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Enhancing Power Plants Performance through Strategic Asset Lifecycle Management: A Case Study of the West Tripoli Power Plant

Khaled El-Akruti [1 *], Othman Khalifa [2], Ali Salem [3], Anas Alnakhli [4]
[1,3] Engineering Asset Management Research Center,
Libyan Academy for Postgraduate Studies, Janzure, Tripoli, Libya
[2] Libyan Centre for Engineering Research and Information Technology. Beni Waleed, Libya
[4] Department of Engineering Management, Faculty of Engineering, University of Tripoli, Tripoli, Libya

تعزيز أداء محطات الطاقة من خلال إدارة دورة حياة الأصول الاستراتيجية: دراسة حالة محطة توليد الطاقة بغرب طرابلس

خالد العكروتي[1*]، عثمان خليفة [2]، علي سالم[3]، أنس النخلي[4]
[1،3] مركز أبحاث إدارة الأصول الهندسية، الأكاديمية الليبية للدراسات العليا، جنزور، طرابلس، ليبيا
[2] المركز الليبي للبحوث الهندسية وتقنية المعلومات، بني وليد، ليبيا
[4] قسم الإدارة الهندسية، كلية الهندسة، جامعة طرابلس، طرابلس، ليبيا

[*]Corresponding author: K.elakruti@academy.edu.ly

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Abstract
This study proposes a Strategic Lifecycle Management Approach (LCMA) to improve power generation asset performance, using Libya's West Tripoli Power Plant (WTPP) as a case study. The retroductive analysis, based on internal documents and interviews, found that the absence of a formal LCMA led to operational deficiencies like frequent outages, high costs, and customer dissatisfaction. These were caused by a lack of integrated maintenance planning and poor departmental coordination. The study concludes that implementing a standardized LCMA, aligned with international frameworks, is essential for optimizing performance. Key recommendations include establishing preventive maintenance protocols, integrating KPIs for monitoring, and adopting smart technologies for data-driven decision-making to enhance energy supply stability.

Keywords: Lifecycle Management, Engineering Asset Management, Power Plant Performance, Strategic Alignment, Operational Reliability, Preventive Maintenance, Libya Energy Sector.

الملخص
تُقدّم هذه الدراسة منهجًا إستراتيجيًا لإدارة دورة الحياة لتحسين أداء أصول توليد الطاقة، باستخدام محطة غرب طرابلس لتوليد الطاقة في ليبيا كدراسة حالة. وكشف التحليل الاسترجاعي، القائم على الوثائق الداخلية والمقابلات، أن غياب منهجية رسمية لإدارة دورة الحياة أدى إلى أوجه قصور تشغيلية مثل الانقطاعات المتكررة للتيار الكهربائي، والتكاليف المرتفعة، وعدم رضا العملاء. وقد نتج ذلك عن عدم وجود تخطيط صيانة متكامل وضعف التنسيق بين الإدارات. وتخلص الدراسة إلى أن تنفيذ منهجية موحدة لإدارة دورة الحياة، بالتوافق مع الأطر الدولية، أمر ضروري لتحسين الأداء. وتشمل التوصيات الرئيسية إنشاء بروتوكولات صيانة وقائية، ودمج مؤشرات الأداء الرئيسية للرصد، واعتماد التقنيات الذكية لاتخاذ القرارات القائمة على البيانات لتعزيز استقرار إمدادات الطاقة.

الكلمات المفتاحية :إدارة دورة الحياة، إدارة الأصول الهندسية، أداء محطات الطاقة، تحقيق الاستراتيجية، الموثوقية التشغيلية، الصيانة الوقائية، قطاع الطاقة الليبي.

Introduction

Power generation systems in many developing countries face serious operational challenges due to rapid aging infrastructure and a lack of proper asset lifecycle management (LCM) [1]. Libya's power generation plants are no exception, with the country's energy sector suffering from chronic underinvestment, political instability, and mismanagement of hydrocarbon infrastructure that have limited investments in both oil and power sectors [2]. The General Electricity Company of Libya (GECOL), which oversees the national grid, has struggled with power shortages and growing energy demand despite Libya's abundant energy resources [3]. For example, the West Tripoli Power Plant (WTPP), a key component of Libya's national generation capacity, has suffered from repeated outages, long downtimes, and costly emergency maintenance interventions for the period from 2008 to 2011 [4]. These challenges have persisted in more recent years, with Tripoli experiencing regular blackouts lasting 9-10 hours per day affecting most Tripoli residents until recently [5]. The WTPP represents a critical infrastructure asset with multiple units. It has faced significant operational challenges, with deficiencies particularly related to a lack of preventive maintenance planning and poor integration between lifecycle functions and supporting departments [6]. These deficiencies have resulted in increased outages and stoppages of generation units, rising operational costs, and customer dissatisfaction [6]. The plant's performance issues reflect broader challenges across Libya's power sector, where most maintenance projects have stopped due to an inability to perform necessary periodic maintenance [6].

As power plants age, their components experience natural wear and increasing operational complexity, which demands a comprehensive and systematic approach to asset management. The application of an LCMA is dependent on principles of the EAM system/standard (e.g., PAS 55 and ISO 55000 standards), to ensure that physical assets perform reliably, cost-effectively, and in alignment with strategic business goals throughout their service life [7, 8, 9]. In this respect, the LCMA provides planning, coordination and control of activities for an organization to enhance performance in support of realizing value from assets in relation to optimizing cost and eliminating or minimizing risk [9, 10].

Reviewing the theoretical background and literature shows that LCMA is the approach based on assuring the existence and adequacy of an EAM system's activities over the lifecycle stages of assets [9]. LCMA is considered a holistic approach that integrates asset-related activities (lifecycle and supporting activities) to achieve optimum performance for competitive advantage [11]. In this respect, EAM is defined as "a systematic approach to activities and practices through which an organization optimally manages its assets and associated performance, risks, and expenditures over their lifecycle to achieve its strategic organizational plan" [7, 8, 11]. LCMA focuses on assets throughout their lifecycle, which begins with identifying the need for physical assets, defining requirements, procurement, installation, operation and maintenance, and ends with asset disposal [10]. The asset lifecycle encompasses all activities from initial need identification to final disposal and provides benefits in terms of extending asset lifespans, reducing downtime, improving operational efficiency, making cost savings and data-driven decision-making [12, 13].

Effective lifecycle management enables asset managers to optimize asset lifespans and maximize utility [14,15]. Every asset undergoes five key lifecycle stages: Planning (identifying needs and evaluating options), acquisition (procuring and installing the asset), usage (implementing maintenance strategies e.g., preventive, predictive, routine), maintenance (executing planned maintenance to sustain performance) and disposal (assessing cost-benefit for replacement or refurbishment). Lifecycle stages are the basis that defines the cost elements for Lifecycle costing (LCC) [12, 13]. LCC's elements provide a means to estimate the total capital, operational, and maintenance costs over an asset's lifespan, including planning, design, acquisition, installation, maintenance, rehabilitation, financing, and disposal [16]. The LCC analysis provides the basis for defining decision-making based on optimum asset functional life criteria. LCC is also critical for long-term financial planning, ensuring optimal resource allocation and avoiding short-term cost-saving measures that may lead to higher expenses later [17]. In this respect, LCMA offers financial, environmental, and social benefits, including: cost savings, enhanced regulatory compliance, risk avoidance, improved customer and employee satisfaction. It provides guidance on how engineering assets can be controlled through their lifecycle. It encompasses the management of both tangible and intangible assets, ensuring processes are designed to minimize risks and maintain high performance metrics [11, 13].

Achieving the goals of power generation plants through life cycle management requires measuring performance against planned objectives in terms of timing, accuracy, and efficiency. The negative impact of power outages compels electricity producers to adopt LCMA for improved performance. LCMA also uses EAM standards for measuring asset lifecycle performance. Frequent power outages often result from ineffective execution of lifecycle activities, reflecting poor performance [18, 19]. Conversely, a well-implemented LCMA system enables power plants to efficiently manage lifecycle activities such as operation and maintenance, enhancing plant performance through improved asset availability and reliability, which in turn ensures uninterrupted power supply [18, 19].

The primary goal of LCM is to maximize returns on investments, including monitoring and maintaining utility systems while delivering optimal user service [1]. Public asset management extends LCM to municipal assets, integrating asset registers with computerized maintenance management systems (CMMS) and geographic information systems (GIS) [20,21]. The primary objective of LCM is optimal management of physical assets and their performance [9].

According to El-Akruti [9], the LCM system control activities comprise planning and control activities that exist at three organizational levels: operational, aggregate, and strategic level. The EAM system's activities control the asset lifecycle activities and their relationship with the supporting activities. The control loop across the three levels involves control activities such as maintenance requirement analysis (e.g., failure analysis, risk analysis, lifecycle cost analysis and prediction), to define proactive/preventive maintenance with optimized repair strategies, to avoid unwanted consequences, achieve optimization, and make database-driven decisions [9]. These control activities are crucial aspects of asset lifecycle management, ensuring operational stability and minimizing unplanned downtime. They ensure system reliability and operational efficiency, reduce production costs (15–40% in industrial sectors), and enhance safety and productivity [22,23].

LCMA integrates engineering, management, finance, and information systems/technology to ensure that physical assets provide the highest value throughout their lifecycle [9,10]. The fundamental aim is to maintain assets in a condition that ensures operational reliability, performance, and economic efficiency while supporting strategic organizational goals. Key components of LCMA include: life cycle cost analysis, risk-based maintenance planning, preventive and predictive maintenance, performance measurement via KPIs and integration with enterprise-level strategic planning. As per El-Akruti et al. [11], LCMA plays a strategic role through planning, control activities, and decision-making mechanisms. It creates a feedback loop that links asset performance directly to business outcomes such as reliability, customer satisfaction, and return on investment.

The LCM in power generation spans several stages, including: needs identification and planning – recognizing the demand or performance gap that requires a new asset or improvement; design and acquisition – engineering and procuring the most suitable solution to meet performance targets; installation and commissioning – ensuring the asset integrates with existing systems and performs as specified; operation and maintenance – maintaining the asset under optimal operating conditions; and decommissioning or disposal – retiring the asset once it is no longer cost-effective or safe. Effective management of this cycle is particularly important in capital-intensive sectors like energy, where plant lifespans may exceed 40–60 years. Lifecycle cost and performance modeling enable organizations to forecast long-term operational costs and make informed investment decisions [24].

The introduction of international standards, such as PAS 55 and ISO 55000, marked a pivotal development to enhance LCM [7, 8]. These standards emphasize: alignment of asset-related decisions with strategic goals, documentation and transparency of asset performance, evidence-based decision-making through KPIs and audits, and continuous improvement. These frameworks are particularly relevant in the Libyan context, where efforts are underway to rehabilitate and expand Libya's power generation capacity, including major projects such as the restoration of existing power plants, upgrading grid infrastructure, and building new capacity [3].

Strategic asset management frameworks model organizations as layered systems. El-Akruti [10], proposed a framework for LCMA that categorizes asset activities into: strategic planning and control (e.g., capacity expansion planning, risk evaluation), aggregate (tactical) planning and coordination (e.g., resource allocation, project supervision), and operational control (e.g., maintenance scheduling, performance monitoring). The framework allows for assessing the degree to which asset decisions are consistent with strategic triggers such as market demands, regulatory changes, or system capacity limitations.

Globally, power generation companies often struggle with: aging infrastructure with outdated technology, lack of integration between lifecycle activities and strategic decision-making, inadequate funding and reliance on corrective maintenance, poor documentation and knowledge transfer and organizational silos between maintenance, operations, and planning units [25]. In a case-based research by El-Akruti et al. [10] , it showed that poorly integrated asset solutions—those that fail to consider lifecycle integration and strategic alignment—lead to underperformance, delays, and excessive costs. Conversely, when lifecycle activities are adequately implemented and synchronized with strategic goals, asset reliability, cost efficiency, and service quality improve significantly [10].

The literature clearly demonstrates that the strategic application of LCMA is essential for improving service reliability in Libya. Adopting a structured EAM framework—aligned with international standards and tailored to WTPP's operating environment—has the potential to transform asset performance and increase the reliability of the national grid. This is particularly important given that Libya has begun to explore renewable energy as part of its long-term strategy to diversify its energy mix, with the Libyan government and GECOL, along with international companies, spearheading a series of solar and wind power projects [3].

This paper explores the strategic role of LCMA in power generation by analyzing the case of the West Tripoli Power Plant. The study aims to identify weaknesses in current asset management practices, map them against internationally recognized frameworks, and propose tailored solutions that can be realistically implemented by WTPP. It is proposed that proper implementation of LCMA leads to highly reliable power plants, uninterrupted supply, and optimal asset lifespans. Conversely, inadequate LCMA results in low reliability, intermittent supply, and shorter lifespans. The research investigates the extent to which the LCMA concepts are known and applied in WTPP, and how the gaps can be addressed in this prospective. The overall objective of the study is to explore LCMA's role in maintaining power plant reliability, supply continuity, and optimal asset lifespans, while addressing challenges faced by WTPP.

The case of WTPP is particularly relevant given that it has been part of recent efforts to improve Libya's power infrastructure. Notably, the new 671 MW Simple Cycle Tripoli West Power Plant project was recognized as an award-winning project whose construction team worked double shifts to fast-track the project to quickly resolve electricity shortages in Tripoli, and the project was completed ahead of schedule and below budget in January 2023 [5,26]. Following the plant's completion, Tripoli experienced no blackouts in 2023 for the first time in six years [5], demonstrating the potential impact of proper investment and management in power infrastructure. This success story provides a valuable foundation for understanding how systematic LCMA implementation can further enhance plant performance and sustainability [27].

Through this case study, the research will contribute to the broader understanding of asset management practices in challenging environments and provide practical insights for power generation companies in developing countries facing similar challenges. The findings are expected to be particularly relevant for utility companies across North Africa and the Middle East where similar conditions of aging infrastructure, political instability, and growing electricity demand prevail.

Methodology

This study adopts a contextual-retroductive case study design methodology as proposed by [28], which is particularly suited for strategic asset management research. This methodology investigates how specific asset-related activities influence strategic outcomes by analyzing both the internal structure of an organization and the contextual triggers that shape its decisions. The approach is grounded in two key theoretical foundations: contextual and retroductive approach. Contextual approach emphasizes the influence of organizational, environmental, and strategic contexts on asset decisions**.** Retroductive approach aims to identify the causal mechanisms behind observed outcomes by tracing backwards from effects to potential underlying causes. By employing a case study embedded in the Libyan power generation sector—specifically the WTPP—the study examines how LCMA play a role in strategic decision-making, resource deployment, and asset performance. The Case Study Framework is an analytical framework that follows a four-stage logical structure derived from El-Akruti and Dwight's asset management model in Table 1:

Table 1: Four-Stage Logical Model Structure [9,10,11]

Stage	Description
1. Strategic Trigger	Identifies external or internal events that create a need for asset response.
2. Asset Solution	Defines the technical or organizational responses related to asset decisions.
3. Solution Provision	Details how the solution was implemented—resources, policies, constraints.
4. Outcomes	Assesses performance results and contribution to strategic goals.

Each stage is analyzed in relation to the West Tripoli case, using both qualitative and quantitative data. The methodology allows for assessing not only what actions were taken, but also why and how they succeeded or failed. To ensure comprehensive and reliable findings, the study uses multiple data sources, including: internal documents, interviews, site observations, archival records and others. Internal documents include technical reports, annual maintenance plans, asset design records, performance logs, etc. Interviews include structured interviews with senior engineers, maintenance staff, and operational managers at WTPP. Site observations include onsite inspections of physical assets, maintenance workshops, and control rooms, etc. Archival records include failure logs, electricity production reports, and project feasibility assessments, etc. This triangulation improves data validity and enables cross-verification of events and decisions. The interview questions were based on a protocol targeting the causal relationships between asset management practices and strategic outcomes[9,10,29].

Case Study Analysis: Investigating the Status of West Tripoli Power Plant

The analysis of the West Tripoli Power Plant (WTPP) as case study serves the objective of the research. Commissioned in the late 1970s, the WTPP plant comprises: 5 steam turbines (65 MW each)**,** 2 additional steam turbines (120 MW each) added in the 1980s. These units feature impulse reaction turbine three cylinder systems manufactured by Rateau Alstom and implemented by Alstom France. All units were connected to the national grid by 1976. A temporary gas turbine module (25 MW each) added in 2013**.** The plant represents a typical case of aging infrastructure operating in a challenging socio-political context. Its history of both attempted expansion and chronic outages makes it an ideal subject for evaluating the role of LCMA in practices.

WTPP faced challenges due to lack of capital investment, proper maintenance and limited human resource capacity. It operated since the late seventies with dramatic overloads every year until it became mostly inactive in 2010. The need for both capacity expansion and intensive refurbishment of existing units was urgent. However, no strategic action took place. Maintenance is largely reactive, performance indicators are rarely documented, and strategic decisions often bypass technical evaluation. This resulted in high failure rates in key assets (generators, turbines), frequent load shedding and escalating cost per megawatt-hour produced. The analysis of WTPP case study involved several aspects:

- Significant Increase in Energy Demand:

The growing energy demand in Libya has resulted in a gradual increase in loads on power generation stations. Reviewing the status of West Tripoli Power Plan as a case study reflect Libya's power generation plants situation as it is one of the oldest steam generation plants in Libya's national power grid. Commissioned in the late 1970s, expanded in 1980, but notably, through the period from 1980 to 2010 there were no capacity expansion projects or new unit additions at West Tripoli Steam Plant. No plans were developed for new power generation facilities in the region during this time. Currently, all steam units at the plant are out of service due to deterioration and obsolescence.

- Generation Capacity and Design Capability Status:

No development or expansion of the plant was planned until 2010, when a severe electricity supply deficit emerged. Then, a contract was signed with Hyundai of South Korea to establish the WTPP project with a total capacity of 1,400 MW, comprising four steam units (350 MW each). The project was never implemented due to Libya's political upheaval in 2011. Facing persistent supply shortages, overstressed generation plants (some collapsing), and prolonged nationwide blackouts, WTPP became unable to perform timely maintenance. By 2013, the situation necessitated deploying mobile power generation units. WTPP received two mobile gas units (25 MW each), GE TM2500 type manufactured by General Electric (USA).

- Strategic Planning:

The gap between electricity demand and generation capacity reveals a lack of the strategic planning and coordination with Ministry of planning in Libya. For example, although Libya's Government of National Unity invested heavily to increase generation units and rehabilitate existing plants over three years, it took long for the coverage of electricity demand and required massive expenditure. There was also evidence of mismanagement; key findings from employee interviews & document review reveal such situation e.g.: a manager stated: *"Our company lacks formal procedures for asset development projects".* Several managers acknowledged that despite efforts to launch projects addressing load increases, deficiencies in strategic planning pre-2011 and post-2011 crippled execution.

- Operational and Production Status:

The idea to improve power generation plants in terms of production planning, as reflected in reports, focused on meeting rising electricity demand. According to one manager:
"The situation was always: 'consumption vastly exceeds production' – essentially consuming all generated output, forcing us to implement load shedding". Although documented quality manual aims to *"achieve qualitative leadership through customer satisfaction"* this goal remains unrealized. Independent publications, production records, and interviews confirm that there was failure to maintain consistent power continuity. All interviewees emphasized that it is a must to increase generation capacity to meet demand growth while preserving quality and cost efficiency.
As noted by most interviewed managers, despite improvement efforts, targets were not fully achieved. One plant manager stated: *'...We couldn't significantly reduce production issues, but have partially managed to balance energy demand with current problems...'.* Multiple improvements were implemented during 2012-2013, including

maintenance and operational control procedures to address major issues. However, asset utilization rates decreased due to deterioration, causing achieved output to fall below projections. Additional operational efforts failed to yield better results, as persistent failures and corrective maintenance disrupted operations/planning while accelerating plant deterioration and outages. Consequently, production and quality enhancement initiatives proved futile. Another manager highlighted numerous complaints and operational delays due to these challenges. This underutilization increased losses and operational costs.

- Maintenance Status: Critical Organizational Deficiencies:

The investigation reveals the absence of maintenance governance; the lack of a dedicated maintenance planning department at any organizational level demonstrates fundamental neglect of asset stewardship and in particular, neglect of preventive maintenance (PM). This structural deficiency directly enabled: unplanned maintenance regime that is exclusive reliance on reactive approaches, breakdown maintenance (post-failure), emergency/corrective interventions and ad hoc routine checks. PM void: no evidence of condition-based or time-based preventive programs, indicating absence of reliability-centered maintenance (RCM) principles. Planning vacuum: zero strategic maintenance planning capability, compromising asset lifecycle management. This voids ISO 55000 requirements for systematic asset care, necessitating data collection to evaluate EAM system maturity. The operational consequences were chronicle; operations managers confirmed 2012-2013 initiatives focused solely on emergency restoration tactics. This reactive approach triggered: cascading equipment failures (secondary damage during rushed repairs), chronic operational instability (short-term shutdowns documented) and safety compromises (rise in maintenance-related injuries per safety logs). The maintenance director explicitly stated:
"Emergency maintenance increased costs while reducing plant availability due to collateral damage and underutilization. Interviews reveal that *"breakdown maintenance originated from load-shedding pressures during peak demand, overriding protection systems to maintain output and deferring minor overhauls."*
From the management perspectives, there was a systemic failure; production & operations leadership consensus that reactive maintenance is financially and technically unsustainable and urgent capital investment in high-capacity units is required to break failure cycles. As a west Tripoli plant manager's stated:
"Proactive capacity expansion was needed by 2009. Delaying this for 14 years directly caused our current operational crisis.".
There were deficiencies in use of technology & training as corroborated by interviews; advanced IMS/CMMS systems underutilized and no digital work orders or maintenance history tracking. Interviews revealed that training gaps: zero formalized operator/maintainer competency programs and failure drivers of outages are mostly linked to, improper procedures (untrained staff), lifecycle expiration (average asset age: 32 years) and repeat component failures (poor repair quality). The maintenance status requires establishing central maintenance planning office with RCM capability, implementing CMMS with PdM modules (vibration analysis, oil monitoring) and adoption of ISO 55001 framework with dedicated asset management division.

- Overall finding Regarding the Status of West Tripoli Power Plant:

Unit configuration details for WTPP are shown in Table 2. Steam units under feasibility study for maintenance or scrapping are shown in Table 3 and those that undergo major maintenance are shown in Table 4. Field inspections and documentation review confirm the plant is in a near-total shutdown state: all steam units are fully offline with varying downtime durations and failure causes. This reflects the absence of asset management system activities including: strategic planning and development, preventive maintenance/operations scheduling, asset replacement planning, monitoring, evaluation, and risk prediction protocols to prevent early-stage failures. It is confirmed that only 1 unit operational at 10MW (40% capacity) and remaining units failed due to technical issues requiring maintenance. Interviews revealed that current management actions is directed toward feasibility studies initiated for decision regarding scrapping/decommissioning units 1 & 2, overhauling units 6 & 7 and maintaining remaining mobile units. On the other hand, a contract was signed in December 2017 for an emergency WTPP, consisting 4 gas-fired units with 350 MW per unit accumulating 1,400 MW in total capacity but was launched in 2021.
Based on the status of WTPP, the absence of a structured LCMA has led significantly to the declining performance of power generation assets. This has led to recurrent power shortages, increased operational costs, loss of public confidence, and economic disruption. Reviewing the case of the WTPP, operational records show a continuous increase in unplanned outages from the early 2000s through 2022.

Table 2: Unit Configuration Details for West Tripoli Plant.

Unit Type	No. of Units	Rated Capacity (MW)	Status & Remarks
Steam	5	65	All stopped (Legacy units, avg. age 45+ years)
	3	120	All stopped (Post-1980 units, severe deterioration)
Mobile Gas	2	25	1 operational at 10MW (40% capacity) 1 stopped (Mechanical failure)
	2	30	All stopped (Fuel system/control failures)
Gas (New)	4	350	Under testing/commissioning (1,400MW emergency project)

Table 3: Steam Units Under Feasibility Study for Maintenance or Scrapping

Unit Name	Capacity (MW)	Year Stopped	Notes
Unit 1	65	2014	Steam unit. Permanently decommissioned.
Unit 2	65	2011	Steam unit. Taken offline during political crisis.

Table 4: Steam Units Undergoing Maintenance

Unit Name	Capacity (MW)	Maintenance Notes
Unit 6	120	Boiler tube renewal & control system upgrade
Unit 7	120	Boiler tube renewal & control system upgrade

A summary of key findings are shown in Table 5. These results affirm the hypothesis that the absence of LCMA in practice within WTPP has directly contributed to poor performance (low reliability, inefficiency, and rising operational risks) that led to loss of alignment with the strategy.

Table 5: Summary of Key Findings.

Observation	Implication
High unit failure rates	Indicates lack of proactive asset lifecycle planning
Short-term fixes (mobile units)	Reflects reactive strategies, not aligned with long-term asset value
Absence of centralized EAM	Leads to inconsistent decisions and missed performance optimization
Escalating emergency maintenance costs	Drains resources that could be allocated to structured preventive actions
Poor integration between strategy and action	Results in failed implementation of strategic expansion (e.g., Hyundai deal)

The Framework Analysis

The process of "data collection, sorting, analysis, and interpretation" is structured to align with the proposed framework for the EAM system, as outlined in the study published by El-Akruti et al. [11]. Data collection and sorting include: identifying the strategic event, identifying the asset solution, providing the asset solution, and identifying the outcomes. Analysis and interpretation involve: establishing and interpreting the control procedure for the EAM system. These steps, encompass the analysis and interpretation of the overall case, which represents a specific phenomenon, event, or activity [11].

- Phase One: Identifying the Phenomenon:

The first phase involves four referenced steps from the functional model of the EAM system [11]. It provides the data required to evaluate the implementation:

- Identifying a phenomenon or strategic change: this includes, within the context of this study, the phenomena of load shedding, escalating load shedding, and complete blackout events.
  - Based on extrapolations from the history of events at WTPP over the past 30 years, phenomena or events relevant to this study were selected.
  - The phenomena selected for this study include specific events, verifying the responses of WTPP 's management, and comparing them with the requirements of EAM system.
  - The identified phenomena or events relate to increased energy demand and the responses through two consecutive projects in production facilities. These reflect two asset-related solutions considered as case studies, as specified in Table 6.

Table 6: Phenomenon, Event or Strategic Change.

Phenomenon/Event and Early Warning Signs	Details
Load Shedding Phenomenon	The phenomenon of load shedding due to production deficits failing to meet increased energy demand since 2000
Escalating Load Shedding and Complete Blackout Phenomenon/Event	The phenomenon of escalating load shedding and complete blackouts due to increased energy demand, deterioration of power plant assets, and complete shutdown of some plants in 2014

- Identifying Asset Solution(s):

This involves two approaches (solutions) in this study:

- Incrementally: enhancing existing production plants.
- Radically: developing production plants and establishing new generation plants in record time to address the phenomena of load shedding, escalating load shedding, and complete blackouts.

To resolve these issues, WTPP's response to rising domestic demand took the form of two consecutive solutions. The first solution was defined as enhancing existing generation plants, and the second as constructing new plants.
First Solution Objectives: the company aimed to achieve sufficient production to cover the energy deficit without impacting the condition or capacity of existing operational plants. A substantial production rate increase was urgently needed within a very short timeframe.
Operational Constraints: reviews of annual production planning reports indicated plants were operating at full capacity, revealing production capacity limitations. Production planning (as documented in reports) was based on meeting rising energy demand.
Management Perspective: as stated by one manager: *"Consumption far exceeded production – we consumed everything generated, forcing us to implement load distribution."*
Quality Shortfalls: though documented quality manual aimed for "quality leadership by ensuring consumer satisfaction," this was not achieved. Independent reporters, public dissatisfaction, production records, and interviews confirm that WTPP failed to maintain consistent power production quality.
Universal Recommendation: all interviewees emphasized the need for WTPP to increase production capacity while maintaining quality and cost control.

Solution Implementation:

- In 2012: internal improvements was initiated to boost production rates.
- Simultaneously: demand exceeded production capacity due to maintenance gaps and asset deterioration.
- Result: transitioned to the second asset solution – constructing a new plant.

Second Solution Requirements: this transition demanded additional time, expansion plans for production capacity, and temporary measures to compensate for shortages. Asset solutions for this phenomenon/event are summarized in Table 7.

Table 7: Phenomenon/Event/Strategic Change and Identified Asset Solutions.

Phenomenon/Event with Early Warning Signs	Identified Asset Solutions
1. Load shedding phenomenon due to production deficits failing to meet increased energy demand (since 2000)	Enhancement of Existing Units to increase production
2. Escalating load shedding and complete blackouts caused by increased energy demand, deterioration of plant's assets, and full shutdown of some facilities (2014)	Development of New Capacity: establishment new generation plant/facilities in record time

These asset solutions reflect implementation of two major asset management strategies:

- Enhancement of Existing Units: Initially, efforts focused on improving the performance of existing units through emergency repairs and overhauls, particularly in response to the surge in demand and frequent outages observed between 2004 and 2010.
- Development of New Capacity: As reliability worsened and national blackouts became more prevalent (2011–2014), the strategy shifted towards developing new capacity. This included the ambitious WTPP expansion project, which aimed to add 1,400 MW through four 350 MW steam turbines, and the deployment of mobile gas turbines (TM2500 units) as a stopgap measure.

Despite the contracting of the WTPP expansion project with Hyundai Engineering in 2010, the project was ultimately suspended after 2011 due to the prevailing national instability. This forced a pivot to temporary solutions, such as the installation of two 25 MW mobile gas turbines in 2013. This shift from a planned, permanent solution to an improvised, short-term fix clearly reflects a significant disconnect between strategic planning and the practicalities of execution.

- Provision of Asset Solution(s):

<u>The first solution</u>: This involved implementing (enhancing existing production plants through improvements). The provision includes detailed plans, resource allocation, budgets, and implementation procedures. During investigations into plant optimization, operations managers stated that:
"*Internal improvements relied on emergency maintenance solutions for failed equipment to restore generation units.*" This approach caused collateral equipment failures and operational stoppages. One manager specifically noted:
"Efforts focused on incremental modifications and enhanced monitoring to gradually reduce problem rates.". It also identified the outcomes in terms of evaluating power generation unit performance and societal value contribution through three steps:

- Assessing Unit Performance: Determines whether output indicators (productivity, reliability, downtime rates) align with improvements.
- Translating Performance Outcomes: attributes results to actions/activities executed by WTPP, where applicable.
- Evaluating Value Contribution: determines whether performance yields positive or negative value using indicators (productivity, reliability, downtime rates); positive value indicates EAM system adequacy and negative value Signals EAM system deficiency or absence.

It also involved doing performance analysis and demonstrating key finding.
Most managers acknowledged unmet performance targets despite improvement efforts.
This reflects a lack of control over lifecycle activities. Managers attributed the performance deterioration to insufficient oversight of planning, operations, and maintenance activities, stating:
"Gradual process control measures were partially implemented, but asset deterioration remained uncontrollable due to maintenance gaps and operational pressure to meet rising demand."
Multiple improvements through maintenance and operational controls were implemented to address core issues. However, they were ineffective improvement measures as utilization rates were reduced due to deterioration, actual production rates fell below projections of intended enhancement. Control of lifecycle activities failed due to persistent problems, breakdown maintenance disrupted operations and planning and accelerated asset degradation and plant stoppages.
Solutions targeting production and quality improvement proved ineffective. Interviews indicated multiple customer complaints registered, production delays encountered and underutilization of assets increased losses and costs. Maintenance managers indicated that emergency maintenance caused operational disruptions that resulted

in equipment failures, increased costs without corresponding benefits, operational incidents, safety risks, and human injuries documented

Interviews with production, operations, and maintenance directors revealed that emergency maintenance strategies were ineffective and large-capacity production units were imperative

One WTPP manager specifically noted: *"High-capacity units should have been constructed since 2009 to prevent the current critical situation at WTPP."*

Implementation revealed critical planning deficiencies: inadequate feasibility analysis (lacked comprehensive studies) and delayed strategic implementation (deployment of the fundamental solution was hindered by external security challenges) and internal shortcomings (delayed workforce training for new plants, technical planning gaps in optimal fuel selection, environmental impact oversight).

The interviews and technical reports revealed significant gaps in how proposed solutions were provisioned and executed:

- Lack of a centralized maintenance directorate meant preventive actions were often reactive and fragmented across departments.
- No digital asset management system (CMMS/EAMS) was in use to track asset performance or trigger scheduled maintenance.
- Budgeting delays prevented timely procurement of spare parts, while political insecurity hindered contractor access.

Management acknowledged these challenges, as one senior operations engineer noted:

"Our maintenance model was breakdown maintenance—only responding to failures. We didn't have a preventive maintenance plan, and reporting was inconsistent."

<u>The Second Solution:</u> establishment of large-scale power plants to address rising energy demand (strategic solution). The need for transition to the second asset solution is realized by early 2016. The new Tripoli West Power Plant commenced operation partially in 2022. It has provided the extra electricity supply to cover the demand for the region. This second solution provided the shortage in electricity supply and illustrated the improvement in operational and maintenance strategies bolsters the reliability and efficiency of power generation units, slashing downtime by 25% and costs by 15-20% [27]. Yet, success hinges on overcoming training deficits and political instability.

Through maintaining this solution, shortcomings were identified in some planning aspects. It is noticed that there was insufficient study of the previous situation, and a delay in implementing the second solution, which is considered a strategic and radical solution to the problem. This delay occurred for several reasons, including factors beyond the control of the WTPP, such as security issues. Additionally, internal reasons affected the speed of completing these new stations, along with organizational deficiencies like delays in training workers for the new stations. Furthermore, this solution itself suffered from planning and technical deficiencies related to securing the ideal fuel for these stations, which would allow to maximize their utilization. Issues also arose concerning fuel costs and the damage caused by the fuel to the generating units, reducing their operational lifespan, as well as the environmental aspects related to pollution from the fuel used and its harmful effects on the surrounding environment. For instance, the newly established West Tripoli station will operate using the light fuel oil available onsite. Therefore, a long-term strategic plan throughout the project's lifespan should have been considered to establish a natural gas pipeline to supply the stations. This would reduce fuel costs, increase station efficiency, reduce technical problems, extend their service life, and decrease pollution in the surrounding environment."

- Stage 2 - Drawing Implications from the Phenomena: Mapping and Interpretation of Status of Activities

This involves establishing and interpreting control procedures for the EAM system within the proposed framework, using data generated from WTPP case study. Establishing and interpreting the existing EAM system at WTPP involves verifying the presence or absence of activities, relationships, and mechanisms of the EAM system within WTPP, as assumed by the framework. This verification of its existence (adequacy) or absence (inadequacy) involves the following four steps:

- Determine how WTPP decided that the phenomena of load shedding, escalating load shedding, and total blackouts require a solution.
- Determine how WTPP selected enhancement of existing units to increase production was chosen over other solutions for achieving strategic objectives.
- Identifying indicator of the presence or absence of strategic planning and control activities, their interrelationships, compared with the control cycle of the framework adopted in this study.
- Determining the resulting performance of power generation stations and analyzing/evaluating the gap between target and achieved performance (energy production deficit).

- Determining how decisions are made based on information flow from various main and supporting departments, and the feedback of information between activity levels (executive, coordination/management, strategic) within the control cycle and feedback loop.
- Determine how the enhancement of existing units is provided to achieve the resulting asset performance:
- Determine how the implementation of enhancement of existing units is done:

As a result of analyzing the enhancement of existing units as a solution in response to the specific load shedding phenomenon, a conclusion is reached regarding the contribution of value towards the resulting customer value derived from related asset performance (WTPP failed to maintain consistent power production to satisfy public demand). This indicate inadequacy or absence of an EAM system's activities as proposed by the adopted framework and WTPP failed to achieve its intended strategy. The same interpretation can be done on the phenomena of blackouts and the solution of new capacity establishment.

Therefore, interpretation requires detailed investigation of causes and resulting effects. For each WTPP case study, two specific phenomena were investigated to understand how it was responded to via an asset solution. The management behavior of organizational activities related to assets and the resulting asset performance were assessed. Both negative and positive outcomes are sought, indicating the reason in the absence or presence of EAM system's activities, relationships, and mechanisms. This presence/adequacy or absence/inadequacy may relate to the duties and responsibilities associated with asset-related activities. Negative outcomes correlate with missing or poorly implemented EAM system's activities. Positive outcomes correlate with appropriate EAM system's activities. Activities were entirely absent, or present to an insufficient degree to serve the strategic objective; they also existed in some instances with conflicting aims or had negative impact on each other. The ultimate conclusion is demonstrated by failure of achievement of strategy due to the presence of an appropriate EAM system, and also by weakness in strategy execution due to an inadequate EAM system. However, outcomes were also be influenced by non- EAM system factors, such as the political instability for Libya in 2011. In such cases, these factors are identified and their concomitant impact clarified.

Table 8, maps the strategic planning and control activities of EAM system. It reveals the complete absence of strategic planning control activities. All elements/activities at this level are missing or inadequately implemented. This has resulted in generation units being unable to meet load generation requirements.

Increased units deterioration due to overall strategic failure, failure to find the appropriate EAM solutions, fluctuating policies and plans, underperformance of maintenance planning activities and reduced efficiency. These consequences have led to deficiencies in the activities of the generation process, failure to define strategic objectives, emergence of performance gaps, randomness in operational decision-making, increased wastage of resources and energy sources, failure to identify economically viable assets matching resources, lack of strategic policy development, causing reduced administrative system efficiency and emergence of gaps in control mechanism plans.

Table 8: Mapping the EAM Planning and Control Activities.

Elements of Framework	Status	Indication of Action and/or Resulting Outcome
Analysis and Evaluation	Absent/ Inadequate	– No real analysis or evaluation to define increase in demand. – As a result, there was shortage in electricity supply. – The capacity of electricity generation units could not satisfy the demand in the long run. – Inadequate analysis and evaluation of generation unit's life cycle requirement resulted in, overloading operational units and insufficient maintenance requirement that lead to early deterioration of the units. – Indications of possible blackouts risks partly ignored. – No action to mitigate risks.
Decision Making	Inadequate	– Decisions were not based on demanded increase or expected conditions. – Decisions were not based on LCC models or risk analysis. – Lack of knowledge & training of EAM principles and experience of employees led to poor decisions.

Coordination and Planning	Inadequate	– Inadequate aggregate coordination and planning between departments or teams – There were delays due to spare parts shortage/unavailability. – No good records of coordination and planning between departments were found. – No records of maintenance planning or control were found, but only emergency handling records were available. – No good performance reports were found. – All coordination were manual or semi manual form.
Work Task Control	Inadequate	– Inadequately existed, e.g. operation and maintenance departments were mismanaged for executing operational tasks. – Overloading units, by-pass modification, and poor installation resulted from the lack of experience of the employee and absence of a well establish framework and illustrated procedures. – Lack of auditing, review or work procedure recording. – Data recording was mostly manual or semi manual.
Measurement and Monitoring	Inadequate	– Poor data gathering and recording – No good measured parameters but mostly lagging indicators. – Lack of condition monitoring.
Control and Reporting	Inadequate	– Poor reports (did not reflect performance) mostly lagging indicators.

Table 9, maps the EAM system strategic relationships. It indicates the near-total absence of aggregate planning for EAM system control activities.

Table 9: Mapping EAM Strategic Relationships.

Elements of Framework	Status	Indication of Action and/or Resulting Outcome
Identification of Strategy Triggers and Definition of Strategy Event/Change	Inadequate	– Lack of interaction & inadequate relationship with the Ministry of Planning; No studies or research to define expected increase in demand – Lack of research and development activities due to missing or inadequate strategic analysis & evaluation activities. – Inadequate capability for providing internal key indicators of change triggers; internal indication of demand increases through reports & increase shown in community needs.
Definition of the Required Outcome and Performance to Achieve Strategy	Inadequate	– Lack of defining the expected demand increase, required development, expansion or enhancement to cope with the demand increase. – Lack of defining the generation capacity and output requirements or units performance to cope with the long run supply of electricity. – Lack of defining the appropriate required type/types of centricity generation plant for Libya's environmental conditions and the performance to cope with the required generation output. – Inadequate operation & maintenance strategies/policies resulted in units deterioration and negative impacts on performance and community satisfaction. – There was no indication of defining targeted or designed or resulting performance or comparing them for achievement. – Performance indicators were not well defined but the performance was reflected as an impact in terms of: poor quality supply of electricity, high maintenance cost, stoppages and blackouts and community dissatisfaction.
Definition & Provision of Assets Solution & Alignment with Required	Inadequate	– No sign on how decision were taken to select the type/types of electricity generation sources (steam, Gas, solar, wind). Decision were not taken based on sound analysis and in many cases failed to achieve targets.

Performance & Resources		– Decisions on design capacity of new units were inadequate for the increase in demand. – The decisions to undertake enhancement/modification or overhaul of exiting generation units were inappropriate and action overlooked the life cycle requirement: operation and maintenance.
Setting Strategies, Policies, Annual Targets and Aggregate Planning	Existed/ Inadequate	– Signs of strategies and policies for generation units' activities were not found (no record found). – No signs of targets to provide direction to implement strategies. – No sign found of adopted standards/frameworks or approval maintained for strategies, policies, target setting or planning of units' life cycle activities such as maintenance & operation and on indication of non-compliance e.g., to plans.

Most elements are partially present and inadequate, signifying the non-existence of effective activities of EAM system strategic relationships. This has led to deficiencies in information-related activities and reporting, procedures for activities of the generation process, monitoring and control of operations, utilization of information and communication systems and integration between activities. This situation has caused fluctuations in finding appropriate decisions and objectives, lack of activity scheduling and understanding of their economic feasibility. Consequently, leading to generation unit’s misuse, increased maintenance costs, inadequate support, time wastage and overall cost increase.

Table 10, Maps operation and PM activities against the EAM system elements/activities. It indicates the EAM system elements availability or absence or inadequacy/shortcomings and illustrates reasons for inadequacy or deficiency manifestations.

Table 10: Mapping operation and Preventive Maintenance (PM) Activities.

EAM System Element	Existence/Availability	Adequacy or Shortcomings	Reasons for Inadequacy / Deficiency Manifestations
Operation and Preventive Maintenance Strategy and Policies	Existence isn't evident. Record did not reflect existence.	Inadequate: mostly operate to failure, emergency maintenance and overloading generation units	Lack of focus on PM & its impact on performance & achieving strategy
Maintenance Plan & Implementation	Existence isn't evident	Inadequate implementation	Overloaded with emergency tasks
Scheduling Preventive Maintenance Activities: **Periodic/Routine - Predictive - Condition-Based - Age-Based**	Existence isn't evident	Only routine tasks schedule records are evident: Others: no records	Insufficient awareness of PM, or Lack of knowledge of its role and lack of training on PM
Operational Policies	Available	Inadequate: Lack of achievement of strategies/policies	Untimely PM and planning execution impact achievement of operational policies/strategies
Operations Plan & Implementation	Plan exists	Inadequate implementation	Material, Spare parts unavailability and mismanagement affects operations plan

EAM System Element	Existence/Availability	Adequacy or Shortcomings	Reasons for Inadequacy / Deficiency Manifestations
Operations Activity Scheduling	Available	Implemented inadequately: operation overloading exists	Lack of awareness of requirement and impact on other departments. Further development & research is needed
CMMS -Work Orders & Execution	Existence isn't evident Record did not reflect existence.	Inadequate: Manual	Lack of Software/ insufficient software
Information System & Inter-Department Links (Operations, Procurement, Stores, etc.)	System exists per department	Inadequate inter-department coordination	Primitive system lacking inter-department integration
Coordination with Other Departments	Coordination exists	Inadequate /Insufficient	Lack of transparency & responsibility integration; lack of advanced technologies
Data Collection & Reporting	Data/Reports exist	**Inadequate**: Lack of KPIs records; lack of transforming metrics to indicators	insufficient data processing/ conversion features
Monitoring Preventive Maintenance Completion & Problem Identification	Monitoring records were not evident but data collection exist	No evidence of data analysis performed	Lack of technology feature for analysis, and decision support
Monitoring Condition, Failure Patterns, Impact & Appropriate Safety Maintenance	No evidence of existence	insufficient determination of failure patterns/impact	Lack of technology, models and training
Monitoring Related Costs & Economically Appropriate Maintenance	Cost monitoring/data exists	Insufficient, no lifecycle cost analysis or modeling or decision support	Lack of senior management awareness and support
Performance Measurement & KPI Development	Exists	Inadequate KPI generation	Lack of senior management awareness and support
Using KPIs for Decision-Making to Improve Maintenance Effectiveness	Existence/usage of KPIs unclear	No signs of using KPIs for Decision-Making	Lack of training, frameworks for maintenance improvement and data-driven support
Preventive Maintenance Training	Unavailable	Insufficient	Lack of Senior management awareness of PM's role in achieving company strategy

Conclusion

This study confirms that the absence of a formal Lifecycle Management Approach (LCMA) is a root cause of declining performance and strategic misalignment at the West Tripoli Power Plant (WTPP). Findings indicate that WTPP's asset management practices are reactive, lack a centralized framework, and fail to use key performance indicators or life cycle costing. This has resulted in increased outages, reduced asset life, higher costs, and weakened customer trust. The research demonstrates that a strategically integrated LCMA, based on international standards, is essential for improving asset longevity, reliability, and cost control, and is critical for stabilizing Libya's power generation infrastructure.

Recommendations

For WTPP and relevant stakeholders, the following actions are recommended:

- Establish a Centralized EAM Framework: Create a dedicated unit to develop and oversee a standardized LCMA, ensuring coordination across departments.
- Implement a CMMS: Adopt digital tools to track asset health and maintenance schedules, enabling data-driven decisions and inter-departmental collaboration.
- Adopt International Standards: Formalize asset management policies aligned with global best practices and ensure compliance through audits.
- Define and Monitor KPIs: Integrate metrics like availability, MTBF, and maintenance cost per MWh into performance evaluations at all managerial levels.
- Develop Long-Term Life Cycle Plans: Use condition assessments and life cycle cost analysis (LCCA) to forecast needs and justify investment decisions.
- Build Technical Capacity: Train staff in asset management principles and software, and establish partnerships with academic institutions.
- Promote a Preventive Culture: Shift from reactive crisis-management to a proactive culture focused on risk anticipation and resilience.

Future research should explore LCMA implementation in other plants, cost-benefit modeling of renewal strategies, renewable integration, and socioeconomic impacts.

Study limitations include its focus on a single plant, a defined time period (2004-2023), and challenges with data availability and personnel access. Despite this, the available data provides a robust analysis of LCMA's strategic implications.

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