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Capability-Based Framework for Standardizing Maintenance and Knowledge Management in Military Ground Support Equipment: Case Study in the Colombian Aerospace Force

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Abstract

Ground Support Equipment (GSE), institutionally referred to as Equipo Terrestre de Apoyo Aeronáutico (ETAA), is essential for sustaining military aerospace operations and operational readiness. However, the Colombian Aerospace Force (COLAF) currently lacks a standardized framework for maintenance capability management and technical knowledge preservation across its air units, generating asymmetries in maintenance performance, infrastructure conditions, personnel competencies, and resource allocation. This research proposes an integrated capability-based framework for the standardization and distribution of GSE maintenance capabilities within the Colombian Aerospace Force (COLAF). The study pursued three objectives: (1) diagnosing the current state of maintenance capabilities and technical knowledge management; (2) identifying strategic alternatives for maintenance standardization and capability distribution through the Guía Metodológica de Planeamiento por Capacidades established by the Colombian Ministry of National Defense (2018) and (3) designing a hierarchical maintenance framework integrating capability planning, modular technical training, and institutional knowledge-management mechanisms. The methodology combined documentary analysis, operational data assessment, interviews, Pareto analysis, SWOT/TOWS analysis, and capability-gap assessment under the Guía Metodológica de Planeamiento por Capacidades established by the Colombian Ministry of National Defense (2018) and MAMAE (2025) quality attributes. The results revealed significant variability in equipment availability, maintenance workload, tooling availability, infrastructure conditions, and technical competencies among operational units, as well as deficiencies in maintenance doctrine, process standardization, and technical knowledge-transfer mechanisms. The principal contribution of this research is the development of an innovative maintenance capability-planning model specifically adapted to distributed military maintenance environments, integrating maintenance standardization, capability distribution, and technical knowledge management into a unified and scalable framework.

Keywords
Maintenance capabilities, Knowledge management, Ground Support Equipment, Standardization, DOMPI.

1. Introduction
The operational capability of military aviation systems depends not only on aircraft availability, but also on the reliability and sustainability of the systems supporting air operations on the ground. In modern air forces, Ground Support Equipment (GSE) plays a critical role in aircraft preparation, servicing, inspection, testing, towing, power supply, and operational support activities. Consequently, deficiencies in GSE maintenance directly affect operational readiness, mission continuity, and flight safety. Figure 1 illustrates the relationship between maintenance capability gaps and their operational consequences within military aviation environments.

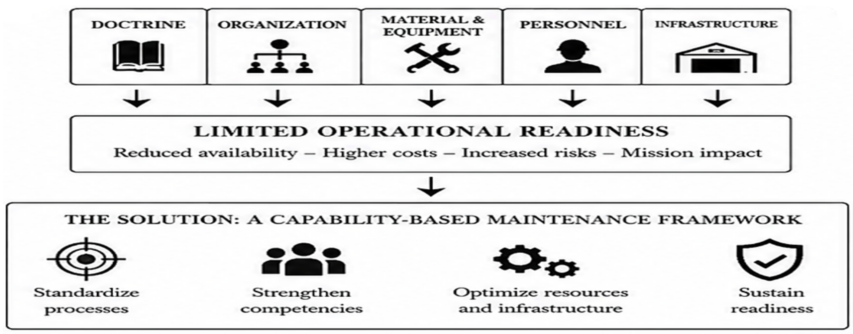

Figure 1. Maintenance Capability Gaps Affecting Operational Readiness

In Colombia, the Colombian Aerospace Force (COLAF) is responsible for maintaining sovereignty and national airspace control through air, space, and cyberspace operations. To fulfill this mission, the institution requires robust technical and logistical capabilities capable of sustaining both aerial and ground assets. Within this framework, Ground Support Equipment (GSE), institutionally referred to as Equipo Terrestre de Apoyo Aeronáutico (ETAA), constitutes an essential component for aircraft sustainment and operational continuity. According to the Colombian Aeronautical Maintenance Manual MAMAE (2025), GSE includes mobile and static equipment used for receiving, handling, inspecting, testing, servicing, launching, and recovering aerospace vehicles and payloads.

Despite its strategic importance, the Colombian Aerospace Force currently lacks a standardized framework for maintenance capability management and technical knowledge management across its air units. Each tactical unit independently defines maintenance criteria, technical procedures, and operational capabilities, generating variability in maintenance quality, infrastructure conditions, traceability, and technical competencies. Additionally, high personnel rotation contributes to the loss of critical technical knowledge due to the absence of formal mechanisms for knowledge capture and transfer. These limitations are aggravated by asymmetries in infrastructure, tooling availability, workshop conditions, and the absence of a structured institutional training plan for GSE personnel.

These deficiencies directly affect operational availability, maintenance sustainability, resource allocation, and mission readiness. From a logistical perspective, inefficient maintenance management increases operational costs, prolongs equipment downtime, and generates dependency on external repair services. Therefore, strengthening maintenance capabilities through standardized and knowledge-based maintenance processes represents both a technical and strategic necessity for preserving operational readiness and institutional sustainability.

The literature review identified studies related to maintenance knowledge management, smart maintenance implementation, and capability-planning models such as DOMPI, and integrates Doctrine (standards and procedures), Organization (structure and coordination), Materiel and Equipment (tools and technical resources), Personnel (competencies and training), and Infrastructure (workshops and operational facilities) as the principal components for capability planning and maintenance management, established by the Colombian Ministry of National Defense (2018), which together make the development of a capability possible. However, no previous study has integrated maintenance capability standardization and technical knowledge management under a DOMPI-based approach specifically focused on Ground Support Equipment within the Colombian military aviation context. This gap highlights the need for an institutional framework capable of standardizing maintenance levels, technical competencies, infrastructure requirements, and knowledge-management processes for GSE workshops.

Therefore, this research aims to design a proposal for the standardization of maintenance capability management and technical knowledge management for GSE personnel within the Colombian Aerospace Force. The study combines documentary analysis, semi-structured interviews, capability assessment matrices, Pareto analysis, and SWOT analysis under the DOMPI framework to identify operational gaps and develop a structured maintenance capability model.

1.1 Objectives
The main objective of this research is to develop a capability-based framework for the standardization of maintenance capabilities and technical knowledge management for Ground Support Equipment (GSE) within the Colombian Aerospace Force. To achieve this objective, the study is guided by the following specific objectives:

1. To diagnose the current state of maintenance capabilities and technical knowledge management across COLAF air units, identifying variability in infrastructure, maintenance processes, resource allocation, and personnel competencies.
2. To identify strategies for the standardization and distribution of maintenance capabilities and technical knowledge management for GSE maintenance personnel through the Guía Metodológica de Planeamiento por Capacidades established by the Colombian Ministry of National Defense (2018).
3. To design a standardized proposal for maintenance capability distribution and a technical training plan for non-commissioned officer personnel responsible for GSE maintenance within the Colombian Aerospace Force.

2. Literature Review
The literature review was developed through a systematic exploratory search process aimed at identifying current trends, operational challenges, and research gaps related to maintenance management, maintenance capability planning, and technical knowledge management in aerospace and military environments. To support the search process, a structured prompt was designed using ChatGPT and implemented in the academic platforms Elicit and Consensus, generating 36 relevant results in Elicit and 521 results in Consensus. The identified studies were consolidated into an Excel-based classification matrix and filtered according to their contribution to this research as shown below in Figure 2.

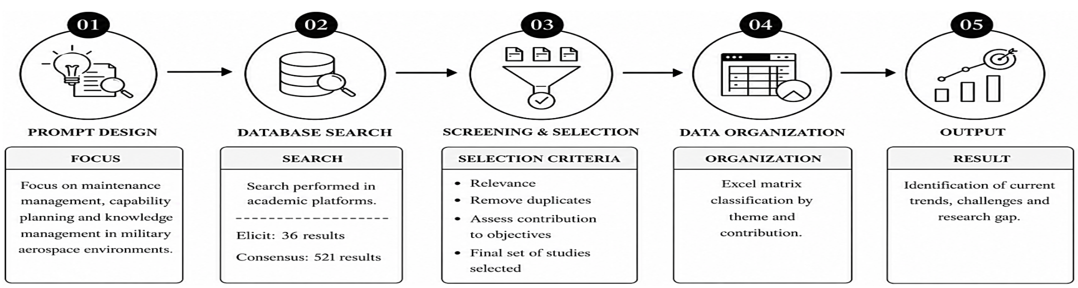

Figure 2. Integrated literature review process

The analysis revealed that most current studies focus on predictive maintenance, Smart Maintenance, Artificial Intelligence (AI), and Industry 4.0/5.0 technologies aimed at improving operational efficiency and maintenance optimization. Authors such as Kusiak et al. (2025), Hammoumi et al. (2025), Taoufyq et al. (2025), and Sala et al. (2025) describe the evolution of maintenance engineering from corrective and preventive approaches toward intelligent and integrated maintenance ecosystems supported by predictive analytics, reliability engineering, and organizational learning mechanisms. However, most studies assume the existence of mature maintenance structures, stable infrastructure, and standardized operational conditions before implementing advanced digital technologies.
This limitation becomes particularly relevant in military aerospace environments characterized by budget constraints, personnel rotation, geographically distributed operations, and uneven maintenance capabilities. Consequently, organizations must first establish standardized maintenance capabilities, technical knowledge-management mechanisms, and operational sustainment structures before implementing predictive or AI-based maintenance systems. In this context, Lundgren (2021) states that successful Smart Maintenance implementation depends not only

on technology adoption, but also on organizational readiness, capability development, and continuous learning mechanisms.

Maintenance engineering literature has progressively evolved from corrective approaches toward preventive and capability-based maintenance systems focused on operational sustainability and reliability. Tavares (2000) highlights the importance of preventive maintenance activities such as LILA (Cleaning, Inspection, Lubrication, and Basic Adjustments) for improving operational continuity and equipment preservation. Similarly, through the principles of Total Productive Maintenance (TPM), emphasizes preventive culture, continuous improvement, and operator involvement as key elements for improving maintenance performance. Recent studies additionally reinforce that modern maintenance engineering increasingly integrates reliability, sustainability, predictive analytics, and proactive maintenance planning as part of Industry 4.0 and Maintenance 5.0 environments (Benhanifia et al., 2025; Giacotto et al., 2025; Bukowski, 2025). Likewise, Taoufyq et al. (2025) states that maintenance systems are progressively transitioning from traditional preventive approaches toward integrated predictive and knowledge-based maintenance models capable of improving operational efficiency and long-term sustainability. Although Mora (2009) is not a recent reference, it remains a foundational contribution to maintenance-management literature, particularly in maintenance planning, execution, and control methodologies. Since this research focuses on maintenance capability management, operational sustainability, and maintenance standardization rather than emerging technologies, the reference continues to provide conceptual validity and theoretical support for the proposed framework.

From a logistics engineering perspective, Blanchard (1995) establishes that maintenance capabilities should be distributed hierarchically according to technical complexity, operational demand, and resource availability. This approach provides the theoretical basis for Organizational, Intermediate, and Depot maintenance structures widely adopted in military aviation systems. Likewise, Lundgren (2021) states that successful maintenance systems depend not only on technology implementation, but also on organizational readiness, capability development, and continuous learning mechanisms. Di Mascolo (2025) proposes distributed maintenance structures integrating centralized and mobile maintenance workshops to improve operational continuity across geographically dispersed environments. Similarly, Song (2023) develops an integrated aerospace support chain model connecting maintenance entities, logistics systems, and spare-parts distribution into a unified operational structure. Adimonyemma (2025), de Brito (2021), and Pan et al. (2024) reinforce the importance of balancing maintenance capacity, logistics coordination, and distributed resource allocation to improve maintenance sustainability, operational readiness, and capability distribution efficiency.

Knowledge management has also become a critical factor in maintenance organizations due to the increasing dependence on technical expertise and operational experience. López et al. (2018) explain that the absence of structured learning systems generates knowledge loss and excessive dependence on individual expertise. Similarly, Cárcel et al. (2020) identify personnel rotation, technical documentation, and knowledge-transfer practices as critical factors affecting maintenance efficiency, while Roham (2025) emphasizes the importance of structured technical learning systems capable of preserving organizational capabilities over time. Recent aerospace studies additionally reinforce the importance of digital knowledge infrastructures and knowledge-based engineering systems for improving information exchange, organizational learning, and operational continuity within maintenance environments. Kusiak et al. (2025), Mealey et al. (2025), and Szejka et al. (2024) highlight the growing implementation of collaborative knowledge ecosystems, maintenance intelligence systems, and knowledge-based expert systems to improve maintenance traceability, interoperability, and technical knowledge exchange in aerospace environments. Awill (2025) highlights the importance of aerospace knowledge infrastructures capable of integrating technical information management, organizational learning, and institutional knowledge preservation. Additionally, describe organizational knowledge creation as the interaction between tacit and explicit knowledge, reinforcing the importance of formal knowledge transfer mechanisms in technical maintenance environments.

Within military aviation environments, international maintenance doctrines recognize that operational readiness depends on effective maintenance capability planning and hierarchical maintenance distribution. The United States Air Force doctrine (AFPD 21-1, 2023) establishes Organizational, Intermediate, and Depot maintenance levels as a reference structure for maintenance capability management. In Colombia, the Ministry of National Defense (2018) formally established the DOMPI framework, integrating Doctrine, Organization, Materiel and Equipment, Personnel, and Infrastructure as the basis for capability planning. The integration of the Guía Metodológica de Planeamiento por Capacidades established by the Colombian Ministry of National Defense (2018) with the quality attributes established in the Colombian Aeronautical Maintenance Manual (MAMAE, 2025) provides a structured framework for evaluating maintenance capability maturity, infrastructure conditions, technical competencies, and maintenance sustainability.

National studies conducted within Colombian military environments reinforce the importance of maintenance capability standardization and technical knowledge management. Ruiz et al. (2023) demonstrated that deficiencies in maintenance procedures, personnel competencies, and resource allocation directly affect Ground Support Equipment operational availability. Similarly, Laverde et al. (2024) highlighted the importance of maintenance standardization, traceability, and capability distribution structures for improving operational sustainability within military maintenance environments.

Overall, the literature review demonstrates that maintenance management, predictive maintenance, distributed maintenance systems, and knowledge management have been widely studied independently. However, Despite the significant advances identified in literature, important research gaps remain unresolved. Current studies mainly focus on predictive maintenance, Artificial Intelligence, digital maintenance systems, and knowledge management as independent research areas; however, no integrated framework was identified combining maintenance capability management, hierarchical maintenance levels, technical knowledge management, and capability distribution within military environments. Additionally, limited research applies to the DOMPI framework as a practical tool for Ground Support Equipment (GSE) maintenance capability planning, particularly under operational conditions characterized by budget constraints, infrastructure asymmetries, personnel rotation, and geographically distributed operations. Based on these gaps, this research proposes an integrated capability-based framework that combines maintenance standardization, capability distribution, DOMPI-based planning, and technical knowledge management to improve operational readiness, maintenance sustainability, and long-term organizational capability development within the Colombian Aerospace Force.

3. Methods

The methodological design was structured into three sequential phases aligned with the specific objectives of the research. This phased approach follows the mixed-methods methodology proposed by Hernández Sampieri (2014), integrating qualitative and quantitative procedures progressively to ensure methodological coherence and analytical continuity throughout the study. The methodology combined documentary analysis, operational capability assessment, strategic analysis, and proposal design under a capability-based maintenance management perspective. The following flow chart summarizes the sequential phases applied in this research (Figure 3).

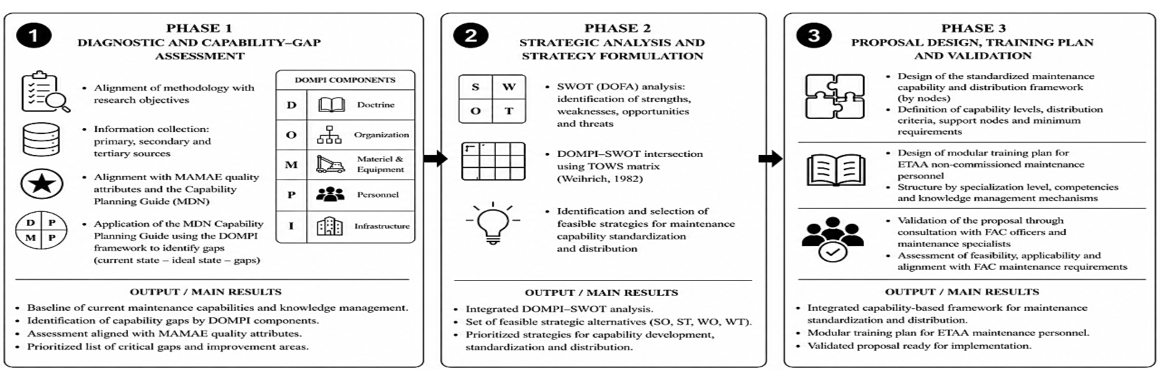

Figure 3. Sequential phases of methodological design

The first phase focused on defining and aligning the methodological structure according to the research objectives and the operational context of Ground Support Equipment (GSE) maintenance within the Colombian Aerospace Force. During this phase, information was collected from primary, secondary, and tertiary sources through documentary review, operational data collection, semi-structured interviews with maintenance personnel, and analysis of institutional maintenance records and regulations. The information search and data collection process were aligned with the quality attributes established in the Colombian Aeronautical Maintenance Manual (MAMAE, 2025) and with the criteria defined in the Capability Planning Guide issued by the Colombian Ministry of National Defense.

These quality attributes included personnel competencies, infrastructure conditions, technical information management, maintenance traceability, tooling availability, operational resources, and maintenance documentation control. Additionally, the Guía Metodológica de Planeamiento por Capacidades established by the Colombian Ministry of National Defense (2018), was applied to perform the capability-gap assessment process. The analysis evaluated the components of Doctrine, Organization, Materiel and Equipment, Personnel, and Infrastructure under three assessment conditions: current state (As Is), ideal state (To Be), and identified capability gaps. This assessment enabled the identification of operational deficiencies, maintenance asymmetries, infrastructure limitations, and technical knowledge-management weaknesses affecting maintenance sustainability and operational readiness across COLAF air units.

The second phase focused on analyzing the diagnostic results obtained during the capability-gap assessment process. The identified findings were classified through SWOT analysis to determine organizational strengths, weaknesses, opportunities, and threats associated with GSE maintenance management and technical knowledge management. Subsequently, the TOWS cross-impact matrix proposed by Weihrich (1982) was applied to analyze the interaction between internal and external factors and to identify feasible strategic alternatives for maintenance capability standardization and distribution. The intersection between DOMPI capability gaps and SWOT factors enabled the formulation and prioritization of strategies related to maintenance capability development, infrastructure strengthening, personnel training, technical doctrine standardization, resource optimization, and institutional knowledge preservation.

The third phase consisted of developing an integrated proposal for the standardization and distribution of maintenance capabilities through a node-based maintenance structure within the Colombian Aerospace Force. The proposal incorporated the strategic alternatives identified during the SWOT–TOWS analysis and established hierarchical maintenance capability levels, maintenance distribution criteria, operational support nodes, minimum infrastructure requirements, personnel allocation criteria, and maintenance execution responsibilities according to operational complexity. Additionally, a modular technical training plan was designed for GSE non-commissioned maintenance personnel, integrating competency-based training, technical specialization levels, operational maintenance requirements, and institutional knowledge-management mechanisms aimed at preserving technical expertise and reducing dependency on individual experience. Finally, the proposed framework was validated through consultation and technical review with Colombian Aerospace Force officers and maintenance personnel, allowing the evaluation of its operational feasibility, institutional applicability, and alignment with the operational requirements of the COLAF maintenance system.

4. Data Collection

The data collection process was conducted through the integration of documentary review, operational data gathering, interviews, and technical assessments performed within Ground Support Equipment (GSE) maintenance environments of the Colombian Aerospace Force. The collected information was aligned with the research objectives and focused on obtaining operational, organizational, technical, and maintenance-related information associated with maintenance capability assessment, maintenance standardization, and technical knowledge management. A mixed-methods approach was adopted by integrating qualitative and quantitative information sources to support the analysis of maintenance capabilities and operational requirements within GSE maintenance workshops (Hernández Sampieri, 2014).

The documentary review included institutional manuals, maintenance procedures, operational reports, capability-planning guidelines, maintenance records, and aerospace maintenance regulations associated with GSE maintenance management. Key institutional and regulatory sources included the Colombian Aeronautical Maintenance Manual (MAMAE, 2025), RACAE 43, MT918, organization chart, GSE documentation, the Guía Metodológica de Planeamiento por Capacidades established by the Colombian Ministry of National Defense (2018), and the U.S. Air Force maintenance management doctrine AFI 21-101 (2023).

Additionally, academic and technical literature related to maintenance engineering, logistics, maintenance capability planning, Total Productive Maintenance (TPM), smart maintenance, and knowledge management were reviewed to support the organization and classification of the collected information. The documentary review facilitated the identification of maintenance levels, personnel competencies, process-standardization criteria, technical documentation requirements, maintenance traceability practices, and institutional doctrine associated with GSE maintenance activities. Furthermore, the reviewed documentation supported the development of a documentary correlation matrix (Table 1) used to classify institutional requirements and capability-planning components associated with the research objectives.

Operational information was collected from maintenance workshops, operational units, institutional databases, maintenance records, and support activities associated with GSE operations. The collected information included maintenance capability records, equipment distribution by air unit, inactive equipment records, workshop operational conditions, tooling and equipment availability, infrastructure characteristics, maintenance resource distribution, maintenance support activities, personnel allocation, and operational support requirements within maintenance environments. Additional information associated with maintenance workflows, workshop organization, operational workload, and maintenance execution activities was also documented during the collection process. The operational information was organized through comparative tables and Pareto charts to facilitate the registration and visualization of maintenance-related information across operational units.

Table 1. Documentary correlation matrix: GSE vs. Research objectives

Military documentation	**Maintenance levels**	**Personal competencies**	**Process standardization**	**Knowledge management,**	**Doctrine**
MAMAE	✓	✓	✓		✓
RACAE 43	✓		✓	✓	✓
MT918	✓	✓	✓	✓	✓
MACET		✓		✓	✓
MFCPM		✓	✓	✓	
Capabilities Guide	✓	✓	✓	✓	✓
NAT GSE	✓		✓		✓
AET GSE	✓		✓		✓
Organization chart	✓	✓	✓		✓
Formas FAC	✓	✓	✓		✓

Interviews and consultation activities were conducted with maintenance personnel, supervisors, workshop chiefs, and technical staff involved in GSE maintenance activities. Semi-structured and non-structured interviews were used to collect information associated with maintenance execution practices, operational experience, technical training processes, maintenance coordination activities, technical documentation usage, maintenance support requirements, knowledge transfer practices, personnel competencies, and operational limitations associated with maintenance activities. The qualitative information obtained through interviews was organized using comparative coding and thematic categorization processes to facilitate the identification and classification of maintenance-related concepts, operational practices, technical requirements, and knowledge management activities associated with GSE maintenance environments. The interviews additionally enabled the identification and registration of recurrent operational terms, maintenance-related concepts (Figure 4), and technical expressions associated with maintenance management and operational support activities.

Maintenance workshops and operational support facilities were additionally assessed to collect information associated with infrastructure conditions, workshop distribution, tooling availability, maintenance equipment, technical resources, operational support areas, safety conditions, and maintenance-support requirements.

The assessment process was aligned with the quality attributes established in the Colombian Aeronautical Maintenance Manual (MAMAE 2025), including personnel competencies, technical information management, maintenance traceability, tooling availability, infrastructure conditions, resource management, and documentation control. These attributes were used as technical evaluation criteria for assessing maintenance capability conditions within GSE maintenance environments.

Figure 4. Cloud of terms from maintenance interviews

Finally, the collected information was organized according to the Guía Metodológica de Planeamiento por Capacidades established by the Colombian Ministry of National Defense (2018). DOMPI was used not only as a classification structure, but also as the analytical framework guiding the capability-gap assessment process. The information was grouped into categories associated with Doctrine, Organization, Materiel and Equipment, Personnel, and Infrastructure, facilitating the organization, traceability, and analysis of the collected information throughout the research process.

The integration of documentary review, operational records, interviews, and technical workshop assessments enabled methodological triangulation, improving the reliability and consistency of the collected information and supporting the identification of maintenance capability requirements and standardization needs within GSE maintenance environments as shown below in Figure 5.

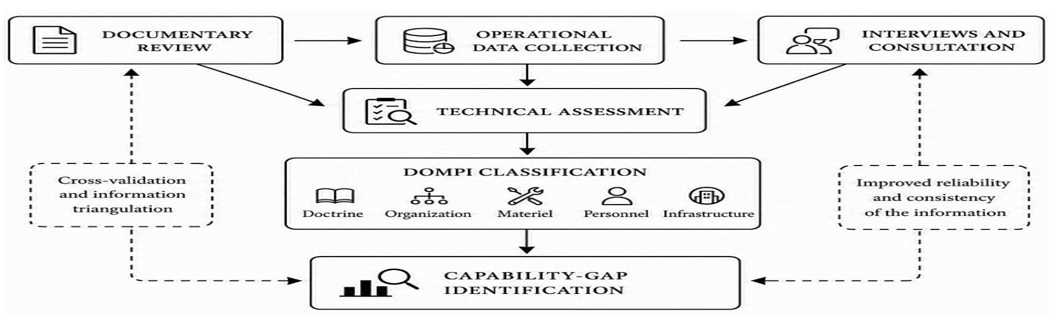

Figure 5. Integrated Framework for Data Collection, DOMPI Classification, and Capability-Gap Identification

5. Results and Discussion

The collected data were analyzed to evaluate maintenance capabilities across the selected Colombian Aerospace Force air units and identify operational gaps affecting Ground Support Equipment (GSE) sustainability. The analysis considered equipment inventories, maintenance personnel distribution, inactivity rates, workload conditions, infrastructure availability, and maintenance resource allocation. Using the Guía Metodológica de Planeamiento por Capacidades established by the Colombian Ministry of National Defense (2018), the results revealed deficiencies in maintenance standardization, uneven capability distribution, limited infrastructure, and insufficient technical competencies among operational units. Additionally, the findings demonstrated weaknesses in technical knowledge transfer and institutional knowledge preservation, particularly under geographically distributed operational conditions. These results support the need for an integrated capability-based maintenance framework focused on maintenance standardization, capability distribution, and technical knowledge management to improve operational readiness and long-term maintenance sustainability within the Colombian Aerospace Force. The contribution of LILA (Cleaning, Inspection, Lubrication, and Basic Adjustments) within this research lies in its role as a foundational preventive-maintenance methodology focused on improving equipment preservation, operational continuity, and early fault detection. As highlighted by Tavares (2000), LILA activities strengthen maintenance reliability and operational sustainability by promoting routine inspection practices, preventive intervention, and maintenance standardization, which are directly aligned with the proposed GSE capability-management framework.

5.1 Numerical Results

The assessment revealed significant variability in equipment availability, maintenance workload, and personnel distribution across the analyzed air units, confirming the existence of operational asymmetries throughout the maintenance system. The collected operational indicators included total Ground Support Equipment (GSE), inactive equipment rates, active equipment availability, maintenance personnel allocation, and workload distribution measured through the GSE-per-technician ratio. As shown in Table 2, substantial differences were identified among operational units regarding maintenance capability conditions, operational demand, and personnel workload distribution.

Table 2. Maintenance capability indicators across air units

Unit	Total, GSE	Inactive GSE	% Inactive	Active GSE	Personnel	GSE per Technician
Unit 1	60	24	40%	36	8	7,5
Unit 2	40	13	33%	65	10	4,0
Unit 3	31	14	45%	17	11	2,8
Unit 4	47	16	34%	31	5	9,4
Unit 5	26	5	19%	21	6	4,3
Unit 6	24	3	13%	21	6	4,0
Unit 7	28	2	7%	26	5	5,6
Unit 8	55	9	16%	46	7	7,9
Unit 9	27	6	22%	21	5	5,4
Unit 10	12	1	8%	11	6	2,0
Unit 11	11	4	36%	7	2	5,5
Unit 12	9	2	22%	7	2	4,5
Unit 13	22	1	5%	21	4	5,5

Inactivity rates ranged from 5% to 45%, with multiple air units exceeding 35% inactivity. Units 3 and 1 presented the highest inactivity levels, directly affecting operational readiness, maintenance responsiveness, and equipment availability. Similarly, the GSE-per-technician ratio showed substantial variability, ranging from 2.0 to 9.4. Units such as Unit 4 and Unit 8 exhibited elevated workload levels per technician, suggesting operational overload conditions capable of reducing maintenance quality, increasing response times, and accelerating personnel fatigue. In contrast, Units 3 and 10 presented lower ratios, indicating underutilization of available personnel and inefficient distribution of maintenance resources.

These findings demonstrate that maintenance inefficiencies are not uniformly distributed but instead reflect structural imbalances in maintenance capability allocation. The coexistence of overloaded and underutilized units suggests insufficient alignment between operational demand, installed maintenance capabilities, and available technical resources. Additionally, the capability-gap assessment performed under the DOMPI framework (Table 3) enabled the identification of deficiencies associated with doctrine, organization, materiel and equipment, personnel, and infrastructure within GSE maintenance environments.

Table 3. Summary of Gaps in GSE Maintenance Management Under the DOMPI Framework

Component (DOMPI)	Current State (As Is)	Ideal State (To Be)	Registered Gaps
Doctrine	Maintenance activities are performed using manufacturer manuals; no institutional doctrine specific to GSE.	Institutional doctrine with unified maintenance criteria and validated procedures.	Development of institutional doctrine, maintenance levels, and standardized procedures.
Organization	Personnel rotation without standardized knowledge transfer protocols.	Capability management system with standardized competency traceability.	Implementation of technical competency tracking and knowledge transfer mechanisms.
Material & Equipment	Partial availability of tools and limited access to certified spare parts.	Complete availability of specialized tools and certified spare parts.	Standardization of tools, spare parts, and technical support resources.

Component (DOMPI)	Current State (As Is)	Ideal State (To Be)	Registered Gaps
Personnel	No standardized technical certifications or institutional training plan.	Defined competency profiles and certified technical training programs.	Implementation of institutional training plans and technical certifications.
Infrastructure	Differences in workshop conditions and lack of standardized infrastructure.	Standardized infrastructure and operational conditions across workshops.	Improvement and standardization of maintenance facilities and storage areas.

The assessment revealed deficiencies in maintenance doctrine, procedure standardization, technical training, tooling availability, and workshop operational conditions across air units. Additionally, personnel rotation without formal knowledge-transfer mechanisms was identified as a critical factor affecting maintenance continuity and institutional knowledge preservation. The results also demonstrated that capability deficiencies are interconnected across DOMPI components, where limitations in infrastructure, resources, doctrine, and personnel competencies directly affect maintenance efficiency, operational consistency, and maintenance sustainability. These findings reinforce the need for an integrated capability-based maintenance framework capable of synchronizing organizational, technical, and operational maintenance requirements.

5.2 Graphical Results

To complement the numerical assessment, graphical analyses were conducted to visualize operational asymmetries, maintenance capability distribution (Figure 6), and the concentration of inactive equipment across the analyzed air units.

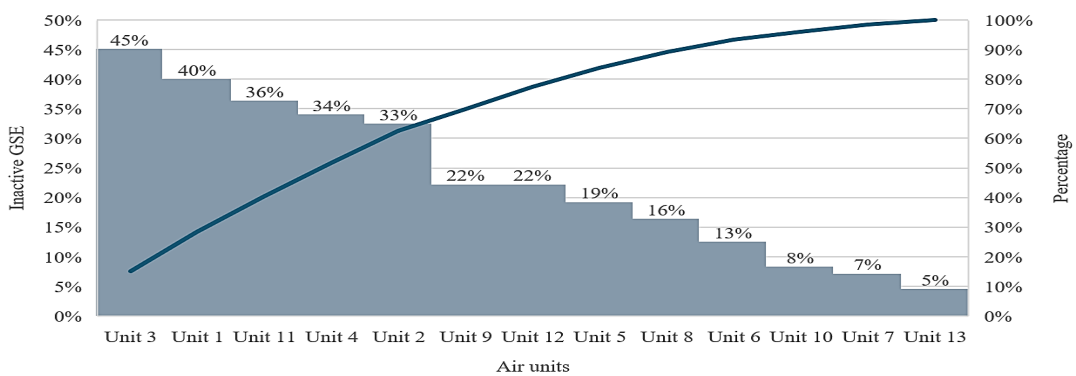

Figure 6. Pareto Analysis of Inactive Ground Support Equipment Across Air Units

The Pareto analysis indicates that equipment inactivity is concentrated within a limited number of operational units rather than being uniformly distributed throughout the maintenance system. Specifically, Units 3, 1, 11, and 4 exhibited the highest inactivity levels, collectively representing most of the inactive equipment identified during the assessment process. The cumulative distribution confirms the existence of a Pareto effect, where a reduced number of operational nodes generate most maintenance-related operational impacts.

From a maintenance management perspective, these findings indicate that maintenance deficiencies are concentrated in critical operational nodes requiring prioritized intervention strategies. Consequently, corrective actions focused on high-impact units may generate disproportionally large improvements in equipment availability, maintenance sustainability, and operational readiness. To complement the capability-gap assessment, a comparative capability analysis was conducted using the Guía Metodológica de Planeamiento por Capacidades established by the Colombian Ministry of National Defense (2018) and MAMAE (2025) quality attributes across the analyzed operational units as shown below in Table 4.

Table 4. Integrated DOMPI Capability Heatmap Across Air Units

Unit	Doctrine	Organization	Material & Equipment	Personnel	Infrastructure
Unit 1					
Unit 2					

Unit	Doctrine	Organization	Material & Equipment	Personnel	Infrastructure
Unit 3					
Unit 4					
Unit 5					
Unit 6					
Unit 7					
Unit 8					
Unit 9					
Unit 10					
Unit 11					
Unit 12					
Unit 13					

	Low capability (Significant deficiencies identified)		Medium capability (Partial compliance / Improvement needed)		High capability (Adequate conditions / Strengths identified)

The heatmap analysis demonstrates the existence of significant asymmetries in maintenance capability distribution throughout the operational system. Several units presented deficiencies simultaneously across multiple DOMPI components, particularly in infrastructure, personnel competencies, and materiel availability. In contrast, other units exhibited relatively balanced operational conditions, suggesting unequal capability development and maintenance resource allocation across the maintenance network. The results confirm the absence of standardized maintenance capability levels and reinforce the necessity of implementing hierarchical maintenance structures aligned with operational complexity, maintenance demand, and technical specialization requirements.

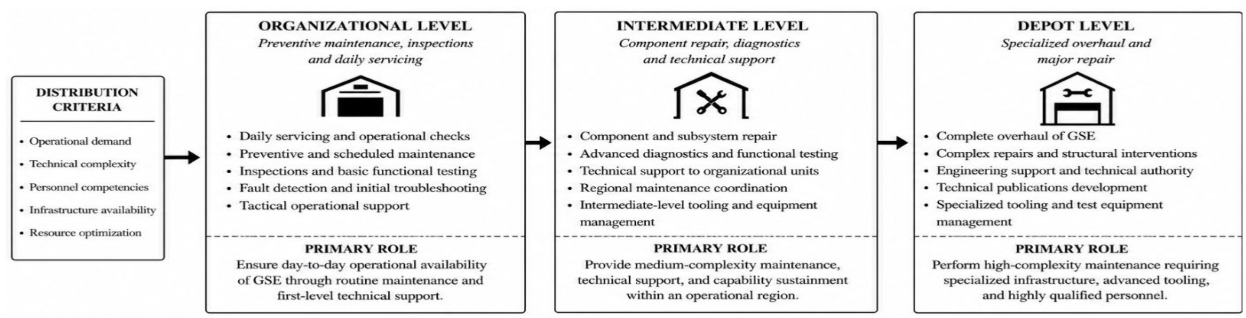

Figure 7. Capability-based maintenance distribution framework

Additionally, the proposed framework establishes a hierarchical capability-distribution structure designed to organize maintenance responsibilities according to operational demand, technical complexity, infrastructure availability, and personnel competencies across COLAF air units. Under this approach, maintenance capabilities are distributed through Organizational, Intermediate, and Depot maintenance levels, allowing high-complexity maintenance activities to be concentrated within specialized operational nodes while routine and preventive maintenance activities remain decentralized at tactical units. This structure reduces operational asymmetries, improves resource utilization, minimizes redundant maintenance capabilities, and strengthens maintenance sustainability throughout geographically distributed operational environments as shown in Figure 7.

5.3 Proposed Improvements

Based on the qualitative and quantitative findings, as well as the identified Pareto distribution of inactive equipment, a capability-based improvement framework was developed to address the operational inefficiencies and maintenance capability gaps identified during the diagnostic phase. The first proposed improvement consists of a prioritized intervention strategy focused on the air units presenting the highest inactivity rates and operational overload conditions. This prioritization mechanism enables optimized resource allocation by concentrating maintenance efforts on high-impact operational areas capable of generating the greatest improvements in equipment availability and mission readiness.

Second, the research proposes the standardization of maintenance levels through the implementation of Organizational, Intermediate, and Depot maintenance structures. This hierarchical distribution allows maintenance activities to be allocated according to technical complexity, operational requirements, and available resources, reducing workload imbalances and improving maintenance efficiency across distributed operational environments.

Third, a capability distribution model was developed to align maintenance resources with operational demand. The proposed model considers equipment volume, inactivity rates, personnel availability, infrastructure conditions, and maintenance complexity as key decision variables for maintenance capability allocation. This constitutes one of the principal contributions of the research, as it transforms maintenance management from a reactive operational activity into a structured capability-planning process.

Additionally, the proposed framework incorporates a modular technical training structure designed to reduce competency gaps among maintenance personnel. The training model is organized by technical systems, including electrical, hydraulic, mechanical, and powertrain systems, enabling progressive competency development and standardization of technical capabilities across air units. Figure 8 illustrates the dynamic relationships embedded in the proposed maintenance capability framework. The reinforcing loop (R) represents the positive effect of training management on personnel competence, maintenance quality, and GSE operational availability, creating additional opportunities for workforce development. The balancing loops (B1 and B2) represent operational constraints associated with corrective maintenance activities. While improved maintenance quality reduces unplanned failures and corrective interventions, excessive corrective maintenance limits the time available for training and slows competency development. Together, these feedback mechanisms explain how the framework balances short-term maintenance demands with long-term capability development and operational readiness.

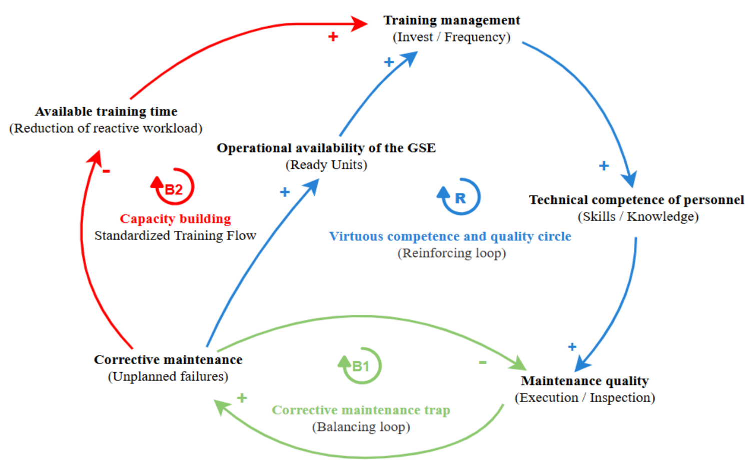

Figure 8. Proposed capability-based maintenance framework

Finally, the proposed improvements include logistics and resource management enhancements related to spare parts planning, inventory control, inter-unit coordination, and maintenance resource traceability. Collectively, these actions are expected to reduce equipment downtime, optimize maintenance workload distribution, improve operational sustainability, and strengthen mission readiness. Overall, the proposed framework demonstrates that integrating maintenance capability planning, hierarchical maintenance structures, and technical knowledge management under the DOMPI model provides a scalable and sustainable solution for improving maintenance performance in distributed military operational environments.

5.4 Validation

The proposed maintenance capability framework was validated through four complementary approaches: doctrinal validation, conceptual validation, expert validation, and operational coherence validation.

First, doctrinal validation was conducted to ensure alignment with the institutional regulatory framework of the Colombian Aerospace Force. The proposal was structured under the Guía Metodológica de Planeamiento por Capacidades established by the Colombian Ministry of National Defense (2018) and integrated the quality attributes defined in the Colombian Aeronautical Maintenance Manual (MAMAE, 2025). Additionally, the proposed maintenance distribution structure follows the hierarchical maintenance philosophy based on Organizational, Intermediate, and Depot maintenance levels adopted by international military maintenance doctrines. This alignment guarantees institutional compatibility and operational applicability.

Second, conceptual validation was performed by integrating internationally recognized maintenance-management and knowledge-management approaches. The methodological design incorporated SWOT/TOWS strategic analysis, capability-gap assessment methodologies, hierarchical maintenance frameworks derived from USAF and NATO maintenance doctrines, and organizational knowledge-management principles proposed by Nonaka and Takeuchi (1995). Therefore, the framework is theoretically supported by validated maintenance-engineering and organizational-learning models.

Third, expert validation was achieved through semi-structured interviews conducted with GSE maintenance personnel, workshop chiefs, and technical specialists from multiple COLAF air units. The diagnostic findings were triangulated with documentary evidence, operational maintenance records, and institutional maintenance procedures, improving the reliability and consistency of the identified operational gaps. The recurrence of similar deficiencies across different units strengthened the validity of the diagnostic assessment.

Although the scope of this research did not include pilot implementation to measure actual outcomes, the proposed framework establishes performance objectives directly linked to the deficiencies identified during the diagnostic phase. As summarized in Table 5, the integration of capacity redistribution, maintenance capability design, personnel training, and knowledge management is expected to reduce GSE downtime, improve workforce utilization, enhance maintenance quality, and increase operational readiness. These improvements are also expected to strengthen the organization's internal maintenance capabilities, reducing operational constraints associated with insufficient technical capacity.

From an economic perspective, the anticipated benefits include a reduction in unplanned corrective maintenance interventions, improved labor productivity, decreased overtime requirements, and more efficient allocation of maintenance resources. Furthermore, by increasing the availability of qualified personnel and expanding in-house maintenance capabilities, the proposed framework is expected to reduce reliance on outsourced maintenance services, generating potential cost savings associated with third-party contracting. The knowledge management component further supports long-term sustainability by preserving critical technical expertise and mitigating the impact of personnel turnover. The expected impacts presented in Table 5 extend the contribution of this research beyond diagnosis by providing a structured and prescriptive framework for improving maintenance capacity management. These impacts establish a basis for future implementation and performance measurement efforts within the organization.

Table 5. Expected Operational Impact of the Proposed Framework

Indicator	**Ambitious Target**	**Expected Improvement**
GSE Downtime Rate	Reduce by 15%	Reduction of workload bottlenecks and more efficient personnel allocation
Workload Balance Across Specialties	Variability ≤ ±10% between specialties	Increased equipment availability and operational readiness
Corrective Maintenance Costs	Reduce by 10%	Optimization of maintenance-related resource consumption
Effective Personnel Availability	Increase by 10%	Greater workforce flexibility and response capability
Coverage of Critical Competencies	Achieving 90% competency coverage	Reduced dependence on individual experts and improved task execution
Preservation of Technical Knowledge	100% documentation of critical positions and procedures	Lower risk of knowledge loss and improved organizational continuity

The performance targets presented in Table 5 were not arbitrarily defined. They were estimated based on the diagnostic findings obtained during the assessment phase, including workload distribution analysis, maintenance capability gaps, competency coverage evaluation, and Pareto prioritization results. The proposed targets represent ambitious but achievable improvement levels considering the magnitude of the identified deficiencies and the expected effects of the recommended interventions. Specifically, reductions in GSE downtime and corrective maintenance costs were estimated from the expected elimination of workload bottlenecks and improved resource allocation. Targets related to personnel availability and competency coverage were derived from the projected impact of the proposed training and capability-development initiatives. Likewise, the objective of full documentation of critical positions and procedures was established to ensure complete preservation of organizational knowledge. Therefore, the values shown in Table 5 should be interpreted as planning targets intended to guide future implementation and performance measurement efforts rather than as validated operational results.

Expected operational improvements were estimated based on comparative workload redistribution, capability-gap analysis, competency assessment results, and Pareto prioritization outcomes obtained during the diagnostic phase. The proposed targets do not represent measured outcomes but rather performance objectives derived from the projected effects of implementing the recommended framework components. Finally, operational coherence validation confirmed that the proposed strategies and maintenance capability distribution directly address the operational deficiencies identified during the diagnostic phase. Traceability was maintained between DOMPI capability gaps, SWOT/TOWS strategic analysis, and the final maintenance-standardization proposal. Additionally, Pareto analysis demonstrated that a limited number of structural deficiencies concentrated most maintenance limitations across operational units, validating the prioritization criteria adopted in the proposed framework.

6. Conclusion

The results confirmed significant asymmetries in maintenance capability distribution across operational units, including differences in equipment availability, personnel workload, infrastructure conditions, technical competencies, and maintenance resource allocation. Through the integration of the Guía Metodológica de Planeamiento por Capacidades established by the Colombian Ministry of National Defense, MAMAE quality attributes, operational indicators, and Pareto analysis, the study identified critical deficiencies affecting operational readiness, maintenance sustainability, and technical knowledge preservation within GSE maintenance environments. The principal contribution of this research is the development of an integrated capability-based maintenance framework combining hierarchical maintenance distribution, preventive-maintenance principles, modular technical training, technical knowledge management, and DOMPI-based capability planning into a unified operational structure adapted to distributed military aerospace environments. Unlike traditional maintenance approaches focused primarily on corrective interventions, the proposed framework aligns maintenance execution, personnel competencies, infrastructure requirements, and operational demand under a standardized and scalable capability-management model. Additionally, the proposed framework is expected to reduce operational asymmetries, improve maintenance workload distribution, strengthen institutional learning, and reduce dependency on individual expertise through standardized maintenance structures and knowledge-management mechanisms. Overall, the study provides an operationally applicable and scalable approach for improving maintenance standardization, maintenance sustainability, and long-term operational readiness within military aerospace support systems.

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