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PREVENTIVE MAINTENANCE STRATEGY FOR PRODUCTION PROCESSES AT CP1Z ARZEW PLANT (ORAN) BASED ON DATA ANALYSIS: OPTIMIZING MAINTENANCE PLANNING AND COST ESTIMATION.

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Dedication

Praise be to God, the source of all wisdom and strength,
for granting me the patience and perseverance to complete
this work.
I dedicate this thesis to my dear parents, for their
unconditional love, silent sacrifices, and unwavering support.
To my family, for their kindness, encouragement, and
constant presence.
To Mr. Mohamed Djemana, my supervisor, for his trust,
insightful guidance, and support throughout this project.
To the National School of Technologies and Engineering of
Annaba (ENSTI), for the education and values it has
instilled in me.
And to all those who believed in me and supported me, near
or far.
May this work be the result of all our combined efforts,
and a sincere expression of my gratitude.

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I would also like to thank all those who supported me, and even those who did not, as their doubts only pushed me to grow, challenge myself, and become better. For that, I thank myself—for my perseverance, for every effort I made, and for never giving up, even in the most difficult moments.

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Abstract

This final year project focuses on the optimization of preventive maintenance planning and cost reduction for industrial equipment. By analyzing key reliability performance indicators such as failure rates, availability, and maintenance costs, the study identifies inefficiencies in the current maintenance strategy. A Particle Swarm Optimization (PSO) algorithm is then applied to generate an optimal maintenance schedule that balances minimizing costs and maximizing equipment reliability and availability. The results demonstrate significant improvements in operational performance and cost efficiency, validating the effectiveness of combining data-driven analysis with advanced optimization techniques. This approach offers a practical framework for sustainable and cost-effective maintenance management in industrial settings.

ملخص

يركز مشروع التخرج هذا على تحسين تخطيط الصيانة الوقائية وتقليل التكاليف المرتبطة بالمعدات الصناعية. من خلال تحليل مؤشرات الأداء الرئيسية المتعلقة بالموثوقية مثل معدلات الأعطال، والتوافر، وتكاليف الصيانة، يحدد البحث نقاط الضعف في لوضع جدول صيانة مثالي يوازن بين (PSO) استراتيجية الصيانة الحالية. ثم يُستخدم خوارزمية تحسين سرب الجسيمات تقليل التكاليف وزيادة موثوقية وتوافر المعدات. تُظهر النتائج تحسناً كبيراً في الأداء التشغيلي والكفاءة الاقتصادية، مما يؤكد فعالية الجمع بين التحليل المستند إلى البيانات وتقنيات التحسين المتقدمة. توفر هذه الطريقة إطاراً عملياً لإدارة صيانة صناعية مستدامة وفعالة من حيث التكلفة.

Résume

Ce projet de fin d'études porte sur l'optimisation de la planification de la maintenance préventive et la réduction des coûts associés aux équipements industriels. À travers l'analyse des indicateurs clés de performance en fiabilité tels que les taux de panne, la disponibilité et les coûts de maintenance, l'étude met en évidence les inefficacités de la stratégie actuelle. Un algorithme d'optimisation par essaims particulaires (PSO) est ensuite utilisé pour élaborer un planning de maintenance optimal, conciliant réduction des coûts et amélioration de la fiabilité et de la disponibilité des équipements. Les résultats montrent des améliorations significatives en termes de performance opérationnelle et d'efficacité économique, confirmant la pertinence de l'approche combinant analyse de données et optimisation avancée. Cette méthode offre un cadre pratique pour une gestion durable et rentable de la maintenance industrielle.

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Introduction

In today’s highly competitive industrial landscape, the efficiency and reliability of production systems are paramount to maintaining operational excellence and achieving sustainable growth. Maintenance management plays a crucial role in ensuring that equipment and machinery operate at optimal performance levels, minimizing downtime, reducing operational costs, and extending asset lifespans. However, traditional maintenance strategies often struggle to balance these competing demands effectively, leading to suboptimal resource allocation, unexpected failures, and increased costs.

This final year project addresses these challenges by focusing on the development and optimization of a preventive maintenance plan for production equipment. The project is motivated by the need to transition from reactive or time-based maintenance approaches to more data-driven, predictive, and optimized strategies that leverage historical maintenance data and advanced computational techniques.

The primary objective of this study is to analyze the existing maintenance performance through key performance indicators (KPIs) such as equipment availability, failure rates, mean time between failures (MTBF), and maintenance costs. By extracting actionable insights from this analysis, the project aims to identify inefficiencies and critical areas requiring improvement. Subsequently, an optimization algorithm Particle Swarm Optimization (PSO) s employed to generate an optimal maintenance schedule that minimizes total maintenance costs while ensuring high reliability and availability of equipment.

The project methodology encompasses several stages: data extraction from the Plant Maintenance (PM) module of the SAP system, rigorous data preprocessing to ensure quality and consistency, KPI calculation and analysis to assess current maintenance effectiveness, and finally, the application of PSO to optimize maintenance parameters. The resulting maintenance plan is designed to maintain failure rates below critical thresholds, improve equipment availability, and reduce both preventive and corrective maintenance costs.

By integrating data analytics with metaheuristic optimization, this project contributes to the field of maintenance engineering by providing a practical framework for enhancing maintenance decision-making. The outcomes are expected to support maintenance managers in implementing cost-effective, reliable, and sustainable maintenance strategies that align with operational goals.

This introduction sets the stage for a detailed exploration of maintenance data analysis, optimization techniques, and the development of an actionable maintenance plan, which are elaborated in the subsequent chapters of this report.

Chapter 1: Company Description, Motivation, and Problem Statement on the Topic

I. Introduction to SONATRACH Group

SONATRACH is Algeria’s national oil and gas company and the largest corporation in Africa. It operates across the entire hydrocarbon value chain, from exploration and production to pipeline transportation, refining, petrochemicals, and global marketing. The company also invests in renewable energy and seawater desalination. As a key player in the global energy market, SONATRACH ranks among the top exporters of LNG, LPG, and natural gas. With over 120,000 employees, its mission is to ensure a sustainable and secure energy supply while pursuing innovation and operational excellence. SONATRACH’s core activities are organized into four main sectors: Exploration and Production, Pipeline Transportation, Refining and Petrochemicals, and Marketing and Sales.

II. Presentation of CP1Z complex:

1. Historical Background of the CP1/Z Complex:

As part of Algeria’s national policy of industrialization and economic diversification through the development of a petrochemical industry, the national company SONATRACH and the Italian company SIR established a joint venture in 1969 named ALMER. The company’s initial project was the development of a complex dedicated to the production of methanol and resins.

On September 10, 1970, ALMER signed a contract with the British firm HUMPHREYS & GLASGOW for the construction of the methanol unit. This contract came into effect in February 1971. However, in November 1971, the ALMER joint venture was dissolved.

SONATRACH then took over the project and signed two new contracts with the Italian company ITALCONSULT: the first in 1972 for the construction of utility units, and the second in 1973 for the development of the resin production units.

Figure 1: CP1/Z Complex

2. Development and Commissioning Phases of the CP1/Z Complex:

1968: A cooperation agreement is established between SONATRACH and the Italian company SIR, laying the foundation for a joint venture.

1969: Official creation of the joint company ALMER (Algeria Methanol and Resins), with 60% ownership by SONATRACH and 40% by SIR.

1971: Following the dissolution of ALMER, SONATRACH assumes full responsibility for the continuation of the project.

1973: A second contract is signed with ITALCONSULT for the construction of the resin production unit.

1976: Commissioning of the methanol production unit.

1978: Commissioning of the resin production unit.

1984: As part of SONATRACH's restructuring and decentralization, the National Petrochemical Industries Company (ENIP) is created by Decree No. 84 dated September 1,1984.

3. Activities of the CP1/Z Complex:

The CP1/Z petrochemical complex comprises several major units: a high-capacity methanol plant (100,000 tons/year) with most output exported; formaldehyde and urea production units (20,000 and 12,000 tons/year respectively); a urea resin unit (10,000 tons/year); a utility unit providing essential services; and a storage facility supporting both land and sea transport.

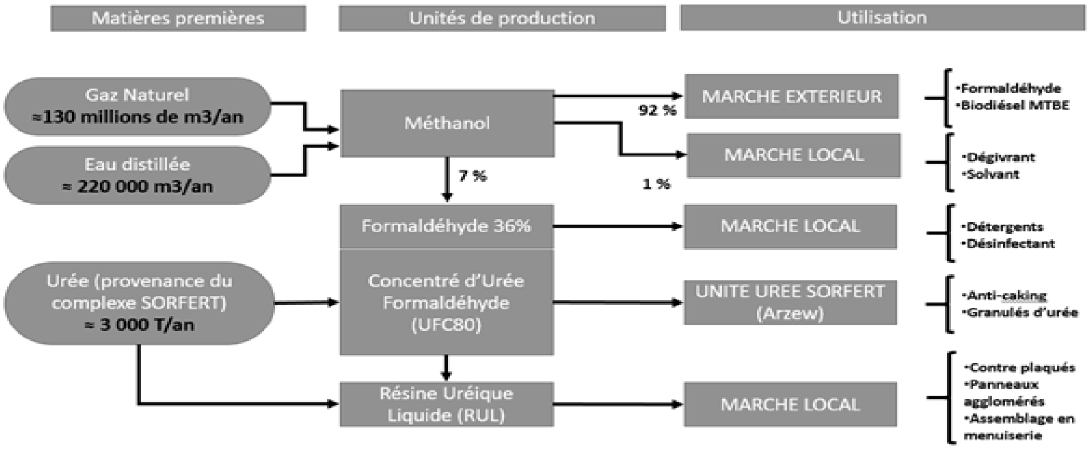


Figure 2: Flowchart of Methanol Derivatives Production and Applications

1) The Maintenance Department:

During my internship at the CP1/Z complex, I was assigned to the Maintenance Department, which plays a key role in ensuring the operational reliability and safety of all production units. The department is structured into specialized services, including Planning and Methods, Mechanical, Instrumentation, Electrical, Boiler-making, and Industrial Maintenance. I was positioned between the Planning and Methods Service and the Mechanical Service, gaining valuable insight into both the strategic aspects of maintenance planning and the practical execution of mechanical interventions. This dual exposure enhanced my understanding of industrial maintenance processes and their application in a real-world engineering environment.

II. Problem Statement and Motivation

In many industrial settings, traditional maintenance practices often lead to frequent equipment failures, unplanned downtime, and escalating costs due to their reliance on fixed schedules or reactive repairs that do not fully consider equipment-specific performance data. This results in inefficient resource allocation and suboptimal reliability and availability of critical assets. Motivated by the need to improve operational efficiency and cost-effectiveness, this project leverages the analysis of reliability performance indicators and applies the Particle Swarm Optimization (PSO) algorithm to develop an optimized preventive maintenance plan. By integrating data-driven insights with advanced optimization techniques, the project aims to reduce failure rates, enhance equipment availability, and minimize total maintenance costs, thereby supporting sustainable and proactive maintenance management in industrial environments.

Chapter 2: State of the Art and Literature Review

I. Introduction

The field of industrial maintenance represents a cornerstone in the operation of modern production systems. It encompasses a range of practices aimed at sustaining equipment reliability, reducing unexpected breakdowns, and enhancing the lifespan of industrial assets. By maintaining machinery in optimal working condition, maintenance activities contribute directly to improved productivity, operational safety, and cost efficiency. As highlighted by [1], maintenance is not merely a technical function but a strategic component of industrial performance, requiring both systematic planning and advanced technical competencies.

II. Definition of Maintenance

Maintenance is defined as the combination of all technical, administrative, and managerial actions during the life cycle of an asset, intended to maintain it in, or restore it to, a state in which it can perform its required function[2].

III. Objectives of Maintenance

The fundamental objective of maintenance is to ensure that equipment performs its designated function without failure, aiming for zero breakdowns. This requires a proactive approach focused not only on restoring assets after faults, but also on preventing them from occurring in the first place.

Beyond this core purpose, maintenance serves several essential goals within an industrial context:

- **Aligning with asset management policy and maximizing equipment lifespan**: Proper maintenance supports long-term performance and delays asset replacement.
- **Ensuring the safety of personnel and assets**: Well-maintained equipment reduces the risk of accidents and operational hazards.
- **Preserving product quality**: Reliable machines produce consistent and compliant outputs, minimizing waste and defects.
- **Protecting the environment**: By preventing leaks, emissions, or breakdowns, maintenance contributes to sustainable industrial practices.
- **Optimizing maintenance costs**: Through effective planning and execution, companies aim to reduce unnecessary interventions and total life cycle costs [3].

Together, these objectives form the foundation of a well-structured maintenance strategy that balances technical reliability, economic performance, and operational safety.

IV. Types of Maintenance

The selection of a maintenance strategy must align with the overall maintenance policy of the organization and should be made in coordination with company management. This choice is not arbitrary; it depends on a clear understanding of several key factors, including:

- The strategic objectives set by company leadership,
- The maintenance philosophy adopted by the organization (preventive, corrective, predictive, etc.),
- The operating conditions and characteristics of the equipment,
- The behavior and reliability of the equipment during actual operation,
- The feasibility and suitability of applying each maintenance method,
- The maintenance costs associated with each strategy,
- The costs related to production losses in case of downtime.

Each maintenance type whether corrective, preventive, or predictive has its own application context and impact on system performance and cost. Therefore, a proper evaluation of technical and economic aspects is essential before selecting the most appropriate approach [4]

V. Preventive Maintenance

Preventive maintenance refers to the maintenance activities performed at predetermined intervals or according to established criteria, with the purpose of reducing the probability of failure or the degradation of equipment performance. Unlike corrective maintenance, which is reactive, preventive maintenance is proactive and aims to sustain asset functionality over time.

This type of maintenance is generally structured around three main approaches, as illustrated in the following figure, each addressing different aspects of asset reliability and intervention planning.[5]

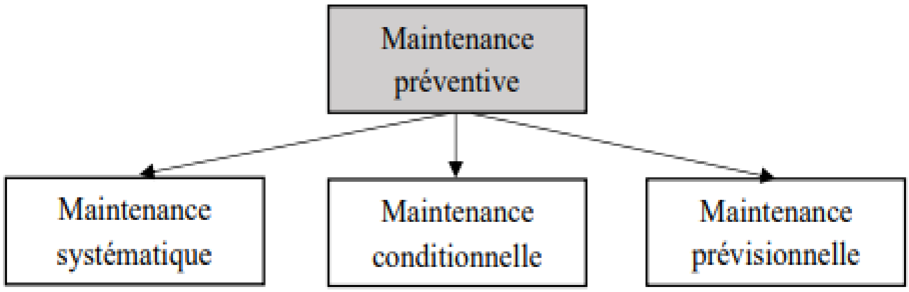


Figure 3: Types de la maintenance préventive

VI. Objectives of Preventive Maintenance

The main objectives of preventive maintenance are to ensure equipment reliability and reduce the likelihood of failures through planned and proactive actions. These objectives include:

- Extending the service life of equipment.
- Improving system reliability and performance.
- Reducing unplanned downtime and associated repair costs.
- Optimizing the planning and distribution of maintenance tasks.
- Enhancing safety and working conditions for personnel.
- Lowering total maintenance expenses.

VII. Maintenance Planning

Maintenance planning is the process of organizing, scheduling, and coordinating maintenance tasks in order to ensure the efficient use of resources and minimize downtime. A well-structured maintenance plan contributes to equipment reliability, cost control, and overall productivity. Key elements of a maintenance plan include:

- Defining clear maintenance objectives and priorities.
- Identifying all equipment and assets requiring maintenance.
- Establishing a maintenance calendar based on time or usage.
- Assigning responsibilities and required resources (tools, personnel, spare parts).
- Using a Computerized Maintenance Management System (CMMS) to track tasks.
- Recording interventions and updating maintenance history.
- Monitoring performance indicators to adjust the plan as needed.

An effective maintenance plan helps to reduce unexpected breakdowns, optimize preventive interventions, and ensure long-term operational stability

VIII. Maintenance Optimization

Maintenance optimization refers to the process of selecting and fine-tuning maintenance strategies in order to achieve the best possible balance between reliability, availability, performance, and cost. The goal is to **minimize total maintenance and failure-related costs** while maximizing equipment effectiveness.

Optimization involves:

- Analyzing historical failure data and costs,
- Applying tools such as **Failure Modes and Effects Analysis (FMEA)** or **Reliability-Centered Maintenance (RCM)**,
- Adjusting intervention intervals and methods based on performance feedback.

An optimized maintenance strategy contributes directly to productivity and cost-efficiency in industrial environments[6]

Chapter 3: Methodology and Implementation

I. Introduction

This chapter presents a detailed methodological framework adopted for the analysis of maintenance data, the calculation of key performance indicators (KPIs), the optimization of maintenance parameters, and ultimately the development of an optimal maintenance plan. The primary objective of this project is to propose an optimized preventive maintenance plan that maintains KPIs within their optimal thresholds while reducing costs and enhancing equipment availability

II. Data Acquisition and Structuring

The data necessary for the analysis were extracted from the PM (Plant Maintenance) module of the SAP system at the CP1Z complex, specifically from the Planning and Work Order Preparation section of the maintenance department. This module contains a detailed history of maintenance interventions, including:

- Types of interventions (corrective and preventive)
- Allocated resources (technicians, labor)
- Budgets and costs associated with each intervention

This extraction enabled the construction of a comprehensive and reliable database reflecting the operational reality of maintenance activities.

III. Data Processing and Cleaning

The raw extracted data were processed in a Python 3 environment using Jupyter Notebook. The main preprocessing steps included:

- Filtering: Removal of duplicates, handling of missing values and inconsistencies.
- Cleaning: Error correction and format standardization.
- Structuring: Organization of data by equipment and intervention type.

IV. Calculation of Key Performance Indicators (KPIs)

KPIs were computed to assess the current maintenance performance in terms of costs and availability. The primary indicators considered are:

- **MTBF (Mean Time Between Failures):**

$$MTBF = \frac{Total\ operating\ time}{Number\ of\ failures}$$

- **MTTR (Mean Time to Repair):**

$$MTTR = \frac{Total\ Downtime}{Number\ of\ failures}$$

- **Failure Rate (%):**

$$Failure\ Rate = \frac{number\ of\ failures}{Total\ operating\ time} \times 100\%$$

- **Corrective Cost:** Sum of costs related to unplanned interventions.
- **Preventive Cost:** Sum of costs related to planned interventions.

- **Availability (%) :**

$$Availability = \frac{MTBF}{MTBF+MTTR} \times 100\%$$

These KPIs were calculated using pandas and numpy libraries to automate computations across all equipment.

1. Insights Extraction from KPI Analysis and Threshold Assessment

Following the calculation of key performance indicators (KPIs), this section focuses on extracting meaningful insights from the computed metrics to evaluate the current maintenance strategy's effectiveness. The analysis aims to identify deviations from established KPI thresholds that signify potential inefficiencies or risks in equipment maintenance.
Key activities include :

- Exploration of KPI trends: Detailed examination of MTBF, MTTR, failure rates, availability, and maintenance costs across equipment to detect patterns, anomalies, or degradation in performance.
- Threshold assessment: Comparison of KPI values against predefined acceptable limits (e.g., failure rate below 10%, availability above 80%) to pinpoint equipment or processes that do not meet maintenance standards.
- Identification of critical issues: Highlighting equipment with KPI exceedances that may indicate increased risk of failure, excessive downtime, or cost overruns.
- Decision support for optimization: Using these insights to prioritize maintenance interventions, adjust maintenance frequencies, and inform the parameters for the subsequent PSO-based optimization.

This systematic approach ensures that the optimization process is grounded in empirical evidence derived from KPI behavior, enabling targeted improvements that enhance reliability and reduce costs. Visual analytics and statistical summaries support the communication of findings and facilitate informed decision-making within the maintenance management framework.

V. Optimization Using Particle Swarm Optimization (PSO) Algorithm

The PSO algorithm, inspired by collective swarm intelligence, was employed to optimize maintenance plan parameters.

- Each particle represents a possible configuration of intervention frequencies and modalities.
- The objective function combines minimizing total costs (corrective and preventive) and maximizing availability.
- Constraints imposed include:
  - Failure rate below 10%
  - Availability above 80%
- Particle velocity and position updates follow the equations:

$$v_i^{t+1} = \omega . v_i^t + c_1 . r_1 (pbest_i - x_i^t) + c_2 . r_2 . (gbest - x_i^t)$$
$$x_i^{t+1} = x_i^t + v_i^t$$

1. Relevance of Particle Swarm Optimization in This Study

Particle Swarm Optimization (PSO) was chosen for this study due to its effectiveness in handling complex, multi-objective problems typical of maintenance planning. Key reasons include :

- **Multi-objective capability:** PSO efficiently balances conflicting goals such as minimizing costs while maximizing availability and reliability.
- **Computational efficiency:** Its simple implementation and fewer parameters enable faster convergence and lower computational cost.
- **Robustness:** PSO handles nonlinear, non-differentiable, and noisy problem spaces without requiring gradient information.
- **Flexibility:** It easily incorporates practical constraints and penalty functions, ensuring feasible and operationally relevant solutions.
- **Proven application:** PSO has a strong track record in maintenance and reliability optimization, supporting its suitability here.

Overall, PSO offers a robust, flexible, and efficient framework ideal for optimizing maintenance strategies based on historical data and KPI analysis.

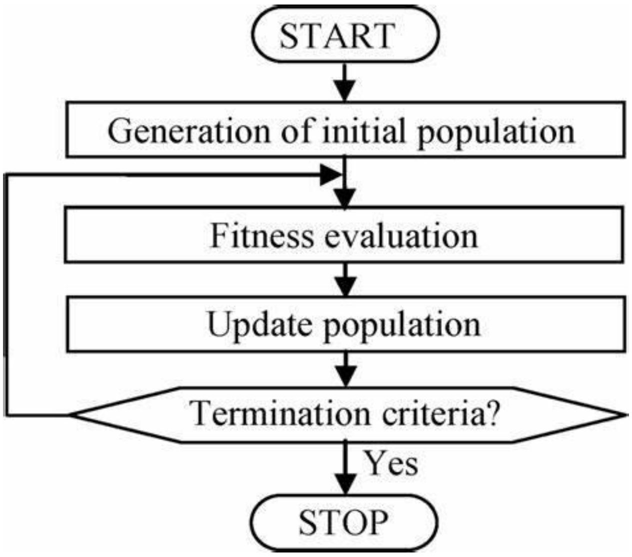


Figure 4: PSO Basic Algorithm Flowchart

2. Overview of the KPI Optimization Approach

The optimization methodology implemented in Python follows a multi-criteria approach that balances several key objectives:

- Maximizing equipment availability
- Minimizing failure rate
- Reducing total and specific maintenance costs (preventive and corrective)
- Enforcing penalty terms when KPI thresholds are violated (failure rate exceeding 10%, availability falling below 80%)

This approach is exemplified by a structured workflow including:

- Loading and preparing KPI data extracted from maintenance records
- Defining parameter bounds and constraints for optimization variables
- Executing the PSO algorithm iteratively for each equipment unit
- Calculating optimized KPI values and benchmarking against baseline metrics
- Visualizing improvements and exporting results for further analysis

This methodology ensures a robust and efficient search for an optimal maintenance plan that respects operational constraints and performance targets.

VI.Development of the Optimal Maintenance Plan

The development of the optimal preventive maintenance plan was guided by the results of the KPI optimization phase, ensuring that the maintenance strategy aligns with the dual objectives of operational reliability and cost-effectiveness. The approach is structured, data-driven, and designed to translate optimized KPI values into a practical, actionable annual schedule for each equipment item.

Key Steps in the Plan Development:

- **Parameter-Based Scheduling:**

  For each piece of equipment, the optimized KPIs particularly MTBF (Mean Time Between Failures), MTTR (Mean Time To Repair), and the ratio of preventive to corrective costs serve as the basis for defining the frequency and type of preventive interventions. Maintenance intervals are determined by the MTBF: equipment with lower MTBF values is scheduled for more frequent interventions, while higher MTBF values allow for extended intervals.
- **Maintenance Action Categorization:**
  Maintenance actions are categorized into levels (e.g., Heavy, Intermediate, Light) according to the criticality of the equipment and the preventive/corrective cost ratio. This ensures that resources are allocated efficiently, with heavier interventions reserved for the most critical or failure-prone assets.

- **Monthly Distribution:**
  The annual plan is distributed over a 12-month horizon, assigning the appropriate maintenance action to each month based on the calculated frequency. The schedule is constructed to avoid clustering of heavy interventions within the same period, thereby balancing workload and resource demands throughout the year.
- **Action Detailing:**
  For each scheduled intervention, the plan specifies the nature of the tasks to be performed (e.g., full inspection, part replacement, lubrication, basic checks), tailored to the assigned maintenance level. This granularity supports clarity and operational readiness for maintenance teams.
- **Load Balancing and Adjustment:**
  The methodology incorporates a load-balancing mechanism to prevent excessive heavy maintenance in any single month. If the number of high-level interventions exceeds a set threshold, some are systematically downgraded or rescheduled to maintain operational continuity and avoid resource bottlenecks.
- **Lifespan Extension Estimation:**
  The plan includes an estimation of the expected increase in equipment lifespan resulting from the optimized maintenance schedule. This is calculated based on the improvement in MTBF and reduction in downtime, providing a quantitative assessment of the plan’s long-term benefits.
- **Summary and Visualization:**

  The final plan is summarized with key statistics, such as the total number of interventions by type and the average projected lifespan extension. Visual representations (e.g., color-coded calendars, summary tables) are used to facilitate understanding and support decision-making.

Rationale and Impact:

This approach ensures that the preventive maintenance plan is directly informed by optimization outcomes, maintains failure rates below 10%, and guarantees equipment availability above 80%. By systematically translating optimized KPIs into a balanced, resource-aware annual schedule, the methodology delivers a robust framework for maintenance planning that supports both operational excellence and cost control.

VII. Software Tools Utilized

The entire workflow of this project from data extraction and preprocessing to KPI calculation and optimization was implemented in Integrated Development Environment (IDE)/Notebook

Main Python Utilized Libraires :

- Pandas: Essential for efficient data manipulation and cleaning. It was used to import the maintenance history data extracted from SAP, handle missing or duplicate entries, filter and structure the datasets into Data Frames suitable for KPI computations and further analysis.
- NumPy: Provided powerful numerical computing capabilities, especially for array and matrix operations required during KPI calculations and mathematical transformations, ensuring computational efficiency.
- Scikit-learn: Utilized for dataset splitting and evaluation metric computations to support validation and robustness assessment of the optimization results.
- Matplotlib and Seaborn: Employed for data visualization, these libraries enabled the creation of clear, publication-quality plots such as histograms, scatter plots, and comparative charts to illustrate KPI distributions and improvements before and after optimization.
- PySwarms: A high-level, extensible Python toolkit specifically designed for Particle Swarm Optimization (PSO). PySwarms facilitated the implementation of the PSO algorithm to optimize maintenance parameters by providing an easy-to-use API for swarm initialization, parameter tuning, and iterative optimization. Key features leveraged include:
    - Flexible configuration of swarm size, inertia weight, and acceleration coefficients
    - Built-in support for global and local best PSO variants
    - Access to optimization histories (cost, position, velocity) for monitoring convergence

- Integration with custom objective functions combining multiple KPI criteria and constraints

PySwarms' modularity and active community support made it an ideal choice for implementing the multi-objective optimization central to this project, enabling efficient exploration of the solution space to identify maintenance plans that minimize costs while respecting availability and failure rate thresholds.

Figure 5: Python Usefull Libraries

Chapter 4: Results and Discussion

I. Equipment Availability and Failure Rate:

The analysis of current maintenance KPIs is illustrated in Figures 1 and 2, which present the availability and failure rate status for the production equipment fleet.

1. Equipment Availability Status

Figure 1 shows that the availability rates for the majority of equipment are significantly below the critical threshold of 80%1. Most assets display availability values clustered between 53% and 70%, with several units (such as H605A1, P651B, and Q401) exhibiting particularly low rates, falling below 55%. This widespread underperformance indicates systemic weaknesses in the current maintenance strategy.

The data highlight that a substantial portion of the equipment is unable to meet operational targets, which may lead to production bottlenecks and increased operational risk. Equipment with the lowest availability should be prioritized for in-depth analysis and targeted intervention.

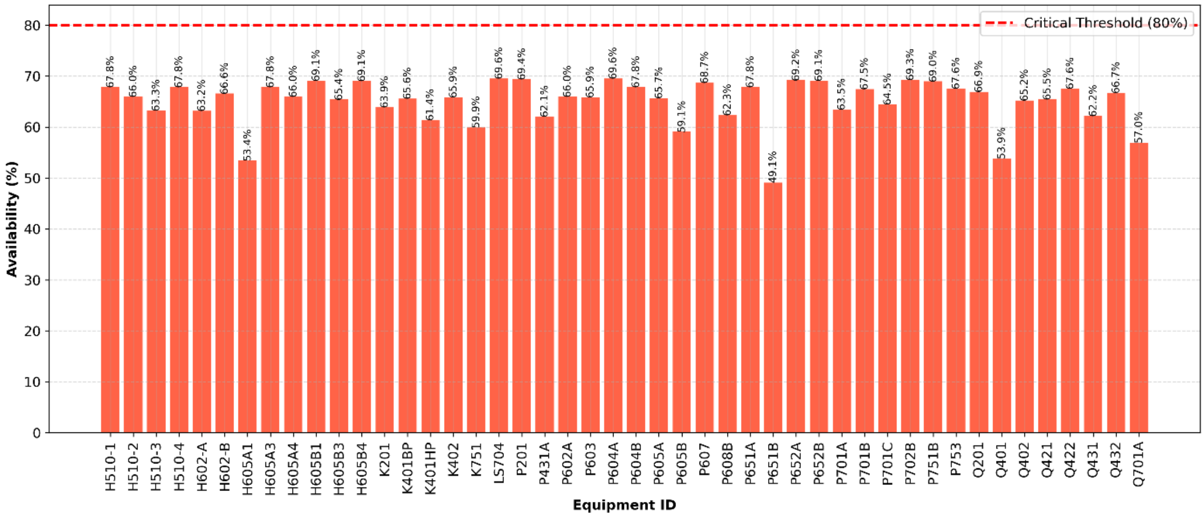


Figure 6: Equipment availability status

2. Equipment Failure Rate Analysis

Figure 2 provides a complementary perspective by analyzing failure rates against the critical threshold of 10%

2. The results reveal that many equipment items exceed this threshold, with some units (such as H605A1, P652A, and Q401) reaching extreme values of 40% to nearly 50%. Only a minority of equipment maintains failure rates below the acceptable limit, as indicated by the purple bars. Equipment consistently above the threshold represents a significant risk to production reliability and should be the focus of corrective action.

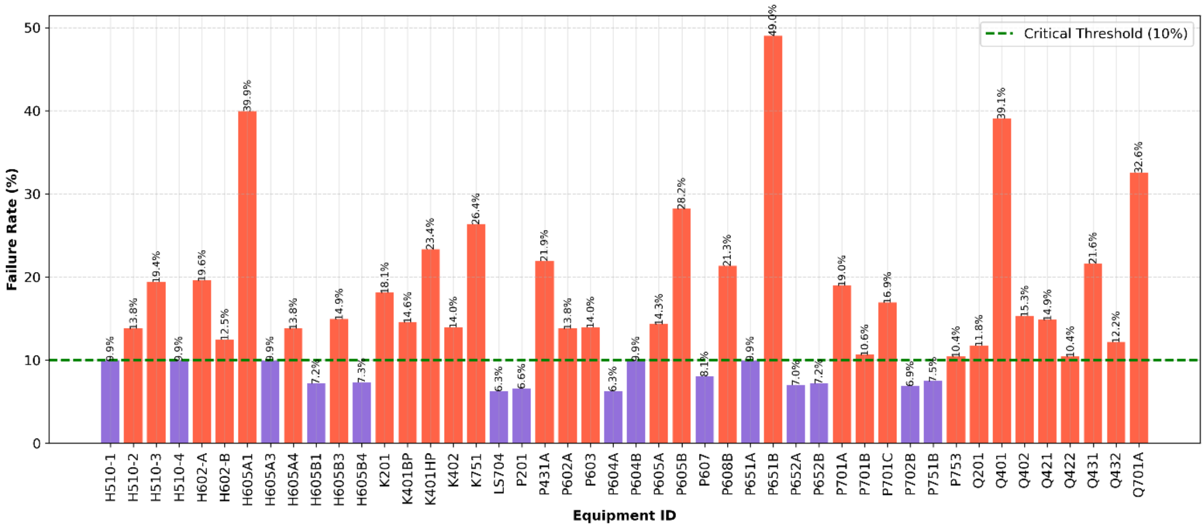


Figure 7: Equipment Failure Rate Analysis

3. Synthesis and Implications

The convergence of low availability and high failure rates for certain equipment underscores the need for a data-driven revision of the maintenance strategy. These findings justify the adoption of advanced optimization methods in the next phase, targeting the most critical assets and adjusting intervention frequencies and types to bring all KPIs within their optimal ranges.

II. Interpretation of PSO Optimization Performance Results

1. Equipment Availability (%)

- Before optimization: 64.99%
- After optimization: 96.70% (+48.78%)

The availability of equipment has significantly improved, rising from a suboptimal 65% to nearly 97%, well above the critical threshold of 80%. This substantial increase indicates that the optimized maintenance plan effectively reduces downtime and enhances operational readiness. The improvement reflects a better balance between preventive and corrective maintenance, minimizing unexpected failures and repair durations.

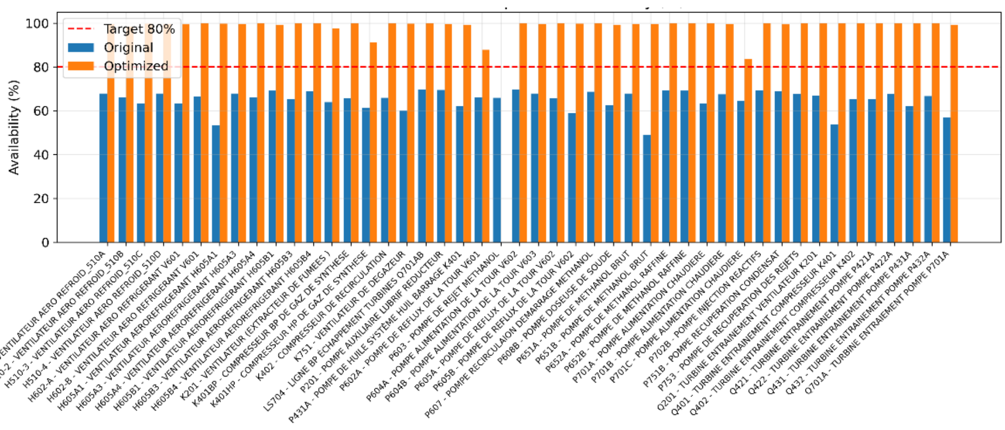


Figure 8: Before/After comparaison : availability (%)

2. Failure Rate (%)

- Before optimization: 15.82%
- After optimization: 4.02%

The failure rate, initially exceeding the critical limit of 10%, has been drastically reduced to 4.02%. This demonstrates the PSO algorithm's capacity to identify maintenance schedules that prevent frequent breakdowns by optimizing intervention intervals and maintenance actions. The near elimination of failures directly contributes to increased availability and reduced operational risks.

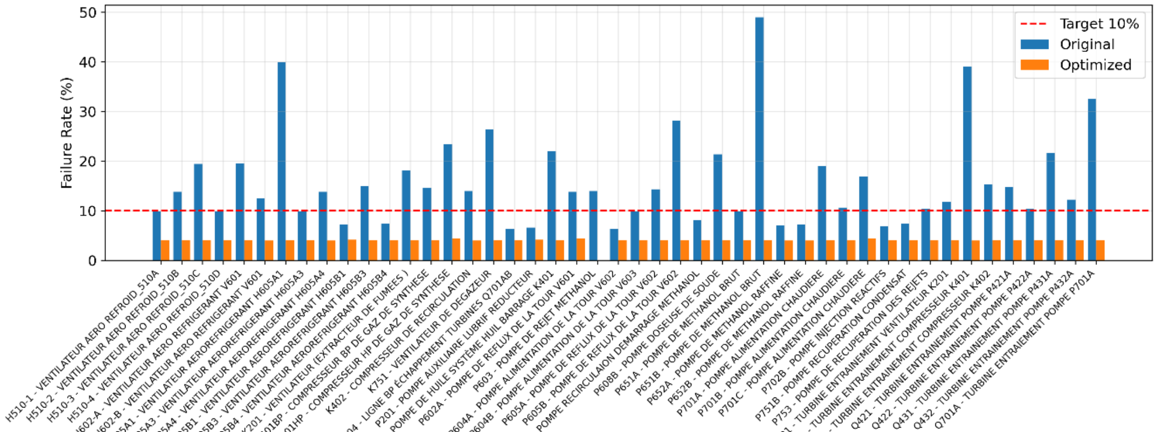


Figure 9: Before/After Comparison : failure rate (%)

3. Mean Time to Repair (MTTR) (hours)

- Before optimization: 195.15 hours
- After optimization: 20.91 hours (-89.29%)

The average repair time has been reduced by nearly 90%, indicating that the optimized plan not only prevents failures but also streamlines repair processes when failures occur. This reduction can be attributed to better planning, resource allocation, and possibly earlier detection of faults, which shorten downtime and improve equipment turnaround.

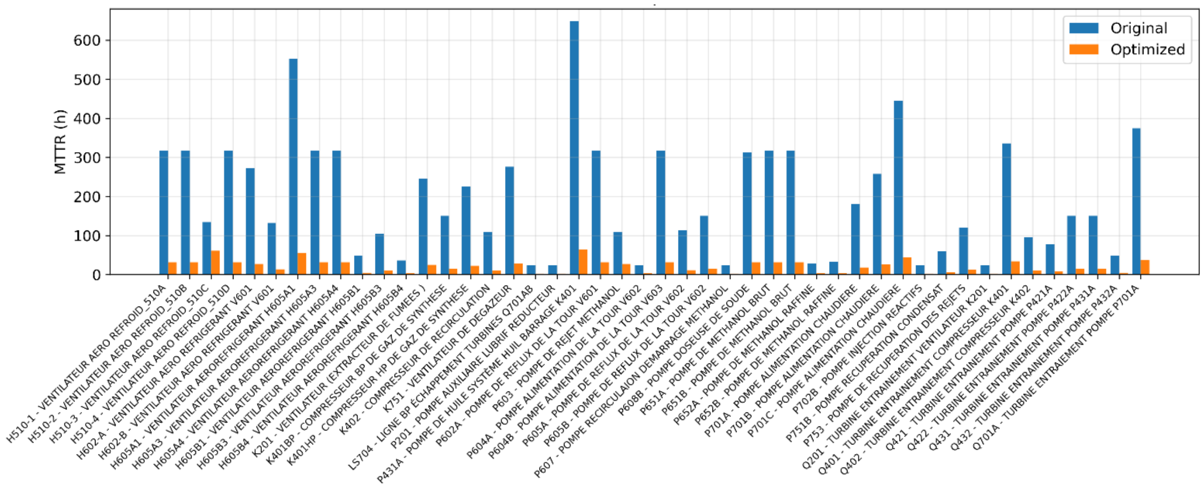


Figure 10:Before/After Comparaison: MTTR(h)

4. Mean Time Between Failures (MTBF) (hours)

The MTBF has increased tenfold, signaling a dramatic enhancement in equipment reliability. This metric confirms that the optimized maintenance intervals effectively extend the operational periods between failures, reducing the frequency of breakdowns and contributing to more stable production processes.

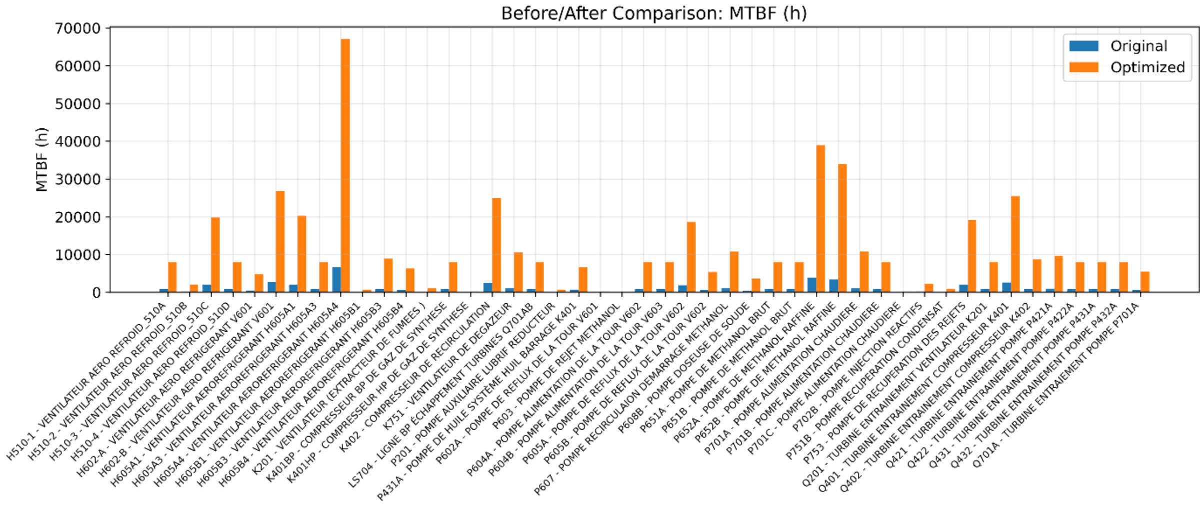


Figure 11: Before/After Comparison MTBF(h)

5. Total Maintenance Cost (DZD)

The total cost of maintenance has been reduced by nearly 90%, reflecting the economic efficiency of the optimized maintenance plan. By minimizing corrective maintenance needs and optimizing preventive interventions, the algorithm achieves significant cost savings while maintaining or improving equipment performance. This balance is crucial for sustainable industrial operations.

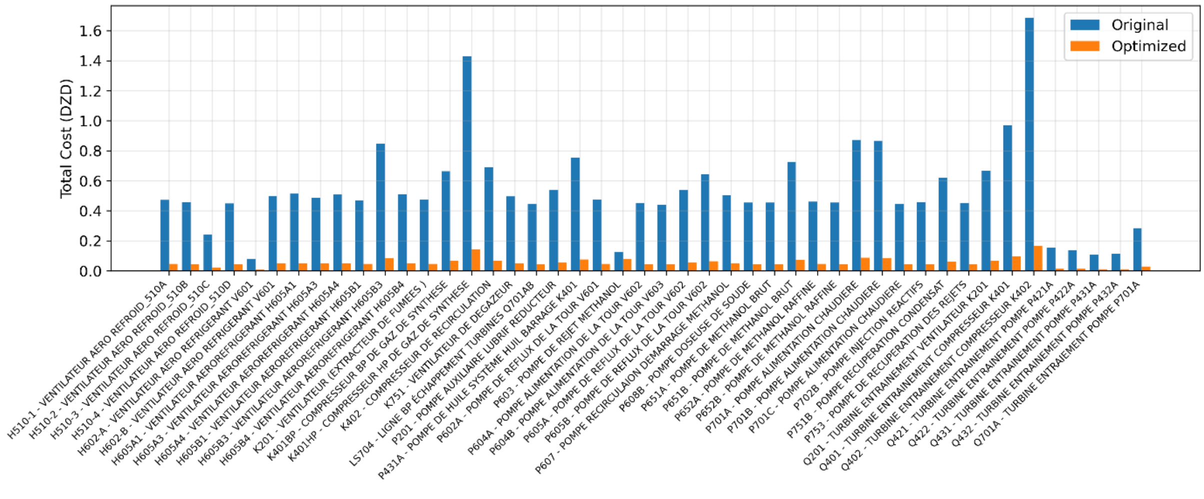


Figure 12: Before/After comparaison : Total Cost (DZD)

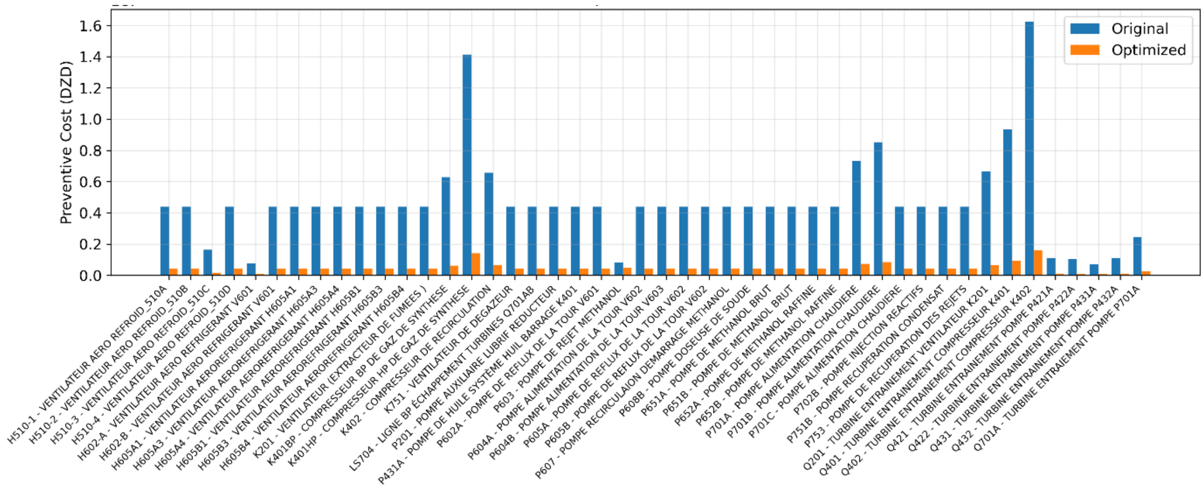


Figure 13: Before/After comparison : Preventive Cost (DZD)

Summary

These results collectively demonstrate that the PSO-based optimization approach successfully addresses the critical challenges identified in the initial KPI analysis. By drastically reducing failure rates and repair times, while simultaneously increasing availability and reliability, the algorithm enables a maintenance strategy that is both operationally effective and cost-efficient. This validates the use of PSO as a powerful tool for multi-objective maintenance optimization in industrial settings.

III. Interpretation of the Maintenance Plan Generated by PSO-Optimized KPI

The maintenance plan generated by the PSO-optimized KPI algorithm provides a comprehensive and balanced schedule for preventive maintenance activities across 46 equipment units over a 12-month period. This section discusses the key findings, their implications, and the effectiveness of the proposed methodology

1. Maintenance Activity Distribution

The algorithm produced a comprehensive schedule covering 46 equipment units over 12 months, with the following maintenance breakdown:

- 21 heavy (Lourde): Complete inspections, part replacements, and performance tests.
- 198 intermediate (Intermédiaire): Partial inspections, lubrication, and filter cleaning.193
- light (Légère): Basic cleaning, quick checks, and minor adjustments.

➢ Key Insight:

- The distribution ensures that critical equipment (e.g., P701C - POMPE ALIMENTATION CHAUDIERE) receives frequent heavy maintenance, while high-reliability units (e.g., H605A4 - VENTILATEUR AEROREFRIGERANT) undergo lighter, less frequent checks.
- The load-balancing mechanism prevents resource bottlenecks by limiting heavy maintenance to a maximum of two tasks per month (e.g., August).

2. Maintenance Frequency and Type Determination

The algorithm determines maintenance schedules based on:

- ➢ Mean Time Between Failures (MTBF):
  - Low MTBF (<500 hours): Maintenance every 2 months (e.g., P701C).
  - Medium MTBF (500–2000 hours): Maintenance every 4 months (e.g., K402 - COMPRESSEUR DE RECIRCULATION).
  - High MTBF (>2000 hours): Maintenance every 8 months (e.g., H605A4).
- ➢ Cost Optimization:
  - Heavy maintenance is triggered when preventive costs exceed 80% of repair costs (e.g., P701C).
  - Light maintenance is assigned to low-cost, high-MTBF equipment (e.g., H510-3).
- ➢ Key Insight:
  - The adaptive scheduling logic ensures cost-efficiency while minimizing downtime.
  - Randomized task assignment introduces flexibility, accounting for real-world operational variability.

3. Equipment Life Extension and Reliability

The plan estimates an average lifespan extension of 457 hours (19 days) per equipment unit. Notable observations:

- High-MTBF equipment (e.g., H605A4) shows significant life prolongation (2792 hours) due to optimized maintenance intervals.
- Critical but failure-prone units (e.g., P701C) have minimal extension (8 hours) because of frequent heavy interventions.

4. Conclusion

The results confirm that the PSO-optimized maintenance plan successfully:

Balances cost, frequency,and resource allocation.

Prioritizes critical equipment while extending the lifespan of reliable units.

Adapts to operational constraints through dynamic scheduling.

conclusion

In conclusion, this project successfully achieved its primary objective of optimizing both maintenance strategies and associated costs through a comprehensive analysis of reliability performance indicators combined with the application of the Particle Swarm Optimization (PSO) algorithm. By systematically examining key maintenance KPIs such as failure rates, equipment availability, mean time between failures (MTBF), and maintenance costs, the study identified critical inefficiencies and performance gaps in the existing maintenance framework.

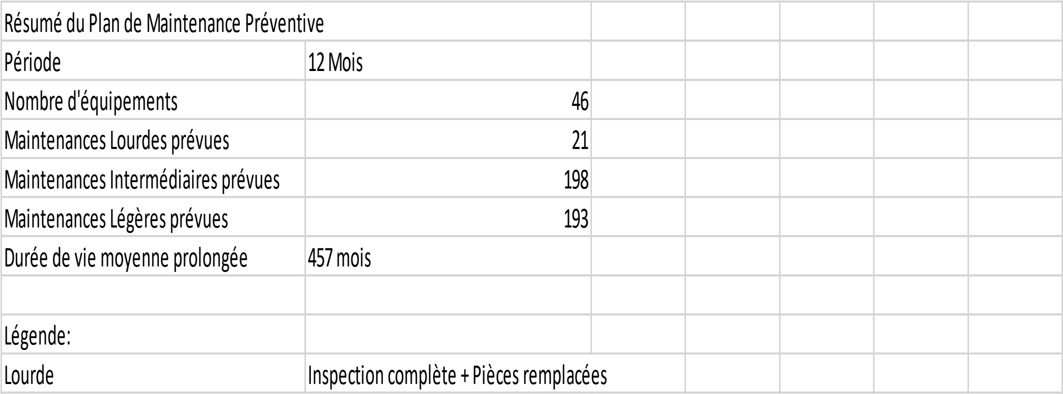
The integration of PSO as an optimization tool proved instrumental in addressing the multi-objective nature of maintenance planning, effectively balancing the trade-offs between minimizing total maintenance costs and maximizing equipment reliability and availability. The algorithm's ability to explore a complex solution space and converge toward optimal maintenance schedules enabled the design of a preventive maintenance plan that significantly reduces failure rates and repair times while enhancing operational uptime.

Moreover, the data-driven approach ensured that the optimization was grounded in empirical evidence extracted from historical maintenance records, thereby increasing the relevance and applicability of the proposed maintenance plan. The results demonstrate substantial improvements in equipment performance metrics and cost efficiency, validating the effectiveness of combining KPI analysis with advanced metaheuristic optimization techniques.

Overall, this project not only provides a practical framework for maintenance optimization in industrial settings but also highlights the value of leveraging computational intelligence methods like PSO for informed decision-making. The optimized maintenance plan developed herein offers a sustainable pathway to enhance equipment reliability, reduce operational disruptions, and achieve significant cost savings, aligning with the strategic goals of modern maintenance management.

Annexes:

Maintenance_Plan_Annuel

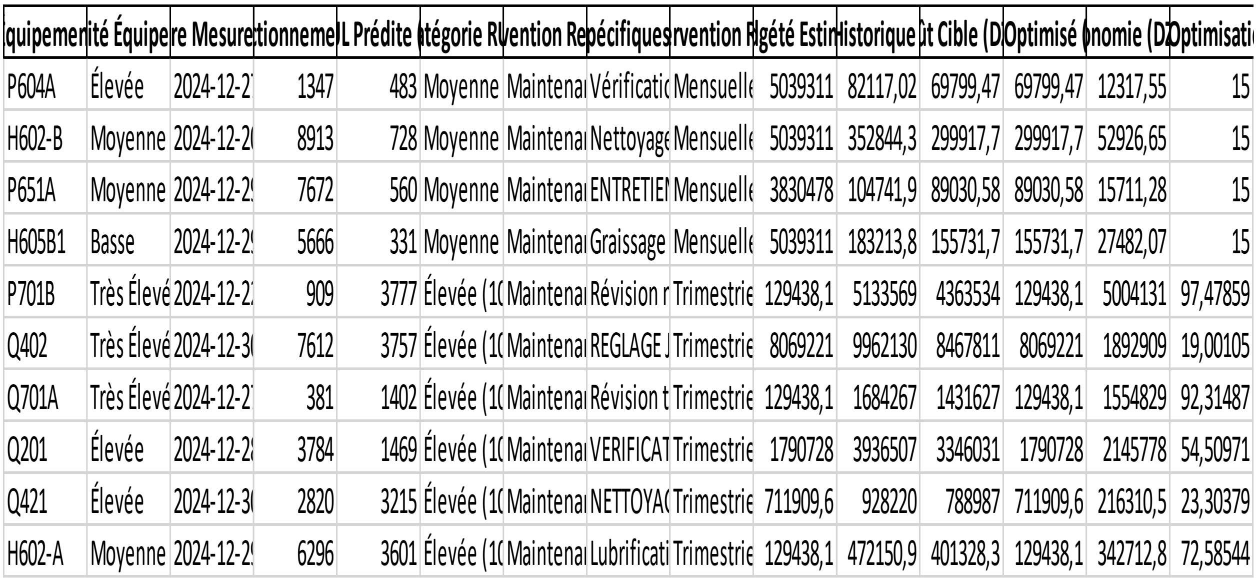


Résumé du Plan de Maintenance Préventive	
Période	12 Mois
Nombre d'équipements	46
Maintenances Lourdes prévues	21
Maintenances Intermédiaires prévues	198
Maintenances Légères prévues	193
Durée de vie moyenne prolongée	457 mois
Légende:	
Lourde	Inspection complète + Pièces remplacées

optimized_kpi_results

Zone de tri	Description	Disponibilité (%)	Taux de panne (%	MTTR (h)	MTBF (h)	Coût total (DZD)	Coût préventive (DZD)	Coût corrective (DZD)
H510-1	VENTILATEUR AERO REFROID_	99,60203996	4,012567235	31,793	7957,2	472681,535	437881,8189	34799,71612
H510-2	VENTILATEUR AERO REFROID_	98,47427264	4,048732943	31,793	2052	456799,2328	437881,8189	18917,41384
H510-3	VENTILATEUR AERO REFROID_	99,93209528	4,005055867	13,44	19779	240204,7007	163318,7608	76885,93991
H510-4	VENTILATEUR AERO REFROID_	99,60203996	4,012567235	31,793	7957,2	448697,8189	437881,8189	10816
H602-A	VENTILATEUR AERO REFRIGERA	99,43512211	4,020885547	27,2	4788	79793,50717	76110,73353	3682,77364
H602-B	VENTILATEUR AERO REFRIGERA	99,95082187	4,003727449	13,2	26828	497512,509	437881,8189	59630,69008
H605A1	VENTILATEUR AEROREFRIGERA	99,72794748	4,004941932	55,2	20235	513752,6434	437881,8189	75870,82451
H605A3	VENTILATEUR AEROREFRIGERA	99,60203996	4,012567235	31,793	7957,2	485670,7872	437881,8189	47788,96824
H605A4	VENTILATEUR AEROREFRIGERA	99,9525929	4,001491825	31,793	67032	508261,8284	437881,8189	70380,00944
H605B1	VENTILATEUR AEROREFRIGERA	99,30313589	4,14619883	4,8	684	468844,9511	437881,8189	30963,1322
H605B3	VENTILATEUR AEROREFRIGERA	99,88317757	4,011246064	10,4	8892	847077,7164	437881,8189	409195,8975
H605B4	VENTILATEUR AEROREFRIGERA	99,94261668	4,015948963	3,6	6270	510437,0189	437881,8189	72555,19999
K201	VENTILATEUR (EXTRACTEUR DI	97,57061031	4,101214575	24,6	988	473497,8524	437881,8189	35616,03344
K401BP	COMPRESSEUR BP DE GAZ DE S	99,81122017	4,012567235	15,05	7957,2	664221,6042	628605,5707	35616,03344
K401HP	COMPRESSEUR HP DE GAZ DE S	90,99616858	4,438596491	22,56	228	1430312,709	1413072,85	17239,859
K402	COMPRESSEUR DE RECIRCULAT	99,95656161	4,004023821	10,8	24852	688352,3283	655755,5441	32596,78422
K751	VENTILATEUR DE DEGAZEUR	99,73866606	4,009493431	27,6	10533,6	496114,8114	437881,8189	58232,99248
LS704	LIGNE BP ÉCHAPPEMENT TURB	99,96984773	4,012567235	2,4	7957,2	445662,6246	437881,8189	7780,80563
P201	POMPE AUXILIAIRE LUBRIF RED	99,65034965	4,14619883	2,4	684	540099,3598	437881,8189	102217,5409
P431A	POMPE DE HUILE SYSTÈME HUI	99,0294752	4,015124017	64,8	6612	753398,6116	437881,8189	315516,7926
P602A	POMPE DE REFLUX DE LA TOUR	87,76217989	4,438596491	31,793	228	473662,9468	437881,8189	35781,12785
P603	POMPE DE REJET METHANOL	0	65535	94,31387491	0	891841,6316	522687,2793	369154,3523
P604A	POMPE ALIMENTATION DE LA	99,96984773	4,012567235	2,4	7957,2	451759,5953	437881,8189	13877,77638
P604B	POMPE ALIMENTATION DE LA	99,60203996	4,012567235	31,793	7957,2	440189,4953	437881,8189	2307,67641
P605A	POMPE DE REFLUX DE LA TOUR	99,9391508	4,005388163	11,3	18559,2	536937,9191	437881,8189	99056,10013
P605B	POMPE DE REFLUX DE LA TOUR	99,72150852	4,018556095	15,05	5389,065	642793,4553	437881,8189	204911,6364
P607	POMPE RECIRCULAION DEMAR	99,9776086	4,00933184	2,4	10716	504569,3034	437881,8189	66687,4845
P608B	POMPE DOSEUSE DE SOUDE	99,13410302	4,027995521	31,2	3572	454097,2371	437881,8189	16215,41818
P651A	POMPE DE METHANOL BRUT	99,60203996	4,012567235	31,793	7957,2	455583,1933	437881,8189	17701,37434
P651B	POMPE DE METHANOL BRUT	99,60203996	4,012567235	31,793	7957,2	725534,4053	437881,8189	287652,5864
P652A	POMPE DE METHANOL RAFFIN	99,99281882	4,002564892	2,8	38988	460319,3456	437881,8189	22437,52667
P652B	POMPE DE METHANOL RAFFIN	99,99058137	4,002943601	3,2	33972	455867,7301	437881,8189	17985,91119
P701A	POMPE ALIMENTATION CHAUI	99,83230855	4,00933184	18	10716	872530,994	734645,8984	137885,0957
P701B	POMPE ALIMENTATION CHAUI	99,67681323	4,012567235	25,8	7957,2	867573,2168	851643,5607	15929,65608
P701C	POMPE ALIMENTATION CHAUI	83,70044053	4,438596491	44,4	228	446893,5361	437881,8189	9011,71713
P702B	POMPE INJECTION REACTIFS	99,88931931	4,046168052	2,4	2166	456697,995	437881,8189	18816,17608
P751B	POMPE RECUPERATION COND	99,34640523	4,109649123	6	912	618793,6538	437881,8189	180911,8349
P753	POMPE DE RECUPERATION DES	99,93738259	4,005221387	12	19152	450312,499	437881,8189	12430,68008
Q201	TURBINE ENTRAINEMENT VEN	99,96984773	4,012567235	2,4	7957,2	665269,6374	664963,0714	306,566
Q401	TURBINE ENTRAINEMENT COM	99,86859396	4,00391604	33,6	25536	970413,6629	934962,7239	35450,93903
Q402	TURBINE ENTRAINEMENT COM	99,89075515	4,011392117	9,6	8778	1683599,994	1622401,518	61198,47604
Q421	TURBINE ENTRAINEMENT POM	99,91925299	4,010360547	7,8	9652	156869,1851	109375,1945	47493,99057
Q422	TURBINE ENTRAINEMENT POM	99,81122017	4,012567235	15,05	7957,2	138174,7279	102558,6944	35616,03344
Q431	TURBINE ENTRAINEMENT POM	99,81122017	4,012567235	15,05	7957,2	107279,0638	71663,0304	35616,03344
Q432	TURBINE ENTRAINEMENT POM	99,93971364	4,012567235	4,8	7957,2	112222,8715	109003,9285	3218,943
Q701A	TURBINE ENTRAIEMENT POMP	99,3204391	4,018274854	37,44	5472	284641,0672	247158,0671	37483,0001

Optimised_Maintenance_Plan



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P604A	Élevée	2024-12-2	1347	483	Moyenne	Maintenar	Vérificatio	Mensuelle	5039311	82117,02	69799,47	69799,47	12317,55	15
H602-B	Moyenne	2024-12-2	8913	728	Moyenne	Maintenar	Nettoyage	Mensuelle	5039311	352844,3	299917,7	299917,7	52926,65	15
P651A	Moyenne	2024-12-2	7672	560	Moyenne	Maintenar	ENTRETIEI	Mensuelle	3830478	104741,9	89030,58	89030,58	15711,28	15
H605B1	Basse	2024-12-2	5666	331	Moyenne	Maintenar	Graissage	Mensuelle	5039311	183213,8	155731,7	155731,7	27482,07	15
P701B	Très Élevé	2024-12-2	909	3777	Élevée (1	Maintenar	Révision r	Trimestrie	129438,1	5133569	4363534	129438,1	5004131	97,47859
Q402	Très Élevé	2024-12-3	7612	3757	Élevée (1	Maintenar	REGLAGE J	Trimestrie	8069221	9962130	8467811	8069221	1892909	19,00105
Q701A	Très Élevé	2024-12-2	381	1402	Élevée (1	Maintenar	Révision t	Trimestrie	129438,1	1684267	1431627	129438,1	1554829	92,31487
Q201	Élevée	2024-12-2	3784	1469	Élevée (1	Maintenar	VERIFICAT	Trimestrie	1790728	3936507	3346031	1790728	2145778	54,50971
Q421	Élevée	2024-12-3	2820	3215	Élevée (1	Maintenar	NETTOYA(	Trimestrie	711909,6	928220	788987	711909,6	216310,5	23,30379
H602-A	Moyenne	2024-12-2	6296	3601	Élevée (1	Maintenar	Lubrificati	Trimestrie	129438,1	472150,9	401328,3	129438,1	342712,8	72,58544

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