

Planning without execution: a mixed-methods maintenance maturity assessment of a sub-Saharan gas processing organisation

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Additional Declarations: Competing interest reported. RKA is employed by Ghana National Gas Company, the operator of the Atuabo Gas Processing Plant that constitutes the case setting for this study, and holds supervisory responsibility for a subset of the personnel invited to participate in the workforce survey. The company granted access to the plant's maintenance compliance records and permission to conduct the survey, but had no role in the design of the study, in the collection, analysis, or interpretation of the data, in the writing of the manuscript, or in the decision to submit it for publication. The measures taken in response to this dual role are described in Sects. 2.6 and 2.7. GO and II declare that they have no competing interests.

Abstract

Maintenance maturity assessments are drawn overwhelmingly from well-resourced industrial settings and typically rest on a single evidence stream. This study assesses the maintenance maturity of a resource-constrained sub-Saharan gas processing organisation, as evidenced at the Atuabo Gas Processing Plant in Ghana, and identifies the specific constraints limiting its progression. A convergent parallel mixed-methods design triangulated 36 months of preventive maintenance (PM) compliance records, covering 7443 scheduled tasks, against a structured questionnaire completed by 84 maintenance and operations personnel. Mean monthly compliance rose from 63.01% in 2023 to 69.80% in 2025, but the year-on-year gains were not statistically significant. Compliance collapsed every June in all three years (odds ratio 0.29, 95% CI 0.15–0.55, $p < 0.001$). Three months reached the 90% benchmark, two of them under normal operating conditions. The survey indicated sound planning structures undermined at the point of execution, a certification base oriented toward general project management rather than reliability-specific competence, and fragmented governance. Triangulation places the organisation in the Developing-to-Competent band of the IAM Asset Management Maturity Scale, assessed against the governance requirements of ISO 55001:2014. Because the dominant compliance failures recur in a predictable annual window, they are plannable, and the evidence points to reliability-specific training and certification as the more targeted workforce investment. The study provides longitudinal, task-level empirical evidence from a sub-Saharan gas processing context that is scarce in the maturity literature, and illustrates a diagnostic approach that reconciles routinely collected compliance data with workforce perception to locate specific, addressable constraints.

1 Introduction

Gas processing plants sit at the centre of national energy supply chains, converting raw wellhead gas into lean gas, liquefied petroleum gas, and condensate under continuous, high-energy operating conditions. In such facilities maintenance is the principal mechanism through which equipment reliability, and therefore safety and throughput stability, is preserved [1, 2]. Asset management, of which maintenance is a core function, is therefore a strategic rather than a purely technical concern [3, 4]. As process industries have moved from reactive repair toward planned and predictive strategies [5], and increasingly toward data-driven approaches in the oil and gas sector specifically [6], the question has shifted from whether maintenance is performed to how effectively it is managed, which is the question that maintenance maturity frameworks were developed to answer [7, 8].

Maintenance maturity describes the degree to which an organisation's maintenance practices are structured, consistently executed, and continuously improved. Maturity models position an organisation on a progression from reactive through developing and competent to optimised practice, scored across dimensions such as planning and scheduling, workforce competence, analytical method use, condition monitoring, documentation, and governance [9–11]. Recent work continues to refine these assessment procedures and to extend them toward the digitalisation of maintenance practice [12, 13]. Within the asset management standards that frame this study, the IAM Asset Management Maturity Scale [14]

supplies a six-level maturity vocabulary, while PAS 55:2008 [15] and ISO 55001:2014 [2] provide the governance requirements against which maturity is judged. A widely used operational proxy for maturity on the planning-and-scheduling dimension is preventive maintenance (PM) compliance, the proportion of scheduled tasks completed within their intended window, which reflects scheduling discipline and execution capability [3] and is captured through computerised maintenance management systems [16]. Compliance data, however, capture only what a plant achieves. They do not explain why performance varies, which is where workforce capability and perception become relevant.

Two limitations recur in the maintenance maturity literature and motivate this study. First, the evidence base is drawn overwhelmingly from well-resourced industrial settings in advanced economies, and existing maturity models define their assessment areas generically, so transferring them to a different organisational and business context is not straightforward [10]. Asset-intensive facilities in resource-constrained sub-Saharan contexts, where formal reliability practices are still emerging, remain under-represented, even though their maintenance challenges, including dependence on imported spares, extended procurement lead times, and constrained contractor access, are materially different and can dominate execution [17]. Second, maturity assessments commonly rely on a single evidence stream, either documented performance records or a workforce survey, rather than reconciling the two. This matters because operational records and workforce perception can diverge, and the points at which they converge offer the strongest available evidence of a structural constraint. The link between workforce capability and operational outcomes is established in the regional sector [18], yet few studies combine that perceptual evidence with longitudinal compliance records in a single, evidence-based assessment.

This study addresses both gaps through a single-facility case at the Atuabo Gas Processing Plant operated by the Ghana National Gas Company, Ghana's principal midstream gas processing facility. The plant is an instructive case precisely because it operates an asset-intensive, safety-critical process within a resource-constrained environment in which reliability practices are developing rather than fully embedded. This characterisation is consistent with evidence from Ghana's oil and gas sector: Achaw and Boateng [19] found no national occupational health-and-safety policy for the industry, leaving individual companies to set their own standards under limited regulatory oversight, an institutional setting in which formal, externally enforced management systems remain weakly embedded.

The aim of the study is to assess the maintenance maturity of a resource-constrained sub-Saharan gas processing organisation, as evidenced at its Atuabo plant, and to identify the specific constraints limiting its progression. Three objectives follow: to quantify PM compliance over a 36-month period and characterise its temporal structure, to evaluate workforce-reported capability and practice across the competence, analysis, condition-monitoring, documentation, and governance dimensions, and to triangulate the two strands in order to position the organisation on the IAM maturity spectrum under ISO 55001 and locate the dimensions that constrain it. The value of this convergent design lies in what the two strands reveal together that neither shows alone: the compliance record quantifies how the organisation performs, while the survey explains why it performs that way. In doing so, the study contributes a transferable diagnostic approach, one that uses routinely collected compliance data

alongside workforce perception to pinpoint specific, addressable constraints rather than attributing underperformance to generalised under-resourcing, and it provides empirical evidence from a sub-Saharan gas processing context that is scarce in the maturity literature.

2 Methods

This study adopts a convergent parallel mixed-methods design [20], analysing quantitative and qualitative survey strands independently and merging them at interpretation stage. The compliance records establish what the facility achieves operationally, while the survey establishes how the workforce experiences and explains that performance. Convergence between these independent sources strengthens the resulting assessment.

2.1 Research setting

The study was conducted at the Atuabo Gas Processing Plant operated by the Ghana National Gas Company (Ghana Gas), Ghana's principal midstream gas processing facility, supplying lean gas, LPG, and condensate domestically. As a single, asset-intensive facility in a resource-constrained sub-Saharan context, it offers an instructive case for examining maintenance maturity where formal reliability practices are still emerging. Single-site limitations are addressed in Sect. 2.7.

2.2 Maturity assessment framework

Maturity was assessed against the six-level IAM maturity spectrum [14], comprising the levels Innocent, Aware, Developing, Competent, Optimising and Excellent, situated within the governance requirements of ISO 55001:2014 [2]. ISO 55001 is the live governance standard, while the IAM maturity vocabulary characterises the plant's position. The 2014 edition is used throughout because it was the edition in force across the 2023 to 2025 study window, although a revised edition of ISO 55001 was published in 2024. Owing to PAS 55 being superseded by the ISO 55000 series in 2014 with neither prescribing numerical compliance thresholds, the maturity-level bands applied here are an indicative heuristic, not a published threshold table, combining the world-class PM-compliance benchmark codified in professional practice [21] with the maturity discussion in Campbell et al. [7]. The framework was operationalised by mapping each assessment area to measurable evidence: PM compliance evidenced planning and scheduling, while survey items evidenced competence, reliability-analysis, condition-monitoring, documentation, and governance, ensuring an evidence-based, reproducible placement.

2.3 Quantitative strand: PM compliance records

Monthly PM compliance records were obtained from the plant maintenance management system for January 2023 to December 2025, comprising 144 weekly observations across 36 months and representing 7443 scheduled PM tasks. Records were held at weekly resolution and aggregated to monthly totals for analysis; the analyses reported below were repeated at weekly resolution as a robustness check. Each record captured scheduled tasks, tasks completed on time, the completion rate, missed tasks, and a descriptor of any shortfall. Shortfall descriptors were selected by maintenance

planners from a recurring set of standard categories rather than entered as open text: 103 of the 144 records carry a descriptor, drawn from 33 distinct strings. The export does not carry a system or recording-method field, so the constancy of the recording system, the grace-period definition and data-entry practice across the 36-month window could not be verified from the dataset itself.

Compliance was analysed at two levels. The aggregate on-time completion rate (tasks completed on time / tasks scheduled) was computed overall and by year and month. Seasonal structure was tested using a binomial generalised linear model of on-time completion with calendar-month and year effects and a Pearson-scaled dispersion correction (Sect. 3.2.4). Shortfall descriptors were categorised as supply, access, environmental, labour or process constraints and cross-tabulated by calendar month for comparison against the survey.

2.4 Survey strand: workforce assessment

A structured 34-item questionnaire assessed workforce perceptions and practices across the maturity-framework domains, comprising a respondent-profile block (role, department, shift, tenure, certification, recent training) and a practice-and-perception block covering PM effectiveness, schedule adherence and barriers, work-order efficiency, reliability-analysis awareness, condition monitoring, root-cause analysis, criticality processes, documentation, training, resource needs, and management support, using Likert scales, multiple-response items, and open-ended questions.

The questionnaire served as the study's primary data-collection instrument. A pilot study was conducted to test the clarity and relevance of the items, and feedback from 10 pilot participants highlighted the need for rewording to improve comprehension and elicit more appropriate responses. On that basis, the final instrument was adjusted by rewording the response-item instructions and refining the Likert-scale response options.

The questionnaire was administered to maintenance and operations personnel, yielding 84 valid responses spanning the principal roles, with engineers ($n = 32$) and technicians ($n = 21$) in the majority; by department, maintenance ($n = 43$) and operations ($n = 28$) predominated. This composition is appropriate to the research questions, as these respondents have direct knowledge of the practices assessed.

The questionnaire was distributed online via a shared link to all available maintenance and operations staff across the target departments at the facility, a sampling frame of 150 personnel. This convenience-sampling approach yielded 84 valid responses, a response rate of approximately 56%. The target sample size was not derived from a power calculation; rather, the questionnaire was distributed as a near-census attempt across the full accessible population of 150 personnel, with response rate rather than a pre-specified minimum n serving as the sample-adequacy criterion. All 84 responses recorded in the survey export were retained without further exclusion; no separate screening step removed additional submissions. Item-level non-response ranged from zero to two responses (valid $n = 82$ to 84), and

percentages are reported on the valid n for the item concerned. The self-selected nature of the sample is acknowledged as a limitation in Sect. 2.7.

Ordinal items were summarised using frequency and percentage distributions, and where appropriate, central-tendency measures, to characterise the prevailing perception on each dimension. Multiple-response items were analysed by response frequency to identify the most commonly cited barriers, tools, and resource needs. Open-ended responses were analysed thematically to contextualise and explain the closed-item results.

2.5 Data integration

Following independent analysis, the two strands were merged through a triangulation matrix juxtaposing the documented drivers of non-compliance against the barriers and capability gaps reported by the workforce. Points of convergence were treated as strengthened findings, and the integrated evidence was mapped onto the maturity framework to position the facility and identify the dimensions limiting its progression.

2.6 Ethical considerations and researcher positionality

Ethical approval

for the survey was granted by the Research Ethics Committee of Robert Gordon University and institutional consent to conduct the assessment and access the compliance records was obtained from Ghana National Gas Company. Participation was voluntary, with informed consent obtained from all respondents and assurance of the right to withdraw. Responses were anonymised with no identifying information retained, and operational records were handled per the data-sharing confidentiality terms.

The lead author is employed by the operating company at the study site and holds supervisory responsibility for a subset of the personnel invited to participate. This dual role is declared as a competing interest and is treated here as a methodological condition of the study rather than an incidental detail, because it bears directly on the voluntariness of consent. Three arrangements were applied in response. The questionnaire was self-administered online through a shared link rather than distributed or supervised in person. No identifying information was collected or retained, so individual responses cannot be attributed to any respondent, and all results are reported in aggregate. Participants were informed that participation was voluntary, that a decision not to participate carried no consequence of any kind, and that they could withdraw at any point. Residual influence on the willingness to participate, or on the candour of responses, cannot be excluded and is revisited in Sect. 2.7.

2.7 Methodological limitations

Several limitations are acknowledged. The single-facility basis constrains generalisation though it supports analytical transferability. The survey data are self-reported and cross-sectional, whereas the compliance data are longitudinal. The self-report and cross-sectional limitations of the survey strand were addressed by guaranteeing respondent anonymity to encourage candid responses, and by checking

self-reported practice against the independent, longitudinal compliance record rather than relying on self-report alone; convergence between the two sources was treated as a check on the cross-sectional snapshot the survey provides, not a substitute for it. The survey strand also relied on voluntary, self-selected responses to an online questionnaire, introducing potential non-response and self-selection bias that constrains the representativeness of the workforce sample.

The lead author's position within the operating company, set out in Sect. 2.6, warrants separate treatment. That position afforded the access to 36 months of compliance records and to workforce participation on which the study depends, but it is also a potential source of interpretive bias. Three features of the design constrain that risk. First, the compliance record is a pre-existing operational dataset generated through routine plant processes rather than by the researcher, so the quantitative strand is not susceptible to researcher framing at the point of collection. Second, the survey was anonymous and analysed in aggregate. Third, the two strands were analysed independently before being merged, so that convergence between them could be assessed rather than assumed. It is also relevant to the assessment of this risk that the analysis reports findings unfavourable to the organisation, including a year-on-year improvement that does not reach statistical significance, two months below 40% compliance in the most recent year, a reliability-specific competence gap, and governance structures that are not yet institutionalised. The direction of the results does not suggest an account shaped to favour the employer. Residual bias nonetheless cannot be excluded, and independent replication, or assessment by a researcher external to the organisation, would strengthen confidence in the interpretation.

3 Results and discussion

3.1 Current reliability engineering practices: survey evidence

3.1.1 Respondent characteristics

Of the 84 valid responses reported in Sect. 2.4, the full role breakdown comprised engineers (38.1%, $n = 32$), technicians (25.0%, $n = 21$), safety officers (11.9%, $n = 10$), supervisors (9.5%, $n = 8$), management (9.5%, $n = 8$), and planners and other technical roles (5.9%, $n = 5$).

The sample skewed towards earlier-career staff: 57.1% ($n = 48$) had one to five years at the plant and 11.9% ($n = 10$) less than one year, so approximately 69% had five years or less. The remainder comprised 17.9% ($n = 15$) with six to ten years and 13.1% ($n = 11$) with more than ten. The dataset is therefore weighted towards newer and mid-tenure perspectives while retaining longer-serving input.

Familiarity with reliability practices differed significantly across role groups (Kruskal–Wallis $H(5) = 27.30$, $p < 0.001$, $\epsilon^2 \approx 0.29$, $n = 83$). The ordinal familiarity item was scored with the 'unsure' response ranked between 'not familiar' and 'somewhat familiar'; the result is robust to the three alternative orderings of

that response ($H = 25.76$ to 27.64 , all $p < 0.001$). Post-hoc comparisons (Dunn's test, Holm-corrected) located the difference in four contrasts: management reported greater familiarity than technicians ($p < 0.001$), engineers ($p = 0.019$) and safety officers ($p = 0.019$), and engineers reported greater familiarity than technicians ($p = 0.037$). The smallest cells (planner/other, $n = 5$; management, $n = 8$; supervisor, $n = 8$) limit the precision of individual group estimates. Technicians and newer entrants emphasised training and tool-exposure gaps in the open-ended responses; no comparable test was conducted by tenure. This pattern is plausibly one of exposure rather than aptitude. Engineers encounter reliability concepts through formal engineering education and consolidate them over years of plant practice, whereas technicians and newer entrants rely mainly on in-service training, which the findings in Sect. 3.1.3 show to be scarce and rarely specialised. Familiarity with reliability practice therefore concentrates in the management and engineering roles rather than being built systematically at entry, and is thinnest among the technicians who execute the work. The capability implications of this pattern are developed in Sect. 3.1.6.

3.1.2 Foundational maintenance practices

Preventive maintenance frequency. Preventive maintenance was dominated by time-based routines: 41.7% ($n = 35$) reported daily or per-shift PM, 28.6% ($n = 24$) weekly, 10.7% ($n = 9$) monthly, 6.0% ($n = 5$) quarterly, and 8.3% ($n = 7$) as-needed. This emphasises routine, calendar-driven intervention over condition- or risk-based approaches; while reducing unnoticed deterioration, this calendar-based approach risks over-maintenance, and the persistence of reactive responses indicates predictive practices are not yet institutionalised.

Planning, scheduling, and CMMS utilisation. Respondents reported relatively strong planning structures, albeit with notable inefficiencies. 36.9% ($n = 31$) stated schedules were followed always ($> 90\%$), and 34.5% ($n = 29$) reported often (70–90%), while the remainder acknowledged occasional lapses. Job plans were consistently updated for 52.4% ($n = 44$) and only occasionally for 35.7% ($n = 30$); work-order processing was rated very efficient by 31.0% ($n = 26$) and moderately efficient by 47.6% ($n = 40$). Although planning and scheduling are embedded, respondents noted barriers such as delays in spare part delivery, limited staffing, and difficulties with CMMS accessibility.

3.1.3 Human capital and skills

Training adequacy. On a five-point scale (1 = highly inadequate, 5 = highly adequate), training adequacy ratings were: highly inadequate 4.8% ($n = 4$), inadequate 33.3% ($n = 28$), moderately adequate 35.7% ($n = 30$), adequate 16.7% ($n = 14$), highly adequate 9.5% ($n = 8$). The mean was 2.93 (mode 3), reflecting moderate inadequacy. On specialised training, 59.5% ($n = 50$) reported none, 26.2% ($n = 22$) some exposure, and 10.7% ($n = 9$) extensive exposure, pointing to a substantial skills gap, especially in advanced areas such as RCM and RCA. This pattern of training inadequacy is most pronounced among technicians and newer staff, indicating a knowledge gap that current programmes do not fully address.

Certifications and professional development. The certification profile reveals an imbalance rather than a wholesale absence of credentials. Approximately half of respondents (51.2%, $n = 43$) held no

professional certification, while the certified remainder skewed toward project-management credentials over reliability-specific ones. The Project Management Professional (PMP) credential was most common (19.0%, n = 16), followed by vendor-specific certifications (9.5%, n = 8). Reliability-specific credentials were scarce: 8.3% (n = 7) held CMRP and 3.6% (n = 3) CRL, with 3.6% (n = 3) holding Lean Six Sigma belts and 4.8% (n = 4) other certifications. The salient finding concerns the orientation of certification, not its absence: reliability-specific certification (CMRP and CRL combined, 11.9%, n = 10) is markedly under-represented relative to general project-management certification.

This finding reinforces the earlier training-exposure gap: the scarcity of reliability-specific certification specifically, as distinct from general professional certification, constrains the plant's ability to benchmark reliability competence against international standards. Read against the ISO 55001 and PAS 55 emphasis on structured competency assurance, the low training adequacy and thin reliability-specific certification mark human-capital development as a critical barrier to reliability excellence.

3.1.4 Governance and institutionalisation

Audit frequency. Audit practice was fragmented: 37.3% (n = 31) reported regular audits, 39.8% (n = 33) occasional, 8.4% (n = 7) none, and 14.5% (n = 12) were unsure, indicating an ad-hoc culture lacking standardised enforcement.

Documentation quality. Documentation quality ratings were: very poor 1.2% (n = 1), poor 14.3% (n = 12), average 42.9% (n = 36), good 17.9% (n = 15), very good 23.8% (n = 20). The mean was 3.49 (mode 3), indicating broadly functional but inconsistent documentation, with shortfalls attributed to insufficient training, log-update delays, and limited CMMS access.

Management support. Management support ratings were: very low 4.8% (n = 4), low 16.7% (n = 14), moderate 42.9% (n = 36), high 22.6% (n = 19), very high 13.1% (n = 11). The mean was 3.23 (mode 3), showing moderate but inconsistent support. These governance findings indicate that recent leadership emphasis has improved compliance while the systemic structures of regular auditing, robust documentation, and sustained commitment are not yet institutionalised. This pattern aligns with the ISO 55001 emphasis on systematic audits, reliable documentation, and leadership commitment, all areas where workforce perception signals underdevelopment.

3.1.5 Application of reliability tools and methodologies

When asked about reliability tools: 33.3% (n = 28) reported no tools are applied, 15.5% (n = 13) cited RCA, and less than 10% referenced FMEA or RCM. On effectiveness, 23.8% (n = 20) rated tools highly effective, 33.3% (n = 28) moderately effective, and 22.6% (n = 19) were unsure. Familiarity was mixed: very familiar 26.2% (n = 22), somewhat familiar 51.2% (n = 43), not familiar or unsure 21.4% (n = 18).

The higher uptake of RCA reflects its reactive, event-driven nature and ease of use, against the more resource-intensive, preventive focus of FMEA and RCM. This disparity indicates that advanced methodologies remain poorly institutionalised, consistent with a reactive maintenance culture. This

weak adoption of advanced methodologies explains the persistence of time-based maintenance seen in the PM-frequency responses and confirms methodology adoption as a critical maturity gap.

3.1.6 A workforce capable on paper but thin in reliability-specific capability

The human-capital findings refine a common assumption about resource-constrained facilities, namely that the workforce is simply under-qualified. The data tell a more specific story. Roughly half of respondents held some professional certification, so the issue is not a wholesale absence of credentials. Rather, the certification base is oriented toward general project management (with PMP the single most common credential) while reliability-specific certification, the CMRP and CRL credentials that signal formal competence in the very discipline under study, was held by only about one in eight respondents. Combined with the finding that around three in five staff had received no specialised reliability training in the preceding three years, this points to a capability profile that is administratively competent but technically shallow in reliability engineering specifically.

This profile also helps explain the role- and tenure-based differences noted in Sect. 3.1.1: engineers and longer-tenured staff are more likely to have accumulated reliability exposure through formal engineering education and years of on-the-job practice, whereas technicians and newer entrants enter directly into a setting where specialised reliability training is scarce, leaving them more reliant on administrative routine than on analytical method. The pattern is therefore consistent with the training gap identified above, not separate from it.

This orientation has explanatory power for the other findings. A workforce strong in project administration but light in reliability methods would be expected to maintain schedules and documentation, which the data show it broadly does, while making limited use of the analytical tools that distinguish proactive from reactive maintenance, which the data also show. This skew also raises a question about the role of leadership and management, since decisions on which certifications to sponsor and which training to fund are typically driven by management, not by individual choice. The administrative-over-analytical profile observed here may therefore reflect organisational resourcing and prioritisation choices as much as workforce preference, though the present data cannot separate the two; this is a question better addressed through management interviews and training-budget records than through a workforce survey alone. The low reported uptake of FMEA and RCM relative to the more accessible, reactive RCA is consistent with this interpretation. The calendar-driven, administratively planned orientation observed here also aligns with the sector norm instead of deviating from it: Adenuga et al. [22] report that time-based preventive maintenance predominates across oil and gas operations, with roughly 90% of companies practising scheduled intrusive PM, and note that in the Nigerian industry this orientation has been reinforced by regulatory guidance that historically mandated schedule-based maintenance, a regulatory environment closely comparable to Ghana's. The link between workforce capability and operational outcomes is supported elsewhere in the West African oil and gas sector. Ayoola [18], surveying 372 employees across Nigeria's five major petroleum-producing companies, found

workforce competence development positively associated with operational performance; drawn from a study of the content-development regime rather than gas plant maintenance, it is read here as regional corroboration rather than a sector benchmark. A comparable mismatch between general credentials and task-specific maintenance capability is documented even in well-resourced settings: Obiajunwa [23], in a mixed-methods study of 160 UK process plants, found that managers of major maintenance events were routinely appointed without assessment against the specific skills those events demand. The present finding sharpens the implication by distinguishing the type of capability that is scarce: not professional development in aggregate, which is reasonably well represented, but reliability-specific competence in particular, a narrower and more precisely targetable gap.

3.2 Preventive maintenance compliance trends

This section presents PM compliance trends across 36 months (January 2023 to December 2025). Preventive maintenance compliance (PMC), the proportion of scheduled PM tasks executed within their timeframes (inclusive of a plant-defined $\pm 10\%$ grace period), is a widely used proxy for maintenance discipline and scheduling fidelity [1, 24, 8].

Analysis proceeded in two stages: descriptive statistics characterised the monthly PMC distribution within each year (Table 1), and inferential comparisons assessed year-on-year differences (Table 2; confidence intervals using the t-distribution, $df = 11$). Normality of paired differences was assessed by the Shapiro–Wilk test before selecting each test. Table 4 reports the complete 36-month record. Figure 1 overlays the three years by calendar month and Fig. 2 plots the series chronologically. The year-by-year detail follows in Sects. 3.2.1 to 3.2.3.

3.2.1 Performance trends for 2023

In 2023, monthly weighted PMC averaged 63.01% (SD 10.27%; 95% CI [56.49%, 69.53%], $t = 2.2010$, $df = 11$), ranging from 43.04% (June) to 81.66% (September), with no month reaching the 90% benchmark (Table 4). The pattern is a mid-year trough (June 43.04%, August 50.00%) flanked by stronger Q1 performance and a September–October recovery; the SD of 10.27% reflects moderate volatility without breakdown of scheduling discipline.

Subsystem-level breakdown is unavailable in the dataset; the shortfall descriptors recorded alongside the compliance figures (Sect. 3.2.6) cite spare-part shortages and loss of asset access to concurrent operations in the mid-year months.

3.2.2 Performance trends for 2024

In 2024, weighted PMC averaged 64.36% (SD 13.96%; 95% CI [55.49%, 73.23%]), ranging from 34.43% (December) to 79.56% (November). The higher SD than 2023 reflects greater variability, driven mainly by the December collapse to 34.43%, the lowest single month across the 36-month period.

The October–November corridor (78.18%, 79.56%) was the strongest sustained two-month performance to that point. The descriptors recorded for December 2024 cite incorrect parts received, spare-part procurement delay, and a job package awaiting engineering review; causal attribution is treated as contextual (Sect. 3.2.6).

3.2.3 Performance trends for 2025

In 2025, weighted PMC averaged 69.80% (SD 17.63%; 95% CI [58.60%, 81.00%]), the highest annual mean, ranging from 34.16% (June) to 93.68% (August). Three months reached the 90% benchmark, the only months to do so in the dataset (August 93.68%, September 91.24%, November 92.18%); October (82.88%) fell below. August coincided with a planned plant shutdown recorded in the maintenance log and carried the heaviest scheduled task load in the dataset (285 tasks against a mean of 205 in the remaining months), conditions in which asset access was not constrained by concurrent production, although shutdown periods at this plant are not generally associated with higher compliance. September and November were normal operating months at ordinary task loads, so benchmark-level execution was achieved twice under routine conditions.

The July–November corridor averaged 86.28% across five consecutive months, the first run exceeding 80% (Table 4), and 84.43% with the shutdown month excluded, suggesting an emerging capability for sustained execution. Excluding August, mean monthly compliance in 2025 was 67.63%, still the highest of the three years. Whether this is durable or transient cannot be determined without a longer window or operational-change records beyond this study’s scope.

Yet the June trough (34.16%) and December decline (62.07%) show high-performance months coexisting with vulnerability to disruption: the two benchmark months recorded under normal operating conditions show the capability exists, while two sub-40% months in the same year confirm it is not yet institutionalised.

3.2.4 Comparative statistical analysis

Table 1 presents the annual descriptive statistics for all three years. Table 2 presents the inferential test results, including test selection rationale and effect sizes. The seasonal model reported below tests the calendar-month structure that these year-on-year comparisons cannot address.

Table 1
Annual descriptive statistics of weighted monthly PM compliance, 2023–2025

Metric	2023	2024	2025
Mean PMC (%)	63.01%	64.36%	69.80%
Standard Deviation	10.27	13.96	17.63
Standard Error	2.96	4.03	5.09
95% CI (t-dist, df = 11)	[56.49%, 69.53%]	[55.49%, 73.23%]	[58.60%, 81.00%]
Minimum Monthly PMC	43.04% (June)	34.43% (December)	34.16% (June)
Maximum Monthly PMC	81.66% (September)	79.56% (November)	93.68% (August)
Months > = 90% (benchmark)	0	0	3 (Aug, Sep, Nov)
Near-threshold (85.0-89.9%)	0	0	0 months. Oct 2025 = 82.88% (below near-threshold range)
n (months)	12	12	12

The Shapiro–Wilk test was applied to paired monthly differences for each year combination. The 2023–2024 differences were non-normal ($W = 0.829$, $p = 0.020$), so the Wilcoxon signed-rank test was used; the 2024–2025 ($W = 0.948$, $p = 0.606$) and 2023–2025 ($W = 0.906$, $p = 0.191$) differences satisfied normality, so paired t-tests were applied.

Table 2
Inferential test results with effect sizes, 2023–2025

Comparison	Test Used	Statistic	p-value	Effect Size	Interpretation
2023 vs 2024	Wilcoxon ¹	$W = 30.0$	0.519	$r = 0.20$ (small)	Not significant
2024 vs 2025	Paired t	$t = -1.061$	0.311	$d = 0.306$ (small)	Not significant
2023 vs 2025	Paired t	$t = -1.505$	0.161	$d = 0.434$ (small)	Not significant

Effect size for the Wilcoxon comparison is reported as rank-biserial correlation r , calculated as $|Z| / \sqrt{n} = 0.20$, where $Z = -0.706$ is the Wilcoxon Z-approximation statistic and $n = 12$ pairs [25].

None of the three comparisons reached statistical significance. With only $n = 12$ monthly observations per year, the study is underpowered to detect the small-to-medium effects observed: a sensitivity analysis indicates that detecting the 2023-vs-2025 effect ($d = 0.434$) at 80% power would require approximately $n = 45$ paired observations.

The non-significant results are consistent with both genuine improvement and stable performance, which these paired comparisons cannot distinguish. The 6.79-point descriptive rise in mean PMC, and the July–November 2025 corridor are reported as descriptively meaningful, with non-significance acknowledged as a limitation rather than a contradiction.

Because monthly compliance is a count of tasks completed on time out of tasks scheduled, comparison of monthly percentages between years discards the underlying sample sizes and cannot test for seasonal structure. A binomial generalised linear model of on-time completion was therefore fitted to the 36 monthly observations, with indicator terms for June and December and for year, and with standard errors scaled by the Pearson dispersion estimate ($\phi = 13.46$) to account for overdispersion. The odds of on-time completion in June were 0.29 times those in a non-June, non-December month (95% CI 0.15–0.55; $t = -4.00$, $p = 0.0004$). The December effect was smaller and weaker (OR 0.48, 95% CI 0.25–0.92; $p = 0.029$). Neither year term reached significance (2024 versus 2023: OR 1.05, $p = 0.839$; 2025 versus 2023: OR 1.36, 95% CI 0.86–2.15, $p = 0.185$), consistent with the paired comparisons reported above (Table 3).

Three checks support this specification. Refitting at weekly resolution ($n = 144$) gave identical point estimates with narrower intervals (June OR 0.29, 95% CI 0.18–0.46; $p < 0.001$). Adding scheduled task volume as a covariate left the June effect unchanged (OR 0.28, $p < 0.001$) while volume itself was not associated with compliance ($p = 0.263$). Excluding August 2025, the month affected by the plant shutdown, left the June effect intact (OR 0.30, $p < 0.001$) and weakened the already non-significant 2025 year term further ($p = 0.383$). Residual diagnostics indicated no significant serial dependence (Ljung-Box at lag 6: $Q = 11.19$, $p = 0.083$).

Table 3
Binomial generalised linear model of on-time PM completion, 2023–2025

Term	Coefficient (log-odds)	SE	p-value	Odds ratio	95% CI
Intercept	0.7285	0.166	0.0001	2.07	1.48–2.91
June	−1.2376	0.310	0.0004	0.29	0.15–0.55
December	−0.7274	0.318	0.029	0.48	0.25–0.92
Year 2024 (vs 2023)	0.0459	0.224	0.839	1.05	0.66–1.65
Year 2025 (vs 2023)	0.3061	0.226	0.185	1.36	0.86–2.15

3.2.5 Monthly PM compliance: the full 36-month dataset

Table 4 presents the complete 36-month dataset and annual summary statistics, including the July–November 2025 corridor average, at the foot of each year block.

Table 4
Monthly preventive maintenance compliance, Atuabo Gas Processing Plant, 2023–2025

Month	Scheduled PM Tasks	Completed on Time	Weighted Completion Rate (%)	Simple Avg Rate (%)	Missed Tasks
2023					
January	149	90	60.40%	60.18%	59
February	126	77	61.11%	61.05%	49
March	158	86	54.43%	53.45%	72
April	214	146	68.22%	68.53%	68
May	193	132	68.39%	67.47%	61
June	230	99	43.04%	43.77%	131
July	243	158	65.02%	64.76%	85
August	228	114	50.00%	49.84%	114
September	229	187	81.66%	81.73%	42
October	215	154	71.63%	72.91%	61
November	183	124	67.76%	68.20%	59
December	183	118	64.48%	64.16%	65
2024					
January	197	132	67.01%	66.61%	65
February	212	165	77.83%	77.80%	47
March	195	119	61.03%	60.76%	76
April	212	153	72.17%	72.21%	59
May	199	146	73.37%	72.52%	53
June	185	85	45.95%	46.09%	100
July	182	103	56.59%	56.64%	79
August	217	123	56.68%	57.12%	94
September	223	155	69.51%	69.64%	68
October	220	172	78.18%	78.47%	48
November	225	179	79.56%	79.37%	46
December	212	73	34.43%	34.40%	139

Month	Scheduled PM Tasks	Completed on Time	Weighted Completion Rate (%)	Simple Avg Rate (%)	Missed Tasks
2023					
2025					
January	218	145	66.51%	67.74%	73
February	207	133	64.25%	64.36%	74
March	213	137	64.32%	63.95%	76
April	244	145	59.43%	59.58%	99
May	193	107	55.44%	54.12%	86
June	243	83	34.16%	34.20%	160
July	189	135	71.43%	71.44%	54
August	285	267	93.68%	93.70%	18
September	217	198	91.24%	91.14%	19
October	222	184	82.88%	83.09%	38
November	179	165	92.18%	92.19%	14
December	203	126	62.07%	62.01%	77
Annual Summary of Corrected Weighted Averages (t-distribution, df = 11, t = 2.2010)					
2023 Mean	63.01%	SD: 10.27	95% CI: [56.49%, 69.53%]	Range: 43.04%–81.66%	
2024 Mean	64.36%	SD: 13.96	95% CI: [55.49%, 73.23%]	Range: 34.43%–79.56%	
2025 Mean	69.80%	SD: 17.63	95% CI: [58.6%, 81%]	Range: 34.16%–93.68%	

3.2.6 The recurring seasonal failure of compliance

The most robust quantitative finding is the recurring collapse of PM compliance every June, observed in all three years (43.04%, 45.95%, and 34.16%), together with a volatile and sometimes severe December decline. The effect is statistically established rather than merely repeated: the odds of on-time completion in June are 0.29 times those in other months (Sect. 3.2.4), and its consistency across three independent years is what distinguishes a structural vulnerability from ordinary month-to-month noise.

The maintenance record was examined for evidence of the mechanisms that might account for this effect. Shortfall descriptors were categorised as supply, access, environmental, labour or process constraints and cross-tabulated by calendar month. June carries more descriptors than the typical

month (11 against a monthly median of 8.5), consistent with its lower compliance, but their composition does not differ significantly from that of other months (chi-square = 1.21, df = 5, p = 0.944). Two mechanisms plausible in this operating context were tested directly and are not supported. No weather or ambient-condition descriptor was recorded in June in any of the three years; the five such descriptors in the 36-month record fall in March, May and January. No descriptor anywhere in the record refers to budget or procurement-cycle timing, and contractor mobilisation, cited three times, does not appear in June. The record therefore identifies the categories of constraint that recur at this facility, principally supply-side delay and loss of asset access to concurrent operations, without identifying a mechanism specific to June. Establishing why these constraints concentrate in that month would require procurement and shutdown-scheduling records outside the present dataset.

The procurement dimension of this finding echoes evidence from comparable sub-Saharan settings: in a study of engineering training facilities in Southern Africa, Nyemba et al. [17] found that the absence of local spares suppliers and the resulting reliance on imported parts produced prolonged lead times and repair delays, the same mechanism observed here. Nyemba et al.'s setting limits direct comparability, but the procurement mechanism it documents is structural to import-dependent operations. Adenuga et al. [22] identify a related mechanism at sector level, observing that reliance on scheduled PM itself encourages deferment when execution windows tighten, with degradation and breakdown as the downstream consequence. The present study extends that observation by locating the constraint in a specific, recurring temporal window rather than treating it as a generalised resourcing problem. This matters because a predictable failure is a manageable one: it can be planned around in a way that a random failure cannot. A scheduling-load artefact is not supported: scheduled task volume was added to the model as a covariate and was not associated with compliance (OR 1.13 per standard deviation of log scheduled tasks, 95% CI 0.91–1.40; p = 0.263), while the June effect was unchanged (OR 0.28, p < 0.001). The June collapse therefore reflects a constraint on execution capacity rather than an increase in scheduled task load. A staffing-availability explanation, in which mid-year leave rotations rather than supply or access constraints drive the June shortfall, is also not supported: of the 144 weekly maintenance-log entries across the study period, only two cite technician unavailability due to leave overlap, occurring in October 2023 and December 2025, with none in June in any of the three years. The mechanism is therefore absent from the month it would need to explain.

3.2.7 The planning-efficiency paradox and the compliance–effectiveness gap

The survey revealed an apparent contradiction that the compliance data help resolve. The majority (71.4%, combining 36.9% reporting always and 34.5% reporting often) of respondents reported high adherence to maintenance schedules, yet fewer than a third rated work-order processing as efficient, and almost half rated it only moderately so. Taken alone, this could be dismissed as inconsistent self-reporting. Read against the compliance record, however, it becomes coherent: the plant has functioning scheduling structures (hence the high reported adherence) but those structures are repeatedly undermined at the point of execution by the same resource and access constraints that drive the

seasonal troughs. In other words, the workforce is accurately perceiving a system that plans well but executes unevenly. This same disconnect appears in comparable maturity assessments: in a thermoplastic facility in Brazil, de Andrade et al. [11] found that maintenance planning was formal on paper but not realised in execution, producing a high backlog because scheduled work was deferred whenever production demanded, a near-identical planning-versus-execution gap in a different sector and economy. Nor is the pattern confined to particular sectors or to resource-constrained settings: Wienker et al. [26] report that only 25 to 40% of CMMS implementations succeed even in large, well-resourced organisations, that as few as 6 to 15% of users exploit the system at full capability, and that the shortfall lies in organisational change management, not in the technology itself. Atuabo's combination of disciplined data entry and limited analytical exploitation is therefore a local instance of a documented global implementation gap, which reinforces the reading that the constraint is organisational, not infrastructural. This reframes the issue from one of planning discipline, which appears adequate, to one of execution capability under constraint, which does not. This separation of planning from execution is well established in the wider literature: Al-Turki et al. [27], reviewing more than 80 studies of turnaround maintenance, treat the two as distinct managerial competences with distinct failure modes, which supports locating the plant's gap at the execution stage, not in its planning structures. The distinction has direct consequences for where improvement effort should be directed, a point developed in Sect. 4.1.

3.3 Benchmarking PM compliance against international standards

3.3.1 Benchmarking framework and standard selection

Benchmarking draws on three frameworks. ISO 55001:2014 Clause 9.1 (performance evaluation) is the primary governance standard for assessing maturity [2]. The IAM Asset Management Maturity Scale [14] supplies the maturity-level vocabulary, applied against the requirements of PAS 55:2008 [15] and ISO 55001:2014, a pairing retained because the IAM scale operationalises both the PAS 55 lineage and its ISO successor. The 90% world-class PMC threshold is drawn from codified professional practice [21], while Duffuaa and Raouf [8] formalise PM schedule compliance among the measures through which a maintenance system is controlled. For oil-and-gas context, API 689 [28] informs reliability and maintenance data collection, while API RP 580 [29] informs inspection prioritisation of pressure-containing equipment.

Neither ISO 55001 nor PAS 55 prescribes numerical PMC thresholds. The percentage ranges associated here with the IAM maturity levels [14] are an interpretive heuristic that combines the world-class benchmark codified in professional practice [21] with Campbell et al. [7], not a published threshold table. Each of these frameworks is applied directly in this paper: the 90% world-class threshold classifies the observed monthly performance in Sect. 3.3.2, the ISO 55001, API 689 and API RP 580 requirements are tested against plant evidence in the standards gap analysis of Sect. 3.3.3, and the IAM maturity vocabulary frames the overall placement in Sect. 3.3.5. On this heuristic, sustained weighted PMC below

50% is read as characteristic of largely reactive practice at the Aware level, 50–70% of a Developing organisation, 70–90% of a Competent one, and 90% or above of Optimising, world-class execution, with only the 90% threshold drawn directly from the literature [21].

3.3.2 Observed performance and maturity classification

Across the three years, mean monthly PMC rose descriptively from 63.01% (2023) to 64.36% (2024) and 69.80% (2025); the corresponding task-weighted plant-wide rates are 63.16%, 64.74% and 69.84%, a 6.79 percentage-point increase that did not reach statistical significance (Sect. 3.2.4). On an indicative mapping that combines the world-class PM-compliance benchmark codified in professional practice [21] with the IAM maturity ladder [14], treated here as an interpretive heuristic rather than a published threshold table, a mean PMC in the 60–70% range is broadly consistent with a Developing-to-Competent organisation, one that has established and tracks scheduled maintenance but has not achieved the scheduling fidelity associated with the Optimising level.

The two benchmark months recorded under normal operation (September, November) show the plant can achieve Optimising-level execution, while the persistence of low-performance months shows this capacity is not yet sustained. Subsystem-level compliance breakdown (electrical, mechanical, instrumentation and control) is unavailable in the current dataset and would require subsystem-tagged CMMS extraction; it is recommended as a priority for future research.

3.3.3 Standards gap analysis

Against ISO 55001 Clause 9.1, the plant satisfies the requirement to monitor and measure asset performance: the 36-month CMMS dataset, validated weekly and cross-referenced with audit records, meets the data-integrity requirement. The gap lies in the analytical feedback loop, with limited evidence that monitoring data systematically drives corrective action on recurring low-performance patterns (Clause 10.1). Campbell et al. [7] make this the defining test of world-class practice, benchmarking organisations by the extent to which their data actually guide maintenance decisions, which marks the closing of this loop as a maturity intervention, over and above an administrative refinement. Duffuaa and Raouf [8] converge on the same test from the scholarly side, defining a world-class PM programme by its use of analytical techniques such as failure mode, effects and criticality analysis and root cause analysis, not by any single metric, which reinforces the conclusion that the plant's remaining gap is analytical, not one of record-keeping.

Against API 689 [28], the CMMS broadly satisfies event recording and categorisation, though the absence of subsystem-level tagging limits resolution. Against API RP 580 [29], the absence of a formal criticality ranking for inspection-governed pressure-containing assets is a gap, while the broader scheduling gap maps to ISO 55001 Clause 8.1 (operational planning and control), requiring strategy selection commensurate with failure consequence.

3.3.4 Performance gap diagnosis

The most consistent structural vulnerability is the recurring June trough, below 46% in all three years (Table 4). December is more volatile than structural: severe in 2024 (34.43%), below the annual mean in 2025 (62.07%), and unremarkable in 2023 (64.48%). The consistency of the June pattern across three consecutive years is unlikely to be coincidental and warrants operational explanation.

The constraint categories recorded in these windows, principally supply-side delay and loss of asset access to concurrent operations, were set out in Sect. 3.2.6. Drawn from the maintenance-log descriptors, they are treated as operational context rather than statistically confirmed causes, and no mechanism specific to June could be identified from the record. The implication is that the scheduling system does not adapt task loading to predictable seasonal and operational constraints, a gap addressable through CMMS-based demand-levelling and advance procurement ahead of known high-risk months.

3.3.5 Positioning the facility on the maturity spectrum

Synthesising the strands against the IAM maturity spectrum, the facility falls within the Developing-to-Competent band rather than at either extreme, where Level 3 (Competent) equates to conformance with ISO 55001 [14]. Applying a maturity model to a single facility in this evidence-based way has precedent. De Andrade et al. [11] positioned a thermoplastic plant on a five-level, ten-class maturity scale by scoring each dimension against documented evidence, establishing single-facility maturity placement through dual-perspective scoring in which an internal staff self-assessment was triangulated against an external specialist's evaluation. The present study extends that logic from two raters of a single construct to between-method triangulation, reconciling an objective performance metric (PM compliance) against workforce perception. The evidence for the present placement is likewise specific rather than impressionistic. On the planning-and-scheduling dimension, the compliance evidence classified in Sect. 3.3.2 places the plant at the boundary between established scheduling and consistent execution. On the competence dimension, the certification and training profile places the plant below the Competent level's expectation of formalised reliability capability. On governance, the fragmented audit practice and merely average documentation and management-support ratings indicate structures that exist but are not yet systematically enforced. The significance of the three world-class months and the co-occurring sub-40% months was established in Sect. 3.3.2. Read together with the survey evidence, the honest characterisation is a facility in transition, with demonstrated capability that is not yet durable. The placement also holds in Campbell et al.'s [7] own vocabulary: the plant sits above their Awareness level, at which daily scheduling is largely undermined by demand maintenance, because its scheduling structures hold outside the seasonal windows, yet below full Competence, at which recorded data actively find problems before they become failures, because the data collected are not yet analytically exploited.

The maturity placement rests on the convergent pattern of evidence across both datasets rather than on a demonstrated upward trend; the year-on-year rise in compliance, though descriptively encouraging, was not statistically significant, so the claim is correspondingly modest: the plant shows the capacity for higher maturity without yet having consolidated it.

4 Implications and limitations

4.1 Practical implications

The findings point to interventions that are specific rather than generic, which is their main practical value. First, because the most damaging compliance failures are predictable, they are plannable: the scheduling system can be adapted to level task loading ahead of the known June and December constraint windows, with advance procurement of critical spares and early contractor mobilisation timed to precede those windows instead of merely reacting to them. This converts a recurring structural loss into a managed one. It is also the direction of regulatory travel in the region: Adenuga et al. [22] note that the Nigerian regulator has moved from historically schedule-based maintenance guidance toward risk-based approaches, so adapting task loading to known risk windows aligns plant practice with an emerging regional norm.

Second, because the capability gap is reliability-specific rather than general, the highest-leverage workforce investment is targeted reliability training and certification (toward credentials such as CMRP) over broad professional development, which the plant already has in reasonable measure.

Third, because the plant plans well but executes unevenly, governance effort is better directed at closing the analytical feedback loop, systematically using the compliance data the plant already collects to drive corrective action, than at building further data-collection capacity it does not lack.

These implications generalise, with appropriate caution, to comparable facilities. Many gas processing and asset-intensive operations in similar resource-constrained settings are likely to exhibit the same combination of adequate planning, seasonally constrained execution, and administratively rather than technically oriented workforces.

4.2 Limitations revisited in light of the findings

The interpretations above should be read against the study's boundaries. The single-site design supports analytical transferability but not statistical generalisation, and while the seasonal effect itself is statistically established, no mechanism specific to the June window could be identified from the maintenance record, so the constraints described are the categories that recur at this facility rather than a demonstrated cause of the June shortfall. The survey strand relies on a single instrument administered on one occasion, so common-method bias cannot be excluded; the compliance record, generated independently through routine plant processes, partially mitigates this. The study observes maintenance activity rather than its reliability outcome: no failure, availability or mean-time-between-failure data were available, so compliance is assessed as an activity measure and not as evidence of equipment reliability. The maturity bands applied in Sect. 3.3.1 are the authors' own interpretive heuristic, and the placement should be read as an assessment against a stated heuristic rather than a determination against a published scale, though it is unchanged when the bands are shifted by five percentage points in either direction. Finally, the maturity placement reflects the dimensions the available data could populate. A

fuller assessment would incorporate subsystem-level compliance and condition-monitoring data that the current dataset does not contain. These boundaries temper the strength of the claims without undermining the central, twice-evidenced findings.

5 Conclusions

This study set out to assess the maintenance maturity of a resource-constrained sub-Saharan gas processing organisation and to identify the specific constraints limiting its progression. Triangulating 36 months of PM compliance records against a workforce survey of 84 maintenance and operations personnel, the assessment places the organisation in the Developing-to-Competent band of the IAM maturity spectrum under ISO 55001. Scheduled maintenance is institutionalised and tracked, and the three world-class months recorded in 2025 demonstrate that Optimising-level execution is within reach, but that capability is not yet consolidated.

Three findings carry the interpretive weight. The most damaging compliance failures are predictable: the June trough recurred in all three years (OR 0.29, $p < 0.001$) and a weaker December effect was also present (OR 0.48, $p = 0.029$), turning what would otherwise be a structural loss into something the plant can plan around. The maintenance record identifies the categories of constraint that recur, principally supply-side delay and loss of asset access to concurrent production, without identifying a mechanism specific to those months. The organisation also plans well but executes unevenly, so improvement effort belongs at the point of execution, not in further planning structures. And the workforce capability gap is specific to reliability, not general, which makes targeted reliability training and certification the more precisely targeted human-capital investment. Because both evidence strands independently converge on each finding, together they provide as strong a basis for these conclusions as a single-site design can offer.

The wider contribution is methodological. For comparable facilities in similar settings, the study offers a diagnostic approach that uses data most plants already collect, reconciling compliance records with workforce perception to locate specific, addressable constraints instead of attributing underperformance to generalised under-resourcing. Future work should extend the assessment with subsystem-level compliance data, management interviews and training-budget records to separate organisational from individual drivers of the capability profile, and a longer observation window to test whether the execution gains observed in late 2025 prove durable.

Abbreviations

API

American Petroleum Institute

CI

Confidence interval

CMMS

Computerised maintenance management system

CMRP

Certified Maintenance and Reliability Professional

CRL

Certified Reliability Leader

FMEA

Failure mode and effects analysis

IAM

Institute of Asset Management

ISO

International Organization for Standardization

LPG

Liquefied petroleum gas

PAS

Publicly Available Specification

PM

Preventive maintenance

PMC

Preventive maintenance compliance

PMP

Project Management Professional

RCA

Root cause analysis

RCM

Reliability-centred maintenance

SD

Standard deviation

SMRP

Society for Maintenance and Reliability Professionals

OR

Odds ratio

Declarations

Ethics approval and consent to participate

Ethical approval for this study was granted by the Research Ethics Committee of Robert Gordon University, Aberdeen, United Kingdom. Institutional consent to conduct the assessment and to access the plant's preventive maintenance compliance records was granted by Ghana National Gas Company. Participation in the survey was voluntary. Informed consent was obtained from all individual participants

prior to completion of the questionnaire, and participants were advised of their right to withdraw at any point. All responses were anonymised and no identifying information was retained.

The lead author is employed at the study site and holds supervisory responsibility for a subset of the personnel invited to participate. To protect the voluntariness of consent, the questionnaire was self-administered online rather than distributed or supervised in person, no identifying information was collected or retained, individual responses cannot be attributed to any respondent, and results are reported only in aggregate. Participants were informed that a decision not to participate carried no consequence. This dual role is set out in the Methods (Sects. 2.6 and 2.7) and declared under Competing interests below.

Consent for publication

Not applicable. The manuscript contains no data relating to any identifiable individual person.

Availability of data and materials

The monthly preventive maintenance compliance data supporting the conclusions of this article are included within the article (Table 4); the underlying 144 weekly records, including the shortfall descriptors, are available from the corresponding author on reasonable request and with the permission of Ghana National Gas Company. The questionnaire dataset generated and analysed during the current study is not publicly available because it comprises workforce responses collected under an institutional confidentiality agreement with Ghana National Gas Company, but it is available from the corresponding author on reasonable request and with the permission of Ghana National Gas Company.

Competing interests

RKA is employed by Ghana National Gas Company, the operator of the Atuabo Gas Processing Plant that constitutes the case setting for this study and holds supervisory responsibility for a subset of the personnel invited to participate in the workforce survey. The company granted access to the plant's maintenance compliance records and permission to conduct the survey but had no role in the design of the study, in the collection, analysis or interpretation of the data, in the writing of the manuscript, or in the decision to submit it for publication. The measures taken in response to this dual role are described in Sects. 2.6 and 2.7. GO and II declare that they have no competing interests.

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Authors' contributions

RKA conceived and designed the study, curated and analysed the compliance dataset, designed and administered the questionnaire, and drafted the manuscript. GO and II supervised the study, contributed to the analytical framework and interpretation, and revised the manuscript critically for intellectual content. All authors read and approved the final manuscript.

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Figures

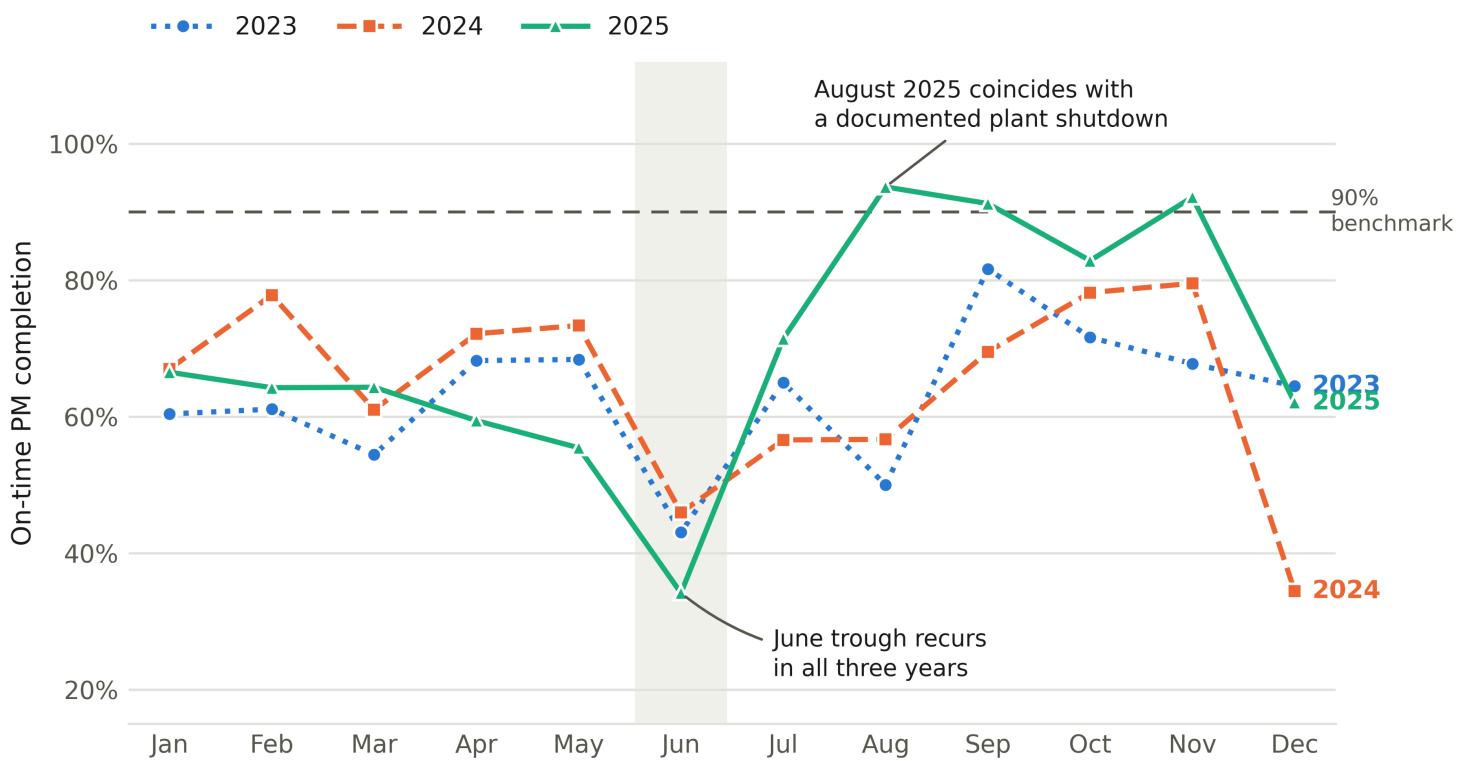


Figure 1

Monthly PM compliance by calendar month, Atuabo Gas Processing Plant, 2023–2025

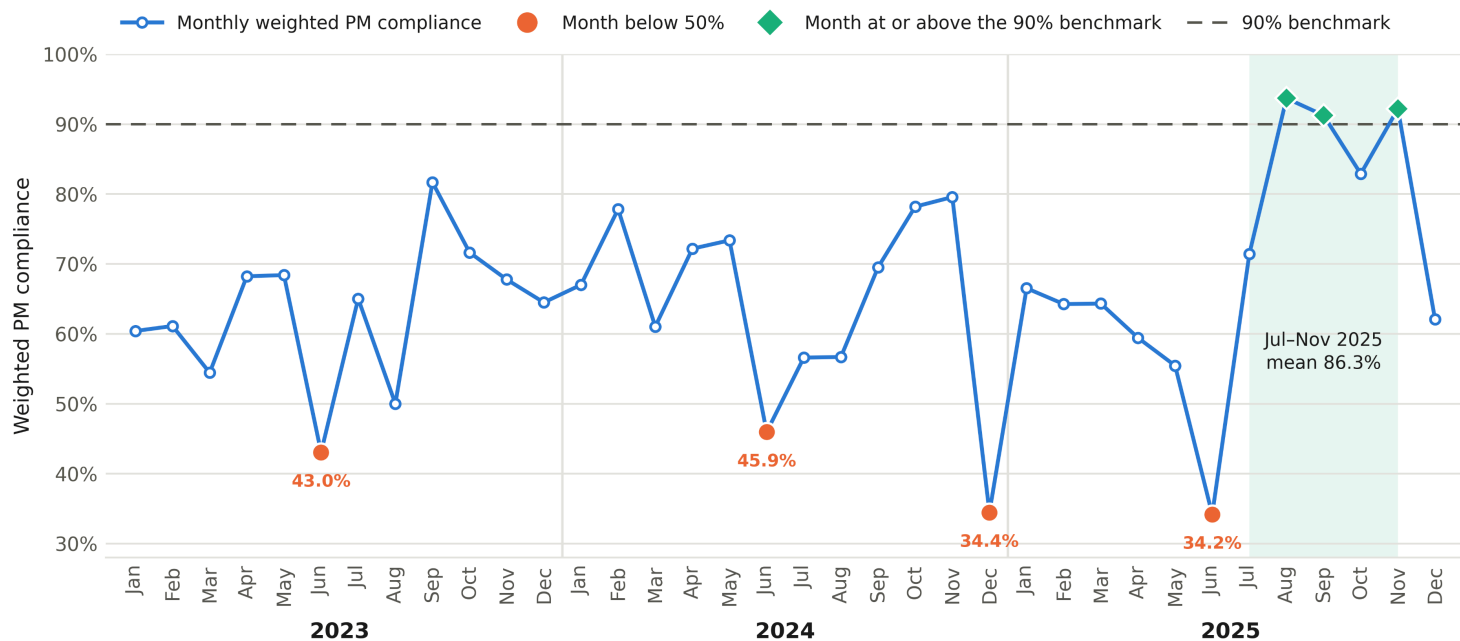


Figure 2

Monthly weighted PM compliance, Atuabo Gas Processing Plant, January 2023 to December 2025