel systems into one schematic is complex, especially when considering fuel pressure and compatibility.*"	Careful calibration and safety protocols must be established.
	"*Educational institutions often lack resources to build multi-purpose test setups.*"	Secure funding and phase-based implementation.
Benefits	"*The design allows direct comparison of carbureted, EFI, and direct injection systems, enhancing student learning.*"	Highlight comparative learning outcomes in lab manuals.
	"*This can simulate real-world scenarios where mechanics deal with multiple engine types.*"	Integrate practical case-based exercises in teaching.

Recommendations	"*Ensure diagrams remain simple enough for students to interpret without confusion.*"	Use standardized labels and clear flow directions.
	"*Adding digital sensors and monitoring tools would make it more relevant to MRO practices.*"	Incorporate readouts for pressure, flow, and temperature.
Validation – Technical Feasibility	"*The schematic captures the essential flow paths and components without overcomplicating the design.*"	Ensure proper calibration of pressure regulation.
Validation – Educational Value	"*Students can simulate and compare three fuel delivery systems in one platform, which is rarely possible in traditional setups.*"	Emphasize comparative learning in training manuals.
Validation – Clarity of Design	"*From a technical standpoint, the diagram is workable; the key will be ensuring clarity of flow.*"	Add standardized labels and annotations.
Validation – Alignment with MRO	"*Including digital readouts aligns the design with industry practices.*"	Incorporate monitoring sensors and visual safety cues.

4.5. Integrated Discussion

The integrated application of the TELOS, TOE, and TBL frameworks provides a comprehensive lens for understanding the feasibility, readiness, and sustainability of the proposed multimodal fuel-delivery system for aircraft reciprocating-engine test cells. While each framework highlights distinct dimensions, their convergence reveals the interdependence of technical design, organizational capacity, regulatory context, and long-term sustainability outcomes (Fig. 4). This integration illustrates how design feasibility (TELOS) enables technological adoption (TOE) and how both reinforce sustainability performance (TBL), forming a systemic feedback loop consistent with integrated innovation models in aviation research (Tan & Masood, 2022; Bryan & Zuva, 2021).

TELOS confirms that the system is technically viable, cost-efficient, legally compliant, operationally suitable, and implementable within a realistic timeframe. TOE situates these findings in context, showing how technological infrastructure, workforce readiness, and environmental pressures shape the potential for adoption. TBL extends the analysis to economic savings, environmental gains through SAF readiness, and social benefits via workforce development. Framework integration shows how modular design supports adaptability and sustainability, as evidenced in sustainable aviation system assessments (Ganguly, 2022). Comparable findings are reported by Kabashkin (2025) and Shmelova et al. (2023), who observe that integrated training systems enhance institutional adaptability and reduce redundancy. However, the present study extends these insights to test-cell applications in emerging aviation markets.

Enablers include the system's modular design, lower long-term costs compared to multiple rigs, regulatory alignment with CAAP and ICAO, and growing demand for advanced workforce training. Barriers persist in uneven facility readiness, limited expertise in EFI and DI systems, and resource constraints. These challenges mirror prior TOE-based analyses, in which institutional capacity and funding asymmetry slow the translation of technological feasibility into operational adoption. Regulatory support is in place, but the lack of clear national guidelines for integrating advanced technologies into training systems may slow adoption. Accelerating adoption requires coherent policies on safety certification, oversight, and ICAO-aligned modernization strategies.

Institutions are required to invest in faculty upskilling, infrastructure, and curriculum redesign to fully leverage the system's economic, environmental, and social value. Cross-framework synthesis suggests that these institutional actions serve as critical feedback nodes—policy reform strengthens organizational readiness (TOE), which in turn sustains technical innovation (TELOS) and amplifies long-term sustainability outcomes (TBL). Strengthening partnerships among regulatory bodies, MRO providers, and aviation schools is expected to create an enabling ecosystem that bridges policy and practice.

Aligned with Research, Development, and Community Extension (RDC) priorities, the multimodal fuel-delivery system is positioned as both feasible and strategically transformative for Philippine aviation. Addressing the remaining barriers through coordinated policy and institutional action is essential to unlocking the industry's full potential for sustainable growth. This integration underscores the frameworks' collective relevance to aviation innovation, confirming that synchronized technical, organizational, and policy advancement is vital for sustainable modernization (Tan & Masood, 2022; Ganguly, 2022). By linking these results to the global literature on aviation modernization and sustainability, the study demonstrates how emerging economies can adapt integrated frameworks to bridge innovation gaps and strengthen human capital alignment with ICAO's long-term aspirational goals.

4.6. Recommendations

The adoption of the multimodal fuel delivery system requires coordinated action across policy, institutional, and industry levels. Practitioner interviews revealed key challenges—funding gaps, limited faculty expertise, and unclear CAAP certification pathways—as well as opportunities such as enhanced training realism, SAF readiness, and long-term cost efficiency. These insights highlight both barriers and actionable strategies for effective implementation. The Civil Aviation Authority of the Philippines (CAAP) and related agencies should develop clear certification pathways and regulatory guidelines that support the integration of advanced test cells and the adoption of SAF.

Aviation schools and MRO facilities must prioritize faculty upskilling, curriculum alignment, and infrastructure investment to build readiness and ensure compliance with evolving standards. Practitioner feedback confirms that the schematic design aligns well with operational realities, reinforcing its practical feasibility. Strengthened partnerships among aviation schools, MROs, regulatory bodies, and the Regional Development Council (RDC) are essential. The RDC can coordinate shared resources, infrastructure, and policy advocacy, enabling joint pilot programs that serve as proof-of-concept initiatives for broader scaling.

Implementation should follow the Triple Bottom Line (TBL) framework, ensuring cost efficiency, environmental responsibility, and workforce development. A phased adoption roadmap (Fig. 4) outlines five stages—from alignment and pilot validation to regional scaling and nationwide integration—providing a structured guide for rollout. By embedding adoption within RDC-led networks and grounding strategies in practitioner insights, the system's scaling can be accelerated, amplifying regional impact and positioning the Philippines as a proactive contributor to global aviation modernization and sustainability goals.

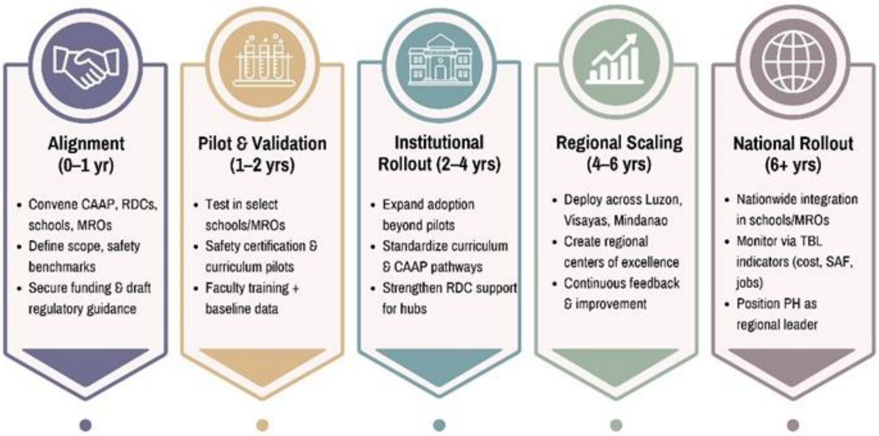


Fig. 4. Phased adoption roadmap for the multimodal test-cell system. The figure is included to link feasibility findings to implementation pacing, showing how policy alignment, training, and procurement are sequenced to manage risk and build readiness in line with TELOS–TOE–TBL integration (Source: Authors' own work)

4.7. Limitations and Future Research

This study is limited by its conceptual and qualitative scope. The analysis was based on document review and a small number of semi-structured interviews, which, while insightful, restrict the breadth of perspectives and render the findings exploratory rather than conclusive. These practitioner insights, however, offered valuable direction by identifying key feasibility challenges and opportunities.

The lack of experimental prototyping and operational testing also limits the validation of technical performance and long-term reliability. While the schematic demonstrates conceptual feasibility, implementation may reveal integration issues, maintenance complexities, or compliance adjustments with CAAP and ICAO standards.

Future research should focus on prototype development and pilot testing in aviation training and MRO settings to empirically assess technical performance, cost efficiency, and safety. Additional studies incorporating SAF and blended fuels are recommended to evaluate environmental impacts and alignment with decarbonization goals. Exploring digital integration with monitoring systems and training simulators may further enhance operational control and pedagogical effectiveness. Addressing these limitations will provide stronger empirical and technological foundations to support broader adoption, scalability, and policy alignment for multimodal fuel delivery systems in aviation education and maintenance.

5. Conclusions

This study assesses the feasibility, adoption readiness, and sustainability of a multimodal fuel-delivery system for aircraft reciprocating-engine test cells using the integrated TELOS, TOE, and TBL frameworks. The findings confirm that the system must be technically viable, economically advantageous, and compliant with CAAP and ICAO standards, with a single stem's modular design physically implementable through shared manifolds, standardized fittings, and safety-compliant controls, suitable for integration into aviation training laboratories. These features establish a pathway for prototype fabrication, performance testing, and curriculum application, bridging conceptual design and operational practice.

The results further demonstrate that modular engineering supports sustainable modernization—enhancing cost efficiency, reducing material use, and strengthening workforce readiness. Future research should involve prototype validation, digital sensor integration, and lifecycle and cost-benefit analyses to quantify performance and sustainability impacts. Overall, the proposed system provides a practical, scalable framework for advancing sustainable aviation maintenance training in the Philippines and contributes to ongoing efforts to make aviation education greener and more adaptable.

Abbreviations

AI	Artificial Intelligence
CAAP	Civil Aviation Authority of the Philippines
DACS	Data Acquisition and Control System
DI	Direct Injection
EGR	Exhaust Gas Recirculation
EFI	Electronic Fuel Injection
FAA	Federal Aviation Administration
ICAO	International Civil Aviation Organization
IoT	Internet of Things
LED	Light Emitting Diode
MRO	Maintenance, Repair, and Overhaul
MSME	Micro, Small, and Medium Enterprises
RDC	Regional Development Council
SAF	Sustainable Aviation Fuel
TAM	Technology Acceptance Model
TBL	Triple Bottom Line
TELOS	Technical, Economic, Legal, Operational, and Schedule (Feasibility Model)
TOE	Technology–Organization–Environment (Framework)
TPACK	Technological Pedagogical Content Knowledge
USD	United States Dollar
VR	Virtual Reality

Conflict of Interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript. The research was conducted independently, without any financial or personal relationships that could have influenced the work.

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Research Article

Application of Artificial Intelligence-Based Digital Technologies in Transport Logistics

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Abstract

The conducted analysis highlights that, in order to effectively stimulate and accelerate the process of digitalization in line with the functioning of different modes of transport, it is necessary to rely on technologies and systems developed on the basis of the latest achievements of scientific and technological progress. Modern experience demonstrates that the integration of such technologies can bring tangible benefits to transport operators, passengers, and society as a whole. For this purpose, it is particularly important to ensure the comprehensive integration of modern digital solutions-currently applied on a limited scale or at the project development stage in certain advanced countries-into a unified transport ecosystem. Such integration can be realized by gradually improving road and transport infrastructure across regions, as well as ensuring the digital support for urban and inter-district transport services.

In the contemporary era, marked by a rapid increase in population, accelerated urbanization, and steadily growing transport volumes, the adoption of innovative technologies acquires critical relevance. Digitalization and artificial intelligence in this context should not be viewed solely as technical instruments for optimizing transport operations. They also act as catalysts for the modernization of logistics chains, the enhancement of transport safety, and the reduction of environmental impact.

Furthermore, the consistent implementation of these measures contributes to significant improvements in citizens' quality of life, ensuring more accessible, reliable, and efficient mobility. At the same time, such progress supports the achievement of long-term sustainable development goals, particularly in terms of fostering economic competitiveness, promoting social well-being, and ensuring ecological balance. The main goal of this study is to scientifically assess the impact of the digital transformation of transport and logistics systems and the application of artificial intelligence technologies on the efficiency and sustainability of the sector.

1. Introduction

It is well known that, as a direct consequence of the rapid integration of digital technologies-developed on the basis of the most recent achievements of scientific and technological progress-into the functioning of various modes of transport worldwide, the role of transport vehicles in meeting the mobility needs of both the state and the population with high quality and efficiency has significantly increased (Əhmədov et al., 2025). This process reflects not only a technical modernization of the transport sector but also a strategic transformation that reshapes how transportation services are planned, managed, and delivered. The improvement of digital ecosystems allows for the optimization of logistics chains, enhancement of operational safety, and provision of more sustainable solutions. In order to successfully stimulate the future implementation of digitalization across different modes of transport, it is therefore essential to conduct a comprehensive examination of a wide spectrum of innovative technologies and systems. According to international practice, many of these solutions are currently at the project development stage or are being applied on a limited scale in several advanced countries. Analyzing these global experiences provides valuable insights for adapting such technologies to local conditions, ensuring their gradual integration into a unified transport system, and ultimately achieving sustainable economic and social benefits.

2. Method

2.1. Research method

Manipulators and Manipulation Technologies. At present, manipulators are widely used in such areas as providing technical maintenance and repair of transport vehicles and infrastructure facilities, aircraft refueling, and automating routine and repetitive operations in logistics (sorting, packaging, loading, unloading, etc.). In the future, with the development of multimodal transport and logistics complexes, the demand for the use of manipulators is expected to increase further.

Sensorimotor Coordination and Spatial Positioning Technologies. The main task in automating transport processes is to determine the positions and trajectories of vehicles during movement, as well as to obtain feedback and model motion in real-time modes. In cases where transport demand increases during operational processes, one of the critical areas of application will be the remote monitoring of vehicles that may pose a danger to movement. The application of these technologies provides an opportunity to address this issue.

Sensors and Data Processing Technologies. During the operation of transport systems, there is a constant flow of rapidly changing and significant amounts of data. The collection and fast processing of this data make it possible to take the necessary measures to improve the efficiency of freight and passenger transportation (Postranskyy & Vovk, 2020). Therefore, in the future, during the transition to highly automated driverless transport, the integration of advanced sensors for the collection of data from various platforms will be of great importance. Such modern sensors also make it possible to monitor the level of harmfulness of exhaust gases and ensure compliance with other environmental requirements. They are considered critical elements of diagnostic devices used for monitoring anti-icing systems for vehicle glass surfaces, controlling external lighting, detecting deficiencies in pipelines used in various systems, and monitoring the operation of transport infrastructure. Consequently, in the future development of transport systems, the role of such sensors and sensor networks in the wireless acquisition of data from diagnostic devices via internet connectivity will significantly increase (Ahmadov et al., 2025).

Wireless Communication Technology Group. It is well known that the greatest effects expected from future communication networks are associated with the fifth generation (5G) networks. The use of 5G-based Wide Area Networks (WANs) is considered one of the key elements for the full implementation of the modern urban transport environment concept (Lin et al., 2017). They belong to the main group of wireless communication technologies that will enable the operation of smart road infrastructure, intelligent transport systems, and, ultimately, driverless ground transport. Other major applications include remote monitoring of vehicles, the organization of wireless communication on high-speed trains, the operation of Vehicle-to-Everything (V2X) systems for the exchange of information about road traffic conditions from various objects, real-time collection of movement status data during operation, and the provision of all possible new services for passengers. In logistics, 5G networks also allow for the use of drones to deliver goods both to end customers and to the required logistics centers.

Wireless Local Area Network (WLAN). Currently, various types of public transport vehicles are equipped with Wi-Fi-based WLAN systems that provide passenger internet access and support the operation of auxiliary systems (video surveillance, vehicle monitoring, regular system updates, etc.). In the future, with the implementation of smart city strategies and the expansion of passenger service options, the use of WLAN networks is expected to increase.

RFID Tag Technology. Personal Area Networks (PAN) and RFID (HF- and UHF-based Radio-Frequency Identification) tag technologies is now sufficiently mature and are widely used in transport infrastructure facilities (e.g., access control and management systems for monitoring logistics processes). In the future, in order to optimize prospective costs, automation of trade and logistics processes will be possible on the basis of cargo tagging.

DHL and Smart Warehouse Technologies. DHL, one of the global leaders in express postal and logistics services, established in the USA in 1969, is currently implementing the "Smart Warehouse" concept using RFID technology and Warehouse Management Systems (WMS). One of DHL's Singapore-based hubs can track the location of every item in the warehouse in real time through RFID. The advantages created by these technologies include:

- reducing shipment errors by up to 60%;
- eliminating stock losses and shortages;
- preparing orders faster and improving customer satisfaction.

Satellite Communication Technologies (SCT). Currently, satellite technologies are used to provide access to communication networks in remote regions and areas with difficult natural and climatic conditions.

Group "Virtual and Augmented Reality (VR/AR) Technologies" (Developer Content Creation Tools and UX Enhancement Technologies). At present, the level of use of content creation tools (VR/AR) and user experience (UX) enhancement technologies in the transport sector remains relatively low, partly due to the immaturity of some of these technologies. In the future, with the growing demand for more functional solutions, particularly in the training of personnel in the skills required for managing various modes of transport, such solutions will be increasingly used, especially in the aviation sector for pilot training and for preparing personnel involved in flight safety.

Demand-Responsive Technology. The implementation of this technology will make it possible to significantly improve the quality of transport management in the field of infrastructure facility design. It can also operate as part of driver assistance systems used to assess road conditions and make decisions in real time.

Motion Capture Technologies in VR/AR and Photogrammetry. Currently, the implementation of VR/AR technology is at an initial stage. In the future, it may be used, along with other technologies, to create simulators and augmented reality applications that allow the development of skills for operating various transport modes and special equipment. Photogrammetry and object recognition algorithms can also be used for the automated construction of spatial models of objects from photographs. By enabling motion capture within VR/AR systems, as well as using photogrammetry technologies, it becomes possible to identify the characteristics of moving objects, thereby improving road traffic safety. Their application is also possible in navigation solutions based on augmented reality and in the technical service sectors of modern logistics centers.

Graphic Output Technologies. Currently, solutions based on this technology for the transport sector are characterized by insufficient functionality. In the future, as the functionality of this field expands, the use of such technologies will naturally increase. This is particularly related to the provision of visual tracking through headset devices when applying VR/AR technologies to prevent hazardous situations on the road. These glasses, used to enhance the realism of three-dimensional object representation, are intended for training drivers and pilots using interactive devices.

VR/AR Data Transfer Optimization Technologies. At present, solutions based on this technology for the transport sector are also characterized by insufficient functionality. In the future, as the functionality of this technology expands, it can be used to improve the accuracy of determining the coordinates of unmanned vehicles during VR/AR data transfer optimization processes.

Feedback Interfaces and Sensors for VR/AR. This technology is also at an early stage of application. In the future, along with other technologies, it may be used to create simulators and augmented reality applications that make it possible to train skills in operating various types of transport and special equipment. The 6D platform interface, acting as a main feedback element, can be applied in multi-channel communication systems for the higher-level training of drivers of motor vehicles and pilots in air transport, as well as for collecting feedback from drivers.

Demand-Responsive Technology. This technology is applied in the Arctic zone and sparsely populated areas. Due to the specific features of maritime transport, satellite communications are used more frequently. They are widely applied to monitor and determine the location of cargo (e.g., containers). Satellite communication systems (GLONASS, GALILEO, GPS) have broad application areas in vehicle navigation, data transmission within vehicles, monitoring the transport of hazardous and special cargo, ensuring the safety of train movements, and monitoring the condition of railway infrastructure facilities. In the future, the expansion of these technologies will be of crucial importance for the implementation of large-scale transport route projects.

Mobility-as-a-Service (MaaS) System. This technology is planned to be implemented in Moscow, aiming to develop flexible transport systems and reduce negative environmental impact by aligning demand and supply for transport services. This concept provides an integrated service that includes direct access to transport system services, real-time travel conditions, and the ability to plan and predict transfers in advance. Currently, various types of transport and logistics infrastructure facilities not only have the ability to generate significant volumes of data but also pose requirements for its rapid reception and processing. Naturally, in order to derive valuable insights from this data, the use of modern automated processing tools and technologies is considered essential. Such technologies must address the collection, recording, storage, analysis, and visualization of data, as well as the automated processing of shipping documents. In this regard, solutions for passenger communication within the development of MaaS are expected to become increasingly popular.

The "Free Flow" Concept Developed in the Russian Federation. This new technology represents an advanced solution not only for Russia but also globally. Using various devices and cameras, it monitors and analyzes traffic conditions, weather, and the state of the road surface. Based on this data, the actual cost of using a certain section of toll road is determined, and invoices are generated for payment (Avtodor, 2021; Korolkov, 2021; Mohammad, 2020).

Robotaxi in Guangzhou (China) and the MaaS Platform Implemented in Moscow. It is known that personalized robotaxis are currently being tested in Guangzhou, China. In addition, based on the MaaS concept developed in the Russian Federation, it is possible to order a personalized service and receive information about travel scenarios via the "Moscow Transport" mobile application. Furthermore, users can access other important functions, such as determining which bus stop they will reach within a 500-meter radius and at what time.

Shared Mobility System. This system is based on the joint use of various modes of transport instead of private cars. It includes mobile services where passengers share the same vehicle (e.g., taxis, minibuses) operated by a driver, as well as shared use of personal mobility devices (bicycles, motorcycles, scooters) with other individuals. Such integration of movement and the multimodal form of travel allows for seamless transfer from one mode of transport to another.

5PL (Fifth-Party Logistics) Provider System. This system represents an approach to providing logistics services that forms an ecosystem delivering a complete package of transport and logistics services based on platform solutions without possessing physical assets (Murmann, 2025).

Technology Change-on-Demand Systems. Technology change-on-demand systems are applied in the digitalization of transport logistics when implementing innovations such as voice assistants for interactive maps (authentication), transport dispatching services, interaction with various transport units, and similar features. These innovations can also be used when reorganizing the operation of service centers based on citizens' requests, including during emergencies or road traffic incidents. For example, in air transport, the future development of this technology may facilitate the acceleration of passenger voice authentication implementation.

Recommendation and Intelligent Decision-Support Systems. These systems stimulate interest in recommendation-generating solutions in response to the increasing freight turnover associated with urbanization and transport infrastructure development. For instance, such a concept is widely used to determine the need for vehicle repairs with the help of predictive maintenance systems.

Decision-Support Systems. Decision-support systems can improve the efficiency of several intra-organizational processes, including human resource management and the hiring of new employees. It is well known that there is currently a growing demand for personalized recommendation systems that use intelligent mapping to build optimal routes for passengers. The scope of decision-support application will expand further with the transition to multimodal transportation, which will take into account many interrelated factors, enabling the construction of the most optimal routes for all participants and ensuring the efficient operation of transport networks.

Technology Change Systems Adapted to Demand. Demand-adapted technology change systems support the provision of intelligent assistance for vehicle maintenance, transportation process management, and the creation of platforms for transport and logistics hubs. The primary task in this area is to ensure the integration of all elements and subsystems into a fully cyclical control system.

“Living Laboratory” Concept for Driverless Transport in Germany. In Germany, a digital testbed has been launched on the A9 federal highway in the format of a “living laboratory” (Digital Motorway Test Bed) to test digital technologies under real conditions. For this purpose, favorable technical conditions have been created on a specific road section to support intelligent infrastructure and autonomous driving, allowing tests to be conducted in both directions simultaneously (Follmer & Gruschwitz, 2017).

Technology Change-on-Demand. Quantum Computing: Quantum computing solutions are currently in the development stage. Promising areas for this technology include modeling and forecasting the development parameters of various modes of transport, taking into account regional characteristics, natural and climatic conditions, and other requirements.

Quantum Sensor Solutions: Solutions based on quantum communications are also under development. In the future, quantum sensors may be used to improve the navigation systems of vehicles in order to optimize traffic flow. In maritime transport, quantum sensors can enhance the performance of mapping systems under conditions where access to other devices and communication networks is limited. This technology is expected to see wider application in the operation of autonomous (driverless) transport.

Digital Design, Mathematical Modeling, and Product Lifecycle Management (Smart Design): At present, information modeling tools such as digital design, mathematical modeling, and product lifecycle management (smart design) are widely applied in the planning of railway and road networks as well as infrastructure facilities. The expansion of digital design usage will facilitate the implementation of large-scale projects for the construction of new surface transport routes. Demand for such systems will also drive the development of smart road surfaces designed for autonomous vehicles.

Technology Change-on-Demand: Neurotechnology and Artificial Intelligence Group: Computer vision is the main artificial intelligence technology actively used in the transport sector. Through various tracking devices that generate computer-based images, it enables the capture and analysis of three-dimensional data on operational conditions adapted to the external environment, including other vehicles, road surfaces, traffic lights, and similar elements.

Robotics Components and Sensors Group: Given the specific safety requirements that arise from interactions between autonomous vehicles and humans, sensors and other digital components from this group can be applied to address these challenges. In the future, the growing demand for such technologies will mainly be driven by the need to automate transport management processes to ensure the population’s mobility needs are met.

Neurointerfaces, Neurostimulation, and Neurosensation in Transport: Neurointerfaces are used to solve a number of small but critical tasks. In the future, vehicles with integrated neural interfaces (“neurocars”) will facilitate easier control by human operators.

Technology Change-on-Demand: It is undeniable that devices enabling the collection of data on road traffic flow, road service operations, traffic violations (photo and video evidence), emission control, and other operational parameters play a crucial role in improving transport efficiency and road safety. Currently, there is already a sufficient number of emerging technologies in this field. However, with the implementation of large-scale autonomous transport projects, the demand for more sensitive computer vision systems will continue to grow.

Speech Recognition and Synthesis:

In transport operations and logistics processes, solutions based on speech recognition and synthesis are primarily used for the automatic analysis of voice messages, enabling the identification of their content and emotional components.

Platform Solutions for Users: Currently, individual projects are being developed to create platform solutions for users. In the future, the demand for advanced VR/AR technologies will increase to enable 3D modeling of transport systems, as well as forecasting traffic conditions and transport flows.

Technology Change-on-Demand: LPWAN (Low-Power Wide-Area Network) Technologies: LPWAN technologies provide wireless access for a wide range of telemetry and Internet of Things (IoT) applications in transport. They enable the transmission of data over long distances with low power consumption and are used for remote monitoring and control of vehicles, transport infrastructure facilities, and cargo. In the future, the use of LPWAN will grow as tasks are implemented to create a unified information and telecommunication environment capable of monitoring virtually all parameters of the integrated transport ecosystem.

2.2. Problem Solution

According to data from information networks, in 2020 the demand for advanced digital technologies in the transport and logistics sector of the Russian Federation was estimated at 89.4 billion rubles based on expert survey results conducted by the Center for Statistics Research and Knowledge Economy (CEMI RAS). By 2030, this figure is projected to increase sevenfold, reaching 626.6 billion rubles (Fig. 1).

Research findings indicate that, at present, the most "digitalized" segment of the transport sector is air transport. The introduction of digital technologies in this field has been regarded as a tool even for mitigating the negative consequences of the COVID-19 crisis. Leading airlines use a wide range of digital technologies both on the ground and in the air, including cloud technologies, wireless services for crews, and automated data management systems (Əhmədov et al., 2025). Currently, PJSC Aeroflot ranks fourth globally among air carriers in terms of digitalization level.

One of the modern trends in airport digitalization is the application of biometric identification during security checks. Such initiatives are already widely implemented in the world's largest airports, including those in Germany, the United States, and the United Kingdom. In the Russian Federation, the introduction of biometric identification and authentication technologies in the largest airports is planned for the near future, with the service expected to be based on the Unified Biometric System, which has been operational since 2018.

In the field of passenger air transport, Unmanned Aerial Vehicles (UAVs) are already undergoing trials. However, according to surveys conducted in several developed countries, 58% of passengers report that they are still not ready to fly on planes controlled by artificial intelligence. According to internet data, by 2026, the number of drones used for cargo delivery worldwide is expected to exceed 1 million, compared to the current figure of approximately 20,000 (Ahmedov & Akhundov, 2025).

It is widely recognized that during the military operations conducted in the region, modern remotely operated Unmanned Aerial Vehicles (UAVs) manufactured by Turkey and Israel were used for the first time as active components of military equipment. This development represented a significant milestone in contemporary warfare, marking the first successful large-scale operational deployment of such technologies in real combat conditions.

At present, serious measures are being taken in the Republic of Azerbaijan for the development and application of digital technologies. Extensive research activities in this field are being conducted at the Azerbaijan Technical University and the National Aviation Academy. According to recent information published in digital platforms, the national defense industry of Azerbaijan has also begun the production of new UAVs that meet modern operational and technological standards.

As previously mentioned, the use of UAVs allows for the fulfillment of a wide range of tasks; however, their economic feasibility must be validated through objective quantitative indicators. In this regard, the following formula (1) can be used to evaluate economic efficiency (Kotenko, 2010):

$$E = R/C \tag{1}$$

where,

(E) – indicator of economic efficiency;

(R) – achieved result (income, savings, or prevented losses expressed in monetary units);

(C) – total capital investment, including operational costs, maintenance expenses, and personnel training.

If (E > 1), this indicates that the use of UAVs generates more benefits than costs, thus being economically justified. When (E = 1), the project is considered break-even, and when (E < 1), it is deemed economically inefficient.

Additional indicators such as Net Present Value (NPV) and Investment Profitability Index can also be applied for comprehensive assessment of UAV efficiency. Since NPV reflects the difference between discounted revenues and expenditures, it serves as a primary criterion for investment effectiveness and is determined as follows formula (2) (Rezer & Gavrilyuk, 2012):

$$X = \sum_{t=1}^{n} \frac{R_t - C_t}{(1+r)^t} \tag{2}$$

where,

(X) – net present value;

(Rt) – expected income or savings from UAV implementation in year t (e.g., savings on fuel, maintenance costs, downtime, etc.);

(Ct) – corresponding costs in the same period;

(r) – discount rate;

(n) – project implementation period.

If (X > 0), the project is considered economically viable, as its current value of benefits exceeds costs.

If (X < 0), the project is inefficient, implying the need to reduce capital expenditures or extend the payback period, which would necessitate revising its parameters.

Another key criterion for evaluating the economic efficiency of UAV application is the Return on Investment (ROI) coefficient. This indicator reflects the project's profitability level and represents the percentage of profit earned per unit of capital invested (3) (Sveshnikova & Nemchinov, 2023):

$$R = \frac{P-I}{I} \times 100\% \tag{3}$$

where

(R) – return on investment;

(P) – total project revenue, including profit, cost savings, productivity growth, and reduction of losses;

(I) – initial investment or capital expenditure.

If (R > 0), the project is considered profitable; otherwise ((R < 0)), the investment results in losses.

A positive ROI contributes to solving the following analytical and practical tasks:

1. Comparative evaluation of different UAV application models in areas such as monitoring, safety, logistics, and emergency management;

2. Assessment of investment returns both at the national and regional levels;

3. Development of a solid foundation for attracting private and public investments into intelligent transport systems.

It should be noted that several countries have already conducted similar economic assessments regarding UAV implementation in their transportation systems. For instance, according to the report of the Department of Infrastructure, Transport, and Regional Development of Australia, the use of UAVs in transport logistics, infrastructure monitoring, and environmental control has generated significant macroeconomic benefits (fig. 1).

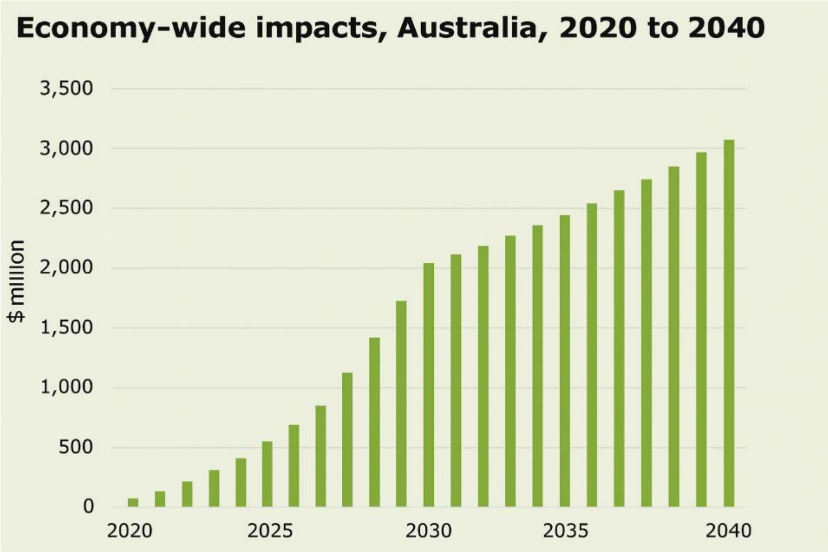

Fig. 1. The impact of UAV adoption on Australia's economy from 2020 to 2040 (Department of Infrastructure, Transport, Regional Development and Communications of Australia, 2020).

According to the analysis, the cumulative increase in Gross Domestic Product (GDP) for 2020–2040 is estimated at AUD 14.5 billion (≈ USD 9.5 billion) at a 7% discount rate. Moreover, direct savings related to reduced monitoring, maintenance, and labor costs amount to approximately AUD 9.3 billion (≈ USD 6.1 billion) (Department of Infrastructure, Transport, Regional Development, and Communications, 2020).

Beyond direct financial impact, the widespread use of unmanned technologies positively influences the labor market. Experts estimate that the development of the drone sector in Australia will create an average of 5,500 full-time equivalent (FTE) jobs annually. The eastern states-Sydney, Melbourne, and Brisbane-as well as Western Australia, where mining and transport infrastructure are actively developing, are expected to contribute most significantly to this overall economic growth (Department of Infrastructure, Transport, Regional Development, Communications and the Arts, 2023).

Similar trends are also observed across the European Union. According to the European Union Aviation Safety Agency (EASA), the integration of UAVs into transport monitoring and logistics systems could reduce overall transport costs by 15–20% through automated inspections and real-time monitoring of bridges, tunnels, and roads (EASA, 2024).

Furthermore, the use of unmanned technologies improves the accuracy and efficiency of infrastructure monitoring, reducing the number of unplanned repairs, accidents, and transportation delays. This directly strengthens the economic sustainability of transport systems by minimizing unforeseen expenses and enhancing the transparency of logistics operations.

Therefore, conducting similar comparative research by relevant institutions in Azerbaijan would create opportunities for achieving more positive outcomes. In this regard, young researchers at the National Aviation Academy and the Azerbaijan Technical University are currently engaged in active scientific research aimed at developing safety systems for railway operations and monitoring within international transport corridors such as TRACECA and Zangezur, as well as optimizing cargo handling technologies in intermodal transport processes at the Baku International Sea Trade Port terminal-logistics complex.

In the future, once the North-South and Zangezur Corridors become fully operational, new research initiatives will continue to focus on the implementation of intelligent technologies in transport operations and logistics management processes.

It is known that the development of (UAVs) currently prioritizes their remote regulatory management. The top five countries with the most favorable regulations for the operation of driverless cars are Singapore, the United Kingdom, New Zealand, Finland, and the Netherlands (European Commission, 2019). Although Russia currently ranks relatively modestly (22nd place) in this field, in recent years the state has introduced several initiatives aimed at accelerating the development of a legislative framework for the use of unmanned transport. Specifically, preparations for testing such technologies and experimental research on public roads have been carried out. In terms of readiness for autonomous vehicle deployment, Singapore, the Netherlands, Norway, the USA, and Finland hold leading positions. Among the 30 countries evaluated in recent years, Russia ranks 26th, reflecting a relatively low level of implementation of advanced solutions in this area.

It is expected that, once a modern digital infrastructure network meeting contemporary standards is established in our country, the operation of autonomously controlled vehicles will commence.

In the maritime transport sector, Russia is also among the countries testing autonomous ships. Norway has been a leader in such trials since 2017. Further impetus has been provided by the International Maritime Organization's 2019 guidelines on testing autonomous vessels. At present, these systems are tested only in experimental conditions. One of the world's first fully autonomous vessels, the Yara Birkeland, had its 2020 trials postponed due to the COVID-19 pandemic.

Azerbaijan's digital transformation in the transport and logistics sector has become a cornerstone of its economic and technological development strategy. The "Digital Azerbaijan 2030" initiative, launched in 2024, aims to integrate advanced technologies such as Artificial Intelligence (AI), Internet of Things (IoT), and Big Data across various sectors, including transportation and logistics.

Strategic infrastructure projects like the Zangezur Corridor, the Trans-Caspian International Transport Route (TITR), and the Baku–Tbilisi–Kars railway are pivotal in enhancing regional connectivity. These corridors facilitate multimodal transportation, linking Azerbaijan to Europe and Asia, and are increasingly supported by digital solutions. Technologies such as GPS/GIS tracking, sensor networks, smart routing systems, and cloud-based logistics platforms are being implemented to improve cargo flow coordination, security monitoring, and operational efficiency (Ministry of Digital Development and Transport of the Republic of Azerbaijan, 2025).

At the Baku International Sea Trade Port, the "Smart Port Baku" concept exemplifies the application of digital technologies in port operations. The port utilizes RFID tags, IoT devices, and Big Data analytics to monitor cargo movements in real-time, optimizing port operations and minimizing delays (DHL, 2024).

The adoption of AI-driven management technologies has significantly enhanced the safety, energy efficiency, and sustainability of transportation processes. Predictive analytics, risk assessment models, autonomous control systems, and voice authentication technologies are now integral in planning and executing transportation operations across various modes, including air, sea, rail, and road.

Furthermore, the integration of intelligent transport systems (ITS) has improved transparency and coordination across different transport modes. These systems enable seamless multimodal transportation, promote eco-friendly mobility, and facilitate the management of digital services through unified platforms.

In summary, Azerbaijan's commitment to digitalizing its transport and logistics sector not only drives technological innovation but also strengthens its position in global trade networks. The country's strategic initiatives and infrastructure developments are poised to enhance its competitiveness and contribute to sustainable economic growth.

In 2020, the Russian Maritime Register of Shipping approved a set of technical measures for automatic navigation to create a regulatory framework for testing unmanned vessels. As part of this experiment, certain vessels under the Russian flag were permitted to use autonomous navigation systems until 2025. According to the latest information, specialists in this field currently favor a hybrid approach, combining traditional and new ship management systems. In this regard, in the Azerbaijan sector of the Caspian Sea, unmanned autonomous SALVO-type light vessels are already in use, equipped for combating drug trafficking, ensuring security, and protecting the sea's resources (fig. 2).

In recent years, significant achievements have also been made in rail transport in unmanned operation. The first autonomous metro trains were deployed in Kobe, Japan, in 1981, and today such technologies account for approximately 7% of metro networks worldwide. Unlike closed underground lines, the operation of fully autonomous trains in open areas for urban and intercity connections remains in the experimental stage. Major companies such as Deutsche Bahn and SNCF have announced that semi-autonomous and fully autonomous trains will be deployed within the next few years. In 2020, China began operating the world's fastest autonomous high-speed train, capable of reaching 350 km/h (Aliyev et al., 2021).

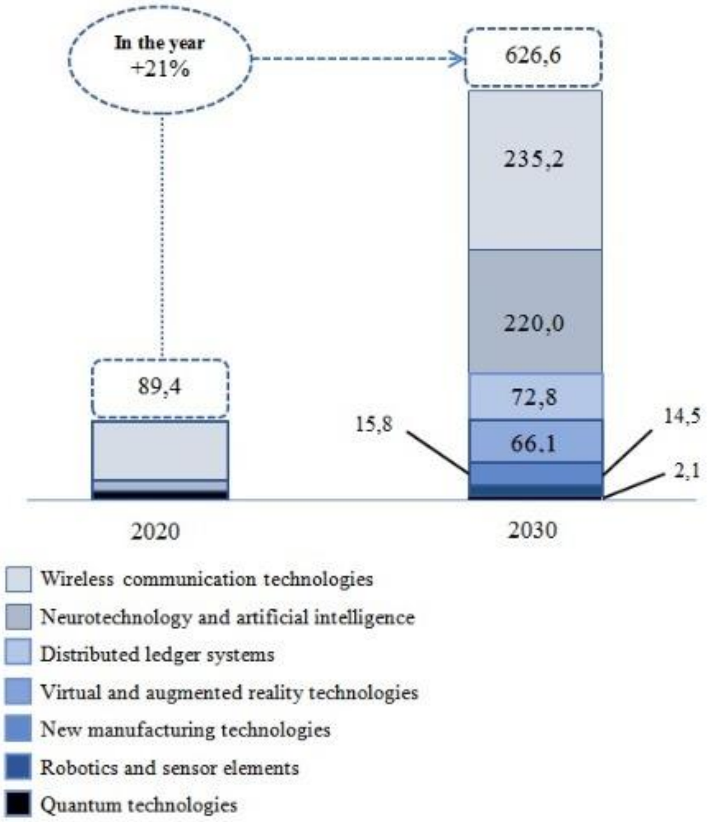

Fig. 2. Potential demand for advanced digital technologies in transport and logistics in 2020-2030, billion rubles (Institute for Statistical Research and Knowledge Economy (ISSEK), 2020)

In the recent past, certain initiatives have been undertaken in the Republic of Azerbaijan to establish networks for such modern high-speed trains (Əhmədov, 2014; Ahmedov, 2014; Ahmadov et al., 2022). Presumably, in order to meet the transportation demand of the population, the operation of autonomous high-speed trains is expected to commence in the future once a suitable railway network is constructed. These trains would provide a convenient and efficient mode of transport, while also being relatively safer in terms of operational and environmental security.

The expansion of shared mobility services (i.e., small-capacity vehicles used alongside other transport modes) into rural areas, in addition to large cities, offers several advantages in terms of enhancing population mobility. Although there are conflicting views regarding the full integration of such shared transport services into a unified urban and regional transport system, the improvement of road infrastructure across all regions makes the implementation of these technologies feasible (Postranskyy & Vovk, 2020). Nevertheless, the COVID-19 pandemic and related restrictions temporarily affected public attitudes toward shared services, particularly in major cities. Currently, in a period of rapid population growth and increasing transport demand, the broad deployment of such prospective technologies remains highly relevant.

3. Results and Discussion

The integration of Artificial Intelligence (AI) and digital technologies into Azerbaijan's transport and logistics systems has evolved from a technological modernization effort to a central component of economic and social transformation. Enhancing the efficiency of modern transport networks, improving service quality, and optimizing resources have become strategic imperatives.

Comparative analyses of Azerbaijan and regional countries indicate a direct positive correlation between the level of digitalization and logistics efficiency. According to the World Bank's 2023 Logistics Performance Index (LPI), the application of digital technologies has led to an average 15–20% improvement in logistics service quality and a 25–30% increase in the agility of transport processes. In Azerbaijan, the rise in digitalization indicators over the past five years has contributed to an increase in the transport sector's share of GDP and a growth in transit cargo volume to over 40 million tons (World Bank, 2023).

One of the most significant components of the digitalization process is the implementation of Intelligent Transport Systems (ITS). Through ITS technologies, real-time route optimization, congestion management, reduced energy consumption, and enhanced safety levels are achieved. In Baku, the "Smart City Transport" program has expanded the capabilities of transport monitoring systems, incorporating AI algorithms for voice control, automatic event detection, and video analytics.

The social and ecological impacts of digitalization are also noteworthy. Extending the operational lifespan of vehicles, reducing fuel consumption, and decreasing carbon emissions demonstrate that AI-based transport models facilitate operations aligned with "green logistics" principles. Azerbaijan plans to double the number of pilot projects for smart logistics centers and energy-efficient transportation models by 2025, directly contributing to the development of the country's ecological transport policy.

The application of AI technologies also enhances the reliability of services. For instance, intelligent maintenance scheduling and predictive technical service systems have reduced the risk of vehicle breakdowns by up to 30% and optimized operating costs by an average of 12–15%. This not only confirms the technical effectiveness but also the economic efficiency of digitalization (fig. 3).

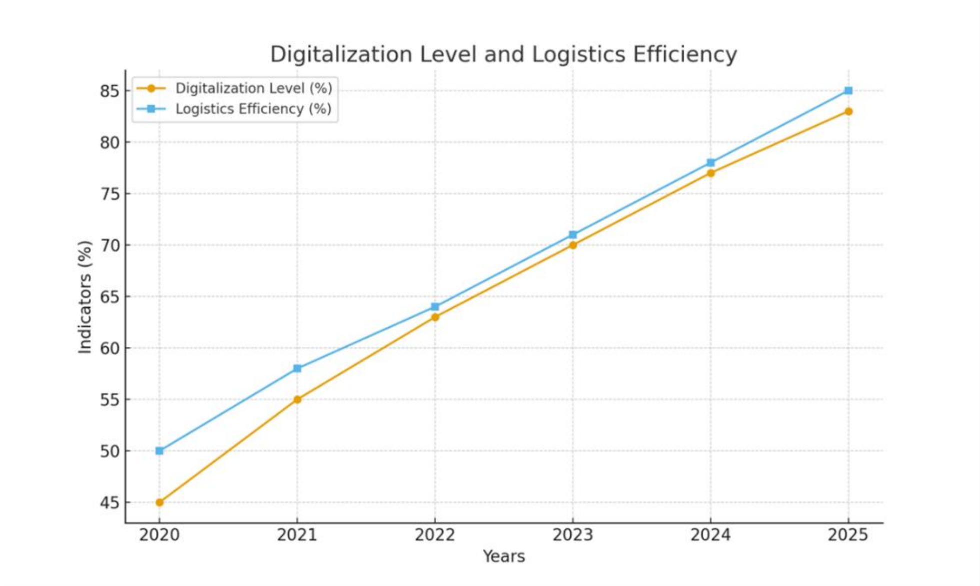

Fig. 3. The impact of the level of application of digital technologies on logistics efficiency (Azerbaijani example) (Source: Authors' own work)

Comparative analyses show that countries like Turkey, Kazakhstan, and the United Arab Emirates have implemented AI-based logistics systems with development dynamics parallel to Azerbaijan's. Specifically, the digitalization of the Zangezur and Trans-Caspian corridors facilitates the integration of multimodal coordination and data exchange platforms among these countries.

For the further digital development of the transport and logistics system, the following measures are deemed appropriate:

- **Integration with international digital platforms:** Establishing a unified information database for regional transport corridors.
- **AI-based forecasting models:** Planning cargo flows, early detection of risks in air and sea transport.
- **Strengthening human resource potential:** Teaching AI and digital logistics modules in transport engineering specialties.

- **Updating the legal and regulatory framework:** Regulating digital document circulation, drone control, and the legal status of autonomous vehicles.
- **Sustainable and ecological transport infrastructure:** Promoting green energy and alternative fuel technologies.

As a result, the integration of digitalization and AI into transport systems not only ensures technological modernization but also enhances service efficiency, safety, and social welfare. Thus, digital transformation in the transport and logistics sector serves as a key driver of Azerbaijan's economic development and the optimization of regional transit connections (Crudu & MoldStud Research Team, 2025).

4. Conclusions

In the present context of rapidly growing population and increasing transport demand, the broad deployment of such prospective technologies is of paramount relevance. In this regard, digitalization and artificial intelligence in the transport sector represent not only technological advancement but also bring about significant social welfare improvements. The implementation of these measures has a high-quality impact on citizens' daily lives and simultaneously contributes to the achievement of sustainable economic development goals.

Research findings demonstrate that the integration of Artificial Intelligence (AI) and digital technologies into transport-logistics systems plays a fundamental role in enhancing efficiency, improving service quality, and optimising resource management. This digital transformation extends beyond mere technological modernisation to strengthen social, economic and environmental sustainability.

Key findings:

1. Digitalisation and efficiency linkage: The application of digital technologies in transport systems increases operational efficiency by approximately 20–30 %, while logistics costs are reduced by around 15 %. This improves both infrastructure utilisation and service quality.
2. Impact of AI-based management systems: AI technologies (predictive analytics, routing optimisation, automated decision support) enable more agile planning of shipments, better risk management and compliance with safety indicators.
3. Regional significance of digital integration: Digital ecosystems created under projects such as the Zangezur Corridor, the Trans-Caspian International Transport Route and the Baku–Tbilisi–Kars railway accelerate Azerbaijan's emergence as an international logistics hub. This integration strengthens coordination of both intra-regional and trans-continental transport links.
4. Ecological and social outcomes: Digital transport systems enhance energy efficiency, reduce emissions and facilitate the application of "green logistics" principles. This not only minimises the environmental impact of transport but also improves urban mobility and the quality of life for the population.
5. Change in management and decision-making culture: The integration of information technologies has shifted transport management toward a data-driven decision-making model, enabling rapid coordination, transparency in reporting and novel approaches to innovation.

Future research and development directions:

- Quantum computing and neuro-technologies: Should be explored as prospective means for high-precision modelling of transport flows and real-time optimisation of decisions.
- Model for unmanned/ autonomous transport vehicles: It is important to develop local frameworks addressing legal, technological and safety aspects of autonomous systems.
- Integration of digital ecosystems: International cooperation should be expanded in order to increase the effectiveness of data-exchange hubs across regional countries.
- Human resource development: Training specialists in AI, data analytics and logistics technologies is a key condition for future success.

In conclusion, this research proves that the integration of AI and digital technologies into transport-logistics systems offers Azerbaijan not only technological renewal, but also strategic advantages in terms of economic sustainability, social welfare and regional leadership.

Abbreviations

5G : Fifth generation

WANs : Wide Area Networks

V2X : Vehicle-to-Everything

WLAN : Wireless Local Area Network

PAN : Personal Area Networks

RFID : Radio-Frequency Identification

WMS : Warehouse Management Systems

SCT : Satellite Communication Technologies

VR/AR : Virtual and Augmented Reality

UX : User experience

MaaS : Mobility-as-a-Service

5PL : Fifth-Party Logistics

UAVs : Unmanned Aerial Vehicles

DWT : Dead Weight Tonnage

IEA : International Energy Agency

IMO : International Maritime Organization

IP : Improvement Potential

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Research Article

Multi-Level Design Space for the Aircraft Exposure Assessment on Environment by Concerting Vehicle-Airport-Fleet Operational Scenarios

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Abstract

A multi-discipline design optimization approach is used by aircraft manufacturers to provide the necessary aircraft performances at conceptual design stage. The concept of the reference aircraft is fundamental to show the achievements in baseline aircraft design, their efficiency to solve the environmental problems. Aircraft noise (AN), engine emission and fuel consumption reduction at source by new technology implementation in aircraft design is a strategic element of the environment protection management in aviation sector, their stepwise development provides closer distances of the protection zone's boundaries between the runways/flight paths and residential areas in vicinity of the airport. In grounding the necessary noise reduction technology for baseline aircraft design its acoustic efficiency should be assessed for appropriate AN standard limits in accordance with ICAO certification procedures, for the single flight event at departure/arrival stages in airport, in overall airport traffic scenario and at least regionally/globally. All of them must show that AN exposure continues to be the not-growing and ICAO Balanced Approach is still feasible for effective AN exposure and impact management. For fuel burn and aircraft engine emission besides the certification requirements the net-zero CO_2 emission for the air traffic should be confirmed. The approach to coordinate the multi-factor exposure assessment at Vehicle-Airport-Fleet scenarios is presented and recommended for the usage in effective implementation of the reduction technologies in aircraft designs. The approach starts at new aircraft design stage, but it is fully connected with expected operational and maintenance performances influencing the exposure levels on environment.

1. Introduction

Designing a new aircraft is an optimization process that encompasses several disciplines that affect the aircraft's performance during operation and maintenance. The aviation industry needs a set of tools for multi-discipline design optimization (MDO) that would provide designers with the means to further improve the aircraft performance of already mature solutions (Park, 2007). The new aircraft design must show that its performances in operation and maintenance confirm airworthiness standards and/or specifications like (EASA, 2023), including the environmental factors (EASA, 2025; ICAO, 2019a). The environmental impact is an aspect which is increasingly being considered in the development of aerial vehicle applications (Papageorgiou et al., 2018), including aircraft noise (AN) (EASA, 2021).

For the past two decades, ACARE - as an Advisory Council for Aviation Research and innovation in Europe - has been addressing strategic policy issues in the European aviation sector based on open discussion and transparent consensus in decision-making, especially in the areas of safety and environmental protection. The EU Green Deal Directive has introduced radically new priorities for the whole EU transportation sector (European Commission, 2021). According to the latest ACARE policy paper (ACARE, 2022), by 2050, 75% of the European regional and short- and medium-range (SMR) aircraft fleet will consist of new aircraft, which are due to enter service from 2035, largely aimed at addressing greenhouse gas (GHG), mainly CO_2, emissions in the aviation sector.

In short- and mid- terms, mainly till the 2035, the contribution to EU FIT-55% program must be provided comparing with the reference year 1990, when the air traffic was much less but fuel consumption and engine emission by aircraft were quite big. The ICAO requirements to aircraft fuel burn and CO_2 emission were absent during that period, like the newish standard limits for the local air quality (LAQ), especially the new limits for the particles (PM) defined by (ICAO, 2019a) for their number and mass. The latest CAEP/13 meeting adopted the new limits for the fuel burn and CO_2 emission, which is 10% stricter compared with the previous. Because of joint stringency investigation of fuel burn/CO_2 emission and noise was implemented the new limits for aircraft noise have been adopted with higher priority for fuel burn and less for the noise performances of the new aircraft, which must start to operate after 2029 (ICAO, 2025).

Regarding aircraft noise (AN) by ACARE vision in 2050, aircraft should deliver a 65% reduction in perceived noise emissions per operation compared to a 2000 reference aircraft – this should be achieved through noise reduction technologies (NRT) in aircraft design, air traffic management (ATM) improvements and operational noise abatement procedures (NAP). As a medium-term goal (by 2035), 'Fly the green deal' (ACARE, 2022) considers the possibility of no population increase within the Lnight=50 dB contour relative to 2019 baseline, as well as no existing population within the Lnight=50 dB contour without noise reduction measures, as well as no population increase within the LDEN=65 dB contour, as well as no existing population within the LDEN=65 dB contour without noise reduction measures.

Thus, the ACARE goals are defined as for the aircraft design and its operational performances directy, so as for the airport exposure by noise on the community. Main accent in short- and mid- term period is done on land use management principles (ACARE, 2022), applied for each airport region in Europe – regional or hub, especially if these airports are with eliminated by noise capacity. In this case, even non-acoustic factors, their role through communication and community involvement, play radically important aspects of the impact of noise on humans, influencing the stability or even reduction of the proportion of the population irritated by noise (Graeme et al., 2020). Such a compromise solution is clear if to take in mind the latest results of the IPCC scientific reports and Long-Term Aspirational Goal (LTAG) of the ICAO to support the elimination of the atmosphere temperature rise not higher than 1.5 degrees. These IPCC and ICAO priorities are the basis for European regional directives and programs, so as for the aviation sectorial program Clean Aviation (Clean Aviation, 2024).

Today the AN exposure around the airports is accurately defined by calculation (ICAO, 2018) for the current and future air traffic scenarios (Fleming et al., 2022) and by noise monitoring directly in situ (Asensio et al., 2012). In principle, calculations and measurements complement each other (Zaporozhets, 2025), solving its own specific problems (Zaporozhets et al., 2011), but their synergy in airport management can significantly increase the effectiveness of noise exposure reduction, and accordingly more effectively regulate its exposure and impact, especially in noise-sensitive areas. The assessment of the AN exposure of current and future air traffic scenarios requires fleet-level studies also where variables such as air traffic trend, fleet composition, available noise reduction technology options, and rate of penetration of novel aircraft into the scenario are considered (Fleming et al., 2011). So, the multi-level assessment of the new aircraft designs or of any NRT is looking obligatory procedure today (Delfs et al., 2018) before their implementation into practice.

The EU EFACA project shoud elaborate TRL3 demonstrations of technologies relevant to the greening of aviation (Dmytriyev et al., 2025) and preliminary designs of regional hybrid-electric (Fil et al., 2025a) and liquid hydrogen fuelled (Fil et al., 2025b) aircraft. Priorities in their designs are predefined by current global ICAO (ICAO, 2025) and regional EU policies (European Commission, 2021). The noise performances are considered as interfering with GHG and LAQ emission of the aircraft, somewhere being in trade-off compromise with them, like it was during the dual standard setting to noise and CO_2 aircraft emission. Such dual standard setting process requires deep coordination across involved working groups to guide the technical steps of this integrated standard setting process along the compromise solution between the priorities. A specific system approach and calculation platform are designed within the EFACA project to look on and solve the interfering priorities at three shown above levels of aircraft noise assessment – single aircraft flight event, airport traffic and fleet traffic scenarios.

2. AN assessment and management – a multi-level approach

Reducing the negative impacts on communities of the environmental noise exposure is one of the key objectives under the EU's zero pollution action plan (European Environment Agency, 2022). It aims to reduce the number of people chronically disturbed in Europe by noise from transport (by 30% by 2030 compared with 2017), which depends directly on the number of exposed people to noise – a metric normally used to estimate noise exposure inside the communities together with areas of noise contours of significant level (for example, 55dB L_{DEN}). Fig. 1 shows an example of noise contours for an airport (one of the main regional airports in Poland, where air traffic is growing faster than the EU average), which are used also for the definition of AN zones (ANZ) to eliminate its exposure on population. The L_{DEN} index (Fig. 1(a)) and night equivalent noise level L_{Night} (Fig. 1(b)) contours for current and forecasted traffic scenarios are compared with the ANZ boundaries (shown separately for this airport in Fig. 2), adopted at the legislative level (Sejmik Województwa Pomorskiego, 2016) for the airport under consideration to show and manage the compatibility of the airport (aircraft fleet and traffic) with nearby communities, defined by the AN protection requirements.

a) b)

Fig. 1. Calculated AN L_{DEN} (a) and L_{Night} (b) contours for current airport scenario, compared with the ANZ boundaries (Source: Authors' own work)

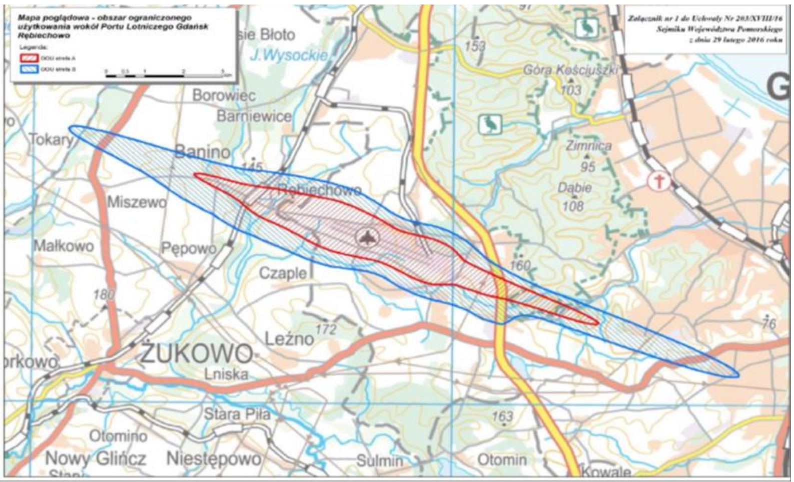


Fig. 2. AN zones' boundaries for the population protection from noise exposure adopted by legislation (Sejmik Województwa Pomorskiego, 2016)

Projections of population growth and transport activity, including the aviation, are (or should be) considered in combination with implementation of the protection measures in all expected scenarios within EU boundaries, including optimistic for aviation sector. Among them, the implementation of the new quiet and less energy consuming aircraft is considered as a main instrument to contribute to achieving the mid-term European goal (European Environment Agency, 2022) by decreasing the number of exposed and annoyed population by up to 70%. The ICAO uses similar approach for AN exposure assessment – noise contour LDN = 55dBA areas and number of people inside them – to show the relevance of the AN problem and assess the coping capacity of the measures – including standard requirements – trying to manage it. During last two decades the effectiveness of the ICAO efforts, realized through the Balanced Approach (BA) to AN management (ICAO, 2008), allows to stable the values of both metrics: total aircraft noise contour 55 DNL area worldwide is close to 15000 km² at the moment (it was 14400 km² in 2015 and 15200 km² in 2024), exposed number of people is ~30 mln. people (Fleming et al., 2022). The effect depends mostly on new quiet aircraft contribution to the fleet – in USA from 2000 to 2023, AN exposure was reduced by 55 % and stabilized (Fig. 3) while air traffic rose by 33 %. The main contribution to the reduction of AN impact was made in 1998-2002, when the ICAO decision to withdraw aircraft complying with Chapter 2 of Annex 16 was implemented. A similar reduction in AN impact was observed in 2019-2022 due to the reduction in air traffic related to COVID, which returned to pre-crisis levels in 2025.

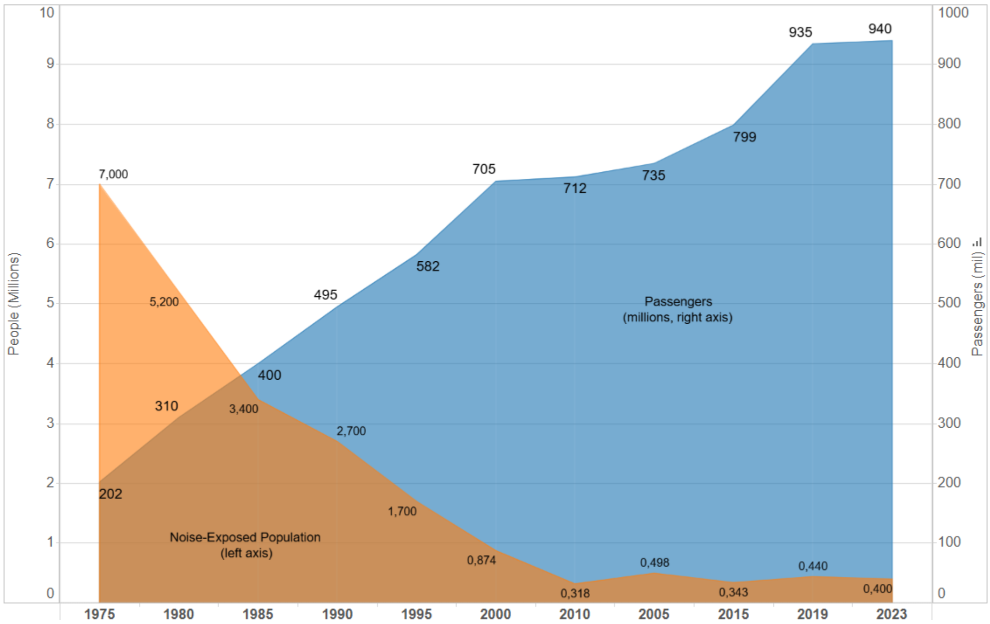


Fig. 3. AN exposure in the USA in comparison with air traffic rise (Airlines for America, 2024)

Looking on the reference aircraft with 2000 technology in its design the Airbus-320ceo is mostly appropriate for SMR flights and 65% of the noise emission reduction means 15 EPNdB reduction of its certification noise level at each point of noise control (ICAO, 2019a). In 2000 the Airbus-320ceo noise was assessed as -5.0 EPNdB to ICAO Chapter 4 cumulative noise limit, further generation aircraft Airbus-320neo achieved -16.0 EPNdB to ICAO Chapter 14 cumulative noise limit (ICAO, 2019b). The Noise-Power-Distance (NPD) data for the A-320 family in ANP data base are changed appropriately, showing the expected decrease of the noise footprint (Fig. 4) for the SMR aircraft more than twice (EASA, 2025): 27 km2 in 2025 (state-of-the-art aircraft design correspondent with adopted in February 2025 new ICAO Chapter 16) via 61 km2 in 2005 (ICAO Chapter 4 aircraft design).

The strategic importance of new quieter aircraft implementation in the operating fleet and air traffic directed by ICAO standard requirements (ICAO, 2019a) is grounded by ICAO/CAEP globally to ensure its feasibility and effectiveness at any airport worldwide (Fleming et al., 2022). A Balanced Approach to AN management at airports (ICAO, 2008) stands on 4 pillars, its effectiveness begins with the ability of the sector to reduce the exposure and impact of aircraft noise by introducing more silent aircraft first of all. This is the main successful driver (without risen AN exposure) of air traffic growth in the future due to the growing demand for air travel. Appropriate noise limits for human activities near airports are determined by the sensitivity of the latter to noise (WHO, 2018) and the compatibility of airport traffic with developing communities around airports (US FAA, 1984). Problems of inappropriate AN exposure and impact on environment are the results of inconsistent solutions in airports, depending mostly on misunderstandings of the subjects that influence the over-limits of the ICAO standard requirements at specific points of noise control in airport surroundings.

ICAO noise limits are the technical requirements to the aircraft, they are defined at specific locations of the departure and arrival flight paths (Fig. 4), which should be realized with specific requirements to flight procedures and environmental (sound propagation) conditions (ICAO, 2019a). Noise measurement conditions during certification tests are also different from AN monitoring in airports (Asensio et al., 2012) in many aspects – emphasizing the misunderstanding between certification and operation measured noise levels. The certification requirements at the sideline and flyover measuring points (Fig. 4) have to be performed for the maximum take-off mass (MTOM) while the operational aircraft mass is usually less, it depends on distance of flight to destination point.

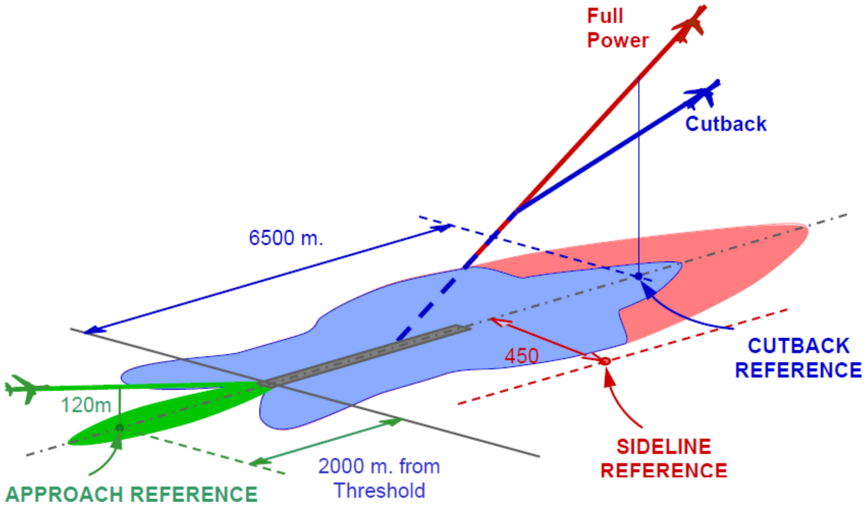


Fig. 4. Aircraft noise footprint and ICAO certification points for departure and arrival (modified from the (ICAO, 2019a))

The certification for the sideline measuring point has to be performed for full take-off thrust and the reduced thrust (engine cut-off) for the flyover point to the value providing the safe climbing of the aircraft during departure (ICAO, 2019a), which is much different from normal climbing procedure in usual operation. For example, for the two-engine aircraft safe climbing gradient should be not less than 3% and flight velocity – not less than V2+20 km/hour, where V2 is a safe velocity for the aerodynamic configuration of the aircraft at take-off, they both provide maximum possible engine cut-off during certification trials and minimum noise level at flyover measurement point. In operational conditions the variation of the aerodynamic configuration (high-lift devices of the wing), flight velocity and operational modes of the engine within the safety limitations is quite big and may differ significantly from the certification. Thus, the comparisons of the monitored noise levels with measured at certification trials must calculate the differences due to these differences, so as the differences changes of monitoring locations relatively the certification points.

Implementing the ICAO methodology, existing AN calculation tools (Zaporozhets & Levchenko, 2021) can fairly accurately estimate the distribution of AN exposure around flight paths, which is required to confirm the ANZ boundaries around the airport, first of all. The current methodology is recommended for equivalent noise levels (ICAO, 2018), which dependent of duration of their equivalence and correlated better with human annoyance by noise (WHO, 2018), and less appropriate for temporally varied noise levels at any specific point of interest because of equivalence averaging of their values. Using a statistical classification process, the commercial aircraft fleet is reduced to four representative-in-class aircraft (Torija & Self, 2018) on the basis of aircraft design and flight performances, noise and engine exhaust emissions. They are also selected to be used as baseline cases for the high-level assessment of the environmental benefit of novel aircraft technologies, in particular specific NRT. With relatively minor decrease in accuracy of noise assessment for the traffic scenario (<5%) a reduction of computational time is achieved essentially when the whole aircraft fleet is replaced with the four representative aircraft – the approach is used by expert analysis in CAEP (ICAO, 2019b).

The equivalent noise levels like L_{Aeq} or combined of them noise indexes L_{DEN}, used for the strategic impact assessment (Torija et al., 2018), definition of ANZ boundaries and community annoyance/impact assessment, are different from sound exposure levels *SEL* or *EPNL* by a number of flight event n contributing to air traffic in airport flight scenario and duration T of their equivalence:

$$L_{Aeq} = SEL - 10 \lg T + 10 \lg n \quad (1)$$

where T is a temporal interval in seconds to which L_{Aeq} or L_{DEN} should be assessed (duration of the equivalence), n – number of single events with sound exposure level SEL. All the levels are defined in dBA except the EPNL, EPNdB. Sound exposure of single flight noise event depends on location and conditions of exposure determination. Here in formula (1) the value of SEL is defined for determining type of the aircraft in scenario under consideration, its flight and engine operation modes. The equivalent level L_{Aeq} is simply a summa of all single event exposures averaged by duration of their supervising at the point of consideration, sometimes including the penalty if supervision (during the equivalence duration) covers the sensitive to noise period of the day like a penalty 10 dBA is given to events that occur during the night time.

AN levels EPNL, measured or calculated during the certification procedures, represent only the point-located noise exposure from the aircraft during the departure and arrival – a noise footprint for the landing-take off (LTO) is a better metric to describe the AN exposure of any aircraft type in total or by flight stage. The EPNL and SEL at certification points correlate well with noise footprints (contours), so if the effect was shown by certification trials the correspondent effect should be expected for the AN footprint. An analytical basis for a trade-off relationship between certification noise levels EPNL and noise contour areas for departure and arrival operations was developed in (Powell, 2003). In (Zaporozhets et al., 2011) this approach was expanded to wider operational conditions than defined by certification procedures to show better correspondence between the certified levels and noise footprints in usual aircraft operation. In (Zaporozhets et al., 2022) it was described how expand the approach to airport noise scenario (footprint) assessment: based on LTO exposure level footprint to define the airport noise footprint bounded by L_{AEq} or L_{DEN} indices. With quieter determining aircraft in a fleet of the scenario under consideration the dominance of the single flight noise exposure contour may not be diminished by noise equivalent contour. The following strengthening of noise requirements for the aircraft in design may provide the conditions of disappearing the single event AN contours (footprints) with sufficient for analysis and management levels (L_{Amax} = 75 dBA for the night and 85 dBA for the day periods), as they are used in Fig. 4 in (Zaporozhets et al., 2022) from consideration in tasks of population exposure by noise.

The ICAO strategic goal in aircraft noise management is formulated globally – to eliminate number of people exposed to AN worldwide – at fleet level. This goal is mostly achieved at current level by two elements of the ICAO BA – AN certification and AN zoning. Other two BA elements are used locally in airports to solve the particular tasks in their vicinity, where the AN levels may violate the limits and eliminate airport operational capacity. A significant reduction in noise emissions at the source and the creation of relatively quiet aircraft have led to the approach of noise contours with levels equal to the established limits for public health protection to the borders of the airport territory. In turn, this allows to bring the activities of the population, including their residence, closer to the airport. But the requirements for determining noise contours and corresponding zones remain unchanged, computational methods are still decisive for them.

3. VALDES simulation platform

Among the basic requirements for the design of new aircraft, in particular the Top Level Aircraft Requirements (TLAR), it is mandatory to comply with the EPNL limits defined by the relevant chapter of Volume 1 of ICAO Annex 16 and the MTOM of the aircraft (ICAO, 2019a). Aircraft Design & Flight Performance Platform (ADFPP) was developed (Fig. 5) as a core element of the wider calculation platform VALDES (Fig. 6) - **V**ehicle-**A**irport-f**L**eet **DES**ign platform - to realize complex environmental assessment and multi-disciplinary optimization (MDO) necessary during the new aircraft design. It must show that new baseline aircraft performances in operation and maintenance confirms airworthiness standards (or certification specifications like (EASA, 2023)) including the environmental factors (EASA, 2025) with AN assessment among them (EASA, 2021), for example, by means of NoiTra and IsoBella calculation tools (Zaporozhets & Tokarev, 1998a; Zaporozhets et al., 2011).

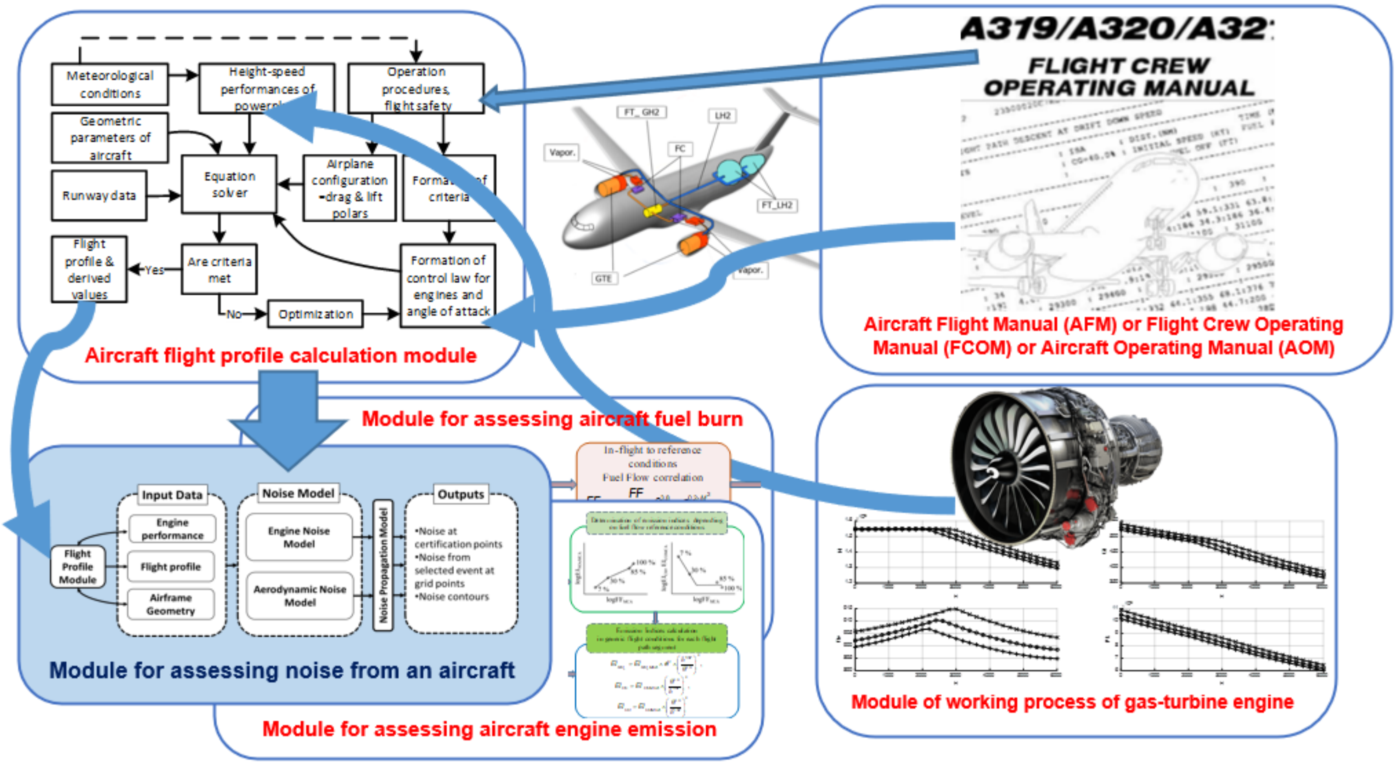


Fig. 5. ADFPP - Aircraft Design & Flight Performance Platform for the complex environmental assessment and multi-disciplinary optimization during the new aircraft design (Source: Authors' own work)

The ADFPP determines aircraft design and flight parameters (Fig. 5) for both baseline and reference aircraft by analyzing their models for aircraft flight and engine operation. In particular, for the liquid hydrogen fuelled aircraft (Fil et al., 2025b) the reference aircraft Airbus-320neo (A320N) was proved. Thus, for modeling the reference aircraft in operation due to TLAR all available technical documents for the A320N and its engine LEAP were used. The core of this approach is the following modules: a module for calculating the working process of gas turbine engines (operation performances of the engine - OpEn module), an in-flight profile calculation module (module New Flight), and the modules for calculating the parameters of environmental exposure defined by the aircraft in flight. An OpEn module realizes the algorithms described in (Yakushenko et al., 2014), a module NewFlight solves flight dynamics equations using convenient interface usually dividing a full flight path on several segments (Makarenko et al., 2024; Synylo et al., 2024).

Flight segments refer to specific portions of the aircraft flight, each with its own unique set of operation procedures (Makarenko et al., 2024). They are predefined by flight safety requirements and accuracy of flight performances. OpEn module calculates the engine operational performances for every flight stage in accordance with required flight parameters. They are quite detailed to engine components – fans, compressors, combustion chamber, turbines and core and bypass exhausts – their air flows, temperatures and pressures are necessary for accurate engine noise, as well for the emission and fuel burn assessment. And the engine thrust and specific fuel burn, which are the inputs for the NewFlight module at every stage of the fight profile.

Currently, the ISA conditions or ISA+10°C – as required by certification standards (ICAO, 2019a) – are considered in OpEn modelling but with availability of the necessary data (for correct OpEn and NewFlight calculations along the TLAR flight conditions) for other meteorological conditions the calculations and analysis are also possible. Because of the highest priority of fuel burn inside the set of environmental factors considered in MDO of new aircraft design a system of equations of aircraft flight is widened by inclusion an equation aircraft flight mass change due to fuel consumption, which is necessary for correct analysis of the aircraft flight profiles due to their TLAR. Thus the ADFPP is similar to aircraft design and flight performances platforms like PRADO/PANAM (Bertsch et al., 2010; Bertsch et al., 2025), FLIGHT (Filippone, 2017), ANOPP2 (Berton et al., 2020) and ASTRID-H (Piccirillo et al., 2022).

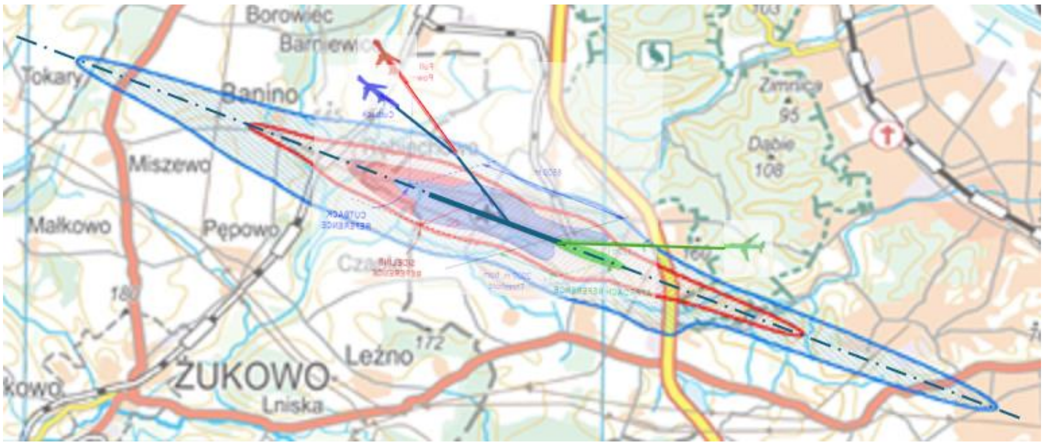


Fig. 6. Modular approach to evaluation of noise, fuel burn and engine emission metrics by ADFPP: combined example for AN exposure assessment is shown by comparison of noise certification, footprint (both shown in Fig. 4) and airport scenario (Fig. 2) platforms (Source: Authors' own work)

Determining a reference (best analogue of the aircraft being designed) aircraft for a new baseline (designed) aircraft allows starting the design process with an existing set of analogue data and to step-by-step compare the required flight characteristics and environmental exposure metrics between the reference and baseline aircraft to show the improved efficiency of the latter compared to the characteristics of the reference aircraft. The novel configuration should not only provide the capability to increase performances and to be economically viable but also reduce fuel consumption, engine emissions and noise essentially to reach the long-term aspirational environmental goals in future (ACARE, 2011). For better understanding of the comparison between the baseline and reference acoustic models the clear difference should be defined between the specific acoustic sources in their aircraft/engine design and how new NRT should be implemented to determine them and make the novel designs quieter. ADFPP provides an iterative process in novel aircraft designing and the design loop should be repeated until the design converges, including that its environmental exposure metrics will be in accordance with required ICAO standard limits.

Platform VALDES (Table 1 and Fig. 6) provides the multi-level assessment and analysis of the environmental exposure and impact of the reference and baseline aircraft to understand the influence of any improvements in their design (or retrofits), operation and maintenance by comparisons with their initial scenarios. Number and scale of the scenarios are dependent of goals of the assessment – if they are defined by strategic values (ICAO, 2022; ACARE, 2011) the scenario scale should be the global aviation system level. The aircraft in its original configuration – the reference aircraft configuration – should be assessed and/or measured in LTO noise trials to describe the initial data set necessary for comparison analysis with baseline concept of new aircraft (Bertsch et al., 2025). The certification flight procedures necessary for the AN exposure evaluation or for the engine emission during the LTO stages of flight are the unified data set for such purposes (Bertsch, 2013; ICAO, 2019a). New conceptual aircraft is usually designed to achieve the far-reaching strategic objectives – currently in Europe defined by the ACARE Strategic Vision (ACARE, 2022), which cannot be accomplished by application of the retrofitting NRT at the level of aircraft components only (Delfs et al., 2018). Their airport (local) and fleet level (global) assessments on a platform of adequate scenario should be provided and platform VALDES serves these purposes.

Table 1. VALDES platform levels of AN assessment and management

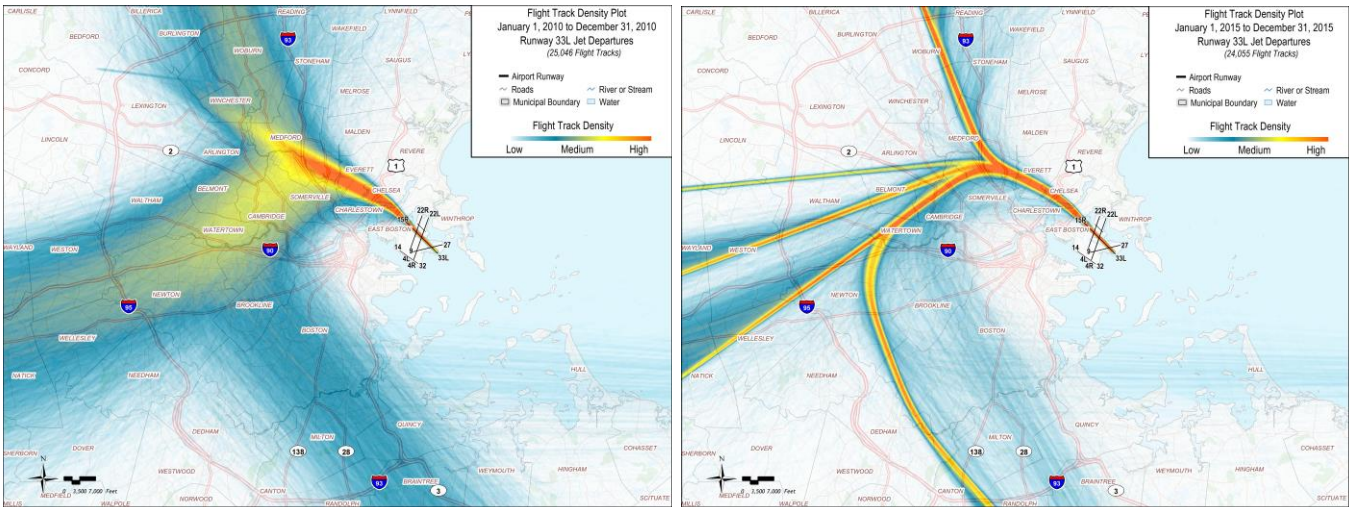
Level	Content	Requirements or recommendations for assessment	Requirements or recommendations for management
0	AN levels at certification points, Fig. 4	ICAO Annex 16, 2019, ICAO Doc 9501, 2018	ICAO Annex 16, 2019, ICAO Doc 9501, 2018
1	LTO AN footprint, Fig. 4	ICAO Doc 10127, 2019	ICAO LTAG, 2022; ACARE, Fly the green deal, 2022
2	Airport noise footprint, Fig. 6	ICAO Doc 9911, 2018	ICAO Doc 9184, 2018
3	Aircraft fleet noise footprint, Fig. 6	ICAO Doc 10127, 2019	ICAO LTAG, 2022; ACARE, Fly the green deal, 2022

AN compatibility of any airport may be considered as broken if the ANZ are defined only by calculation of flight AN exposure, and their measurement results are definitely higher at their borders. If the ANZ distances from the runway axis are smaller due to quieter aircraft implemented in operation such situation is looking obvious, so the calculations of AN contours, which are used for ANZ border defining, should be confirmed by AN level measurements. Accuracy of AN measurements and calculations must be equalized where this is possible in practice because of their simultaneous importance and even synergy effect on accuracy, reliability and efficiency of the AN zoning as an element of ICAO balance approach to AN management in airport. Of course, the data are compared for the same conditions of generation and propagation of AN. If the calculations are performed for ISA conditions, but the measurements are not, then the measurement results should be given under the conditions of the calculations or vice versa.

4. Discussion of AN exposure assessment at certification and airport scenario conditions

The certification levels EPNL are defined for quite specific conditions – flight mass must be MTOM for the aircraft type, atmospheric conditions are equal to ISA at sea level and the temperature 25℃ (ISA+10℃). Their fundamental differences from normal operating conditions are the following: the difference in the values of meteorological parameters both at the level of the ground surface - the runway surface, and at the height of the atmosphere; the difference in the take-off mass from the maximum MTOM, which is mandatory for the conditions of the ICAO standard; the difference in the flight parameters - aerodynamic configuration, flight speed and engine operating mode from the recommended values of the certification procedures. Also, an important element is the so-called piloting culture and the influence of meteorological phenomena, which cause unexpected changes in flight parameters, especially flight speed and engine operating mode, and which may be at the level of flight safety limits.

The noise exposure from each take-off or landing of an aircraft is significantly affected by the presence of so-called corridors at the airport, installed by ATM rules along nominal routes in order to prevent noise exposure above the established limits over the territory of settlements under the flight paths (Fig. 7(a)). Today, the implementation of the principles of performance-based navigation (PBN) allows for maximum localization of noise exposure along nominal routes and corridors limited by boundaries (Fig. 7(b)). PBN can optimize aircraft routes and ATM for a more efficient and sustainable air transportation by permitting aircraft operation on any desired flight path within the coverage of 'ground or space-based navigation aids (GNSS) or within the limits of the capability of self-contained aids, or a combination of these' as predefined by RNAV (Area Navigation) concept (ICAO, 2013a). The PBN can be used for every phase of flight to achieve the sustainability benefits by reducing lateral and vertical clearance within the flight corridors' limits, in particular reducing the noise exposure over the residential areas, for example by implementing the principles of Continuous Climb (ICAO, 2013b) and Descend (ICAO, 2010) Operations.



a) b)

Fig. 7. AN exposure in the vicinity of the Boston airport without (a) and with (b) PBN rules implemented in ATM (Salgueiro et al., 2021)

An approach for significantly reducing the combinatorial nature of fleet-level studies, and for enabling more flexibility to analyze aviation scenarios with multiple technology, operational and ATM options is to reduce the aircraft fleet to a number of representative aircraft categories (Torija & Self, 2017), which is similar with approach used by Independent Expert panel (IEP) in CAEP for the analysis of new available NRT in aviation sector (ICAO, 2019b). In case of AN exposure assessment, the modelling tools due to recommendations of (ICAO, 2018) are highly sensitive to the number of aircraft types in the flight scenario. If the whole aircraft fleet is replaced with the four representative-in-class aircraft for computing AN contours a computational time may be reduced on ~80% with relatively minor decrease in accuracy +5% (Torija et al., 2017). A significant number of airports, particularly single-runway regional airports, have a reduced volume of operations carried out by short-medium-range (SRM) aircraft, such as the Airbus-A320 and/or Boeing-737 families – they dominate the fleet in the scenario and accordingly dominate the AN exposure.

For example, in Gatwick airport the 70% of aircraft flights in 2015 were made by Boeing 737-800. As shown in (Torija & Self, 2017), by selecting the Boeing 737-800 as a representative-in-class aircraft, the relative error of about 5% was observed in airport scenario noise assessment. Using the representative vehicles approach the more robustness demonstrated then for the computation of noise outputs in the set of 94 US airports evaluated due to the better performance of the representative vehicles approach in airports with a low volume of operations. The representative-in-class approach achieved similar high accuracy in evaluating the AN contours even for Heathrow airport scenario (Torija et al., 2017) with all operations more evenly distributed across the 4 aircraft categories: CRJ-900, A321-232, 747-8 and A330-343. All of them are used by ICAO/CAEP IEP for the for AN technology study (ICAO, 2019b), which are necessary for the ICAO standard limits proving procedures by analysis of the forecasted fleet-level noise exposure.

The same approach is realized inside the VALDES platform. The reference aircraft type used for the stepwise improvement by implementing the new NRT in design and achieving the design and flight performances of the baseline aircraft should be used as representative aircraft for the airport and fleet scenarios to show their efficiency at all three levels of the assessment. The layout of the virtual airport at the VALDES platform is used from a real case of a regional airport based on an analysis of the fleet, air traffic and other operational conditions, including flight routes and the effect of the wind rose on the annual distribution of flights between routes, and even the AN zonning principles (first of all their boundaries as shown in Fig. 1 and 2) to be included in overall noise management analysis similar to ICAO BA management. AN exposure analysis in the course of baseline aircraft enables an early identification of dominant acoustical sources in its conceptual design and promising NRT proving the low-noise configuration within given limits and boundaries (Bertsch et al., 2010). AN levels are predicted at separate points around the flight path with semi-empirical parametric noise source models (Zaporozhets & Tokarev, 1998a). Their formulations together with sound propagation effect models enable prediction of the various effects on noise radiation and propagation caused by the variations of aircraft aerodynamic configuration, engine operation, flight velocities and other operating conditions throughout simulated flight operations (Zaporozhets et al., 2011). Such analysis provided the possibilities to define the efficient low-noise flight procedures in any airport scenario, which are essential components of airport noise management programs (Zaporozhets & Tokarev, 1998b). For the reference aircraft the measured AN levels are essential support of its correct noise simulation (Bertsch et al., 2010), which are better compared with calculated levels if the flight path parameters are also supervised in measurements and transferred to calculation scheme with all necessary details of the operating procedure accurately (Zaporozhets et al., 2023, Chyla et al., 2023). Such reference AN model validation is a fundament for baseline AN study accuracy because the uncertainty of calculated results should accompany the modelled EPNL values like for AN certification trials.

Similar AN measurements were conducted for the EU EFACA project in regional Polish airports by means of AN monitoring systems (ANOMS), where the reference aircraft types are operated with essential contribution to traffic and noise exposure (Kazhan et al., 2025). Measurements by ANOMS are different from the AN certification requirement (ICAO, 2019a), their correct comparison with calculation must include the normalization of the measured data with calculated (or wise-versa). The normalization must include the atmosphere and topographical conditions influence, height over the ground surface and location to flight path of the microphone, flight procedure details – which are strictly defined in certification and widely varied in real operation.

The Airbus-320neo are operated in Polish airports, their noise and flight performances are supervised by ANOMS (Table 2, Fig. 8) including flight performances and analyzed for EFACA purposes, their corrected flight performances data are used for NoiTra, IsoBella, INM and AEDT calculations of noise exposure in EFACAport.

Reference aircraft noise exposure model for the novel EFACA hydrogen fueled aircraft – Airbus-320neo powered by CFM LEAP engines – is described in (Michel, 2013). Flight events from the RWY29 for A320N departure noise analysis were measured at NMT 2 (Sosnowa) with averaged sound levels: SEL=81,8 dBA; L_{AMAX} = 74,7 dBA. Flight Noise Test Campaign on A320 was done at Moron Spain, Airforce base in 2004 under the umbrella of the EU project SILENCE(R) (Malbéqui, 2018). Engine noise (Jet & Fan) were found predominant at aircraft take-off, baseline intake (Fig. 9): aircraft speed close to 150 kt; engine power settings between 75 to 95 %; slat / flap deflection at 18°/10°; Landing Gear was in Up position. Their spectra for arrival and departure noise are very similar with measured in Gdansk airport at the NMT 2 as shown in Fig. 9. The calculated spectra are also very close to the measured in certification trials and in operation - they confirm the adequacy and accuracy of the A320N noise model during LTO flight stages. Also the calculated AN levels for the certification conditions are compared well with measured data in trials – AN model for the Airbus-320neo is correct to be reference model for the new baseline LH_2-fueld design.

For the arrival noise the contribution from the dominant acoustic sources is shown – engine fan and wing slats and flaps. To reduce the overall aircraft noise means to implement noise reduction technologies (NRT) to these sources at first stage. These NRT are different, very specific to noise source. For example, the acoustic liners are used for the engine fan noise control, for both tonal and broadband components. For the wing slats and flaps noise the specific NRT exists also, but they may influence the aerodynamic performances of the wing at departure and arrivals, again a compromise solution is needed.

Table 2. Certified and calculated EPNL for A320NEO and Hydrogen at certification points

Aircraft name	Profile	Lateral	Flyover	Approach
EASA Data for A320-271N / PW1127G-JM		92-92.4	79.7-80	86.4-86.9
A320-271N	CONV	91.72	80.93	88.25
A320-271N	HYDRO	92.02	84.35	88.81
A320-271N_NDPs	UCON	89.75	77.94	85.05
A320-271N_NDPs	HYDRO	90.05	81.36	85.31

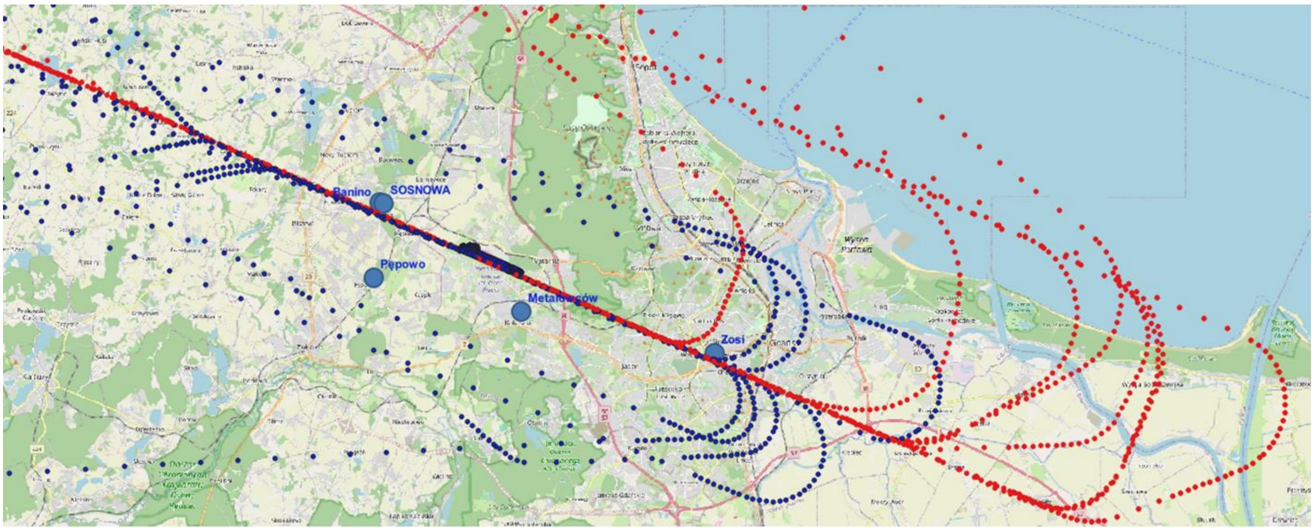


Fig. 8. Measured flight tracks of the arrivals (red) and departures (blue) in Gdansk airport for AN monitoring purposes: point Sosnowa is correspondent with NMT 2 location (Source: Authors' own work)

The NPD data of this aircraft is provided by ANP Data base from EASA for both approach and departure modes, for *SEL* and *EPNL* noise metrics used in LTO noise footprint and airport/fleet scenario assessment. Spectral analysis of the measured data at monitoring terminals and certification flight tests confirms the dominant contribution of engine fan and airframe (landing gear and wing high-lift devices) at departure (Fig. 9) flight stages.

Further noise reduction of the aircraft propulsion noise is expected to reach with UltraFan technology from Rolls-Royce (Rolls-Royce Press Release, 2023) within the EU Clean Aviation UNIFIED project (Flight Test Demonstrator). The expected environmental objectives of the Rolls-Royce UHBR turbofans are the following: ~10% fuel efficiency improvement demonstrated in comparison to 2020 state-of-the-art engines; ~40% reduction of NO_x; ~30% (or ~5 EPNdB at departure certification point) reduction of noise.

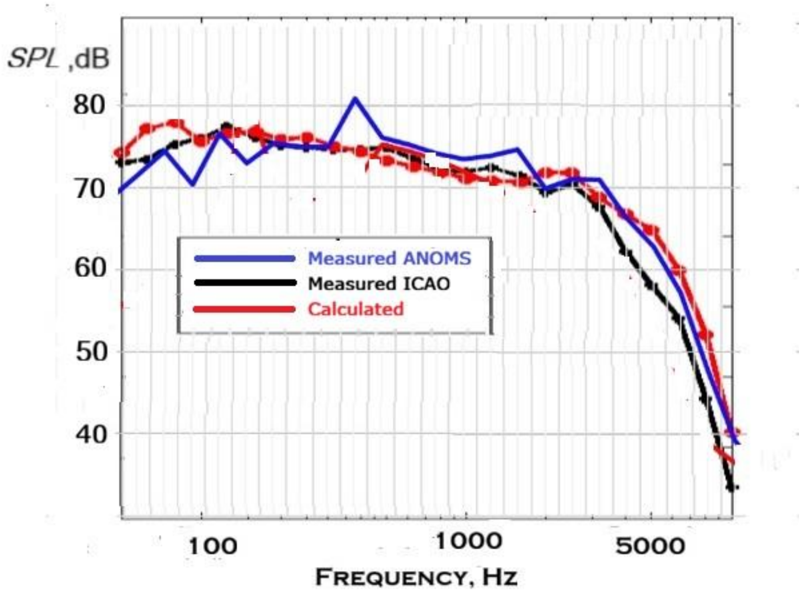


Fig. 9. Comparison between the measured SPL spectra for the Airbus-320neo departures (a) and arrivals (b) at the Gdansk airport by AN monitoring and flight noise trials close to certification requirements (Malbéqui, 2018): calculated spectra for arrivals include the contribution from dominating in aircraft overall SPL spectrum noise sources – engine fan, wing slats and flaps (Source: Authors' own work)

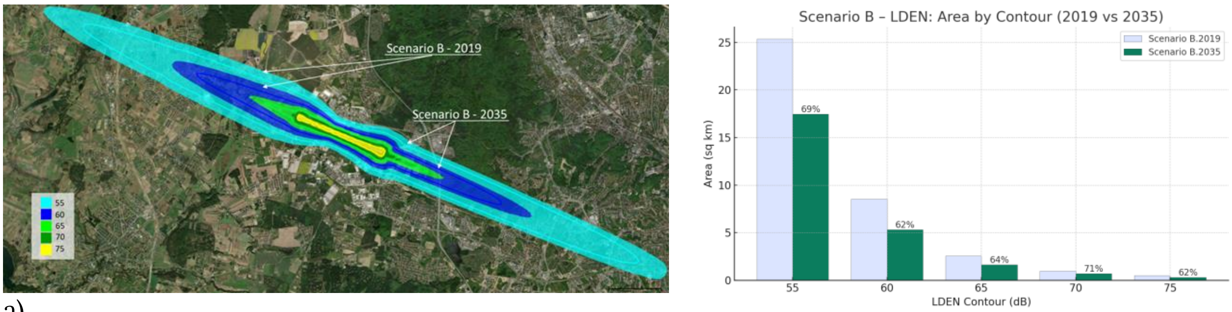
The Rolls-Royce UHBR turbofans are expected to be available in a few years for two most important aircraft classes – single-aisle narrowbody (for the short and middle rage distances) and two-aisles widebody (for the long-range distances) aircraft (Clean Aviation, 2024). The A321/320neo's (2015-year technology) noise footprint at take-off has been reduced by 50% compared to its predecessor the A321/320ceo (2000-year technology). To reach similar effect in future perspective aircraft with UHBR engines needs for the inclusion of the new NRT airframe designs also because their contribution in overall SPL spectrum at aircraft arrival noise is quite big. It is done at current step of EFACA project for the grounding of the overall noise performances of the LH_2-fuelled aircraft as following: the NPD data of the EFACA LH_2-fuelled aircraft for the departure flight modes are found equal to NPD data of the A320-270N reference aircraft minus 3 EPNdB; and for the arrival NPD data – the NPD data of the A320-270N reference aircraft minus 2 EPNdB (Table 2 data for UCON and HYDRO profiles). They were used for comparison of the regional airport (called EFACAport now) noise exposure for L_{DEN} (Fig. 10(a)) and L_{night} (Fig. 10(b)) in 2019 and 2035 air traffic scenarios as shown in Fig. 10. If the new Rolls-Royce UHBR turbofans will be available, the ACARE mid-term goal for noise will be achieved. All air traffic scenarios for EFACA port are developed according to the current state and forecast data at European regional airports to show the expected changes in AN exposure and to assess the adequacy of NRT applied in new aircraft designs.

5. Conclusions

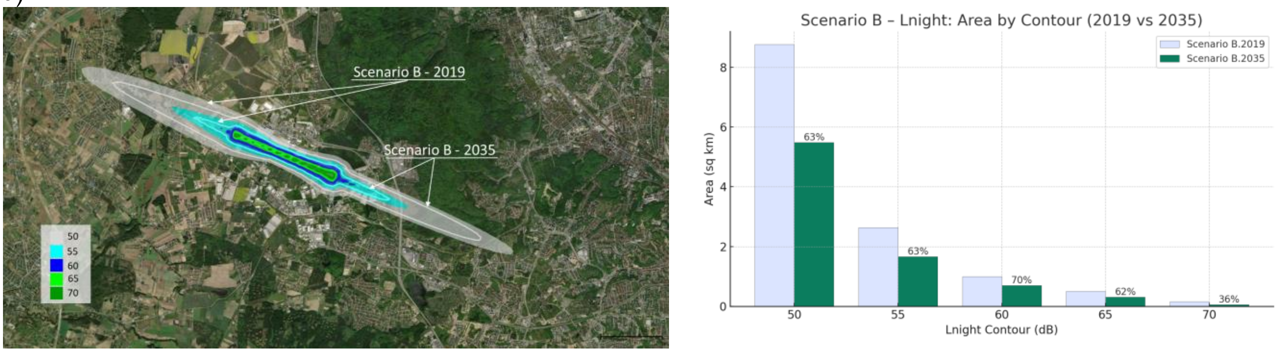
ACARE noise goals (ACARE, 2022) for new aircraft designs are defined for short-term (2030), mid-term (2035), and long-term (2050) perspectives in comparison with aircraft 2000-year reference noise performances and pre-COVID 2019-year traffic and fleet noise scenarios. Reference EFACA aircraft designs and traffic/fleet scenarios are consistent with these ACARE comparison requirements. The ICAO CAEP/13 meeting established a new Chapter 16 noise standard for new subsonic aircraft (ICAO, 2025), making it 6 dB quieter for large aircraft and 2 dB for small aircraft (cumulative EPNL reduction to Chapter 14 is considered), with applicability starting January 1, 2029, for new aircraft type designs. CAEP/13 also recommended a new Chapter 15 noise standard for supersonic aircraft, with a similar applicability date. These standards are part of an integrated ICAO effort to make noise and

CO_2 emissions standards more stringent simultaneously to drive the development of more sustainable aircraft designs – the EFACA aircraft concept also.

The specified operational and noise performances of the aircraft are modelled by means of the forecasting tool – called currently VALDES (**V**ehicle-**A**irport-f**L**eet-**DES**ign) platform or space for calculating the whole flight profile of the aircraft in accordance with the TLAR for reference and baseline aircraft designs (Makarenko et al., 2024). All the modules of the calculation platform were improved further during current stage of the EFACA project research to consider the low-noise and certification flight performances of the baseline aircraft in addition to normal operational conditions. The accuracy and adequacy of the approach were proved by comparison with available engine operational and aircraft flight performances with conventional power plants – for example for the reference aircraft Airbus-320neo.



a)



b)

Fig. 10. Comparison of the EFACAport noise exposure for L_{DEN} (a) and L_{night} (b) in 2019 and 2035 air traffic scenarios (Source: Authors' own work)

The EFACAport is introduced as a virtual EU regional airport in EFACA project and grounded in current aircraft noise exposure studies. Over the 80% of the flights per day are produced by narrowbodies (Airbus-320 and Boeing-737 of various modifications) within the distances covered by TLAR for the EFACA LH_2-fuelled aircraft and with still small and decreasing contribution of the SMR turboprops. The introduction of more advanced ANP (minus 2-3 dB for the NPD data for the departure flight modes) for the LH_2-fuelled aircraft configurations demonstrates a clear reduction in noise contour areas in middle perspective scenario compared to the baseline in 2019 (Fig. 10) and the ACARE mid-term goal for noise will be achieved. In such way the efficiency of the new aircraft designs is proved by noise certification limits and by airport noise scenario, which are required by current ACARE document (ACARE, 2022).

Abbreviations

ACARE : Advisory Council for Aviation Research and Innovation in Europe

ANZ : Aircraft Noise Zones

CAEP : Committee on Aviation and Environmental Protection

EFACA : Environmentally Friendly Aviation for all Classes of Aircraft

ICAO : International Civil Aviation Organization

IPCC : International Panel on Climate Change

LAQ : Local Air Quality

LH_2 : Liquid Hydrogen

LTAG : Long-Term Aspirational Goal

LTO : Long-Term Aspirational Goal

NRT : Noise Reduction Technology

TLAR : Top-Level Aviation Requirements

VALDES : Vehicle-Airport-fLeet-DESign

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Research Article

Comparative Evaluation of PID and Fuzzy Electronic Stability Control via Differential Braking in a Double Lane Change Maneuver

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Abstract

Electronic Stability Control (ESC) is central to preventing loss-of-control crashes, yet its on-road behavior still reflects design trade-offs between rapid error correction and ride comfort. This study builds a high-fidelity ESC evaluation platform by coupling a spatial vibration model with a two-track handling model in a CarSim–MATLAB/Simulink co-simulation. Two representative controllers—a classical PID and a fuzzy-logic design—utilize identical inputs (driver steering angle and measured yaw rate) and a common supervisory layer (a dead-zone around minor errors and left/right brake distribution logic). Interventions are applied as wheel-specific brake pressures; the fuzzy controller employs nine membership sets for yaw rate and steering and five for brake pressure. Performance is assessed in an ISO-style Double Lane Change at 40 km/h using trajectory RRMSE, yaw-rate IAE, control-effort IACA (from brake pressure), and peak lateral acceleration.

Both controllers keep the vehicle close to the reference path (RRMSE < 10%). The PID achieves faster yaw-rate convergence and smaller IAE but at the cost of higher control activity (larger IACA) and more pronounced oscillations, particularly in lateral acceleration. The fuzzy controller yields smoother, step-like brake actions that reduce oscillatory behavior and control effort, while converging more slowly. These head-to-head results quantify a practical trade-off relevant to calibration: prioritize PID when rapid stabilization is paramount, or favor fuzzy logic when comfort and restraint of intervention are critical. The framework provides a reproducible basis for ESC benchmarking and suggests targeted tuning of PID gains and fuzzy rule bases, as well as extensions to advanced controllers (e.g., LQR, MPC), for improved stability and comfort balance.

1. Introduction

Electronic Stability Control (ESC) is a mature technology that prevents loss of control by generating corrective yaw moments-typically via differential braking or individual wheel torque control. In the recent literature, three complementary trends stand out. First, there is continued interest in classical designs because of their transparency and ease of calibration, including PID-based yaw-rate tracking tailored for ESC (Arronte et al., 2023). Second, researchers strive for real-time, implementable solutions that directly act on wheel torques/pressures while estimating or regulating both yaw rate and sideslip (Tristano et al., 2022). Third, more advanced or hybrid formulations aim to balance yaw-rate and sideslip objectives under varying tire–road conditions (Gimondi et al., 2021), or to explicitly cope with delays and uncertainties introduced by sensing, computation, and brake actuators (Wang et al., 2022). These developments are accompanied by broader surveys that contextualize stability control for electrified powertrains and brake-by-wire architectures (Anand & Srinivaas, 2023) and by adaptive schemes oriented toward electric-braking implementations in production-like settings (Hieu, 2024). General overviews of ESC fundamentals remain relevant for framing system objectives and evaluation procedures (Gupta et al., 2020).

Despite this progress, several practical challenges persist. Vehicle lateral dynamics are nonlinear and strongly dependent on tire–road friction, speed, and steering inputs; a controller tuned for one regime may over- or under-actuate in another. Aggressive tracking can quickly reduce yaw-rate error, but may excite oscillations in lateral acceleration and degrade ride comfort; gentler or quantized actions improve comfort but risk slower convergence. Realistic execution involves non-negligible sensing/communication delays, as well as actuator limits/saturation (Wang et al., 2022), and modern ESCs must allocate left/right brake pressure (or wheel torque) to synthesize the desired yaw moment without chattering. Finally, credible assessment requires representative testbeds-e.g., two-track (double-track) vehicle models and standardized maneuvers such as the Double Lane Change (DLC)—and metrics that expose tracking–effort–comfort trade-offs.

Motivated by these gaps, this study builds a co-simulation testbed (CarSim for high-fidelity vehicle dynamics; MATLAB/Simulink for reference generation and control logic) and implements two philosophically different ESC strategies under identical conditions: a PID controller and a fuzzy-logic controller (a common heuristic approach in ESC practice). The vehicle executes an ISO-style DLC at 40 km/h, and performance is evaluated using (i) trajectory-tracking error (e.g., RRMSE), (ii) yaw-rate tracking error (IAE), (iii) control activity based on brake pressure (IACA), and (iv) peak lateral acceleration.

Building on the system descriptions translated earlier, the paper's main contributions are:

- Integrated modeling and execution: a coupled spatial-plus-two-track vehicle model in a CarSim–Simulink co-simulation loop that produces sensor-level signals and wheel-level brake commands suitable for ESC studies.
- Fair, head-to-head comparison: PID (continuous action) and fuzzy logic (step-like action) are embedded in the same supervisory structure (dead-zone around minor errors and left/right brake-distribution logic tied to yaw-rate error sign), enabling an apples-to-apples evaluation.
- Quantitative trade-off evidence: results on RRMSE/IAE/IACA and lateral-acceleration peaks show that PID achieves faster yaw-rate regulation with higher control activity and greater oscillation risk, whereas fuzzy logic yields smoother behavior with lower intervention but slower convergence-findings that align with recent practice-oriented ESC studies.
- Actionable guidance for tuning and extensions: the study identifies areas where PID gains and fuzzy rule bases warrant optimization, pointing to future exploration of adaptive/advanced schemes suited to electric-brake systems and delay-aware designs.

Together, these results provide a concise, evidence-based understanding of how PID and fuzzy controllers behave in an ESC context, offering a reproducible path to extend the analysis to alternative control laws, vehicle platforms, and road conditions.

2. Method

2.1. Vehicle dynamics model

The vehicle dynamics framework comprises 14 degrees of freedom, organized into two submodels: a seven-degree-of-freedom (DOF) spatial (ride) vibration model and a seven-DOF planar (handling) model. These DOFs include six rigid-body motions of the vehicle-translation and rotation about the x, y, and z axes-plus four vertical motions for the suspension units and four wheel-spin states. In the spatial vibration model (Fig. 1), the body is treated as perfectly rigid; springs and dampers are modeled as linear elements; tire resistance is neglected; and the road is assumed to be flat and uniform.

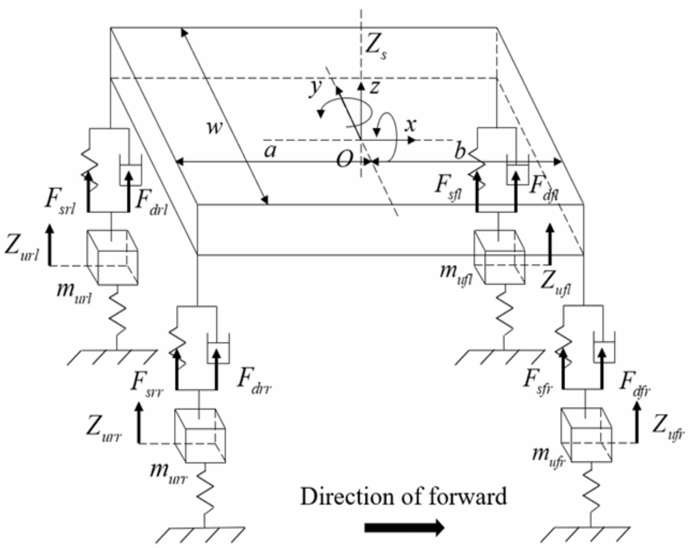


Fig. 1. Dynamic model of Vehicle (Wu et al., 2024)

Fig. 2 presents a double-track (two-track) vehicle model for analyzing the car's motion under these assumptions: elastic tires roll on a rigid roadway and remain in continuous contact; all wheels share the same constant rolling-resistance coefficient; aerodynamic drag and the static load are symmetrically distributed about the vehicle's direction of travel; steering is applied at the front axle with identical steering angles on the two front wheels. The coordinate axes are oriented as shown in the figure. For rotational variables, the positive sense is defined as counterclockwise when viewed from above.

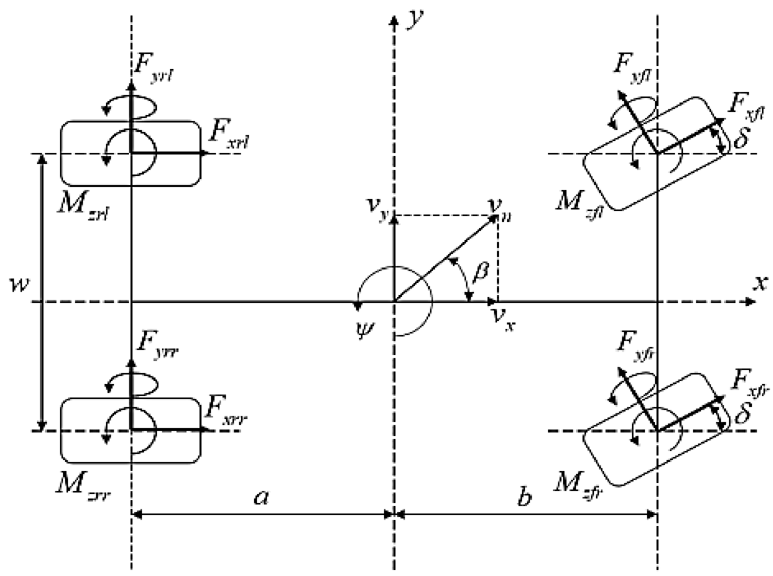


Fig. 2. Dynamic model of two-track motion of a Vehicle (Wu et al., 2024)

Dynamic equations of a Vehicle (Wu et al., 2024)

$$F_{xfl}\cos\delta - F_{yfl}\sin\delta + F_{xfr}\cos\delta - F_{yfr}\sin\delta + F_{xrl} + F_{xrr} = m_t(\dot{v}_x - v_y\dot{\psi}) \quad (1)$$

$$F_{yfl}\cos\delta + F_{xfl}\sin\delta + F_{yfr}\cos\delta + F_{xfr}\sin\delta + F_{yrl} + F_{yrr} = m_t(\dot{v}_y + v_x\dot{\psi}) \quad (2)$$

$$\frac{w}{2}F_{xfl}\cos\delta + \frac{w}{2}F_{xfr}\cos\delta - \frac{w}{2}F_{xrl} + \frac{w}{2}F_{xrr} + \frac{w}{2}F_{yfl}\sin\delta - \frac{w}{2}F_{yfr}\sin\delta + bF_{xfl}\sin\delta + bF_{yfl}\cos\delta + bF_{xfr}\sin\delta + bF_{yfr}\cos\delta - aF_{yrl} - aF_{yrr} + M_{zfl} + M_{zfr} + M_{zrl} + M_{zrr} = I_z\ddot{\psi} \quad (3)$$

Where, F_{sfl}, F_{sfr}, F_{srl}, F_{srr} - elastic force of suspension at left front wheel, right front wheel, left rear wheel and right rear wheel;

F_{dfl}, F_{dfr}, F_{drl}, F_{drr} - suspension damping resistance at the front left wheel, front right wheel, rear left wheel and rear right wheel;

a, b - the distances from the center of gravity to the rear and front axles;

w - the wheelbase of the vehicle;

I_x, I_y - moment of inertia of suspended mass about x-axis and y-axis;

F_{xfl}, F_{xfr}, F_{xrl}, F_{xrr} - force acting in x direction at left front wheel, right front wheel, left rear wheel and right rear wheel;

F_{yfl}, F_{yfr}, F_{yrl}, F_{yrr} - force acting in y direction at left front wheel, right front wheel, left rear wheel and right rear wheel;

m_t - the mass of the vehicle; δ - the steering angle;

F_{tfl}, F_{tfr}, F_{trl}, F_{trr} - elastic force of tire at left front wheel, right front wheel, left rear wheel and right rear wheel;

m_{ufl}, m_{ufr}, m_{url}, m_{urr} - the mass must not be suspended from the front left wheel, front right wheel, rear left wheel and rear right wheel;

Z_{ufl}, Z_{ufr}, Z_{url}, Z_{urr} - displacement of unsprung mass at left front wheel, right front wheel, left rear wheel and right rear wheel;

M_{zfl}, M_{zfr}, M_{zrl}, M_{zrr} - moment around z-axis at left front wheel, right front wheel, left rear wheel and right rear wheel;

The system of equations representing the dynamics of four wheels is as follows:

$$I_w\dot{\omega}_{fl} = M_{dfl} - M_{bfl} - F_{xfl}R_w \quad (4)$$

$$I_w\dot{\omega}_{fr} = M_{dfr} - M_{bfr} - F_{xfr}R_w \quad (5)$$

$$I_w\dot{\omega}_{rl} = M_{drl} - M_{brl} - F_{xrl}R_w \quad (6)$$

$$I_w\dot{\omega}_{rr} = M_{drr} - M_{brr} - F_{xrr}R_w \quad (7)$$

Where, I_w, R_w - moment of inertia and dynamic radius of the wheels;

ω_{fl}, ω_{fr}, ω_{rl}, ω_{rr}; M_{dfl}, M_{dfr}, M_{drl}, M_{drr}; M_{bfl}, M_{bfr}, M_{brl}, M_{brr} - angular velocity, transmitted driving torque and braking torque at the front left wheel, front right wheel, rear left wheel and rear right wheel.

2.2. PID controller synthesis

The PID controller is formulated to minimize the tracking error eee between the target body angular velocity (e.g., yaw rate) and the measured body angular velocity during vehicle operation.

The actual body angular velocity is obtained from the sensor signal (fed by the CarSim vehicle-dynamics simulation block), while the desired body angular velocity is computed from the steering angle and vehicle speed (via the MATLAB/Simulink calculation block) using the following equation:

"ψ" "=" ("δ" "x")/("a+b+" ("m" ("x ") "(a" "C" _"αr" "- b" "C" _"αf" ")")/("2" "C" _"αr" "C" _"αf")) (8)

Where, "C" _"αr" , "C" _"αf" - lateral stiffness of front and rear tires

Fig. 3 illustrates an Electronic Stability Control (ESC) scheme governed by a PID controller. The main elements include the inputs-vehicle speed, steering angle, and measured yaw rate-together with a block that computes the reference (desired) yaw rate and the PID controller itself. A Dead Zone block follows the PID to introduce a small deadband, filtering out minor errors (noise or tiny offsets) so the ESC doesn't intervene unnecessarily. The Product (×) block scales the PID output by a brake-distribution vector, and a downstream Switch selects among three control commands corresponding to different instability scenarios. The switch uses the post–Dead Zone signal as its condition: a positive value biases braking to the left to create a counter-clockwise yaw moment (viewed from above), while a negative value biases braking to the right to generate a clockwise yaw moment.

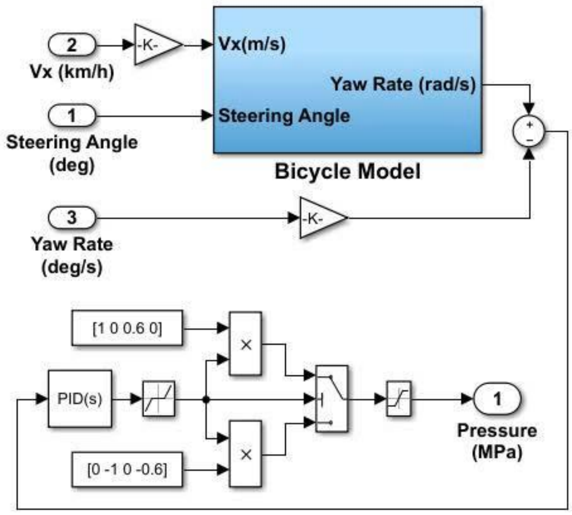


Fig. 3. The Electronic stability control system with a PID controller (Source: Authors' own work)

When the switch input is zero, it selects a zero command, meaning no control action is applied. The PID controller takes the tracking error between the desired and measured body angular velocity (yaw rate) as input and provides a brake-pressure command for each wheel.

The method of synthesizing the parameters of the PID controller is presented in (Nguyen et al., 2025). Applying this method, the parameters of the PID controller are synthesized as follows:

KP = 37; KI = 100; KD = 0.1.

2.3. Fuzzy logic controller design

The study designs the fuzzy controller using MATLAB® (Natick, MA, USA) and the Fuzzy Logic Toolbox™. As a first step, the input and output variables are specified. For the ESC, the inputs are the vehicle's yaw rate and the driver's steering angle (see Fig. 4). The ESC becomes active when the brake pedal is applied and deactivates once the vehicle speed falls below 8 km/h. Its output is the commanded brake pressure, which is fed to the CarSim vehicle-dynamics model. The ESC's fuzzy controller issues commands for both sides of the vehicle, allowing the system to increase brake pressure on either the right or left wheels, depending on the sign of the body's rotational motion.

Both the inputs and the output are modeled using fuzzy membership sets Hi (for i = 1, 2,...). The first input to the fuzzy controller is the vehicle's yaw rate, partitioned into nine fuzzy sets H1–H9 over a universe of discourse from [−4, 4] (Fig. 4(a)). The second input is the steering angle, which likewise employs nine symmetrically arranged sets over [−180 o, 180 o] (Fig. 4(b)). We assume that, in emergency conditions, the driver's steering action is limited to a half-turn of the wheel to either side—an overall range of 360 o. The braking system's maximum pressure in this study is 6.5 MPa. The output variable, brake pressure p (Fig. 4(c)), spans the range [0, 6.5] MPa and is described by five membership sets, H1–H5.

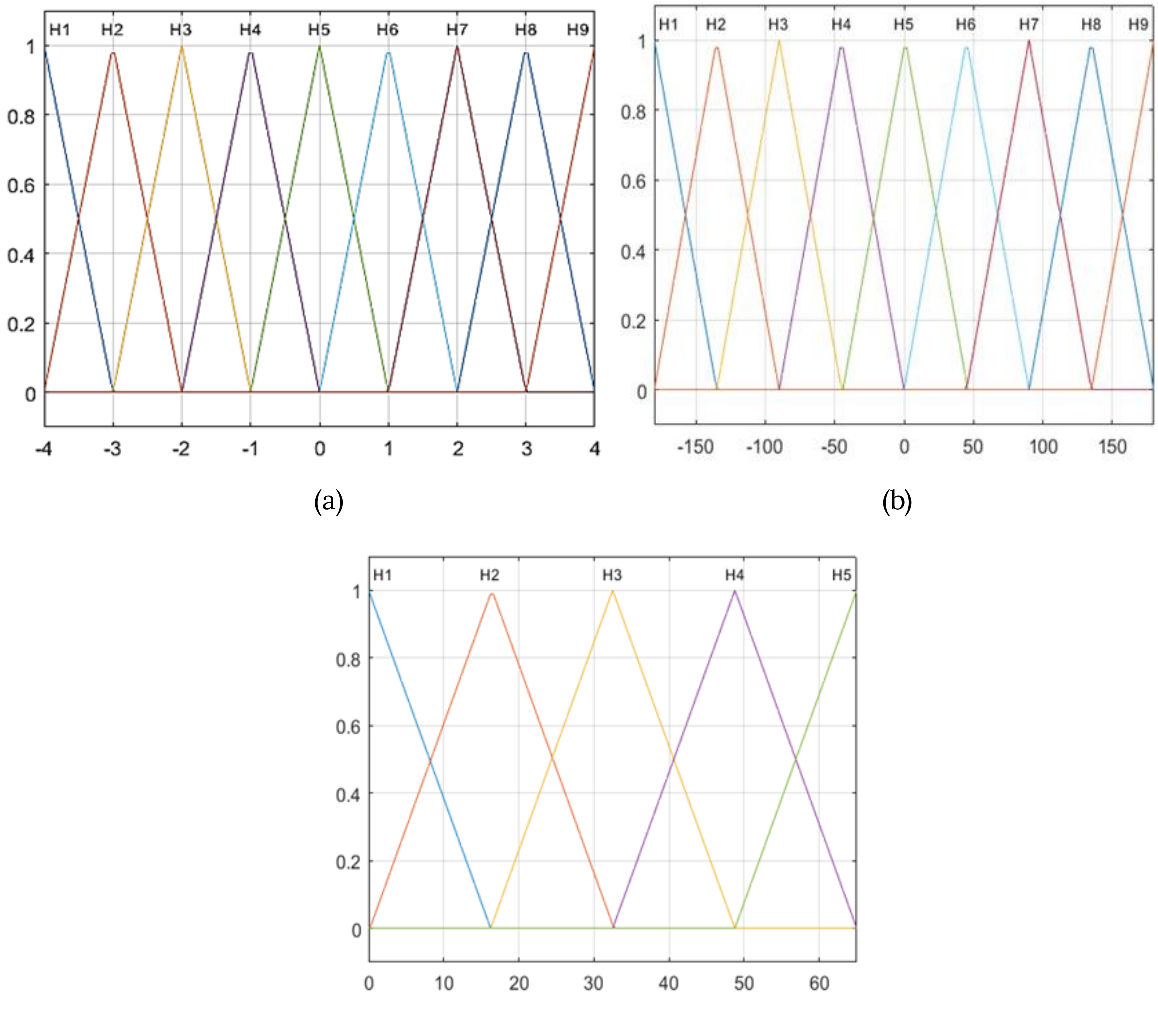


Fig. 4. Input and output of fuzzy logic controller: (a) Input ψ; (b) Input δ; (c) Output p. (Source: Authors' own work)

Fig. 5 illustrates the electronic stability control system with a Fuzzy-Logic Controller. The steering angle (deg) and measured yaw rate (deg/s) are fed into the fuzzy-logic block, which outputs a normalized brake demand. This demand is split into left and right channels and weighted by distribution gains to set wheel-brake pressures. Positive output biases the left side and negative the right, producing a corrective yaw moment; the combined signal yields the commanded brake pressure (MPa).

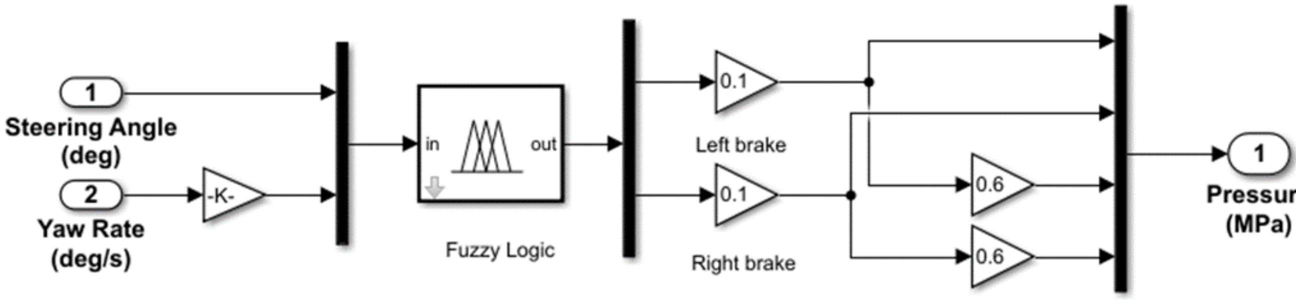


Fig. 5. The Electronic stability control system with a Fuzzy Logic controller (Source: Authors' own work)

3. Results and Discussion

The ESC is evaluated in CarSim using a D-Class SUV. The CarSim vehicle parameters were provided in the Appendix 1. The test maneuver is a double-lane change (Fig. 6) performed at a constant 40 km/h.

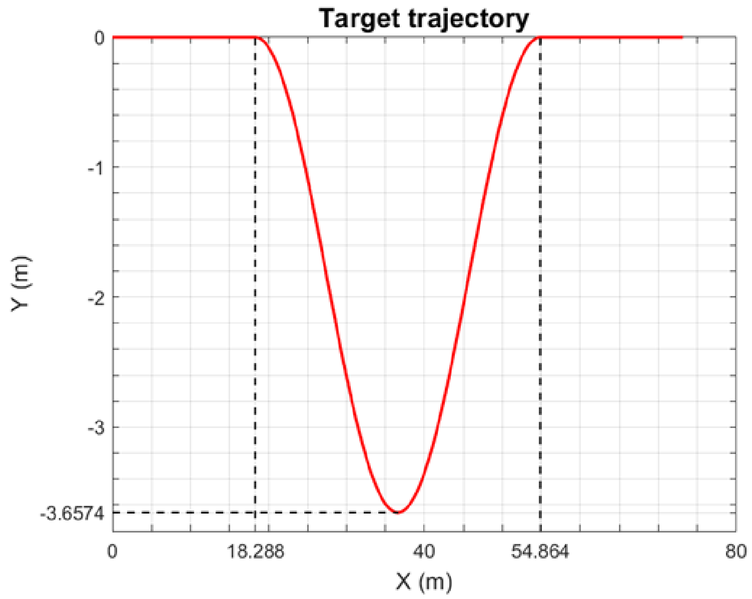


Fig. 6. Dual lane change simulation trajectory (Source: Authors' own work)

Fig. 7 plots the vehicle's center-of-mass path in the double-lane-change test under both PID and fuzzy-logic control. In each case, the trajectory of the vehicle's center of gravity stays close to the desired path, and the vehicle settles stably as it returns to the correct lane.

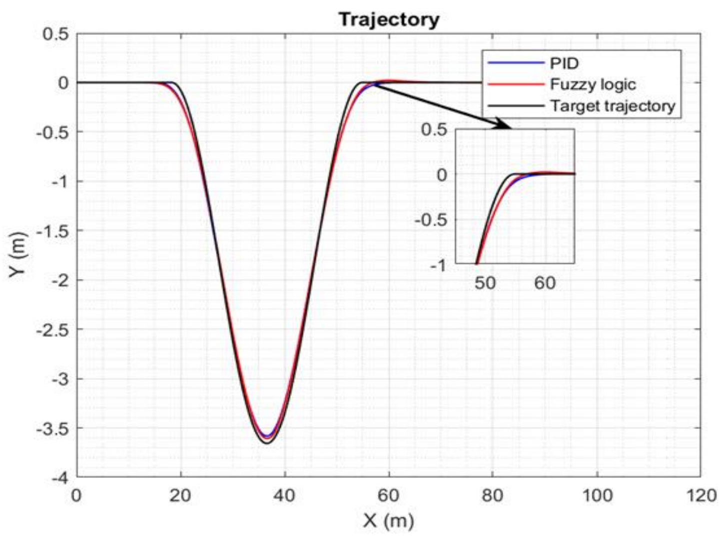


Fig. 7. Trajectory of the vehicle's center of gravity with PID controller and Fuzzy Logic (Source: Authors' own work)

Fig. 8 presents the time histories of steering angle (Fig. 8(a)), lateral acceleration (Fig. 8(b)), vehicle yaw rate (Fig. 8(c)), and yaw-rate tracking error (Fig. 8(d)). When comparing the two controllers, it is clear that the PID controller suppresses the yaw-rate error (Fig. 8(d)) more effectively, bringing the yaw rate (Fig. 8(c)) to its target faster than the fuzzy-logic scheme. However, this improvement comes at a cost: the PID controller produces larger oscillations-especially in lateral acceleration (Fig. 8(b))-which can cause noticeable shake or discomfort for vehicle occupants during the lane-change maneuver.

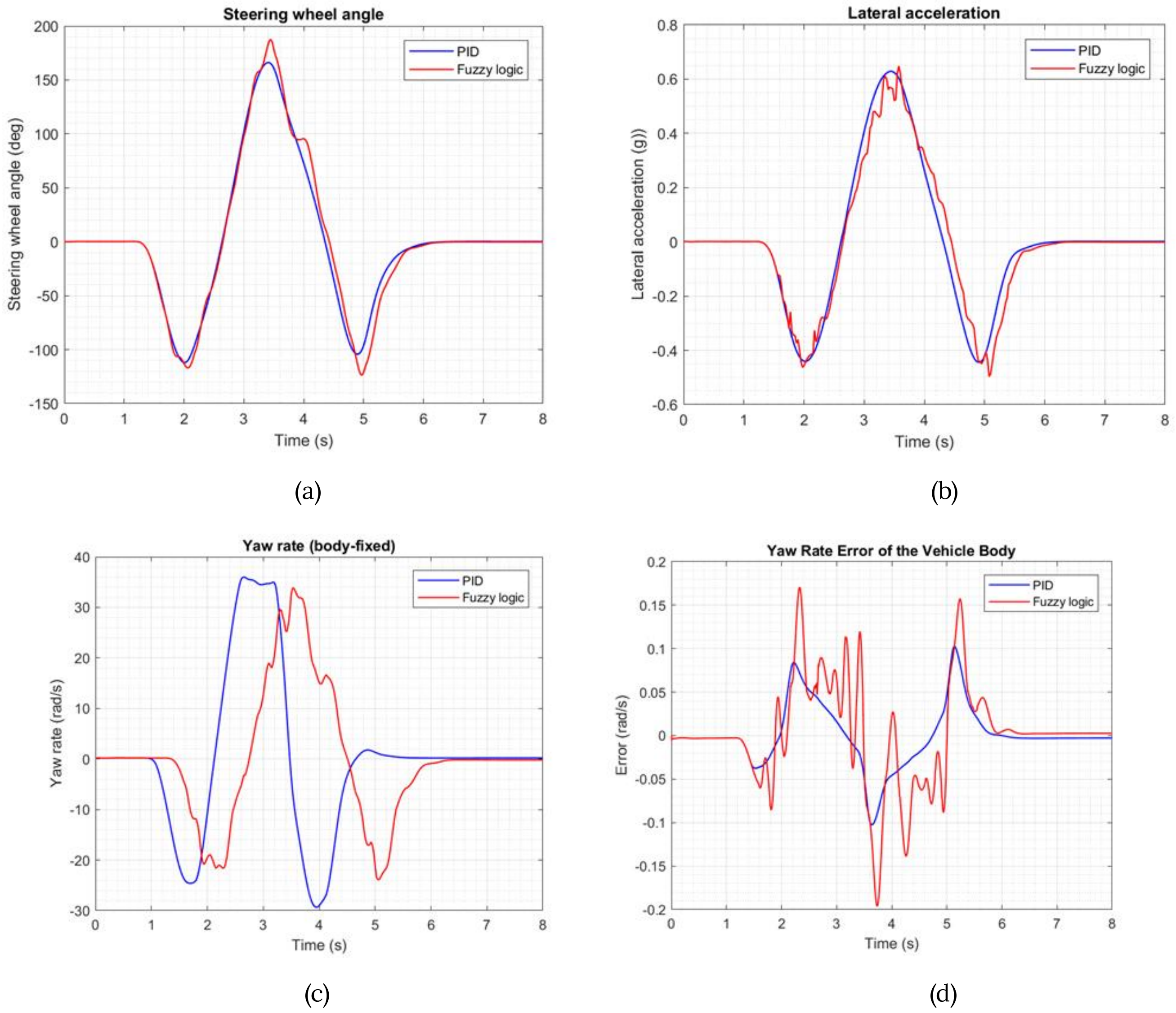
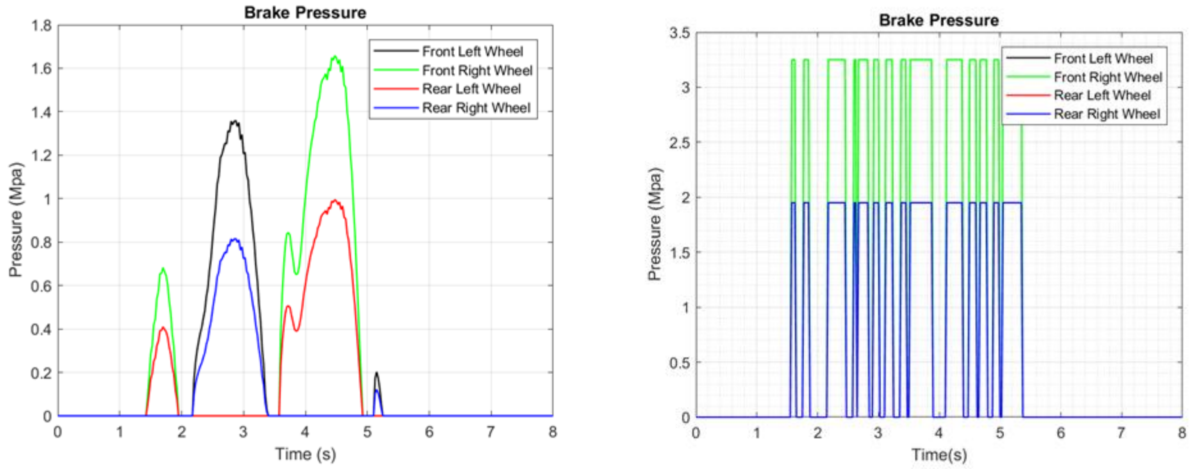


Fig. 8. Simulation results of ESC system with PID controller and Fuzzy logic: (a) Steering angle; (b) Lateral acceleration; (c) Vehicle body angular velocity; (d) Vehicle body angular velocity deviation (Source: Authors' own work)

Fig. 9 shows wheel-brake pressures under PID (Fig. 9(a)) and fuzzy-logic (Fig. 9(b)) controllers. Modulating individual wheel pressure is crucial for balance and stability. If the vehicle tends toward oversteer or understeer, the ESC adjusts pressure at select wheels to generate a corrective yaw moment, guiding the yaw rate toward its reference. This intervention appears as time-varying pressure traces for each wheel in Fig. 9a and 9b.

With the PID controller, brake pressure changes continuously (smooth curves), enabling a rapid response to yaw-rate error but also tending to excite oscillations that can reduce stability—most notably in lateral dynamics. The fuzzy controller, by contrast, issues step-like (quantized) pressure commands that make the braking action more settled and suppress unwanted oscillations, though the response can be slower in some urgent scenarios. Consequently, PID is preferable when fast reaction is the priority.

To compare the two controllers quantitatively, we report the following metrics: the mean-squared relative trajectory error, the integral of absolute error (IAE), the integral of absolute control activity based on brake pressure (IACA), and the peak lateral acceleration. The IAE and IACA values, in particular, indicate the tracking performance and the control effort required by each strategy.



(a) (b)

Fig. 9. Brake pressure on wheels with PID controller (a) and Fuzzy Logic (b). (Source: Authors' own work)

Table 1 shows the comparison of results when simulating the ESC system with PID and Fuzzy Logic controllers.

Table 1. Comparison of results when simulating the ESC system with PID and Fuzzy Logic controllers

	Trajectory	Vehicle body angular velocity deviation	Maximum horizontal acceleration	Brake pressure
	RRMSE	**IAE**	a_{max}	**IACA**
PID controller	0.21%	0.177	0.797	100.40
Fuzzy Logic controller	0.49%	0.304	0.648	120.44

From Table 1, the fuzzy-logic controller intervenes less—indicated by a lower IACA (larger IACA implies greater cumulative intervention (higher control effort))—and therefore shows a larger yaw-rate tracking error, as seen in the higher IAE. This is partly attributable to a rule base that has not been fully optimized. By comparison, the PID controller keeps the yaw-rate error more minor but requires more frequent/stronger actuation.

As a result, the PID case yields a trajectory that follows the reference more closely (lower RRMSE). Even so, both controllers maintain acceptable path adherence relative to the designed trajectory, with RRMSE values of less than 10% in both scenarios.

Why 40 km/h DLC remains non-trivial. The ISO 3888 double-lane-change imposes tight lateral displacement over a short longitudinal distance. Even at 40 km/h, the required curvature produces peak lateral acceleration nearing the tire linearity limit for compact vehicles on dry asphalt. Transient effects—tire relaxation length, yaw inertia, and coupling between longitudinal deceleration from differential braking and front-axle cornering—induce overshoot/undershoot in yaw rate and sideslip. Because ESC authority is realized via brake torque, interventions reduce speed and can shift the vehicle toward understeer during high-demand segments, complicating precise path following.

Expected changes at higher speeds. Small increases in speed materially raise required tire slip angles and the likelihood of local saturation. We therefore expect (i) larger yaw-rate overshoot and longer settling, (ii) higher IACA (more intervention) for both controllers, and (iii) a sharper trade-off between tracking accuracy and comfort (jerk). Controllers that emphasize damping (e.g., fuzzy) should maintain smoother lateral acceleration but will likely require more anticipatory logic or gain/rule scheduling with speed to preserve path accuracy. We have flagged a speed-sweep study (e.g., 40–80 km/h) as future work to quantify these trends.

4. Conclusions

This study develops a vehicle dynamics framework that couples a spatial ride model with a two-track handling model, utilizing a CarSim–Simulink co-simulation setup. On this basis, two ESC strategies—one PID-based and one fuzzy-logic—are designed to modulate brake pressure at individual wheels, aiming to stabilize the vehicle during a 40 km/h double-lane change test. The simulations show that both controllers keep the vehicle on the intended path and maintain stable behavior.

The PID approach achieves tighter yaw-rate tracking by issuing continuously varying brake commands, while the fuzzy controller intervenes more conservatively yet still preserves satisfactory path following. This comparison clarifies the trade-offs and supports the selection of suitable control laws for practical ESC deployment. Both methods are viable, but performance depends on tuning—PID gains and fuzzy linguistic rules should be further optimized. Future directions include systematic gain optimization, refining the fuzzy rule base for the ESC, and assessing alternative or hybrid schemes, such as the Linear Quadratic Regulator (LQR) and Model Predictive Control (MPC), to further improve stability and accuracy.

Abbreviations

ESC : Electronic Stability Control

LQR : Linear Quadratic Regulator

MPC : Model Predictive Control

PID : Proportional-Integral-Derivative

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Appendix 1.

Table A1

Parameters	Value
Mass of Vehicle	1429 kg
Moments of inertia	I_x = 1765 kg.m^2; I_y = 377 kg.m^2; I_z = 1765 kg.m^2
Brake torque/brake pressure ratio	Front wheel: 350 Nm/Mpa; Rear wheel: 200 Nm/Mpa
Length, width, height	4.8 m; 1.8 m; 1.7 m
Engine power	150 kW

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Research Article

Indeterminacy Fuzzy TOPSIS Framework for Unmanned Stealth Aircraft Selection

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Abstract

Decision-making problems in defense procurement are inherently complex due to multiple conflicting criteria, subjective expert judgments, and pervasive uncertainty. To address these challenges, this study proposes a comprehensive indeterminacy fuzzy TOPSIS (IFS–TOPSIS) framework for the selection of unmanned stealth aircraft in strategic national defense missions. Linguistic evaluations provided by multiple decision makers are modeled using indeterminacy fuzzy sets, allowing the simultaneous representation of truth, indeterminacy, and falsity degrees. Decision-maker importance and criterion weights are determined through indeterminacy fuzzy aggregation, while alternative performances are evaluated via a distance-based ideal solution approach.

The proposed framework is applied to a realistic case study involving three unmanned stealth aircraft alternatives evaluated against five key criteria: stealth capability, payload capacity, communication effectiveness, survivability, and affordability. The results identify the second alternative as the most suitable option, exhibiting the closest proximity to the positive ideal solution. Sensitivity analysis confirms the robustness of the ranking under varying criterion weight scenarios, and a comparative analysis demonstrates the superior discrimination capability of the proposed method over classical TOPSIS. The findings indicate that IFS–TOPSIS provides a robust, transparent, and doctrine-aligned decision-support tool for defense system selection under uncertainty.

1. Introduction

Multiple criteria decision-making (MCDM) has become an indispensable analytical paradigm for addressing complex decision problems involving multiple, often conflicting criteria across diverse application domains. Its importance is particularly pronounced in strategic and high-stakes contexts such as defense acquisition, where decisions entail long-term operational, economic, and security implications (Ardil, 2020; Ardil et al., 2019). The selection of an optimal unmanned stealth aircraft represents a quintessential example of such a complex MCDM problem, as it requires the simultaneous evaluation of heterogeneous criteria spanning technical performance, operational effectiveness, and economic feasibility (Shafiee, 2015).

In unmanned stealth aircraft evaluation, decision criteria typically encompass technical attributes such as speed, operational range, payload capacity, stealth capability, survivability, and communication effectiveness, in addition to logistical and economic factors including maintainability and affordability (Ardil, 2023a). The assessment of these criteria is inherently challenging due to uncertainty, incomplete information, and the subjective nature of expert judgment. These difficulties are further exacerbated by dynamic operational environments, rapid technological evolution, and constraints associated with classified or limited intelligence. Consequently, decision-makers often struggle to articulate their preferences using precise numerical values. Under such conditions, conventional MCDM techniques—particularly classical TOPSIS—are limited in their ability to adequately represent imprecision and ambiguity, as they rely on deterministic and crisp input data (Kaya et al., 2019).

To overcome these limitations, a wide range of extensions to classical MCDM methods has been proposed, incorporating alternative uncertainty modeling frameworks (Kacprzak, 2024). Since the introduction of fuzzy set theory by Zadeh (Zadeh, 1965, 1975), fuzzy-based approaches have played a central role in managing vagueness and imprecision in decision-making processes. Subsequent developments, including interval-valued fuzzy sets (Turksen, 1986; Bustince, 2010), intuitionistic fuzzy sets (Atanassov, 1986, 1989; Atanassov & Gargov, 1989), type-2 fuzzy sets (Mizumoto & Tanaka, 1976), and hesitant fuzzy sets (Torra, 2010), have further enriched uncertainty modeling by capturing hesitation and partial knowledge in expert evaluations. More recently, picture fuzzy sets (Cuong, 2014; Dinh & Thao, 2018) and neutrosophic sets (Smarandache, 2019) have gained increasing attention due to their enhanced capability to model indeterminacy, inconsistency, and incomplete information—phenomena that frequently arise in real-world and defense-related decision environments (Kharal, 2014; Abdel-Basset et al., 2022). Unlike neutrosophic formulations that permit unconstrained information components, the bounded structure of the proposed IFS ensures numerical stability and interpretability, which are essential for operational defense acquisition decisions.

Within this evolving methodological landscape, indeterminacy fuzzy sets have emerged as a practical and expressive extension of classical fuzzy models. Unlike vagueness or hesitation addressed in conventional fuzzy extensions, indeterminacy in defense decision-making primarily arises from conflicting expert evidence, incomplete intelligence, and evolving threat assessments. This feature provides a more flexible and realistic framework for representing epistemic uncertainty, particularly in defense-oriented decision problems where expert assessments are often influenced by conflicting technical evidence, insufficient data, and evolving threat perceptions.

Among available MCDM techniques, the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) remains one of the most widely adopted methods due to its conceptual simplicity, intuitive rationale, and computational efficiency (Hwang & Yoon, 1981; Chen, 2000). TOPSIS ranks alternatives based on their relative distances from a positive ideal solution (PIS) and a negative ideal solution (NIS). To improve its applicability in uncertain decision contexts, numerous researchers have extended the classical TOPSIS framework using fuzzy and uncertainty-based representations, including fuzzy TOPSIS (Tüysüz & Kahraman, 2023), intuitionistic fuzzy TOPSIS (Rouyendegh, 2015), interval-valued fuzzy TOPSIS (Lanbaran et al., 2020), hesitant fuzzy TOPSIS (Ambrin et al., 2021), and other generalized fuzzy-based TOPSIS variants (Zeng et al., 2019). However, most existing approaches implicitly treat uncertainty as a byproduct of vagueness or hesitation, without explicitly distinguishing indeterminacy arising from conflicting or insufficient information. This limitation reduces their effectiveness in defense acquisition problems, where indeterminacy often constitutes a dominant source of uncertainty rather than a secondary effect.

In response to these challenges, this study proposes a refined indeterminacy fuzzy set–based TOPSIS (IFS–TOPSIS) framework that explicitly incorporates truth, indeterminacy, and falsity information throughout the decision-making process. By embedding indeterminacy fuzzy representations into the TOPSIS structure, the proposed approach preserves uncertainty semantics across all methodological stages, including decision-maker weighting, aggregation of expert evaluations, normalization, and distance-based ranking. Indeterminacy fuzzy numbers are employed to represent both criterion evaluations and decision-maker importance, thereby capturing the inherent subjectivity, hesitation, and partial confidence present in expert judgments. These assessments are aggregated using an indeterminacy fuzzy weighted averaging (IFWA) operator (Khan et al., 2019), ensuring that heterogeneous expert opinions are combined without information loss.

The methodological novelty of the proposed IFS–TOPSIS framework lies in three key aspects:

(i) the explicit modeling of indeterminacy as an independent informational dimension rather than implicitly absorbing it into membership or non-membership degrees;

(ii) the simultaneous incorporation of indeterminacy fuzzy representations for both criteria evaluations and decision-maker weights; and

(iii) the extension of the classical TOPSIS distance-based ranking mechanism to an indeterminacy fuzzy space.

Compared to classical and existing fuzzy TOPSIS variants, the proposed approach yields more robust, interpretable, and diagnostically informative decision outcomes under uncertainty. Its applicability and effectiveness are demonstrated through a numerical case study focused on unmanned stealth aircraft selection, highlighting its practical relevance for strategic defense decision-support.

The remainder of this paper is organized as follows. Section 2 introduces the fundamental concepts and mathematical properties of indeterminacy fuzzy sets and details the classical TOPSIS and the proposed IFS–TOPSIS methodology. Section 3 presents a numerical application illustrating the effectiveness of the approach in the context of unmanned stealth aircraft selection. Finally, Section 4 concludes the paper by summarizing the main findings, methodological contributions, and potential directions for future research.

2. Methodology

A frequent concern in the fuzzy MCDM literature relates to the conceptual and practical distinction between newly proposed uncertainty frameworks and existing models such as neutrosophic TOPSIS (Bakioğlu, 2025) and picture fuzzy TOPSIS (Jin et al., 2021; Khan et al., 2019). The present study differs from these approaches in several fundamental aspects.

First, unlike neutrosophic TOPSIS, which is often formulated in a highly generalized logical setting and may involve unconstrained truth, indeterminacy, and falsity components, the proposed Indeterminacy Fuzzy Sets (IFS) operate within a strictly bounded and decision-oriented structure. The constraint $0 \leq \mu + \eta + \nu \leq 1$e nsures numerical stability, interpretability, and direct applicability in engineering decision problems, where overly abstract representations may hinder practical adoption.

Second, in comparison with picture fuzzy TOPSIS, indeterminacy in the proposed framework is not treated as a residual or auxiliary membership degree but as an independent and explicitly modeled informational dimension. This distinction is critical in expert-based evaluations where hesitation and incomplete knowledge cannot be adequately captured by positive, neutral, and negative preference degrees alone. As a result, the IFS–TOPSIS framework provides enhanced expressive power while preserving mathematical simplicity.

Third, the novelty of the proposed method lies not only in the uncertainty representation but also in its systematic integration into all stages of the TOPSIS procedure, including decision-maker weighting, criterion aggregation, and distance-based ranking. This end-to-end indeterminacy-aware design distinguishes the approach from many existing fuzzy TOPSIS variants that incorporate uncertainty only at the evaluation stage.

Algorithm. IFS–TOPSIS for Unmanned Stealth Aircraft Selection

Input:

- Set of alternatives $A_i = \{A_1, A_2, \ldots, A_m\}$
- Set of criteria $C_j = \{C_1, C_2, \ldots, C_n\}$
- Set of decision makers $DM_k = \{DM_1, DM_2, \ldots, DM_l\}$
- Linguistic evaluations for criteria and alternatives

Output:

- Ranking of alternatives based on closeness coefficients

2.1. Preliminaries of Indeterminacy Fuzzy Sets (IFS)

Indeterminacy Fuzzy Sets (IFS) extend classical fuzzy constructs by allowing three independent membership degrees: truth (μ), indeterminacy (η), and falsity (v), each bounded in [0,1] and jointly constrained to ensure informational consistency. This tripartite representation enables the explicit modeling of hesitation, conflict, and incomplete knowledge, which are pervasive in expert-based evaluations.

Arithmetic operations, scalar transformations, and aggregation rules defined over indeterminacy fuzzy numbers preserve mathematical closure and interpretability. In particular, distance measures defined in the indeterminacy space provide the foundation for ranking alternatives within IFS-TOPSIS.

Definition 1. (Ardil, 2024a, 2024b) Let X be a universal set. An indeterminacy fuzzy set A on a universe X is an object of the form

$$A = \{< x, \mu_A(x), \eta_A(x), v_A(x) > | \, x \in X\}$$

where the truth-membership function $\mu_A(\mathrm{x})\colon \mathrm{X} \to [0,1]$, the indeterminacy-membership function $\eta_A(\mathrm{x})\colon \mathrm{X} \to [0,1]$, and the falsity-membership function $v_A(\mathrm{x})\colon \mathrm{X} \to [0,1]$ are three maps in X that satisfy the mathematical constraint condition: $0 \leq \mu_A(\mathrm{x}) + \eta_A(\mathrm{x}) + v_A(\mathrm{x}) \leq 1 | \, \mathrm{x} \in \mathrm{X}$.

Geometrically, each element of an indeterminacy fuzzy set can be visualized as a point within a three-dimensional unit cube $[0,1]^3$, defined by the membership coordinates (μ,η,v), which represent the degrees of truth, indeterminacy, and falsity, respectively. The admissible region is bounded by $0 \leq \mu_A(x) + \eta_A(x) + v_A(x) \leq 1$. Points lying on the plane $\mu_A(x) + \eta_A(x) + v_A(x) = 1$ correspond to cases of complete information, whereas points beneath this plane represent partial or uncertain knowledge.

The indeterminacy fuzzy numbers $\mu_A(x)$, $\eta_A(x)$, and $v_A(x)$ represent the degree of truth, indeterminacy, and falsity of element x to the indeterminacy fuzzy set A, respectively.

Definition 2. Let X be a nonempty set and I be the unit interval [0,1]. An indeterminacy fuzzy set A and B of the form, and $A = \{< x, \mu_A(x), \eta_A(x), v_A(x) > | \, x \in X\}$ and $B = \{< x, \mu_B(x), \eta_B(x), v_B(x) > | \, x \in X\}$. Then

$A \subset B$ if and only if for all $x \in X$

$$\mu_A(x) \leq \mu_B(x), \eta_A(x) \leq \eta_B(x)$$

or

$$\eta_A(x) \geq \eta_B(x), v_A(x) \geq v_B(x)$$

$$A^C = \{< x, v_A(x), \eta_A(x), \mu_A(x) > | \, x \in X\}$$

$$A \cup B = \Big\{\big(x, max(\mu_A(x), \mu_B(x)), min(\eta_A(x), \eta_B(x)\big), min(v_A(x), v_B(x)) | x \in X\}$$

$$A \cap B = \{(x, min(\mu_A(x), \mu_B(x)), min(\eta_A(x), \eta_B(x)), max(v_A(x), v_B(x)) | x \in X\}$$

$$A \oplus B = \{(x, \mu_A(x) + \mu_B(x) - \mu_A(x)\mu_B(x), \eta_A(x)\eta_B(x), v_A(x)v_B(x) | x \in X\}$$

$$A \otimes B = \{(x, \mu_A(x)\mu_B(x), \eta_A(x) + \eta_B(x) - \eta_A(x)\eta_B(x), v_A(x) + v_B(x) - v_A(x)v_B(x) | x \in X\}$$

$$O_i^+ = \{< (x, 1,0,0) > | \forall x \in X\}$$

$$O_i^- = \{< (x, 0,0,1) > |\forall x \in X\}$$

Definition 3. The scalar multiplication operation over indeterminacy fuzzy sets A of the universe X is denoted by nA and is defined by

$$nA = \{(x, 1 - (1 - \mu_A(x))^n, (\eta_A(x))^n, (v_A(x))^n | x \in X\}$$

Definition 4. The exponentiation operation over indeterminacy fuzzy sets A of the universe X is denoted by nA and is defined by

$$A^n = \{(x, \mu_A(x))^n, 1 - (1 - \eta_A(x))^n, 1 - (1 - v_A(x))^n | x \in X\}$$

where $n > 0$.

Definition 5. The score *s(A)*, accuracy *h(A)*, and certainty *c(A)* functions for an indeterminacy fuzzy number $A = (\mu, \eta, v)$ are defined as follows:

$$s(A) = \mu_A - v_A$$

$$h(A) = \mu_A + \eta_A + v_A$$

$$c(A) = \mu_A$$

where $s(A) \in [-1,1]$ and $h(A) \in [0,1]$. For any two indeterminacy fuzzy numbers $A = (\mu_A, \eta_A, v_A)$ and $B = (\mu_B, \eta_B, v_B)$

$$if s(A) > s(B), then (A) > (B)$$

$$if s(A) = s(B), then$$
$$i. if h(A) > h(B) \Rightarrow A > B$$
$$ii. if h(A) = h(B), then\ A \approx B$$

Definition 6. A function $d(A, B)$ is called a distance measure between indeterminacy fuzzy numbers (IFNs) if it satisfies the following properties:

P1. $d(A, B) \geq 0$

P2. $d(A, B) = 0$ if and only if $A = B$ for all $A, B \in IFNs$

P3. $d(A, B) = d(B, A)$ (*symmetry*)

P4. For all $A, B, C \in IFNs$,

$$d(A, C) \leq d(A, B) + d(B, C)$$

This is the triangle inequality.

Definition 7. Given two indeterminacy fuzzy numbers $A = (\mu_A, \eta_A, v_A)$ and $B = (\mu_B, \eta_B, v_B)$, the Minkowski distance between A and B is defined as

$$d(A, B) = \left[\frac{1}{3n}\sum_{i=1}^{n}(|(\mu_A(x) - \mu_B(x)|^\gamma + |(\eta_A(x) - \eta_B(x)|^\gamma + |(v_A(x) - v_B(x)|^\gamma)\right]^{1/\gamma}, \gamma \geq 1.$$

where $\gamma \geq 1, \infty$. When $\gamma = 1$, the Minkowski distance degenerates to the Hamming distance. When $\gamma = 2$, the Minkowski distance degenerates to the Euclidean distance. When $\gamma = \infty$, the Minkowski distance degenerates to the Chebyshev distance:

$$d_{\gamma_\infty}(A, B) = max(|\mu_A(x) - \mu_B(x)|, |\eta_A(x) - \eta_B(x)|, |v_A(x) - v_B(x)|)$$

2.2. Classical TOPSIS Method

The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method is a valuable approach to multiple criteria decision-making (MCDM). Developing an effective method for solving MCDM problems remains a challenging task. TOPSIS is one such method that has been developed to address this challenge (Hwang & Yoon, 1981).

In general, an MCDM problem aims to assess and rank alternatives, denoted as A_i based on a set of attributes or criteria, denoted as C_j. Each alternative A_i represents a possible choice for the decision-maker, and the goal is to rank these alternatives in order of preference. Each criterion C_j represents a factor that influences the decision-maker's evaluation and ranking of the alternatives. Furthermore, the relative importance or significance of each criterion C_j is often represented by a weight, denoted as ω_j.

The classical TOPSIS method is a distance-based approach that aims to identify the best alternative by determining which one is farthest from the negative ideal solution and closest to the positive ideal solution. In the classical TOPSIS method, decision-makers express their opinions and evaluations by assigning crisp (i.e., precise) values to the alternatives under each criterion. The five steps of the classical TOPSIS method are outlined below (Hwang & Yoon, 1981):

Step 1: The decision matrix X is normalized.

$$Y = \begin{pmatrix} y_{11} & \cdots & y_{1j} \\ \vdots & \ddots & \vdots \\ y_{i1} & \cdots & y_{ij} \end{pmatrix} \tag{1}$$

where y_{ij} is calculated as:

$$y_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{I} x_{ij}^2}} \tag{2}$$

where, x_{ij} denotes the performance of alternative A_i with respect to criterion C_j.

Step 2: Calculate the weighted normalized decision matrix V.

$$V = \begin{pmatrix} v_{11} & \cdots & v_{1j} \\ \vdots & \ddots & \vdots \\ v_{i1} & \cdots & v_{ij} \end{pmatrix} \tag{3}$$

where $v_{ij} = \omega_j y_{ij}$.

Step 3: Obtain the positive ideal solution A^+ and the negative ideal solution A^-.

$$\begin{aligned} A^+ &= [\, v_1^+, v_2^+, \ldots, v_J^+ \,] \\ A^- &= [\, v_1^-, v_2^-, \ldots, v_J^- \,] \end{aligned} \tag{4}$$

where v_j^+ is given by:

$$v_j^+ = \begin{cases} max\, v_{ij}\,, if\, C_j\ is\ a\ beneficial\ criterion \\ min\, v_{ij}\,, if\ C_j\ is\ a\ non-beneficial\ criterion \end{cases} \tag{5}$$

and v_j^- is given by:

$$v_j^- = \begin{cases} min\, v_{ij}\,, if\, C_j\ is\ a\ beneficial\ criterion \\ max\, v_{ij}\,, if\ C_j\ is\ a\ non-beneficial\ criterion \end{cases} \tag{6}$$

Step 4: Compute the separation measures S_i^+ and S_i^- for each alternative.

$$S_i^+ = \sqrt{\sum_{j=1}^{J} \left(v_{ij} - v_j^+\right)^2} \tag{7}$$

and

$$S_i^- = \sqrt{\sum_{j=1}^{J} \left(v_{ij} - v_j^-\right)^2} \tag{8}$$

Step 5: Determine the closeness coefficient Z_i value for each alternative.

$$Z_i = \frac{S_i^-}{S_i^+ + S_i^-}, 0 \leq Z_i \leq 1 \tag{9}$$

The alternatives A_i are then ranked in descending order based on the calculated Z_i values.

2.3. IFS-TOPSIS Method

The selection of an appropriate distance measure is a critical component of any TOPSIS-based methodology, as it directly influences the discrimination power and stability of the resulting rankings. In this study, an indeterminacy-aware Euclidean distance is employed to measure the separation between alternatives and the ideal solutions.

This choice is motivated by several considerations. First, the Euclidean distance preserves geometric interpretability within the three-dimensional indeterminacy space (μ, η, ν), allowing each alternative to be visualized as a point whose proximity to the ideal solutions is intuitively meaningful. Second, compared with Manhattan or Chebyshev distances, the Euclidean metric provides balanced sensitivity to deviations across all three components, preventing dominance by any single dimension.

Furthermore, the Euclidean distance exhibits desirable computational properties, including numerical stability and scalability, which are essential for large-scale decision problems. Its widespread adoption in classical and fuzzy TOPSIS variants also facilitates methodological comparability, enabling fair benchmarking against existing approaches. These characteristics make the chosen distance measure particularly suitable for high-stakes engineering and defense applications where robustness and transparency are paramount.

The proposed IFS–TOPSIS method follows a structured sequence of steps. First, decision-makers are assigned weights derived from indeterminacy fuzzy assessments of their expertise. Second, criterion weights are aggregated using the IFWA operator. Third, alternative evaluations are aggregated into an indeterminacy fuzzy decision matrix. This matrix is subsequently weighted by the criterion weights to obtain the final decision matrix.

Positive and negative ideal solutions are then defined by accounting for the nature of each criterion (benefit or cost). Separation measures between each alternative and the ideal solutions are computed using an indeterminacy-aware Euclidean distance. Finally, closeness coefficients are derived to rank the alternatives.

This formulation ensures methodological coherence across all stages of the decision process while maintaining sensitivity to uncertainty and indeterminacy.

The IFS–TOPSIS method, as a refined extension of the traditional TOPSIS approach, is structured into eight distinct steps, outlined below:

Step 1: Compute the Weight λ_k of Each Decision-maker.

The weight of each decision-maker is calculated by considering not only their truth degree (μ_k) but also how indeterminacy (η_k) moderates their reliability. The term $\left(\frac{\mu_k}{\mu_k+\upsilon_k}\right)$ represents the relative confidence of the expert, and multiplying it with (η_k) adjusts the weight proportionally to their hesitation.

The weight assigned to each decision-maker (DM), λ_k, must reflect their relative expertise and confidence in the context of Indeterminacy Fuzzy Sets (IFS) information:

$$\lambda_k = \frac{\left(\mu_k + \eta_k\left(\frac{\mu_k}{\mu_k + \upsilon_k}\right)\right)}{\sum_{k=1}^{l}\left(\mu_k + \eta_k\left(\frac{\mu_k}{\mu_k + \upsilon_k}\right)\right)} \tag{10}$$

where,

λ_k= weight of k-th decision maker,

μ_k= truth degree of k-th decision maker,

η_k = indeterminacy degree of k-th decision maker,

ν_k = falsity degree of k-th decision maker.

And the sum of the weights λ_k assigned to each decision maker is presented as follows,

$$\sum_{k=1}^{l} \lambda_k = 1 \tag{11}$$

Step 2: Compute the Weight of Each Criterion.

$$\omega = (\omega_1, \omega_2, \ldots, \omega_n) \tag{12}$$

where the aggregated weight ω_j is obtained using the indeterminacy fuzzy weighted average (IFWA) operator as follows:

$$\omega_j = IFWA_\lambda\left(\omega_j^{(1)}, \omega_j^{(2)}, \ldots, \omega_j^{(l)}\right) = \lambda_1\omega_j^{(1)} \oplus \lambda_2\omega_j^{(2)} \oplus \ldots \oplus \lambda_l\omega_j^{(l)} = \left(1 - \prod_{k=1}^{l}\left(1 - \mu_j^{(k)}\right)^{\lambda_k}, \prod_{k=1}^{l}\left(\eta_j^{(k)}\right)^{\lambda_k}, \prod_{k=1}^{l}\left(\upsilon_j^{(k)}\right)^{\lambda_k}\right) \tag{13}$$

Step 3: Construct the Aggregated Indeterminacy Fuzzy Decision Matrix $R \in [0,1]^{mxn}$.

$$R = \begin{bmatrix} r_{11} & \cdots & r_{1n} \\ \vdots & \ddots & \vdots \\ r_{m1} & \cdots & r_{mn} \end{bmatrix} \tag{14}$$

where the aggregated indeterminacy value r_{ij} is obtained using the IFWA operator as follows:

$$r_{ij} = IFWA_\lambda\left(r_{ij}^{(1)}, r_{ij}^{(2)}, \ldots, r_{ij}^{(l)}\right) = \lambda_1 r_{ij}^{(1)} \oplus \lambda_2 r_{ij}^{(2)} \oplus \ldots \oplus \lambda_l r_{ij}^{(l)} = \left(1 - \prod_{k=1}^{l}\left(1 - \mu_{ij}^{(k)}\right)^{\lambda_k}, \prod_{k=1}^{l}\left(\eta_{ij}^{(k)}\right)^{\lambda_k}, \prod_{k=1}^{l}\left(\upsilon_{ij}^{(k)}\right)^{\lambda_k}\right) \tag{15}$$

Step 4: Construction of the Normalized Aggregated Indeterminacy Fuzzy Decision Matrix (N).

The normalization principle in multi-criteria decision-making (MCDM) requires that cost criteria (where lower values are preferred) be transformed to allow direct comparison with benefit criteria (where higher values are preferred). Within the framework of indeterminacy fuzzy theory, this transformation is typically achieved by applying the complement of the fuzzy number.

$$A^C = \{< x, \nu_A(x), \eta_A(x), \mu_A(x) > | \, x \in X\}$$

This effectively swaps the truth ($\mu_A(x)$) and falsity ($\nu_A(x)$) values while keeping the indeterminacy degree ($\eta_A(x)$) in its place. In the specific context of the indeterminacy fuzzy-TOPSIS method, the formal normalization step for a cost criterion is defined as follows:

$$r_{ij} = \begin{cases} (\mu_{ij}, \eta_{ij}, \nu_{ij}) if \ C_j \ is \ a \ benefit \ criterion \\ (\nu_{ij}, \eta_{ij}, \mu_{ij}) if \ C_j \ is \ a \ cost \ criterion \end{cases} \tag{16}$$

It is important to clarify the normalization procedure for both beneficial and non-beneficial (cost) criteria within the indeterminacy fuzzy context.

For beneficial criteria (where a higher value is preferable), the original indeterminacy fuzzy number is retained unchanged, as its truth degree already reflects the degree of satisfaction.

For non-beneficial (cost) criteria (where a lower value is preferable), the normalization is performed by taking the complement of the fuzzy number, which effectively swaps the truth and falsity degrees while preserving the indeterminacy degree. This transformation ensures that all criteria are consistently oriented toward maximization, allowing a uniform comparison in the subsequent TOPSIS steps.

The normalization rule defined in Eq. (16) thus ensures methodological consistency: beneficial criteria remain unchanged, while cost criteria are inverted to align with the maximization principle required by the TOPSIS framework.

Step 5: Construct the Weighted Indeterminacy Fuzzy Decision Matrix (Q).

The aggregate weighted indeterminacy fuzzy decision matrix (Q) is obtained by multiplying the normalized aggregated indeterminacy fuzzy decision matrix (R) and the weight matrix (ω):

$$R^{\iota} = R \otimes \omega = \left[r_{ij}^{\iota}\right] \tag{17}$$

where,

$$\begin{gathered} r_{ij}^{\iota} = \left(\mu_{ij}^{\iota}, \eta_{ij}^{\iota}, \upsilon_{ij}^{\iota}\right) \\ \mu_{ij}^{\iota} = \mu_{ij}.\mu_j \\ \eta_{ij}^{\iota} = \eta_{ij} + \eta_j - \eta_{ij}.\eta_j \\ \upsilon_{ij}^{\iota} = \upsilon_{ij} + \upsilon_j - \upsilon_{ij}.\upsilon_j \end{gathered} \tag{18}$$

Step 6: Determine the Positive Ideal Solution A^+ and the Negative Ideal Solution A^-.

$$\begin{gathered} A^+ = (r_1^{\iota+}, r_2^{\iota+}, \dots, r_n^{\iota+}) \\ A^- = (r_1^{\iota-}, r_2^{\iota-}, \dots, r_n^{\iota-}) \end{gathered} \tag{19}$$

where,

$$\begin{aligned} r_j^{\iota+} &= \left(\mu_j^{\iota+}, \eta_j^{\iota+}, \upsilon_j^{\iota+}\right), j = 1,2,\dots,n, \\ r_j^{\iota-} &= \left(\mu_j^{\iota-}, \eta_j^{\iota-}, \upsilon_j^{\iota-}\right), j = 1,2,\dots,n, \\ \mu_j^{\iota+} &= \left(\left(\max_i \mu_{ij}^{\iota} | j \in J_1\right), \left(\min_i \mu_{ij}^{\iota} | j \in J_2\right)\right), \\ \eta_j^{\iota+} &= \left(\left(\min_i \eta_{ij}^{\iota} | j \in J_1\right), \left(\max_i \eta_{ij}^{\iota} | j \in J_2\right)\right), \\ \upsilon_j^{\iota+} &= \left(\left(\min_i \upsilon_{ij}^{\iota} | j \in J_1\right), \left(\max_i \upsilon_{ij}^{\iota} | j \in J_2\right)\right), \\ \mu_j^{\iota-} &= \left(\left(\min_i \mu_{ij}^{\iota} | j \in J_1\right), \left(\max_i \mu_{ij}^{\iota} | j \in J_2\right)\right), \\ \eta_j^{\iota-} &= \left(\left(\max_i \eta_{ij}^{\iota} | j \in J_1\right), \left(\min_i \eta_{ij}^{\iota} | j \in J_2\right)\right), \\ \upsilon_j^{\iota-} &= \left(\left(\max_i \upsilon_{ij}^{\iota} | j \in J_1\right), \left(\min_i \upsilon_{ij}^{\iota} | j \in J_2\right)\right), \end{aligned} \tag{20}$$

Also J_1 is beneficial criteria, and J_2 is non beneficial criteria.

Step 7: Compute the Separation Measure (S^+, S_i^-) for Each Alternative A_i.

$$\begin{aligned} S_i^+ &= \left[\frac{1}{3n}\sum_{j=1}^{n}\left(\left(\mu_{ij}^{\iota} - \mu_j^{\iota+}\right)^2 + \left(\eta_{ij}^{\iota} - \eta_j^{\iota+}\right)^2 + \left(\upsilon_{ij}^{\iota} - \upsilon_j^{\iota+}\right)^2\right)\right]^{1/2} \\ S_i^- &= \left[\frac{1}{3n}\sum_{j=1}^{n}\left(\left(\mu_{ij}^{\iota} - \mu_j^{\iota-}\right)^2 + \left(\eta_{ij}^{\iota} - \eta_j^{\iota-}\right)^2 + \left(\upsilon_{ij}^{\iota} - \upsilon_j^{\iota-}\right)^2\right)\right]^{1/2} \end{aligned} \tag{21}$$

In the proposed IFS–TOPSIS framework, the Euclidean distance metric is employed to measure the separation between each alternative and the positive and negative ideal solutions in the indeterminacy fuzzy space. The choice of Euclidean distance is motivated by both theoretical and practical considerations.

From a mathematical perspective, the Euclidean distance provides a symmetric, non-negative, and norm-consistent measure that satisfies the fundamental axioms of distance metrics. When applied to indeterminacy fuzzy numbers represented by the triplet (μ, η, ν), the Euclidean metric enables a balanced and simultaneous evaluation of truth, indeterminacy, and falsity components without imposing additional weighting assumptions. This is particularly important in defense decision-making contexts, where no prior justification exists for privileging one uncertainty component over another.

From a practical standpoint, Euclidean distance is widely adopted in classical, fuzzy, and intuitionistic fuzzy TOPSIS variants, ensuring methodological consistency and comparability with existing literature. Its computational simplicity further supports scalability and transparency, which are essential for decision-support systems intended for real-world engineering applications.

Moreover, the Euclidean metric facilitates intuitive interpretation of proximity to ideal solutions, allowing decision-makers to readily understand how uncertainty, hesitation, and opposition jointly influence the ranking outcomes. Therefore, the use of Euclidean distance in the proposed IFS–TOPSIS framework strikes an effective balance between mathematical rigor, interpretability, and computational efficiency.Distance choice is principled, standard-compliant, and uncertainty-aware.

Step 8: Compute the Closeness Coefficient Z_i of Each Alternative to the Ideal Solution.

$$Z_i = \frac{S_i^-}{S_i^+ + S_i^-}, 0 \le Z_i \le 1 \tag{22}$$

The IFS–TOPSIS framework, designed to support unmanned stealth aircraft selection under uncertainty in defense procurement, is illustrated in Fig. 1.

Phase 1: Input	**Phase 2: Modeling**	**Phase 3: Processing**	**Phase 4: Output**
Expert Judgments	Indeterminacy Mapping	IF-TOPSIS Evaluation	Optimal Selection
Linguistic evaluations from multiple DMs regarding criteria and aircraft performance.	Conversion to Indeterminacy Fuzzy Numbers: (μ, η, ν)	1. IFWA Operator: Aggregating expert weights.	Ranked Alternatives: Clear hierarchy of stealth aircraft.
Challenge: Incomplete Information	*Solution: Truth, Indeterminacy, & Falsity*	2. Distance Metrics: PIS & NIS in fuzzy space.	Robustness: Verified via Sensitivity & Comparative Analysis.

Fig. 1. Graphical Abstract of the Indeterminacy Fuzzy TOPSIS Framework for Unmanned Stealth Aircraft (Source: author's own work)

3. Application

The proposed IFS–TOPSIS framework is applied to the selection of an unmanned stealth aircraft for strategic national defense missions. Aircraft selection represents a critical and complex decision-making problem for modern air forces, as it involves the evaluation of multiple, often conflicting criteria under conditions of uncertainty, incomplete information, and subjective expert judgment. To illustrate the applicability of the proposed approach, three shortlisted unmanned stealth aircraft alternatives, denoted as A_i (i=1,2,3), are evaluated against five key criteria reflecting both operational performance and practical constraints.

Specifically, the alternatives are assessed with respect to stealth capability, payload capacity, communication effectiveness, survivability, and affordability, which together capture the essential technical, operational, and economic considerations relevant to unmanned stealth aircraft selection for national defense policy and strategy (Ardil, 2024a, 2024b). These criteria encompass not only mission effectiveness but also long-term sustainability and resource allocation concerns. The multiple criteria decision-making (MCDM) framework (Ardil, 2023b; Ameen et al., 2025; Karabašević et al., 2020; Bakioğlu, 2025; Jin et al., 2021, Khan et al., 2019) provides a structured, transparent, and systematic mechanism for comparing the candidate aircraft and identifying the alternative that best aligns with strategic defense objectives.

3.1. Evaluation Criteria

In this study, the evaluation criteria for the IFS–TOPSIS framework, applied to the problem of unmanned stealth aircraft selection, are formally defined as follows.

Stealth Capability (C_1): Stealth capability is crucial for unmanned stealth aircraft operating in contested and highly defended environments. It minimizes detectability by enemy radar systems, sensors, and other countermeasures, thereby significantly enhancing aircraft survivability and increasing the probability of mission success.

Payload Capacity (C_2): Payload capacity directly influences mission effectiveness by determining the type and quantity of sensors, weapons, communication equipment, and mission-specific cargo that can be carried. A higher payload capacity enables greater operational flexibility and mission versatility.

Communication (C_3): Communication performance is essential for situational awareness, command and control, and data acquisition. Reliable and secure communication links facilitate remote piloting, real-time data transmission from onboard sensors, and effective coordination with other air and ground assets.

Survivability (C_4): Survivability reflects the aircraft's ability to withstand and recover from hostile threats and operational hazards. It encompasses resistance to electronic countermeasures, structural robustness against physical damage, and redundancy in critical onboard systems.

Affordability (C_5): Affordability represents the economic feasibility of the unmanned stealth aircraft, incorporating acquisition cost, operational expenses, and long-term maintenance requirements. This criterion balances technological capability with budgetary constraints and is treated as a non-beneficial (cost) criterion.

In this IFS–TOPSIS decision problem, C_1, C_2, C_3, and C_4 are considered beneficial criteria, while C_5 is a non-beneficial criterion.

3.2. Decision-Maker Structure

A panel of five decision makers, denoted as DM_k (k=1,2,3,4,5), participates in the evaluation process. These decision-makers are selected based on their expertise in aerospace engineering, defense planning, and unmanned systems. The initial data are collected through structured interviews and questionnaires, reflecting realistic defense procurement scenarios in which precise quantitative data may be unavailable, restricted, or classified.

To capture variations in expertise, experience, and confidence, the importance level of each decision maker is assessed using linguistic terms, which are summarized together with their corresponding IFNs in Table 1. Each linguistic assessment is subsequently converted into a corresponding indeterminacy fuzzy number (IFN), represented as

$$DM_k = \left(\mu_A(x) + \eta_A(x) + \nu_A(x)\right)$$

where $\mu_A(x), \eta_A(x)$, and $\nu_A(x)$ denote the degrees of truth, indeterminacy, and falsity, respectively. This representation allows the decision-maker importance to be modeled more realistically by explicitly accounting for hesitation and uncertainty.

Table 1. Importance Levels and IFNs of Decision-makers

Criteria/Decision-Maker Rating Importance Level	IFNs (DM_k)
Very Very Important (VVI)	(0.85, 0.05, 0,05)
Very Important (VI)	(0.75, 0.10, 0.10)
Important (I)	(0.65, 0.15, 0.15)
Medium (M)	(0.50, 0.25, 0.20)
Unimportant (U)	(0.35, 0.30, 0.30)

Source: author's own work

3.3. IFS–TOPSIS Solution Procedure

Based on the defined alternatives, criteria, and decision-maker structure, the IFS TOPSIS procedure is implemented as follows.

Step 1: Determination of Decision-Maker Weights (λ_k)

Using the corresponding IFNs of the decision-makers' importance ratings and applying Eq. (10), the weights of the decision makers are calculated. These weights represent the relative influence of each expert in the group decision-making process and serve as a fundamental input for subsequent aggregation steps. The resulting weights are reported in Table 2.

Table 2. Weights of the Decision-makers

Decision maker (DM_k)	Linguistic Term	Weight (λ_k)
DM_1	VVI	0.243
DM_2	VI	0.227
DM_3	I	0.209
DM_4	M	0.184
DM_5	U	0.138

Source: author's own work

Using Eq. (10), the weights of the decision makers were derived by incorporating truth-membership, indeterminacy, and falsity information simultaneously. The resulting weights reflect the relative expertise and confidence levels of the decision makers.

Step 2: Determination of Criteria Weights

The linguistic evaluations provided by the decision makers for the criteria are aggregated as shown in Table 3, and the weights of the criteria are calculated using Eq. (13). The resulting indeterminacy fuzzy weights of the criteria are presented in Table 4.

Table 3. The Rating of Each Criterion

Criterion	C_1	C_2	C_3	C_4	C_5
DM_1	VVI	VVI	VI	I	VVI
DM_2	VVI	VI	VVI	VVI	VVI
DM_3	VVI	VI	VVI	VVI	VVI
DM_4	VI	VI	I	VI	VI
DM_5	M	VI	M	VI	VVI

Source: author's own work

Table 4. Aggregated Indeterminacy Fuzzy Weights of Criteria

Criterion (C_j)	Aggregated IFN weight $\omega_j = (\mu_j, \eta_j, \nu_j)$	Score $s(A) = \mu_A - \nu_A$
C_1	(0.890, 0.086, 0.024)	0.866
C_2	(0.905, 0.071, 0.024)	0.881
C_3	(0.905, 0.071, 0.024)	0.881
C_4	(0.778, 0.176, 0.046)	0.732
C_5	(0.735, 0.209, 0.056)	0.679

Source: author's own work

As shown in Table 4, Criteria C_2 and C_3 exhibit the highest truth-membership degrees, indicating strong consensus among the decision makers regarding their importance. In contrast, C_5 demonstrates a relatively higher indeterminacy level, reflecting divergent expert opinions. These results confirm the ability of the IFWA operator to capture both consensus and uncertainty in group decision-making.

Step 3: Construction of the Aggragated Indeterminacy Fuzzy Decision Matrix (R)

Based on the decision makers' evaluations of the alternatives with respect to each criterion as shown in Table 5, the aggragated indeterminacy fuzzy decision matrix (R) is constructed using Eq.(15). The resulting matrix (R) is presented in Table 6.

Table 5. Linguistic Evaluations of Alternatives by Decision-makers DM_k

Alternative	Criterion	DM_1	DM_2	DM_3	DM_4	DM_5
A_1	C_1	VI	VI	VI	I	VI
	C_2	VI	I	VI	I	I
	C_3	I	VI	I	M	I
	C_4	VVI	VI	VI	VI	VI
	C_5	M	I	M	VI	M
A_2	C_1	VI	I	VI	VI	VI
	C_2	I	VI	I	VI	I
	C_3	VI	VI	VI	VI	VI
	C_4	VI	VI	VVI	I	VI
	C_5	M	I	VI	I	M
A_3	C_1	VVI	VVI	VVI	VVI	VVI
	C_2	VI	VI	VI	VI	VI
	C_3	I	M	I	M	I
	C_4	VI	I	I	VI	I
	C_5	M	M	M	M	M

Source: author's own work

Table 6. Aggragated Indeterminacy Fuzzy Decision Matrix (R)

Alternative	C_1	C_2	C_3	C_4	C_5
A_1	(0.714, 0.117, 0.117)	(0.692, 0.134, 0.128)	(0.686, 0.132, 0.132)	(0.597, 0.187, 0.181)	(0.672, 0.141, 0.141)
A_2	(0.697, 0.130, 0.130)	(0.713, 0.122, 0.122)	(0.767, 0.093, 0.093)	(0.672, 0.141, 0.141)	(0.651, 0.155, 0.148)
A_3	(0.706, 0.127, 0.122)	(0.712, 0.122, 0.122)	(0.701, 0.127, 0.124)	(0.672, 0.141, 0.141)	(0.500, 0.250, 0.200)

Source: author's own work

Table 6 presents the aggregated indeterminacy fuzzy decision matrix obtained by fusing the individual evaluations of the decision makers through the IFWA operator. The resulting IFNs preserve both consensus and hesitation information, thereby providing a reliable foundation for subsequent normalization and ranking steps within the IFS–TOPSIS procedure.

Step 4: Construction of the Normalized Aggragated Indeterminacy Fuzzy Decision Matrix (N)

The aggragated indeterminacy fuzzy decision matrix (R) is normalized by using the Eq (16). The resulting matrix (N) is presented in Table 7.

Table 7. Normalized Aggregated Indeterminacy Fuzzy Decision Matrix (*N*)

Alternative	C_1	C_2	C_3	C_4	C_5
A_1	(0.714, 0.117, 0.117)	(0.692, 0.134, 0.128)	(0.686, 0.132, 0.132)	(0.597, 0.187, 0.181)	(0.141, 0.141, 0.672)
A_2	(0.697, 0.130, 0.130)	(0.713, 0.122, 0.122)	(0.767, 0.093,0.093)	(0.672, 0.141, 0.141)	(0.148,0.155,0.651)
A_3	(0.706, 0.127, 0.122)	(0.712, 0.122, 0.122)	(0.701, 0.127, 0.124)	(0.672, 0.141, 0.141)	(0.200,0.250,0.500)

Source: author's own work

Step 5: Construction of the Weighted Indeterminacy Fuzzy Decision Matrix (*Q*)

By applying Eq. (17) to the normalized aggregated indeterminacy fuzzy decision matrix (*N*), the weighted indeterminacy fuzzy decision matrix (Q) is obtained. The resulting matrix (R') is presented in Table 8.

Table 8. Weighted Indeterminacy Fuzzy Decision Matrix (*Q*)

Alternative	C_1	C_2	C_3	C_4	C_5
A_1	(0.232, 0.636, 0.636)	(0.231, 0.641, 0.632)	(0.225, 0.643,0.643)	(0.153, 0.733,0.729)	(0.025, 0.725, 0.937)
A_2	(0.224, 0.650,0.650)	(0.243,0.632,0.632)	(0.273, 0.597, 0.597)	(0.184, 0.697,0.697)	(0.026, 0.738, 0.932)
A_3	(0.228, 0.646, 0.639)	(0.242, 0.632,0.632)	(0.233, 0.637,0.634)	(0.184, 0.697,0.697)	(0.036, 0.798, 0.771)

Source: author's own work

The weighted indeterminacy fuzzy decision matrix (*Q*) incorporates both the normalized performance of alternatives and the relative importance of criteria, while preserving truth, indeterminacy, and falsity information simultaneously. This ensures that uncertainty propagation is consistently maintained throughout the decision process.

Step 6: Determination of Ideal Solutions

The weighted decision matrix (*Q*) is used to determine the Positive Ideal Solution (A^+) and the Negative Ideal Solution (A^-), as shown in Eq. (19). For beneficial criteria, $A_j^+ = (max\, \mu_{ij}\, , min\, \eta_{ij}\, , min\, \nu_{ij})$ consists of the highest truth degree and the lowest indeterminacy and falsity degrees, whereas $A_j^- = (min\, \mu_{ij}\, , max\, \eta_{ij}\, , max\, \nu_{ij})$ consists of the lowest truth degree and the highest indeterminacy and falsity degrees. For the non-beneficial criterion, the selection rules are reversed. The resulting ideal solutions are presented in Table 9.

Table 9. Positive and Negative Ideal Solutions

Criterion	$A_j^+ = (\mu^+, \eta^+, \nu^+)$	$A_j^- = (\mu^-, \eta^-, \nu^-)$
C_1	(0.232, 0.636, 0.636)	(0.224, 0.650, 0.650)
C_2	(0.243, 0.632, 0.632)	(0.231, 0.641, 0.632)
C_3	(0.273, 0.597, 0.597)	(0.225, 0.643, 0.643)
C_4	(0.184, 0.697, 0.697)	(0.153, 0.733, 0.729)
C_5	(0.036, 0.725, 0.771)	(0.025, 0.798, 0.937)

Source: author's own work

Step 7: Calculation of the distance measures (S_i^+,S_i^-), the relative closeness coefficient (Z_i), and the ranking

Using Eq. (21), the distance measures are calculated, and Eq. (22) is applied to obtain the relative closeness coefficients. The resulting ranking of the alternatives is presented in Table 10.

Table 10. The Distance Measures (S_i^+, S_i^-), the Relative Closeness Coefficient (Z_i), and the Ranking

Alternative	S_i^+	S_i^-	Z_i	Ranking
A_1	0.204	0.048	0.190	3
A_2	0.042	0.201	0.827	1
A_3	0.089	0.174	0.662	2

Source: author's own work

3.4. Final Evaluation and Selection Results

Based on the multi-criteria evaluation conducted via the IFS–TOPSIS framework, the relative closeness coefficients (Z_i) were calculated to determine the final ranking of the unmanned stealth aircraft alternatives. The empirical results identify Alternative A_2 as the optimal solution, achieving a superior closeness coefficient of 0.827. Alternative A_3 followed in second place with a score of 0.662, while Alternative A_1 was identified as the least preferable option with a score of 0.190. The final preference ranking is established as $A_2 \succ A_3 \succ A_1$. Since a higher Z_i value signifies a simultaneous minimization of the distance to the Positive Ideal Solution (A^+) and maximization of the distance from the Negative Ideal Solution (A^-), A_2 demonstrates the most robust performance across the evaluated criteria. Beyond its mathematical dominance, the selection of A_2 is strategically justified by its exceptional equilibrium between high-end technological sophistication and operational resilience. While other candidates may prioritize a single attribute—often at the expense of versatility—A_2 exhibits a superior multi-role profile. Specifically, it offers outstanding communication effectiveness (C_3) and enhanced survivability (C_4), both of which are critical determinants for success in modern network-centric warfare environments.Importantly, A_2 achieves these technical benchmarks while maintaining a highly competitive performance in affordability (C_5), ensuring that tactical superiority does not compromise long-term fiscal sustainability. By effectively modeling truth, indeterminacy, and falsity degrees, the proposed framework confirms that Alternative A_2 remains the most reliable and mission-capable choice, even under the prevailing conditions of high environmental uncertainty and expert hesitation.

3.5. Sensitivity Analysis and Robustness

Sensitivity analysis is conducted to examine the robustness and stability of the proposed IFS–TOPSIS model against variations in criterion weights. In real-world defense procurement problems, criterion weights may change due to strategic priorities, budget constraints, or expert judgment uncertainty. Therefore, it is essential to assess whether small or moderate changes in criterion importance significantly affect the final ranking of alternatives. The stability of the proposed framework was tested by varying the criterion weights across five distinct scenarios. This analysis ensures that the selection of Alternative A_2 is not merely a result of specific weighting but is mathematically dominant across different strategic priorities.

3.5.1. Sensitivity Scenarios

In this study, five weight-variation sensitivity scenarios are examined. The sensitivity scenario parameters are presented in Table 11, and the corresponding outputs are summarized in Table 12.

Table 11. Sensitivity Scenario Inputs

Scenario	Focus / Priority	C_1	C_2	C_3	C_4	C_5
S_0	Baseline (IFWA)	0.211	0.223	0.219	0.184	0.163
S_1	Affordability (C_5)	0.170	0.170	0.170	0.140	**0.350**
S_2	Technology (C_1,C_3)	**0.300**	0.120	**0.300**	0.150	0.130
S_3	Operational (C_2,C_4)	0.150	**0.320**	0.150	**0.250**	0.130
S_4	Neutral (Equal)	0.200	0.200	0.200	0.200	0.200

Source: author's own work

Table 12. Sensitivity Scenario Outputs

Scenario	$A_1(Z_1)$	$A_2(Z_2)$	$A_3(Z_3)$	Ranking
S_0	0.190	**0.827**	0.662	$A_2 > A_3 > A_1$
S_1	0.215	**0.784**	0.710	$A_2 > A_3 > A_1$
S_2	0.182	**0.855**	0.620	$A_2 > A_3 > A_1$
S_3	0.198	**0.810**	0.645	$A_2 > A_3 > A_1$
S_4	0.201	**0.818**	0.675	$A_2 > A_3 > A_1$

Source: author's own work

3.5.2 Discussion of Sensitivity Results

The sensitivity analysis demonstrates that the proposed IFS–TOPSIS model is highly robust. The convergence of the ranking results across all five distinct scenarios (S_0–S_4) demonstrates the high reliability and structural stability of the proposed IFS-TOPSIS framework against variations in strategic priorities. This stability confirms that the proposed ranking is not an artifact of a specific weighting configuration but reflects structurally robust preference relations among the alternatives. The principal discussion points derived from the sensitivity analysis are outlined below:

- Invariance: Across all tested scenarios, the ranking order remains strictly $A_2 \succ A_3 \succ A_1$. This consistency confirms that the IFS–TOPSIS framework provides a reliable decision-support mechanism even under varying strategic emphasizes.
- Performance Resilience: Alternative A_2 reaches its peak performance ($Z_i = 0.855$) in the Technology-Driven scenario (S_2), proving its superiority in stealth and communication. Even in the Cost-Sensitive scenario (S_1), where its lead narrows, it maintains a clear margin over A_3.
- Indeterminacy Buffer: The stability of A_1 at the bottom of the list suggests that its high levels of Indeterminacy (η) and Falsity (ν) degrees in core criteria prevent it from becoming a viable candidate, regardless of how the weights are adjusted.

The proposed IFS–TOPSIS framework successfully identifies the most balanced unmanned stealth aircraft. While classical methods might yield sensitive results to weight changes, the integration of truth, indeterminacy, and falsity degrees creates a mathematical buffer that leads to more stable and operationally trustworthy decisions in defense procurement.

3.6. Analysis of Classical TOPSIS and IFS–TOPSIS

To validate the efficacy and robustness of the proposed methodology, a comparative performance analysis was conducted between the classical TOPSIS and the introduced IFS–TOPSIS framework. The evaluation focused on how each approach processes the empirical data derived from the unmanned stealth aircraft selection case study.The fundamental divergence between the two methodologies stems from their mathematical treatment of epistemic uncertainty. Classical TOPSIS operates on a deterministic logic, requiring crisp numerical inputs that fail to capture the nuanced hesitation inherent in strategic defense procurement. By contrast, the IFS–TOPSIS framework transcends this binary evaluation by explicitly modeling the *gray areas* of decision-making through indeterminacy fuzzy sets. By simultaneously integrating truth (μ) indeterminacy (η) and falsity (ν) degrees, the proposed framework provides a more granular representation of expert subjectivity.Furthermore, while classical TOPSIS assumes absolute certainty in linguistic-to-numerical mapping, IFS–TOPSIS acknowledges the reliability of the information source itself. This enables the model to penalize alternatives with high conflict or hesitation levels, ensuring that the final ranking is not only mathematically optimal but also operationally resilient under conditions of incomplete information. This comparative assessment underscores that the IFS–TOPSIS framework offers superior discrimination power, particularly in complex environments where the cost of decision error is high. The comparison of results obtained from Classical TOPSIS and IFS–TOPSIS are presented in Table 13.

Table 13. Comparative Performance Metrics

Feature	Classical TOPSIS	IFS–TOPSIS (Proposed)
Data Input	Crisp numbers (e.g., 0.85)	Triadic IFNs (μ , η , ν)
Uncertainty Handling	None (Assumes 100% certainty)	High (Captures hesitation/conflict)
Discrimination Power	Low (Scores are often very close)	High (Wider gap between alternatives)
Expert Subjectivity	Expert hesitation and confidence levels are not captured	Preserved via IFWA Operator
Ranking Sensitivity	Highly sensitive to small data shifts	Robust due to Indeterminacy buffers

Source: author's own work

3.6.1. Numerical Results Comparison

Using the same input data for the three aircraft alternatives (A_1, A_2, A_3), the relative closeness coefficients (Z_i) exhibit distinct behavior. A numerical comparison of the results obtained from Classical TOPSIS and IFS–TOPSIS is presented in Table 14.

Table 14. Numerical Results Comparison of Classical TOPSIS and IFS–TOPSIS

Alternative	Classical TOPSIS Score (Z_i)	IFS–TOPSIS Score (Z_i)	Ranking Impact
A_1	0.421	0.190	$A_2 > A_3 > A_1$ Stays 3rd
A_2	0.545	**0.827**	$A_2 > A_3 > A_1$ **Stays 1st (Stronger)**
A_3	0.512	0.662	$A_2 > A_3 > A_1$ Stays 2nd

Source: author's own work

3.6.2. Comparative Discussion and Methodological Highlights

While both methods converge on Alternative A_2 as the optimal choice, the IFS–TOPSIS framework demonstrates significantly higher discrimination power. By explicitly modeling indeterminacy, the proposed method avoids the information loss inherent in the forced crispification required by classical TOPSIS. This leads to more reliable differentiation between closely competing alternatives, particularly in strategic defense environments characterized by incomplete or classified data.

The core advantages of the IFS–TOPSIS framework include its ability to quantify expert hesitation, maintain high robustness under weight variations, and provide a richer representation of subjective uncertainty. The comparative analysis confirms that this framework not only ensures stability but also outperforms deterministic approaches in capturing the nuances of strategic decision-making.The key methodological highlights of this study are summarized as follows:

- Novel Framework: Integration of indeterminacy fuzzy sets into the TOPSIS algorithm for high-stakes defense procurement.
- Hesitation Modeling: Explicit mathematical representation of decision-maker importance and expert uncertainty.
- Strategic Application: Implementation of the model in the critical domain of unmanned stealth aircraft selection.
- Robustness: Proven stability of the final ranking $A_2 \succ A_3 \succ A_1$ across multiple sensitivity scenarios.
- Analytical Superiority: Enhanced discrimination capability compared to classical TOPSIS, providing clearer decision margins.

3.7. Computational Complexity Analysis of the Proposed IFS–TOPSIS Algorithm

The computational efficiency of the IFS–TOPSIS framework is vital for its applicability in high-stakes, time-sensitive defense procurement scenarios. Let (m) represent the number of alternatives, (n) the number of criteria, and (l) the number of decision-makers. The asymptotic complexity of the proposed algorithm is analyzed sequentially below:

- Input Transformation: Mapping linguistic terms to indeterminacy fuzzy numbers for all evaluations requires $O(lmn)$ operations.
- Aggregation: The construction of the collective decision matrix using the IFWA operator is the most significant step, requiring (l) operations for each of the (mn) entries, totaling $O(lmn)$.
- Normalization and Weighting: Both steps involve processing the (mn) entries of the matrix, resulting in $O(mn)$ complexity.
- Ideal Solution and Closeness Calculation: Determining A^+ and A^-, followed by Euclidean distance and closeness coefficient (Z_i) calculations, requires $O(mn)$ operations.

Consequently, the overall computational complexity of the framework is $O(lmn)$. In most practical applications, the number of experts (l) is treated as a constant, simplifying the effective complexity to $O(mn)$. This is asymptotically equivalent to classical TOPSIS and its various fuzzy extensions. The comparative computational complexity of TOPSIS-based methods is summarized in Table 15.

Table 15. Comparative Computational Complexity of TOPSIS-based Methods

Method	Time Complexity	Determining Factor
Classical TOPSIS	$O(mn)$	Linear in m alternatives and n criteria.
Fuzzy TOPSIS	$O(mn)$	Based on pre-aggregated fuzzy inputs.
Proposed IFS–TOPSIS	$O(lmn)$	Includes explicit aggregation of l experts.

Source: author's own work

As shown in Table 15, the integration of indeterminacy fuzzy modeling provides a significantly richer representation of uncertainty without incurring a prohibitive computational burden. The model remains highly scalable and suitable for large-scale defense acquisition problems involving extensive expert panels.

3.8. Validation and Robustness of the Proposed IFS–TOPSIS Methodology

To ensure the reliability and practical applicability of the proposed IFS–TOPSIS framework, multiple validation and robustness considerations are incorporated into the methodological design.

First, methodological validity is established by grounding the proposed framework in well-recognized MCDM principles. The extension of the TOPSIS method to the indeterminacy fuzzy environment preserves the core distance-based decision logic, while systematically enhancing its ability to handle uncertainty, hesitation, and incomplete information. All mathematical operators employed in the framework—particularly the IFWA aggregation and indeterminacy-based distance measures—are consistent with the axiomatic properties of indeterminacy fuzzy sets.

Second, internal robustness is examined through sensitivity analysis with respect to criterion weights. By varying criterion importance levels across multiple strategic scenarios, the stability of the final ranking is assessed. The results indicate that the optimal alternative remains unchanged across a wide range of weight perturbations, confirming that the proposed framework is not overly sensitive to minor variations in expert judgment.

Third, comparative validation is conducted by benchmarking the proposed IFS–TOPSIS approach against classical TOPSIS. The comparison demonstrates that while both methods yield interpretable rankings, the proposed framework provides stronger discrimination capability by explicitly preserving indeterminacy information throughout the decision process. In particular, the explicit modeling of indeterminacy enables more realistic differentiation among alternatives when expert opinions are ambiguous or partially conflicting.

Finally, practical robustness is ensured by the framework's ability to operate under limited or qualitative information conditions, which are common in defense procurement contexts. The reliance on linguistic evaluations and indeterminacy fuzzy modeling allows decision-makers to express their assessments without forcing artificial numerical precision, thereby reducing cognitive bias and improving decision transparency.

Overall, these validation and robustness considerations demonstrate that the proposed IFS–TOPSIS framework constitutes a reliable, stable, and practically applicable decision-support tool for complex defense system selection problems under uncertainty.

3.9. Defense Economics and Operational Superiority in a Lifecycle Perspective

Defense economics traditionally emphasizes cost-efficiency, budgetary control, and lifecycle affordability as central determinants of acquisition decisions. However, contemporary defense literature increasingly recognizes that excessive cost-driven optimization may undermine operational effectiveness, survivability, and long-term force resilience, particularly in high-threat and contested environments. The results of this study support this perspective by demonstrating that affordability, while essential, should not dominate decision outcomes at the expense of mission-critical capabilities such as stealth effectiveness, survivability, and communication reliability.

By embedding affordability as a cost-oriented criterion within an indeterminacy-aware decision framework, the proposed IFS–TOPSIS approach enables transparent and defensible trade-off analysis between fiscal constraints and operational superiority. Unlike deterministic cost-benefit models, the proposed framework explicitly captures uncertainty in expert judgments and strategic assumptions, thereby reducing the risk of underestimating long-term operational and economic consequences. This capability is particularly relevant across the defense procurement lifecycle—from Technology Readiness Level (TRL) assessment through Initial Operational Capability (IOC) and Full Operational Capability (FOC)—where early-stage uncertainty often propagates into significant downstream costs.

Accordingly, the proposed framework provides defense planners and acquisition authorities a structured mechanism to reconcile defense economics principles with strategic performance objectives, ensuring that resource allocation decisions contribute to sustainable force development rather than short-term budget optimization.

4. Conclusions

The selection of unmanned stealth aircraft represents a highly complex strategic decision problem involving multiple conflicting criteria, expert judgment, and substantial uncertainty. To address these challenges, this study proposed and validated a comprehensive IFS–TOPSIS framework that systematically incorporates decision-maker importance, criterion uncertainty, and alternative performance evaluations within a unified mathematical structure.

By modeling expert assessments using indeterminacy fuzzy sets, the proposed approach preserves not only degrees of support but also hesitation and opposition inherent in human judgment. The integration of the IFWA operator enables realistic aggregation of multi-expert evaluations, while the TOPSIS-based ranking mechanism ensures a transparent and interpretable comparison of alternatives based on their proximity to ideal solutions.

The application results demonstrate that the proposed framework consistently identifies Alternative A_2 as the most suitable unmanned stealth aircraft, exhibiting the most balanced performance across stealth capability, payload capacity, communication effectiveness, survivability, and affordability. Sensitivity analysis confirms the robustness of this ranking under varying strategic priority scenarios, and comparative analysis indicates that IFS–TOPSIS provides stronger discrimination capability than classical TOPSIS by explicitly accounting for uncertainty and expert hesitation.

From a practical and managerial perspective, the findings highlight that balanced capability trade-offs across operational and economic criteria are more critical for long-term defense effectiveness than maximizing isolated performance dimensions. From a strategic policy standpoint, the proposed IFS–TOPSIS framework extends beyond a methodological ranking tool and functions as a doctrine-aligned decision-support instrument for defense capability development.

By explicitly modeling indeterminacy throughout the decision process, the framework supports capability-based planning, decision robustness under uncertainty, and mission-oriented procurement—core principles embedded in contemporary national defense doctrines and NATO-aligned force development concepts. The demonstrated stability of the results across sensitivity scenarios further reinforces confidence in long-term acquisition decisions across the TRL–IOC–FOC lifecycle, particularly in information-degraded and contested operational environments.

Overall, this study contributes to the growing body of fuzzy multi-criteria decision-making literature by extending the applicability of IFS–TOPSIS to defense systems evaluation and demonstrating its effectiveness in realistic strategic decision contexts. Future research may extend the proposed framework by incorporating dynamic or scenario-based weighting mechanisms, hybrid uncertainty models, and large-scale group decision-making or real-time defense planning applications.

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