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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.

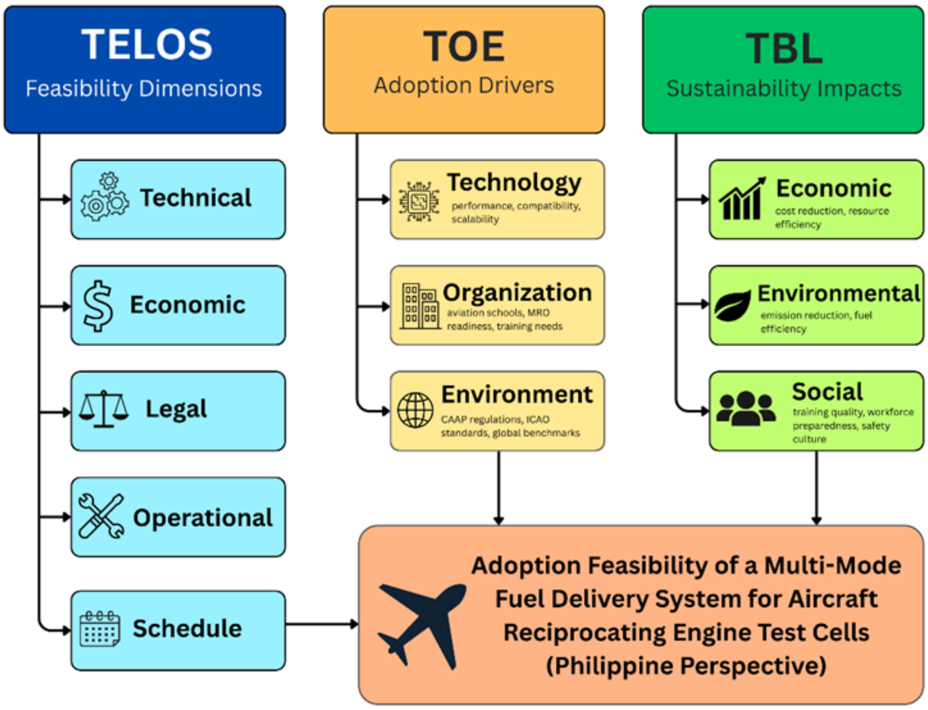


Fig. 1. Conceptual framework integrating TELOS feasibility dimensions, TOE adoption drivers, and TBL sustainability impacts for assessing the adoption feasibility of a multi-mode fuel delivery system in Philippine aircraft engine test cells (Source: Authors' own work)

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.

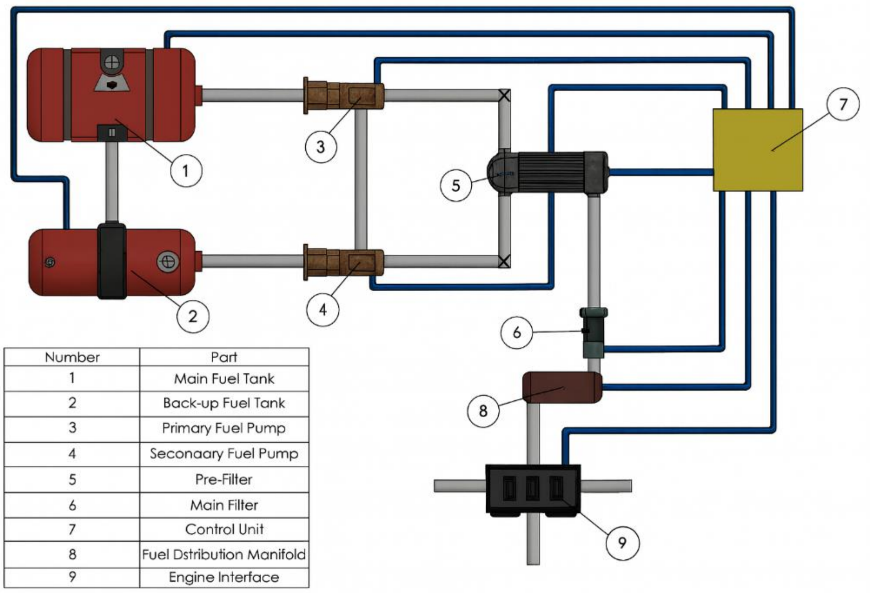
Recruitment continues until thematic saturation is achieved, reinforcing the credibility and robustness of findings → is achieved to ensure data adequacy and credibility. Participant details—role, experience, and affiliation—are summarized in a coding sheet to maintain transparency and anonymity.

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)

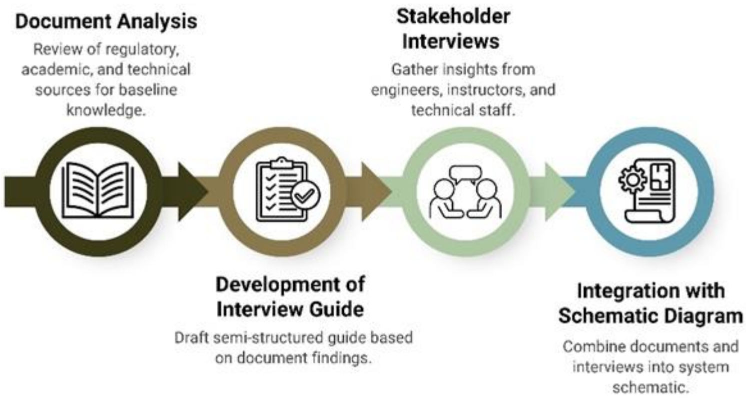


Fig. 3. Flowchart of data-collection procedures from document analysis to schematic integration. The figure is included to clarify methodological triangulation and to show how evidence from documents and interviews is systematically funneled into the design, ensuring analytic rigor (Source: Authors'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

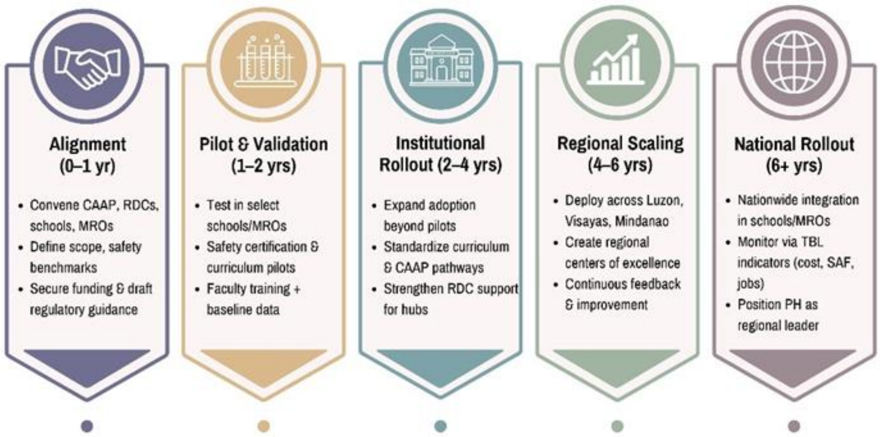


Fig. 4. Phased adoption roadmap for the multimodal test-cell system. The figure is included to link feasibility findings to implementation pacing, showing how policy alignment, training, and procurement are sequenced to manage risk and build readiness in line with TELOS–TOE–TBL integration (Source: Authors'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