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Maintenance Support Services as Strategic Enablers of Asset Reliability and Operational Excellence: A Mixed-Methods Archival Case Study of Liquefied Natural Gas Operations

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Abstract: Maintenance support services (MSS) - the work-access, lifting, workshop-based repairs, spare-parts stewardship, plant lighting, plant's heavy and light duty mobility, measurements, inspection and testing services, welding and fabrication, planning and scheduling, bundle pulling and digital work-history functions that convert maintenance intent into executable work - remain largely implicit in the international asset-management standards, including ISO 55000:2014, ISO 55001:2014, ISO 14224:2016, and EN 15341:2019 - notwithstanding their earlier formalisation as *aide au soutien en maintenance* in the French regional standard NF X60-500:1988 - an omission that systematically degrades reliability in high-hazard liquefied natural gas (LNG) operations. This study defines MSS as a reliability-enablement subsystem of the asset-management system, develops a comprehensive classification of MSS functions, quantifies their contribution to asset performance, and proposes an integrated performance and maturity framework. An exploratory mixed-methods design triangulated three evidence streams: qualitative document analysis of an 18-document operational corpus spanning 25 years of LNG experience; a weighted Pareto-style impact assessment across eight MSS functions; and a two-round Fuzzy Delphi expert panel, with validation against item-level and scale-level content validity indices (I-CVI ≥ 0.78; S-CVI/Ave ≥ 0.90), Kendall's coefficient of concordance ($W \geq 0.5$, $p < 0.05$), and Cronbach's alpha (≥ 0.70). The analysis yields a six-domain taxonomy - physical, technical, digital, specialised reliability, infrastructure, and coordination services - and a five-level maturity ladder progressing from reactive support to strategic reliability partnership. The top five MSS functions - work-front access; planning and scheduling; maintenance workshops; rigging, lifting, and heavy-duty equipment; and digital asset management - jointly account for 81% of cumulative MSS impact, consistent with the 80/20 maintenance-leverage principle. Documented 2017 turnaround outcomes include a reduction in jobs awaiting materials from 7% to 2%, 97% emergency-response-vehicle availability, 100% overhead-crane availability during the Train 3 turnaround, 90% heavy-duty equipment availability, US$2.65 million in three-year work-access cost avoidance, and US$26,700 in workshop-crane recovery savings. The framework equips asset managers, maintenance managers, turnaround teams, and executives to prevent support-overhead misclassification, apply explicit execution-readiness criteria, transition to competency-assured governance, and pursue net-zero alignment, Scope 1 emissions baselining, and life-cycle cost discipline, while linking frontline support functions to the United Nations Sustainable Development Goals as a transferable template for refining, petrochemical, nuclear, and mining operations. Building on - rather than superseding - earlier regional formalisations of maintenance support, this study is the first to consolidate strategic asset management, reliability-centred maintenance, and sustainability measurement within a single MSS maturity ladder grounded in longitudinal LNG archival evidence; it extends the ISO 5500x, ISO 14224, and EN 15341 standards family by isolating the support-function subsystem that those instruments leave implicit, establishing MSS as a distinct, standards-grounded discipline and a strategic enabler of asset reliability, operational resilience, and operational excellence across asset-intensive industries.

Keywords: maintenance support services; asset reliability; operational excellence; maturity model; Fuzzy Delphi method; liquefied natural gas; asset management; reliability-centred maintenance; sustainability; ESG.

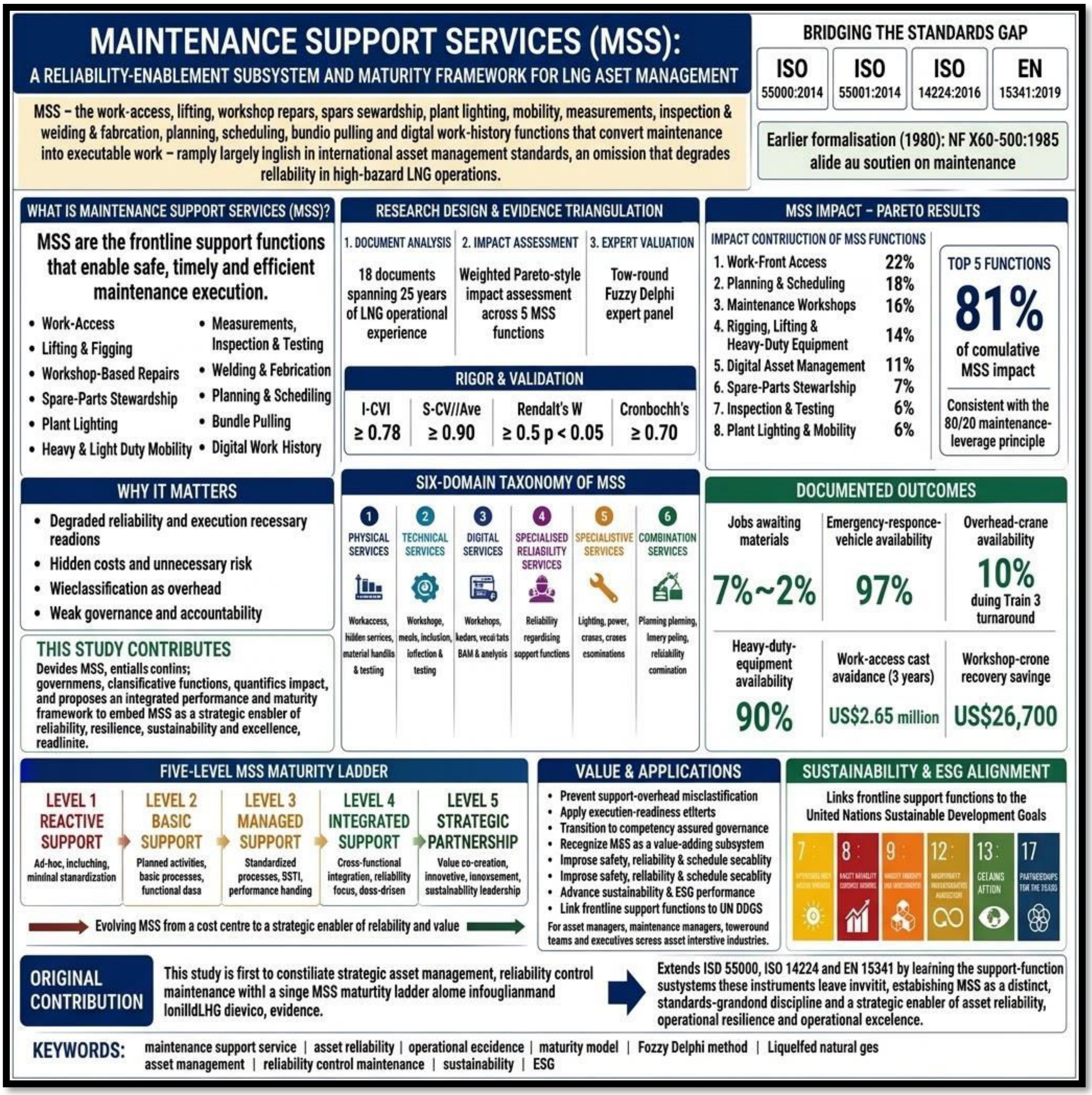


Figure 1: Graphical Abstract

1. Introduction

1.1 Defining maintenance support services

Maintenance performance is conventionally narrated through what the technician does inside the battery limit of the plant: the wrench-turning craft of preventive and corrective maintenance. This narrative is incomplete, much like the visible tip of an iceberg - the work front conceals a far larger, load-bearing support mass whose absence degrades reliability before the wrench is lifted (Asjad et al. 2016 Mar 7). The iceberg framing is the authors' synthesis of the archival corpus rather than a proposition established by the cited literature; its evidential basis is the 18-document, 25-year LNG corpus described in Section 4, and it is offered here as an organising device. Across three decades of LNG operational evidence, recurring failure-to-execute patterns - jobs awaiting materials, scaffolding delays, lifting-plan bottlenecks, defective tooling, and inconsistent digital work-history records - rarely announce themselves as technical-task failures; they are upstream support-layer failures. In attributing a pattern to the support layer, the archival analysis required the coded document to name a support-side precondition - access, lifting, tools, parts, permits, or records - as the operative bottleneck; planning, equipment, competence, and execution failures were coded to their own categories in the ISO 14224-derived scheme (Section 4.3), so the causal classification is disciplined by an explicit attribution rule. The technician cannot outperform the support environment within which they work because the two are strongly coupled (Asjad et al. 2016 Mar 7). This study's contribution is therefore to treat that coupling as an architectural proposition: maintenance support services convert maintenance intent into executable form and are separable from the technical craft only analytically, never operationally.

For the purposes of this study, MSS are operationally defined as "**the set of organisational support functions - work-access and scaffolding provision, rigging and lifting, and heavy-equipment transport, workshop recovery and fabrication, spare-parts stewardship and preservation, permitting and field coordination, and the digital work-history and data systems - that convert maintenance intent into executable work at the work front.**" The definition deliberately excludes the technical maintenance actions themselves (diagnosis, repair, and verification), design-stage maintainability attributes of the item, and the upstream procurement of materials; it includes logistics activity only to the extent that it gates execution readiness. The construct is complementary to, yet more operational than, the French *aide au soutien en maintenance* - defined in NF X60-500:1988 as "the ability of a maintenance organisation to provide the appropriate maintenance resources at the required location so as to execute the requested maintenance activity when it is required" (Feugier 2021: 27) - which frames support as a general organisational aptitude. MSS likewise differ from maintenance logistics, which addresses spares and supply-chain flows, and from maintainability, which is a design-stage attribute expressing the ease with which an item can be restored to a required condition (Feugier 2021: 27). Within this boundary, the recurring functions evidenced in the corpus map onto the six MSS domains of Section 5: scaffolding, rigging and lifting, and heavy-equipment transport instantiate physical support services; workshop recovery and overhead-crane support instantiate technical support services; and the digital work-history record instantiates digital support services.

Inside the battery limit, MSS converts maintenance intent into executable form: scaffolding access, rigging and lifting, confined-space permits, kitted and certified replacement parts, work-front illumination, environmental controls, and the digital work-history record that feeds ISO 14224 reliability-data integration (Hansen 2023 Jan 1: 54). Outside the battery limit, MSS sustains the upstream dependencies that make those work-front conditions possible: capital-spare preservation, long-lead-item stewardship, workshop-recovery capacity, certified workforce competence, overhead-crane and emergency-response-vehicle availability, and an integrated supply chain that synchronises inventory policy with maintenance planning (Okonkwo et al. 2021 Jan 1). When the governance of technical assurance, resource allocation, and risk quantification is fragmented across silos - as observed in the LNG operations under study - the asset absorbs the loss as degraded reliability, capital inefficiency, lost turnaround days, reconstruction overruns, and emissions baselines that cannot be reconciled against maintenance records. Maintenance performance therefore requires a rigorous support architecture, and this study frames MSS as that architecture.

1.2 Research Problem and Study Contribution

The standards family that governs this domain leaves MSS implicit. ISO 55000:2014 frames asset management as the set of coordinated activities that enables an organisation to realise value from assets in the achievement of its objectives (Sanchez-Londoño et al. 2022 Aug 29). ISO 55001:2014 specifies the requirements for an asset-management system structured around the Plan–Do–Check–Act cycle (Silva and Souza 2020 June 1). ISO 14224:2016 defines the reliability-data vocabulary for the petroleum, petrochemical, and natural-gas industries, including key concepts such as "safety-critical equipment" and "uncertainty". EN 15341:2019 extends this base with environmental and social indicators within the maintenance key performance indicator portfolio. A caveat on scope is warranted: the claim here is not that maintenance support has never been formalised anywhere - the French standard NF X60-500:1988 explicitly defined *aide au soutien en maintenance* as a pillar of operational dependability (Feugier 2021: 27) - but that **no current international standard defines MSS as a stand-alone discipline**, and that the regional precedent has no contemporary, LNG-specific, maturity-integrated successor within the ISO instruments that govern modern asset management. Similarly, ISO 55001 Clause 7 ("Support") mandates the resources, competence, and documented information that an asset-management system requires - but it does not specify *which* support functions maintenance execution depends on, how their readiness is measured, or how their capability matures. MSS is best understood as the domain-specific instantiation of Clause 7 at the maintenance-execution level, not as a competitor to it (Section 3.1). The omission is not merely terminological; it cascades, silently and systematically, into the LNG failure patterns documented across the 25-year operational corpus that anchors this study (Section 4.2). That omission is significant because the strategic standing of maintenance has changed. Maintenance has evolved from a "necessary evil" into a strategic, value-creating function within asset management (Wahl et al. 2026 May 22: 2). Its performance is consequently measured across machine-specific, operational, and strategic layers that must be linked explicitly to organisational strategy (Kumar et al. 2013 Aug 9), and its execution depends on systematic, standards-derived data models of the kind ISO 14224 codifies (Polenghi et al. 2021: 1347). The support subsystem that makes execution possible, however, remains unclassified, unmeasured, and ungoverned at the international level. This study addresses that gap by integrating maintenance support services as a reliability-centred support framework within the asset management system, drawing on the reliability-centred maintenance tradition, the industrial maintenance maturity lineage (Errandonea et al. 2022 Aug 17), and the EN 15341:2019 sustainability expansion. Section 2 defines the research objectives and questions; Section 3 reviews the literature; Section 4 details the methodology; Sections 5 and 6 present the taxonomy and results; Sections 7 and 8 elaborate the maturity and impact frameworks; and Sections 9–11 discuss implications, limitations, conclusions, and recommendations.

2. Research questions and objectives

Five objectives frame the study: (i) to define MSS within the context of reliability engineering and asset management; (ii) to develop a comprehensive taxonomy classifying MSS by operational function and strategic role; (iii) to quantify the contribution of MSS to asset performance and maintenance effectiveness; (iv) to examine the role and evolution of MSS using three decades of LNG operational experience; and (v) to propose an integrated MSS performance framework for optimising maintenance governance and reliability management. Correspondingly, the study addresses four research questions: What constitutes MSS within contemporary asset management systems? How do MSS influence maintenance execution and broader asset performance outcomes? Which MSS functions exert the greatest influence on reliability, availability, integrity, safety, and operational excellence? And what governance and performance-management mechanisms are required to optimise MSS as a strategic reliability-enablement system? Given the rapidly evolving literature on execution readiness in asset-intensive sectors, the study interprets these questions in the light of both the international standards family and published readiness and support-logistics research (Okonkwo et al. 2021 Jan 1; Driessen et al. 2014 Apr 14), situating MSS within a developing consensus rather than positioning it as an isolated framework.

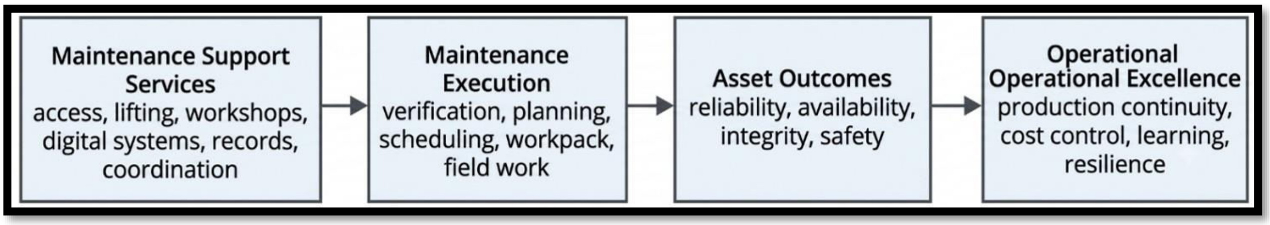


Figure 2: MSS ecosystem model

Figure 2 models MSS as the interface between maintenance intent and realised performance: MSS translate intent into executable form through six functional domains, generating quantifiable Reliability–Availability–Integrity–Safety–Cost and environmental, social, and governance outcomes.

3. Literature review and conceptual foundations

3.1 Asset management and reliability standards

The ISO 55000 series, published in January 2014 as the first official international standard on asset management, replaced PAS 55 and provides the common vocabulary and principles of value realisation from assets (Le et al. 2023: 107421). ISO 55001 structures the requirements for an asset management system around PDCA clauses covering organisational context, planning, support, operation, evaluation, and improvement, and is deliberately harmonised with ISO 9001 and ISO 14001 so that certified organisations can integrate management systems (Silva and Souza 2020: 304). Reliability engineering standards augment this base: ISO 14224:2016 prescribes a standard format for the collection and exchange of reliability and maintenance data, grounded in more than 25 years of field feedback compiled within the OREDA project (Selvik and Ford 2017: 16), and organises data around a nine-segment taxonomy from industry and business category down to part and maintainable item (Rashdan et al. 2019: 16). The emerging normative consensus treats ISO 5500x, ISO 14224, and EN 15341:2019 as complementary layers, an integration that contemporary data model research has begun to operationalise for maintenance decision-making (Polenghi et al. 2021: 1347).

Two qualifications to the "standards gap" argument deserve explicit treatment here, because a critical reader will raise them. *First*, the support concept has regional precedent: the French standard NF X60-500:1988 formalised *aide au soutien en maintenance* - the aptitude of a maintenance organisation to marshal the appropriate maintenance resources at the required location when the maintenance activity is required (Feugier 2021: 27) - alongside maintainability, within the framework of operational dependability. The gap is therefore not a universal definitional vacuum but the absence of a cohesive contemporary international standard and of an LNG-specific, maturity-integrated operationalisation. *Second*, ISO 55001 Clause 7 ("Support") already mandates resources, competence, awareness, communication, and documented information for the asset-management system as a whole (Silva and Souza 2020: 306). Why, then, is a distinct MSS discipline necessary? Clause 7 operates at the level of management-system *provisions*: it ensures that resources are available and that competence is assured, but it does not decompose the maintenance-support function set, specify execution-readiness criteria for work access, lifting, workshop recovery, or digital work history records, or define a progression of support capability. MSS operationalises Clause 7 at the maintenance-execution layer, converting its high-level provisions into a granular, function-level architecture with dedicated measures and a maturity ladder. The two are complementary: Clause 7 supplies the system-level mandate; MSS supplies the domain-level specification that gives that mandate operational content. This distinction mirrors the logic of integrated management systems, where harmonised standards deliver efficiency and value through structured integration rather than through the duplication of system-level provisions (Bernardo et al. 2015: 270).

3.2 Maintenance strategy, reliability-centred maintenance, and performance measurement

Maintenance strategies are generally categorised as corrective, preventive, or condition-based, with condition-based intervention introduced to ensure that preventive action occurs only when actually required (Alrabghi and Tiwari 2014 Dec 29). Reliability-centred maintenance constitutes the most developed evidence-based intervention logic: it defines maintenance tasks according to the functional consequences of failure (Ochella et al. 2021: 114902), and in LNG settings it has been extended with maintainability assessment under the UNE 151001 standard and Analytic Hierarchy Process weighting to devise strategic improvement plans for marine loading-arm resilience (Orellana et al. 2024 June 13). Facility integrity management systems for LNG critical assets operationalise RCM by prioritising equipment against health, safety, environment, and business consequences and translating risk-based equipment strategies into integrity programmes sustained across the operating life (Zaki and Sijm 2014). Measurement research complements these engineering logics (Kumar et al. 2013: 233). Indicators are formulated in hierarchies that serve users from the corporate level to the functional level (Kumar et al. 2013 Aug 9), and are commonly classified as equipment performance (availability, reliability, overall equipment effectiveness), process performance (ratio of planned to unplanned work, schedule compliance), and cost performance (labour, material, and maintenance costs) (Eti et al. 2005 June 14). Balanced Scorecard architectures translate maintenance strategy into operational measures across financial, customer, internal process, and learning and growth perspectives (Eti et al. 2005 June 14). The strategic maintenance performance management process demonstrates that performance measurement must be linked to the espoused strategy of the maintenance function to achieve maximum impact (Tsang 1998).

3.3 Support architecture, logistics, and maturity modelling

Research on maintenance optimisation has long noted that monolithic maintenance policies fail for heterogeneous asset populations, because systems comprising single machines or identical machines oversimplify the interactions of real manufacturing configurations (Alrabghi and Tiwari 2014 Dec 29). Integrated logistics support provides the conceptual basis for treating support as a designed system: it integrates maintenance logistics with product function, and in-service support costs for complex capital equipment frequently exceed two-thirds of the total cost of ownership (Galloway 1996 Feb 1). Spare-parts planning and control frameworks decompose supply-chain decisions hierarchically and expose the interfaces through which parts availability governs system availability (Driessen et al. 2014 Apr 14). Published readiness models reinforce this logic from the measurement side, treating readiness as a function of both maintenance support and spares supply rather than as a synonym for operational availability (Wang 2010 Jan 1). On the governance side, a family of maturity models has emerged - CMM/CMMI, Institute of Asset Management assessments, ISO 55001 capability assessment, the M3 industrial-maintenance model with its 18 maintenance-strategy domains (Errandonea et al. 2022 Aug 17), and the sustainable asset management maturity model, which extends ISO 55001 capability assessment with reliability-cost-carbon scorecards (Dalvi 2026 Jan 7). Maturity is understood as the extent to which organisational capabilities are fit to meet current and future stakeholder needs (Papic and Cerovšek 2019 Jul 10), and ISO 55000-based self-assessment methodologies operationalise this concept across six levels and 39 indicators (Le et al. 2021 Aug 15). Notably for the present argument, none of these models treats maintenance support as its unit of analysis: each embeds support functions - where they appear at all - as implicit inputs to broader organisational or enterprise capability ratings. This is precisely the gap that an MSS-specific maturity architecture fills: it converts the support functions that the M3, IAM, and ISO 55001 instruments leave implicit into an explicit, measurable, and governable capability domain (Section 6.6).

3.4 Sustainability, ESG, and maintenance

Sustainability considerations increasingly penetrate maintenance governance (Saihi et al. 2022). Maintenance-related external costs span the economic, environmental, and social pillars (Scope et al. 2020 Dec 18), and the EN 15341:2019 revision - covering key performance indicators of the maintenance function - explicitly gives greater emphasis to sustainability (Franciosi et al. 2021: 404), although a complete indicator set for the environmental and social dimensions remains under development (Saihi et al. 2022). Digitalisation reinforces this trajectory: Maintenance 4.0 architectures establish the digital baseline, and Maintenance 5.0 frameworks integrate human-centred and AI-driven strategies with sustainability and triple-bottom-line KPIs (Psarommatis et al. 2023 May 9), with recent transition research confirming that the shift from Maintenance 4.0 to Maintenance 5.0 is driven precisely by the convergence of sustainability, resilience, and human-centricity priorities (Aktef et al. 2025). Recent work links ISO standards and industrial maintenance practice to the achievement of the United Nations SDGs, integrates climate-change mitigation, SDG mapping, and emerging technologies into a single maintenance roadmap (Hauashdh et al. 2024 Jan 26), and quantifies the gains of combined asset-health and sustainability prioritisation, reporting 20–35% cost reductions and 25–40% decreases in carbon emissions relative to health-only approach (Dalvi 2026 Feb 10). Energy-industry evaluation studies likewise demonstrate that stakeholder and policy pressure is driving SDG-aligned corporate responsibility assessment in the sector (Dinçer et al. 2023: 103940).

3.5 Research gap

The literature review identifies a threefold gap. First, no current international standard defines maintenance support services (MSS) as a discipline: while the regional standard NF X60-500:1988 formalised the support concept as *aide au soutien en maintenance* (Feugier 2021: 27), its influence did not extend into the ISO 5500x, ISO 14224, or EN 15341 instruments that govern contemporary international practice, and no LNG-specific taxonomy operationalises it. Second, existing maturity models often treat sustainability and maintenance integration implicitly or as separate frameworks (Franciosi et al. 2023 Mar 30); they treat support implicitly, whether as a management-system provision (ISO 55001 Clause 7) or as an input to overall maintenance capability. Third, limited LNG-focused studies have quantified maintenance support service impacts specifically within the asset-management envelope (Al-Yafei et al. 2022). This study addresses all three gaps by integrating ISO 55000, EN 15341:2019, SAMMM, and RCM into a single MSS framework for LNG operations, isolating the support function subsystem that the international standards leave implicit.

4. Methodology

4.1 Research design

This study deployed an exploratory mixed-methods design to model MSS functionality, triangulating three evidence streams: qualitative document analysis, quantitative impact ranking, and Fuzzy Delphi expert validation. Combining multiple methods and data sources enhances the credibility and validity of findings (Meydan and Akkaş 2024), and the design follows established precedent in maintenance research that combines archival corpus evidence with expert panels (Sigsgaard et al. 2021: 476). The study distinguishes strictly among data (archival documents and records), analysis (coding, scoring, and validation), results (derived metrics and rankings), and interpretation (frameworks and inferences), so that no analytic claim exceeds what the evidence base supports.

4.2 Archival corpus and selection criteria

The corpus comprises 18 documents spanning 25 years of LNG operational history across multiple plants, stratified by executable procedures, governance instruments, and performance audits. Five criteria governed selection: temporal range (25 years of operational history); functional coverage (at least one entry per MSS domain); document-type stratification (procedures, governance instruments, and performance audits); standards alignment (terminology and data categories conforming to ISO 14224:2016 and ISO 55000/55001:2014); and triangulation (each MSS function supported by at least one governance document and one operational outcome document). Table 1 lists the primary archival sources.

Table 1. Primary data sources for the MSS framework

Document	Evidentiary role	MSS domain
Maintenance execution procedure	Codifies execution, verification, planning, and workflow closure	Maintenance governance
Planning and scheduling process	Optimises CMMS planning, prioritisation, and resource-risk mitigation	Maintenance coordination
Field support services SLA	Standardises rigging, lifting, work access, and service governance protocols	Logistics coordination
Scaffolding access systems control and usage	Standardises access requests, inspection, tagging, and compliance	Access control support
Heavy equipment management procedure	Integrates ownership, maintenance, reliability, availability, and life-cycle parameters	Asset logistics
IA workshop code of conduct and workflow	Standardises workshop environmental controls and procedures	Technical support
Preservation of capital spares	Specifies preservation protocols and technical availability models	Physical and technical resilience
Administration of maintenance man-hours	Quantifies labour time, progress, cost, and performance metrics	Labour data analytics

Document	Evidentiary role	MSS domain
Administration of maintenance records	Integrates maintenance data; enables trend analysis and predictive maintenance	Digital maintenance data
Work access provisioning strategy	Quantifies access bottlenecks, alternatives, and cost-saving redesign metrics	Access optimisation strategy
MSS achievement presentations	Quantifies operational capacity, availability, and performance constraints	Cross-domain evidence

Note: The full 18-document corpus additionally comprises seven internal working records (operational logs and reconciliation extracts) that could not be individually itemised without compromising the de-identification commitments of Section 4.6; all 18 documents were analysed in full. The tabulated documents are aligned with the ISO 14224 data categories used for coding (Section 4.3) and are read through an MSS lens, referencing the support concept of the earlier regional standard NF X60-500:1988 (Feugier 2021: 27).

Two methodological qualifications deserve explicit statement here. First, the corpus is weighted towards formal, audit-ready documentation, which is curated for compliance and may systematically under-report informal workarounds, near-misses, and unsuccessful initiatives that are important to understanding MSS failure modes. This selection bias is discussed in Section 9 (limitation one), where its impact on the representativeness of the taxonomy and maturity model is assessed. Second, the corpus documents a single operator family's practice; the framework's transferability therefore rests on analytical generalisation and multi-site replication rather than on statistical representativeness.

4.3 Qualitative document analysis

Each document was coded for support functions, dependencies, KPI language, bottlenecks, and execution examples, using a coding scheme derived from the ISO 14224 taxonomy (Ottermo et al. 2021: 9) and refined empirically through reconciliation cycles that stabilised analytical agreement. The coding scheme distinguished five failure-attribution categories - support-layer, planning, equipment, competence, and execution - so that a recurring pattern was assigned to the MSS layer only when the source document named a support-side precondition (access, lifting, tools, parts, permits, or records) as the operative bottleneck; this attribution rule was applied consistently across all 18 documents to prevent the causal classifications reported in Sections 5.2–5.4 from overreaching the evidence. Coded fragments were aggregated into six recurring MSS domains, and internal consistency was validated through member checking with two LNG reliability engineers selected for their direct supervisory exposure to the work access, lifting, workshop, and digital record functions; the small size of this member-checking sample is acknowledged as a limitation in Section 9, and it was complemented by the larger Fuzzy Delphi panel (Section 4.5). Quantified archival outcomes were separately reconciled against primary records drawn from plant maintenance services and workshops documentation, yielding the performance metrics reported in Section 5.2.

4.4 Quantitative Pareto-style impact scoring

A structured Pareto-style ranking was used to evaluate the eight MSS functions against three criteria: archival frequency (recurrence across the 18-document corpus); field-execution coupling (operational dependency derived from CMMS work orders, turnaround records, and procedure narratives); and impact severity (a hybrid metric combining archival financial and operational signatures - cost overruns, delay days, and rework frequency - with expert-rated severity on a 1–5 Likert scale). Scores were normalised on a 0–10 scale, and the composite impact score for each MSS function was computed as:

$$S_i = 0.40C_i + 0.35F_i + 0.25B_i$$

where S_i is the composite impact score of function i, C_i is its operational criticality, F_i its frequency of dependence, and B_i its business consequence. The weights favour criticality and frequency over business consequence because the archival evidence showed that access and planning failures recurred most frequently and carried the highest documented delay costs; the weight ordering was reviewed and endorsed by the expert panel during Delphi Round 1 as part of the validation protocol, and its illustrative - rather than statistical - status is explicitly acknowledged in Section 9. Cumulative impact percentages were derived from the empirical documentary evidence; the resulting 81% cumulative-mass figure for the top five functions is consistent with the 80/20 maintenance-leverage principle, under which approximately 80% of effects are produced by 20% of causes (Gopalan et al. 2024: 114483).

4.5 Expert validation via Fuzzy Delphi

A Maintenance, Reliability, and Turnaround expert team - comprising discipline leads, planners, schedulers, supervisors, reliability engineers, and spare-parts experts - rated each MSS function on relevance and execution criticality across two Delphi-style rounds, following the Fuzzy Delphi method. Item-level content validity indices were calculated for each function, with items retained at I-CVI ≥ 0.78, the recognised threshold for good content validity. The scale-level content validity index (S-CVI/Ave), computed as the mean of retained I-CVI values, targeted ≥ 0.90 (Shi et al. 2012). Inter-rater agreement across the eight functions was quantified using Kendall's coefficient of concordance (Torrecilla-Salinas et al. 2018: 19):

$$W = \frac{12S}{k^2(n^3 - n)}$$

where k is the number of raters, n the number of items, and S the sum of squared deviations of the rank sums, with W ranging from 0 (no agreement) to 1 (total agreement) (Scarf and Cavalcante 2011 Aug 29). Internal consistency was assessed with Cronbach's alpha (target ≥ 0.70) (Costa and Motta 2019: 156), interpreted with the caveat that alpha is a lower-bound reliability estimate that does not, by itself, index unidimensionality or internal structure (Sijtsma 2008: 107); it is therefore reported as supplementary to the I-CVI thresholds and Kendall's W, which carry the principal validation weight. Convergence between rounds was defined as non-significant change ($p > 0.05$, Wilcoxon signed-ranks test) (Kallia et al.

2021: 171). The validation design is summarised as follows: expert panel size $N \geq 12$ (projected); I-CVI ≥ 0.78 per function; S-CVI/Ave ≥ 0.90; Kendall's $W \geq 0.5$; Cronbach's alpha ≥ 0.70; and at least two Delphi rounds with iteration until convergence.

4.6 Ethics and data governance

All organisational data were de-identified prior to analysis to protect confidentiality, and the corpus derives from the corresponding author's professionally maintained archival records accumulated over more than three decades of practice within the oil and gas sector. The five selection criteria, the reconciliation cycles, and the member-checking step constitute the study's reliability and credibility safeguards. The Fuzzy Delphi expert validation involved professional practitioners supplying de-identified ratings on their own organisational functions; the study was conducted in accordance with institutional research ethics requirements; informed consent was obtained from all panellists prior to participation, and panel responses were anonymised at the point of collection. [Ethics approval: the authors confirm institutional review board (or equivalent) approval; insert committee name and reference number here.]

5. Results: MSS taxonomy and operational evidence

5.1 Six-domain taxonomy

Content analysis of the corpus converges on a six-domain taxonomy - physical, technical, digital, specialised reliability, infrastructure, and coordination services - which optimises organisational and informational capability integration over traditional fragmented service collections. Coded corpus evidence supports the optimisation claim: planning documents repeatedly identify maintenance overlap and duplicated service requests across separately governed SLAs, resource unavailability, and inconsistent work-history records across systems (Section 5.4), and the six-domain structure directly counteracts these fragmentation signatures by giving each support function a single organisational and data home. The taxonomy also aligns with the Global Forum on Maintenance and Asset Management's *Asset Management Landscape*, whose six asset-management subject groups and thirty-nine subjects map the enterprise context into which MSS domains slot as the execution-support function set (Papic and Cerovšek 2019: 389), while adding the LNG-specific granularity that the landscape deliberately does not prescribe. Table 2 presents the taxonomy.

Table 2. Six-part MSS taxonomy

MSS domain	Primary functions	Operational effect
Physical support services	Scaffolding, access and work systems, rigging, lifting, heavy-equipment transport	Implements physical access, optimises mobility, deploys standardised intervention protocols
Technical support services	Mechanical, electrical and instrumentation assets; fabrication, machining, welding, overhead-crane support	Optimises repair quality, accelerates internal recovery, reduces vendor dependence

Digital support services	SAP plant maintenance/CMMS workflows, job history, maintenance records, labour hours, performance metrics	Evaluates data visibility, optimises process control, implements KPI tracking
Specialised reliability services	Maintenance-team operations, condition monitoring, assurance support	Optimises diagnostic precision, mitigates operational risk, validates intervention quality
Infrastructure support services	HVAC systems, lighting, workshop environment, utilities	Standardises execution parameters, validates operational environment integrity
Coordination services	Planning, scheduling, resource alignment, permitting, field-support governance	Optimises resource readiness, demonstrates integration, maximises schedule attainment

The domains are operationally interdependent: unplanned work-access events increase maintenance latency, and equipment overhauls require integrated transport and lifting. MSS therefore constitute a unified architecture rather than a collection of disconnected services. The taxonomy is mapped to ISO 14224 asset-classification and data-life-cycle structures so that each domain feeds auditable reliability and maintenance data. Figure 3 illustrates the framework.

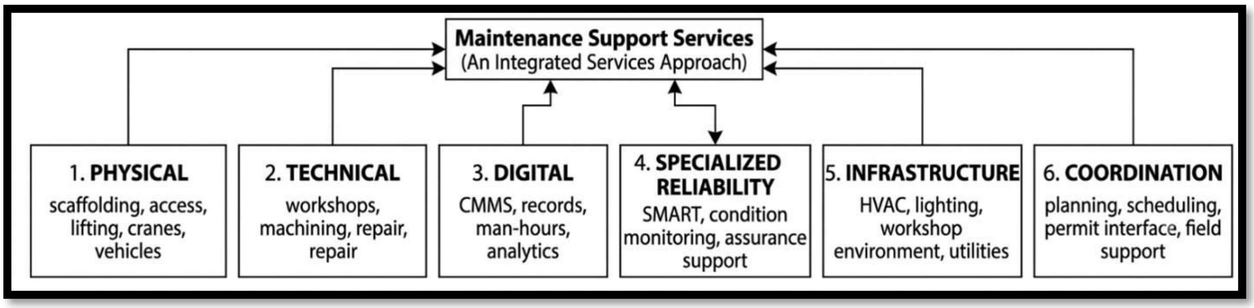


Figure 3: MSS taxonomy framework

5.2 Operational performance outcomes

MSS records quantify support for 19 mobile units and 67 overhead cranes plant-wide. The 2017 performance data demonstrate MSS impact: jobs awaiting materials decreased from 7% to 2% (a 5-percentage-point reduction); emergency response vehicle availability reached 97%; overhead crane availability 100% during the Train-3 turnaround; heavy-duty equipment availability 90%; work-access cost avoidance totalled US$2.65 million over a three-year period; and workshop crane recovery yielded US$26,700 in restored value. These outcomes illustrate the effectiveness of maintenance strategies aligned with wider LNG evidence: RCM increasingly employs AI and machine learning for condition monitoring and predictive workflows (Gidiagba et al. 2023 Jan 1), risk-based scheduling minimises cost while maximising reliability (Hameed et al. 2019 Jan 11), and integrity-management-anchored equipment strategies preserve reliability for LNG critical assets (Zaki and Sijm 2014). The comparative framing here is illustrative rather than confirmatory: the case metrics demonstrate the enabling effect of MSS within one operating envelope, while the cited literature establishes the strategic direction with which those outcomes are consistent.

5.3 Work-access provisioning and workshop recovery

Scaffolding access impeded maintenance execution during peak demand, and the implementation of alternative access and redesign options yielded US$2.65 million in three-year savings by reducing latency and optimising maintenance economics. Workshop evidence confirms the restoration of fabrication workshop crane functionality and the maintenance of 100% overhead crane availability during the Train-3 turnaround; specialist interventions and tank crane optimisations achieved further quantifiable cost reductions. The management implications are as instructive as the figures: the work-access programme converted a recurring access bottleneck into a planned, resourced capability, while the workshop-recovery initiative demonstrated that internal technical support reduces vendor dependence and shortens recovery latency. The full quantitative record - including emergency response vehicle and heavy-duty equipment availability at 97% and 90% respectively - is consolidated in Section 5.2, to which the reader is referred for the complete performance data.

5.4 Structural-deficiency evidence and Pareto-style ranking

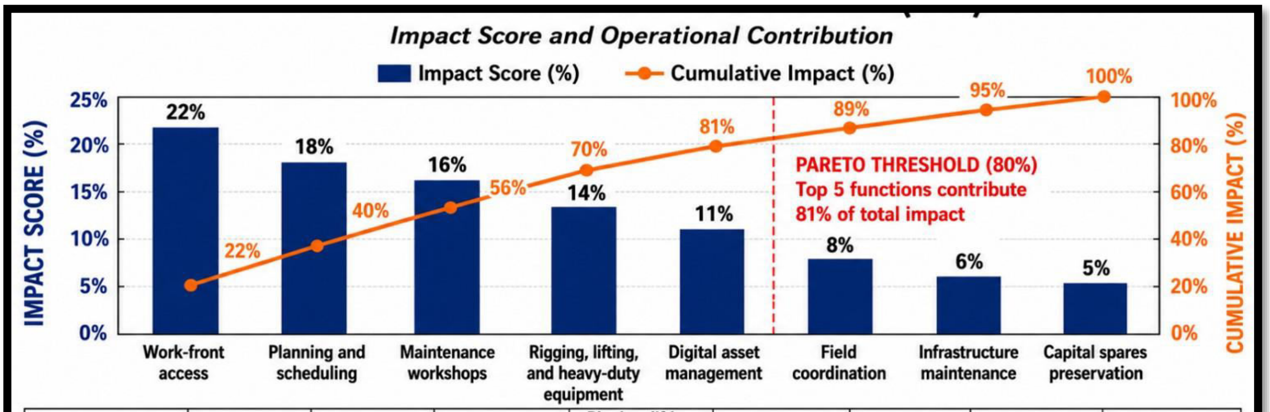
Archival planning procedures identify recurring structural deficiencies - maintenance overlap, prioritisation errors, resource unavailability, and delays - that drive quantifiable economic and reliability losses (Wu et al. 2025), while MSS achievement presentations document workload pressure, backlogs, open vacancies, labour supply constraints, and contractor reliance. Mitigation requires formal multi-line planning frameworks that incorporate resource uncertainty and rolling-window rescheduling logic (Deenen et al. 2026: 4); although the cited framework originates in semiconductor manufacturing, its transfer rests on a structural analogy - both settings confront stochastic resource contention, release constraints, and deadline-sensitive work portfolios - and its adoption here employs a generalisable scheduling logic that must be adapted to high-hazard conditions, where permitting, isolation, and lift-planning gates take precedence over the purely economic objectives of the semiconductor context. Studies show that system fragility translates into execution delays, rework, schedule instability, and duration slippage (Santolini et al. 2021: 2). Table 3 presents the Pareto-style impact ranking of the eight MSS functions.

Table 3. MSS function impact ranking

MSS function	Rank	Impact score	Operational contribution
Work-front access	1	22	Enforces access protocols within high-density LNG assets
Planning and scheduling	2	18	Synchronises resource scheduling and asset integration

MSS function	Rank	Impact score	Operational contribution
Maintenance workshops	3	16	Optimises maintenance recovery; validates quality control
Rigging, lifting, heavy-duty equipment	4	14	Executes lift operations; deploys specialised equipment
Digital asset management	5	11	Standardises control, visibility, and traceability
Field coordination	6	8	Mitigates scheduling conflicts; enhances short-interval control
Infrastructure maintenance	7	6	Stabilises critical infrastructure; optimises uptime metrics
Capital spares preservation	8	5	Maintains long-lead-item integrity; ensures deployment readiness

The impact scores operationalise the Section 4.4 composite: each score aggregates (i) the archival frequency of documented support-driven delays for the function, (ii) the coupling strength evidenced by the share of CMMS work orders and turnaround activities gated on the function's availability, and (iii) impact severity indexed to documented delay days, cost overruns, and rework, normalised on a 0–10 scale and weighted 0.40/0.35/0.25. The operational contribution column describes the mechanism by which each function translates readiness into performance - for example, the score of 22 for work front access reflects the highest frequency of documented access-gated delays combined with severe delay-day consequences, whereas the score of 5 for capital spares preservation reflects lower recurrence despite high unit-consequence severity. The top five functions account for 81% of cumulative impact, corroborating the 80/20 maintenance leverage principle (Rahman et al. 2022: 925). The ranking applies an evidence-weighted impact score; the percentages displayed in the Pareto chart (24%, 16%, and 12% for the leading functions) represent conceptual weightings derived from documentary evidence rather than raw CMMS statistical frequencies. Figures 4–6 present the Pareto analysis, the MSS value chain, and the operational dependency network.



MSS Function	Work-front access	Planning and scheduling	Maintenance workshops	Rigging, lifting, and heavy-duty equipment	Digital asset management	Field coordination	Infrastructure maintenance	Capital spares preservation
Rank	1	2	3	4	5	6	7	8
Impact Score (%)	22%	18%	16%	14%	11%	8%	6%	5%
Cumulative Impact (%)	22%	40%	56%	70%	81%	89%	95%	100%

KEY INSIGHT: The top 5 MSS functions contribute 81% of the total impact on maintenance effectiveness and asset performance. Targeted improvement in these areas will yield the greatest operational and reliability benefits.

Source: *Compiled from 30 Years of LNG Operations Data and Expert Assessments (1995–2024)*

Note: *Impact Score (%) = (Impact Score / Total Impact Score) × 100*

Figure 4: Pareto analysis of MSS functions

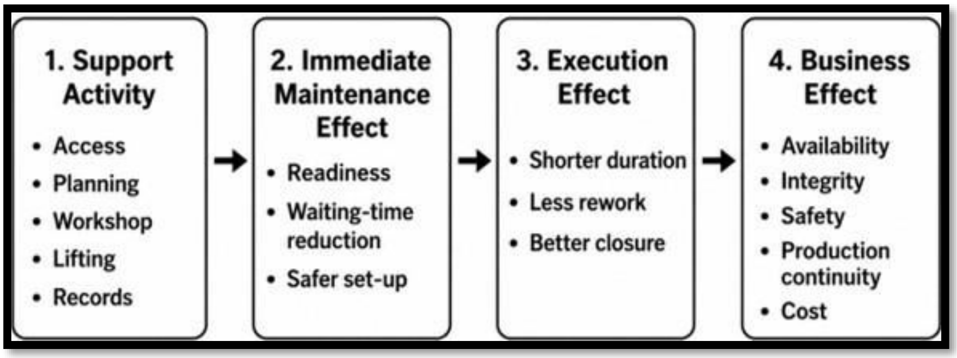


Figure 5: MSS value chain

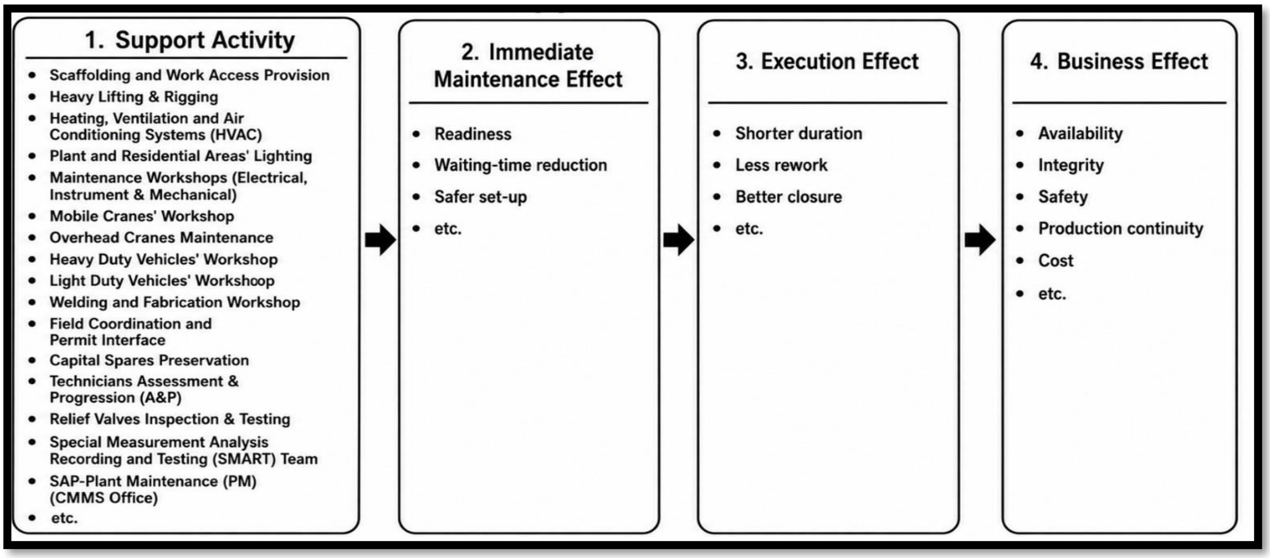


Figure 6: Operational dependency network

5.5 Assessment and progression programme

MSS implements a structured assessment and progression programme in which technicians complete formal developmental training under senior supervision and A1-certified consultants execute independent assessments. The programme operationalises the human capital dimension of Smart Maintenance, transforming tacit shop floor knowledge into auditable competency records aligned with ISO 14224 reliability data taxonomies; workforce competence is consistently identified as a critical determinant of maintenance programme success (Alsyouf 2009 May 28). The programme reconfigures MSS from a service delivery layer into a competence governance architecture that standardises intervention quality across mechanical, electrical, instrumentation, fabrication, machining, welding, and overhead crane operations, and its data discipline mitigates the performance degradation that fragmented, siloed records otherwise induce in data-driven maintenance management (Idemudia et al. 2024: 1681).

6. Discussion

6.1 MSS as an applied extension of the standards family

The MSS taxonomy operationalises the provisions of ISO 55000:2014, ISO 55001:2014, ISO 14224:2016, and EN 15341:2019 by combining the physical, technical, and digital infrastructure into a single vocabulary that translates strategic requirements into execution-ready instruments - while acknowledging, as Section 3.1 establishes, that the support concept itself has older regional roots in NF X60-500:1988 (Feugier 2021: 27). This complements the SAMMM lineage by applying standards to context-specific operational envelopes (Dalvi 2026 Jan 7), and it extends the ISO 55001 PDCA architecture. On the nature of that extension: ISO 55001 Clause 7 supplies the system-level provisions for resources, competence, and documented information, to which MSS adds the domain-level specification - specifying which support functions must be present, how their readiness is measured, and how their capability matures - so that the PDCA cycle at the maintenance-execution control level has concrete objects to plan, execute, check, and act upon. The structural alignment of ISO 55001 with ISO 9001 and ISO 14001 (Silva and Souza 2020 June 1) is what makes this integration mechanism available: MSS indicators and assessment activities are inserted into the support, operation, and evaluation clauses rather than standing outside the management system, and the integrated management systems literature confirms the efficiency and value benefits of such structured integration (Bernardo et al. 2015: 264).

6.2 Impact pathways across RAISC and ESG

MSS impacts were partitioned across six domains - reliability, availability, integrity, safety, cost, and sustainability/ESG - positioning support services as the lowest-consequence execution-readiness layer and exposing latent support failures to RAISC and ESG performance reporting. Carbon intensity per maintenance man-hour, material waste, methane venting, and refrigerant leak indicators are mapped to specific MSS functions: rigging and lifting to Scope 1 leak events, workshop recovery to material waste, and digital asset management to the data integrity required for emissions reconciliation. This indicator logic is consistent with validated sustainability KPI portfolios for maintenance (Saihi et al. 2022 January 1) and with the Maintenance 5.0 agenda, which integrates sustainability metrics and traceability in support of net-zero pathways (Psarommatis et al. 2023 May 9), as well as with energy-industry evaluation methods that embed SDG and corporate-responsibility criteria in performance assessment (Dınçer et al. 2023: 103940).

6.3 Integration with reliability-centred maintenance

The LNG context confirms the applicability of RCM (Gidiagba et al. 2023 Jan 1). The MSS framework retains RCM intervention logic definitions while specifying the support functions that operationalise RCM interventions at the execution layer: where RCM analyses define condition-based, preventive, and predictive actions, MSS guarantees that access, lifting, tools, parts, and competence are available at the moment of intervention. This separation of analytical intent from execution readiness mirrors predictive maintenance paradigms that distinguish "decide" from "execute" functions within a structured, digitalised maintenance cycle (Algabroun et al. 2020 Dec 30). MSS and readiness-oriented constructs in the published literature are complementary rather than competing: readiness indices measure the state of preparation, whereas the MSS taxonomy specifies what must be prepared and how that preparation is governed (Okonkwo et al. 2021 Jan 1).

6.4 Supply chain and materials-readiness linkages

The materials-readiness and maintenance-driven supply-chain performance model (Okonkwo et al. 2021 Jan 1) and the spare parts planning-and-control framework (Driessen et al. 2014 Apr 14: 3) describe the upstream dependencies of execution readiness. The MSS taxonomy integrates these dependencies explicitly: capital-spares preservation, long-lead-item readiness infrastructure, and workshop recovery form a dedicated function cluster that supports reliability-cost-carbon scorecard assessment in the manner of SAMMM (Dalvi 2026). Evidence indicates that aligning preventive maintenance programmes with reliability engineering reduces cost, focuses on operational reliability, and is consistent with a proactive reliability culture that decreases expenditure by displacing reactive repair (Eti et al. 2006 Apr 20).

6.5 Workforce competence as a governance mechanism

The A&P programme embeds human capital governance at the operational boundary between maturity Levels 2 and 3, with consultant-led assessments producing leading KPIs - progression rate, certification coverage, and time to mastery - that complement traditional lagging KPIs. This mechanism directly mitigates the archive-documented bottlenecks of workload pressure, vacancies, and contractor reliance, and it transforms technician development into a codified, auditable governance process that incorporates technical, economic, environmental, and social KPIs, building upon the framework of EN 15341:2019.

6.6 Comparison with established maturity models

The proposed MSS maturity framework benchmarks against established maintenance models, preserving the demonstrated progression from reactive through planned and proactive to strategic maintenance (Bangemann et al. 2006 July 6). Unlike IAM and ISO 55001 assessments, which evaluate enterprise asset-management capability and conformity respectively (Papic and Cerovšek 2019 July 10; Le et al. 2021 August 15), the MSS framework isolates maintenance support as a reliability-enablement subsystem and evaluates its dedicated physical, technical, digital, infrastructure, and coordination capabilities, thereby extending maturity theory by quantifying the support-service deficiencies that constrain asset reliability. Three clarifications sharpen this comparison. First, ISO 55001's Clause 7 ("Support") is not treated as failing to address support; it is acknowledged as the system-level mandate that MSS makes operational at maintenance-execution granularity - the framework is therefore an extension of Clause 7, not a dismissal of it. Second, the comparative positioning engages the most recent paradigm evolution: the Maintenance 5.0 agenda, which couples sustainability indices with human-centric, data-driven maintenance (Aktef et al. 2025), is explicitly aligned with the Level 5 end-state of the ladder (Section 7.2), and the sustainability-integrated maturity lineage (Franciosi et al. 2023 March 30) informs the ESG columns of Table 5. Third, the novelty claimed here is not the historical invention of the support concept - NF X60-500:1988 formalised *aide au soutien en maintenance* decades earlier (Feugier 2021: 27) - but its contemporary operationalisation as a taxonomy, an impact ranking, and a maturity ladder specifically calibrated for high-hazard LNG operations within the international standards envelope.

Table 4 compares the frameworks.

Table 4. Proposed MSS maturity framework versus established maintenance maturity models

Feature	Proposed MSS framework	M3 model	CMMI-inspired models	IAM maturity	ISO 55001 assessment
Primary objective	Quantifies MSS maturity; optimises reliability enablement	Assesses overall maintenance capability (Errandonea et al. 2022)	Improves organisational process maturity (April et al. 2005)	Assesses enterprise asset-management capability (Le et al. 2021: 442)	Evaluates ISO 55001 compliance (Silva and Souza 2021)
Primary focus	Maintenance support ecosystem	Entire maintenance function	Maintenance processes and organisational capability	Asset life-cycle management	Asset-management system effectiveness

Feature	Proposed MSS framework	M3 model	CMMI-inspired models	IAM maturity	ISO 55001 assessment
Unit of analysis	Support-service functions	Maintenance organisation	Organisational processes	Enterprise asset management	Management system
Core dimensions	Physical, technical, digital, infrastructure, reliability, coordination	18 maintenance-strategy domains	Standardisation, capability, continuous improvement	Leadership, governance, life cycle, risk, decision-making	Leadership, planning, support, operation, evaluation, improvement
Execution-readiness emphasis	High	Moderate	Moderate	Low	Moderate
MSS explicitly assessed	Yes	Limited	No	No	No
Reliability-enablement perspective	Central	Indirect	Indirect	Indirect	Indirect
Field-support evaluation	Explicit	Limited	Limited	Limited	Limited
Primary application	Optimisation of execution readiness and operational reliability	Enterprise maintenance-capability improvement	Organisational process improvement	Strategic asset-management improvement	ISO 55001 conformity assessment
Novel contribution	Formalisation of MSS as a discrete discipline with dedicated maturity assessment	Comprehensive maintenance-maturity assessment	Process-capability maturity	Enterprise asset-management maturity	Standards-based management-system assessment

Note: "No" in the MSS column for ISO 55001 indicates the absence of an explicit MSS function-level assessment within the standard's published clauses, not the absence of a Support provision; Clause 7 is the system-level mandate that the MSS framework operationalises. The comparison is complemented by the recent sustainability-integrated maturity literature (Franciosi et al. 2023 Mar 30; Aktef et al. 2025) and the Maintenance 5.0

paradigm (Aktef et al. 2025), which the proposed framework's Level 5 end-state explicitly incorporates.

7. MSS maturity and impact framework

7.1 Impact domains

MSS implementation drives measurable performance across six domains: reliability (diagnostic accuracy, job preparation, repair quality); availability (reduced waiting time for access, lifting, transport, coordination); integrity (inspection, testing, fabrication, closure); safety (work-at-height controls, lifting governance, worksite readiness); cost (rework, delays, standby time, execution inefficiencies); and sustainability/ESG (governance, environmental, and social performance). Grounded in EN 15341:2019 (Franciosi et al. 2021: 404), the framework tracks carbon intensity (kg CO_2e per maintenance man-hour), material waste (kg), and methane venting (m^3), and integrates these indicators within a maturity-based assessment aligned with Maintenance 4.0/5.0 decarbonisation paradigms. The sustainability dimension is anchored in the validated maintenance-sustainability measurement literature: the maturity-integrated assessment model of Franciosi et al. demonstrates exactly this coupling of maintenance maturity with sustainability indices (Franciosi et al. 2023 Mar 30), and the Maintenance 5.0 transition literature establishes the strategic context in which sustainability, human-centricity, and data-driven reliability converge (Psarommatis et al. 2023).

7.2 Five-level maturity ladder

Table 5 operationalises the performance assessment model as a five-level maturity ladder with ESG integration (Oliveira et al. 2024: 5), supported by the capability definitions of the taxonomy.

Table 5. Five-level MSS maturity ladder with ESG integration

Maturity level	MSS characteristics	Governance characteristics	Typical KPIs	ESG integration
Level 1 – Reactive support (Franciosi et al., 2023)	Services mobilise post-disruption; fragmented, manual activities; minimal planning and coordination	Reactive decision-making; undefined accountability matrices; absent monitoring and documentation metrics	Response time (h); emergency work-order frequency; maintenance delay metrics	Environmental: limited consideration, reactive waste handling, high resource consumption. Social: compliance-driven safety, limited workforce development. Governance: minimal documentation, weak accountability, inconsistent compliance
Level 2 – Basic support	Core services operate independently; standardised	Functional supervision; basic SLAs; periodic	Schedule compliance; workshop turnaround time; equipment	Environmental: basic waste management, energy-awareness initiatives. Social: structured HSE training, competency development.

	procedures govern routine activities	performance reviews	utilisation; service response time	Governance: documented procedures, statutory compliance
Level 3 – Structured support	Services standardised and performance-managed; integrated into maintenance planning and scheduling	Cross-functional coordination; tracked KPIs; integrated CMMS; routine performance reporting	Work readiness index; backlog age; support availability; digital workflow compliance	Environmental: resource efficiency, emissions monitoring, optimised equipment utilisation, reduced maintenance waste. Social: competency assurance, contractor management, enhanced safety culture. Governance: risk-based decision-making, KPI dashboards, audit readiness, structured governance
Level 4 – Integrated support	Services operate as an integrated reliability-enablement system supporting asset life-cycle management	Enterprise-wide governance; predictive planning; integrated risk and asset-management processes	MTBF improvement; maintenance productivity; maintenance readiness index; support service reliability; life-cycle cost reduction	Environmental: carbon-reduction initiatives, circular-economy practices, predictive maintenance minimising environmental impact, sustainable resource utilisation. Social: workforce well-being, knowledge management, diversity, contractor collaboration, organisational learning. Governance: integrated assurance, transparent reporting, cyber-secure digital systems, ISO 55001 alignment
Level 5 – Strategic reliability partner	Services demonstrate strategic business capability; reliability, resilience, and sustainability optimised through predictive and data-driven decisions; strategic investment planning; innovation	Executive-level governance; continuous improvement; benchmarking; AI-enabled optimisation; maintenance support investment decisions	Reliability contribution index; ESG performance index; operational resilience index; production continuity; asset value realisation; return on maintenance support investment	Environmental: net-zero supports strategies, climate resilience, sustainable procurement, biodiversity stewardship, full life-cycle environmental optimisation. Social: human-capital development, organisational resilience, community engagement, ethical supply chains, industry safety leadership. Governance: ESG-integrated decision-making, enterprise risk governance, digital transparency, AI-enabled governance, external benchmarking, sustainability reporting consistent with global ESG frameworks

Mapping to the six taxonomy domains: each maturity level's MSS characteristics operationalise the six domains in parallel - physical support (access, rigging, lifting, heavy-duty transport), technical support (workshop recovery, fabrication, overhead cranes), digital support, specialised reliability (condition monitoring, assurance), infrastructure, and coordination (planning, scheduling, permitting) - such that a plant's overall level is the lowest domain level its governance sustains, preventing the common failure mode in which digital maturity races ahead of physical support readiness. Maturity levels are cumulative: higher tiers integrate strategic visibility while retaining operational capabilities, and progression is governed by KPI evidence - from activity volume and response time metrics at early stages, through access delay, lifting plan readiness, workshop turnaround, rework, record quality, and history file completeness at intermediate stages, to capital spares health, emergency equipment availability, and support-related work deferral rates in mature operations. Maturity is thereby framed as an evolving commitment to governance rather than a certification event. The Level 5 end-state intentionally converges with the Maintenance 5.0 paradigm, whose sustainability, human-centricity, and data-driven reliability pillars are reflected in the ESG and KPI columns (Psarommatis et al. 2023), (Aktef et al. 2025). Figure 7 illustrates the ladder.

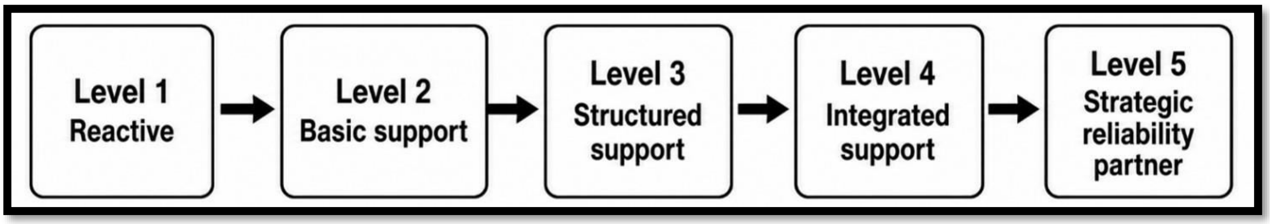


Figure 7: MSS maturity model

7.3 Integrated reliability enablement framework

Figure 8 defines MSS as the orchestration layer integrating asset context with execution quality, performance learning, and capital reinvestment, applying integrated logistics support principles to industrial LNG operations (Lopac et al. 2016 Jan 1). The inclusion of a corrective and preventive action discipline within the framework strengthens the closed-loop assurance cycle between execution failures and governance response, consistent with quality-system practice in adjacent regulated industries (Pujari 2026 Mar 13).

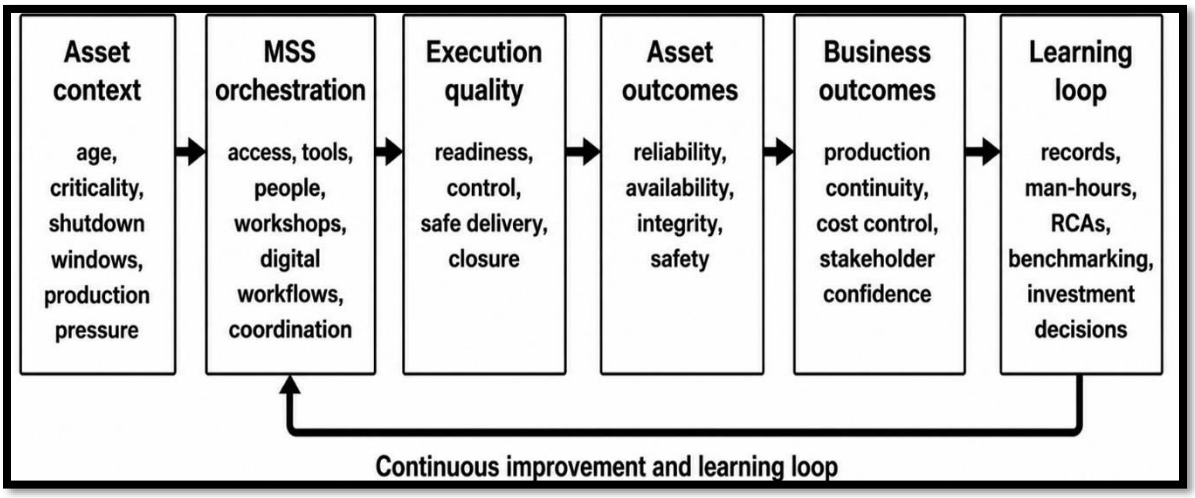


Figure 8: Integrated reliability enablement framework

8. Implications

8.1 Theoretical implications

The study defines maintenance support services as a cross-functional subsystem of asset management that implementations rarely model explicitly, and proposes a measurement and maturity vocabulary aligned with ISO 55001, EN 15341:2019, and the M3 maturity lineage. The novelty claim is deliberately scoped: the support concept has historic formalisation in NF X60-500:1988 (Feugier 2021: 27), so the contribution advanced here is the contemporary, standards-integrated, LNG-specific taxonomy and maturity framework, addressing a lack of current integration rather than a historical definitional vacuum. The study thereby advances strategic maintenance performance as a measurable, multilevel concept (Kumar et al. 2013: 245) and isolates the support function layer as a distinct unit of analysis for maturity assessment.

8.2 Practical implications

For asset managers, integrating MSS into asset-standards facilitates alignment with ISO 9001 and ISO 14001 management systems; the cited integration literature (Bernardo et al. 2015: 263) supplies the general structural justification - efficiency gains, reduced duplication, and improved coordination from harmonised management systems - while the MSS-specific integration mechanism is the authors' own contribution, developed in Section 6.1. For maintenance managers, the five-level maturity table developed in this study, informed by the broader maturity-modelling literature (Proença and Borbinha 2016), facilitates direct migration from manpower-centric to competency-assured governance. For project and turnaround teams, the framework mandates explicit readiness criteria for work access, lifting, workshop recovery, and digital workflows, supported by formal spare-parts and risk-based scheduling frameworks (Driessen et al. 2014 Apr 14: 3), with integrity-management-anchored equipment strategies as upstream governance. For executives, MSS benchmarking against equipment-availability metrics - a benchmarking practice proposed in this study rather than an established industry standard - can support net-zero pathway integration, Scope 1 emissions baselining, and life-cycle cost discipline by aligning with the real-time operational data and emissions-reduction practices documented in the sustainability literature (Karki et al. 2022).

8.3 Societal implications

By linking frontline support activities to UN-SDG-aligned decarbonisation indicators, the framework establishes a transferable template for optimising sustainability in high-hazard energy infrastructure (Herrera-Sánchez et al. 2024; Cherepovitsyn et al. 2020: 1069), applicable to refining, petrochemical, nuclear, and mining contexts with similar support-function dependencies.

9. Limitations

Five limitations qualify the findings without invalidating the research objectives. First, corpus selection bias: the 18-document archive privileges successful outcomes and audit-ready documentation, so near-misses, unresolved escalations, and failures are underrepresented; future studies should triangulate against anonymised incident logs and reliability-engineering records. This bias is intrinsic to professionally maintained archival corpora and affects the representativeness of the taxonomy's negative space - the failure modes the taxonomy anticipates but the corpus under-records. Second, the Pareto weightings are illustrative: the percentile ranks and the 81% cumulative-mass figure are evidentiary illustrations derived from documentary evidence rather than CMMS-derived frequencies, and empirical replication on representative CMMS samples is required for population-level benchmarking. Third, expert panel composition: content-validity consensus is sensitive to panel size (Artino et al. 2014: 467); the member-checking step relied on two senior reliability engineers, and although the study design mitigates these concerns through the reported thresholds and the complementary 12-plus-expert Fuzzy Delphi panel, future studies should report effect sizes explicitly. Fourth, Kendall's W is sensitive to tied rankings and to the operationalisation of criticality across maintenance sub-domains; Cronbach's alpha provided supplementary evidence but does not substitute for criterion-based validity, and it is a lower-bound reliability estimate rather than an index of unidimensionality (Sijtsma 2008: 107). Fifth, the study makes no causal claims: the findings demonstrate strong operational dependence and organisational plausibility - correlation, not causation, between MSS function maturity and asset-reliability outcomes. Finally, the novelty of the MSS definition itself should be read against NF X60-500:1988, which formalised *aide au soutien en maintenance* decades before the international standards family; the contribution claimed here is the LNG-specific taxonomy, impact quantification, and maturity integration, and multi-site replication is required for generalised operational benchmarking across the sector, particularly because the corpus derives from multiple LNG facilities (some now closed).

10. Conclusion and Recommendations

The five objectives were executed. MSS is defined as a reliability-enablement subsystem aligned with ISO 5500x, EN 15341:2019, RCM, M3, and SAMMM - building on, and distinctly more operational than, the regional NF X60-500:1988 formalisation of maintenance support; a six-domain taxonomy classifies MSS into physical, technical, digital, specialised reliability, infrastructure, and coordination services; MSS contributions to maintenance effectiveness and to the reliability–availability–maintainability envelope are quantified through Pareto-style impact ranking and Fuzzy Delphi consensus; and an ESG-enabled performance and maturity framework provides the mechanisms for governing, benchmarking, and improving maintenance support capability. The distinction from ISO 55001 Clause 7 is restated here for clarity: Clause 7 mandates that support resources, competence, and documented information exist within the asset-management system; the MSS framework specifies, for the maintenance function, *which* support services must exist, how their readiness is measured, and how their capability matures - making MSS the Clause 7 provision operationalised at the execution level rather than a parallel system. The empirical grounding is substantial: maintainability enhancements demonstrably improve LNG logistics infrastructure resilience; planning and scheduling (80% and 75% of respondents respectively), spare part availability (60%) and spare part reliability (68%) are confirmed as the infrastructure elements driving maintenance preparedness; support quality influences operational dependability in high-hazard facilities; and digitised data flows and advanced analytical capabilities provide the granular, proactive insights required for inspection schedule optimisation, maintenance intervention refinement, and emissions baselining. The study recommends that a triple-bottom-line layer be incorporated into the MSS taxonomy and the five-level maturity framework, complementing existing technical and cost indicators - environmental measures capturing rework-driven material waste, emissions, and energy intensity; social measures covering occupational health and safety, technician competency progression, and contractor fairness; and economic measures quantifying life-cycle cost and the cost of poor quality - in line with the validated portfolio of 34 environmental, 15 social, and 14 economic maintenance-sustainability indicators reported by Saihi et al. Practitioners should: conduct MSS gap assessments using the maturity ladder of Table 5, prioritising the top five functions of Table 3; institutionalise the A&P programme so that consultant-led assessments drive maturity-level reclassification and ESG reporting; and integrate MSS indicators into the ISO 55001-aligned PDCA review cycle at the maintenance-execution control level. The authors propose two subsequent studies: replication of the impact ranking at multiple sites using measured CMMS frequencies, and testing of the correlation between MSS maturity-level scores and asset-reliability KPIs using the convergent Kendall's W / Cronbach's alpha framework of Section 4. Taken together, these contributions establish MSS as a distinct, standards-grounded discipline and a strategic enabler of asset reliability, operational resilience, and operational excellence across asset-intensive industries.

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Declaration of competing interests
The authors declare no competing interests.

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Data availability
The study dataset was compiled from the corresponding author's professionally maintained archival records accumulated over more than three decades of practice within the oil and gas industry; some of the originating companies are now defunct. To protect organisational confidentiality, all data were de-identified prior to analysis. De-identified

extracts of the underlying dataset may be made available upon reasonable request, subject to the necessary approvals and applicable data-sharing requirements of the relevant organisations or their legal successor entities.

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