SSRG International Journal of Mechanical Engineering
ISSN: 2348-8360/ https://doi.org/10.14445/23488360/IJME-V12I3P107

Volume 12 Issue 3, 78-92, March 2025

Review Article

Maintenance Optimization on Critical Electromechanical Equipment: A Case Study in Sasol Synfuels Catalyst Preparation Unit

Pretty Maphosa[1], Patrick Nziu[2]

[1]*Department of Mechanical Engineering, Mangosuthu University of Technology, 511 Griffiths Mxenge Hwy, Umlazi, Durban, South Africa.*
[2]*Department of Mechanical Engineering, Walter Sisulu University, P.O. Box 1421 East London, South Africa*.

[1]*Corresponding Author : memephumla@gmail.com*

Received: 12 January 2025 Revised: 11 February 2025 Accepted: 10 March 2025 Published: 29 March 2025

Abstract *- The challenge of optimizing maintenance strategies in industries is not a new one. It remains a relevant topic of investigation because each industry is unique in terms of its products, machinery, and operations, among other factors. Therefore, a single optimal maintenance solution cannot be universally applied across all industries. The purpose of the study was to investigate and optimize the maintenance practices used on critical electromechanical equipment in Sasol Synfuels Catalyst Preparation. Using both the Analytical Network Process (ANP) and Analytical Hierarchy Multi-Decision Approach (AHP), the analytical network and hierarchy process application and the super decision network model framework were analyzed to obtain the ideal maintenance solution for the critical electromechanical equipment within the Sasol unit. Criteria nodes such as maintenance cost, machinery availability, mean repair time, and environmental safety were chosen through a qualitative approach. The ANP and AHP approaches have different problem identification frameworks and cluster dependencies; however, it is seen that both methods portray more or less similar results, as both methods indicate that the condition-based maintenance strategy is the most weighted alternative node for optimal maintenance solution. The least weighed alternative node is corrective maintenance. Fixed-time maintenance is the second most weighed maintenance strategy, followed by the operate-to-failure strategy. For criteria nodes, it was drawn that the ANP approach resulted in the environmental safety impact being the most important criterion to consider when applying the optimal maintenance strategy in the Sasol Synfuels Catalyst preparation unit.***

Keywords *- Maintenance strategy, Analytical Network Process, Analytical Hierarchy Process, Maintenance optimization, Electromechanical equipment, Petrochemical, Criteria node, Alternative node*.

1. Introduction

Petrochemicals refer to products that are produced from hydrocarbon organic chemicals such as crude oil and natural gas, and their natural gas condensates are raw materials. The petrochemical industry uses dome products from oil refineries as raw materials for specific chemical products, thus differing from the refinery industry. The products thereof produced include plastics resins, synthetic fibers, synthetic rubbers, surface coating materials, and various types of adhesives, as reported by the Department of Alternative Energy Development and Efficiency, 2006. The Petrochemical industry developed turn-around maintenance plans, a scheduled maintenance plan, to overhaul all equipment in a unit according to the various frequency setups (BEVILACQUA, 2012). A planned shutdown is when major maintenance is planned, which needs the production to stop for a certain period, and if properly implemented, the period given may be needlessly long (Frediksson, 2012). An unplanned shutdown occurs when a breakdown occurs, requiring the production to discontinue until the problem is resolved. However, most industries are transitioning from practising reactive maintenance to preventive through the turn-around process in petrochemical plants. However, if not properly done, this setup can do more harm than good because preventative maintenance is done on a scheduled basis regardless of the status of the machines (MOBIUS Institute, 2016). Equipment is unique in operation and failure; thus, the same maintenance strategy cannot be set for all equipment. Electromechanical equipment is equipment that requires both mechanical and electrical components to function. Such equipment includes synchronous motors, electric valve actuators, pump sets, conveyors, and compressors, amongst others (Sondalini, 2018). This equipment and machinery are subject to electrical and mechanical wear, each with a different lifespan expectancy and failure rate. The right combination of maintenance strategies to be applied should be obtained to ensure that the equipment performs as required and has a prolonged life expectancy (Sondalini, 2018). The principal objective of maintenance and repair policies in modern industry is to ensure that all available machinery and equipment are being used for production (Ondieki, 2008). It is also to preserve the value of machinery, equipment, and plant by keeping deterioration to a minimum as well as to accomplish the mentioned objectives as economically as possible, for a longer duration, considering the safety of all employees (Ondieki, 2008). These objectives can be achieved by ensuring the proper selection of machinery and equipment for long, useful life. The correct choice and adaption of the most suitable maintenance, repair systems, and techniques should be used (Ondieki, 2008). Irregularities in the production and maintenance procedures could result in a disorganized resource allocation, ineffective scheduling, and needless downtime for the operational equipment (Sadraoui et al., 2024). Maintenance optimization is defined as determining the most effective and efficient maintenance plan used to obtain the best possible balance between direct maintenance costs and the consequences of maintenance being performed (Shafiee, 2017).

The main objectives of maintenance optimisation are minimum cost, minimum production loss, and maximum availability, including reliability (Hilber, 2008). By balancing these aspects, an optimisation method can be determined (Hilber, 2008). This method supports asset management decisions through a solution to the problem of optimal balance between corrective and preventive maintenance (HILBER, 2008). The maintenance optimisation techniques are categorized into two, which are qualitative and quantitative techniques (Shafiee, 2017). Qualitative techniques are subjective and realise estimates and opinions, whilst quantitative techniques use multiple mathematical models and statistical analysis (Shafiee, 2017).

Eleven generic maintenance optimisation solution techniques have been developed: operations research models, stochastic, Markov models, Petri Net models, analytical models, simulation models, Bayesian networks, fuzzy models, data mining techniques, intelligent-based models, and multiple-objective models. These are widely used due to the proposed solutions to maximize the expected energy rate and minimize the total expected maintenance costs (Shafiee, 2017). The initial step in performing maintenance optimisation is to choose the system's most critical components. Different indices can reflect the risk level of different components of the system (shayesteh, 2018), including risk analysis, risk reduction worth, risk achievement worth, sensitivity analysis, time-independent component reliability importance measures, and Failure Mode and Effects Criticality Analysis (FMECA). These are the several types of methods used to determine the criticality of the equipment (Jaderi, 2019). Petrochemical companies process multiple hazardous materials. As a result, they can be classified as a high-risk industry (Jaderi, 2019). Due to the systematic risks that the process entails and its complexities, many major accidents have occurred, of which asset failure is regarded as one of the main causes. The widely used risk-based analysis to determine the most critical assets is used to assess the most critical component in the system (Jaderi, 2019). It provides tools for maintenance planning and decision-making, reducing the probability of equipment failure and the consequences thereof (Jaderi, 2019).

The pursuit of obtaining the optimal solution to maintenance strategies is not new; however, the relationship between maintenance, reliability, and costs is not entirely solved (Hilber, 2008). The requirements from owners, authorities, and customers create needs and incentives for still other or enhanced methods to handle maintenance effectively and efficiently (Hilber, 2008). Previous research focussed on the maintenance strategies through turn-around management and implementation within the petrochemical industry (Bevilacqua, 2012). Ghosh (2010) presented a multi-criterion decision-making methodology for selecting the optimal mixture of maintenance approaches (Bevilacqua, 2012). The important subject is that most studies assume that the aging of components is time-dependent. Other factors also play a role, such as the operational conditions of equipment, environmental factors, etc. (Bevilacqua, 2012). However, to obtain an optimal maintenance strategy, factors such as environmental factors need to be incorporated to maximize the equipment's reliability and availability based on the plant's operation.

2. Novelty of Study

Turnaround management is the most used strategy in petrochemical industries due to its robust repair approach; however, this type of maintenance strategy slowly relies on the plant's availability to shut down. Therefore, plants that are continuously running need a different maintenance approach; hence, downtime remains the biggest challenge, especially within the Synfuels catalyst preparation unit. Although maintenance strategies are employed on the equipment, obtaining the right balance of all applied strategies remains challenging.

The ageing of components may be time-dependent; however, other factors that affect the equipment's lifespan also play a role, such as the operational conditions of equipment and environmental factors. Hence, the purpose of this study is to use a multi-objective tool to obtain the right balance of the maintenance strategy applied to each critical electromechanical equipment in the Sasol Catalyst Preparation unit. The multi-objective will factor in the different indices that influence the type of maintenance strategy to apply, such as maintenance cost. Availability, environmental safety impact, etc.

3. Maintenance Optimization Models

Maintenance optimization models are classified based on the description and representation of natural variability and uncertainty in a parameter, including the model and scenario. Furthermore, deterministic methods do not explain the potential risk, resulting in non-optimal maintenance planning for process plants. Probabilistic models, however, use probability distributions to describe and represent natural variability and uncertainty in multiple cases.

By balancing these aspects, a method that supports asset management decisions can be determined by determining a solution to the optimal balance between corrective and preventive maintenance (Hilber, 2008).

Furthermore, Shafiee, (2017) research work describes the eleven generic possible maintenance optimization solution techniques developed with different advantages and disadvantages. The description of these generic solutions techniques is as follows (Shafiee, 2017):

1. Operations research models consist of inter-programming models based on maintenance expenses and production losses, which are linear cost functions.
2. Stochastic Models have the allowance to include key random factors to obtain the system condition.
3. The Markov Model is a sequence of realized states in which the transition probability to a state only depends on the current state and not the history of states.
4. The Petri net model is both a graphical and mathematical tool. It was originally developed for the modeling and analysis of distributed systems with concurrency and resource sharing.
5. Analytical models are a mathematical tool with a closed-form solution; thus, the solution to the equations describing any changes in the system is expressed as a mathematical analytic function.
6. Simulation models are used in complex systems as they can generate various maintenance scenarios according to the stochastic variables of the model and then evaluate the quantities of interest.
7. A Bayesian network is a probabilistic graphical model representing conditional dependencies between failure root causes and symptoms.
8. Fuzzy models are used when systems dynamics cannot be directly concluded, and information is mainly based on an expert's knowledge and experience.
9. Data mining techniques is a SCADA system that usually dumps large amounts of data from different sources being updated periodically.
10. Intelligent-based models play a major role in predicting the system's residual life and currently is one key success factor in implementing condition monitoring systems for wind farms.
11. The proposed solution for the multiple-objective model is to maximize the expected energy rate and minimize the total expected costs connected to maintenance efforts.

In multi-criteria decision-making scenarios, Decision-Makers (DMs) develop a comparison matrix to present a range of choices. Saaty's Analytic Hierarchy Process (AHP) stands out as an apt approach for multi-criteria decision-making, as it offers statistical support for evaluating the optimal choice using both quantitative and qualitative criteria (Kaushik et al., 2024). Abedini (2016) presented a paper comparing the Analytical Network Process (ANP), Analytical Hierarchy Process (AHP), Fuzzy Analytical Hierarchy Process (AHP), and Fuzzy Analytical Network Process (FANP) in maintenance decision-making. The study compared alternative maintenance strategies using the Multiple Criteria Decision-Making method (MCDM) under certain and uncertain numbers, considering the various criteria methods.

Shahin (2012) further elaborates that AHP was introduced in 1980 as a solution to specific decision-making problems. Although it has been widely applied to multiple situations with considerably adequate results, it is arguable that the AHP contains some shortcomings in handling the complexities of interdependent problems due to the severely hierarchical structure. Many researchers have proposed that ANP is the most practical tool for solving such problems.

The ANP model depicts a decision-making problem as a network of criteria and alternatives (known as elements), which are grouped into clusters. All these elements in the network can be connected, therefore meaning that a network can allow feedback and interdependent relationships within and between clusters.

Similarly, Abedini, (2016) study explains that the AHP is considered as one the most practical multi-criteria decision-making methods, mainly due to its simplicity and ease of use, to name a few. It is, nevertheless, not an efficient tool for resolving decision-making issues, which require modeling the interactions, interdependencies, and feedback within different levels of elements.

However, Thor J (2013) argues that AHP is one of the most common decision-making techniques for selecting the optimal maintenance alternative for an integrated gasification combined cycle plant. Azizi's (2014) study also states that it has specific applications in group decision-making. It is applied worldwide in various decision situations in fields such as engineering and, more specifically, maintenance engineering. The AHP assists decision-makers in detecting the one that best fits their objective and understanding of the problem rather than giving a solution decision. Through the decision problem framework, the problem is easily identified, and elements are easily quantified and related to the objective.

The first step in ANP and AHP analysis is determining the goal, criteria, and alternatives. The goal is what needs to be achieved through analysis. Criteria are the prerequisites or challenges that impact the goal, and alternatives are the second prerequisite that ultimately feeds into the goal. These are then broken down into nodes, which are combined into clusters. With the super decision software, the network or hierarchy can be drawn up, and each criteria node and alternative are linked. The hierarchy approach links the nodes from the top down depending on their influence on the alternatives. In the network process, the nodes are considered independently of each other and the alternative or goal. This is elaborated in Figure 1.

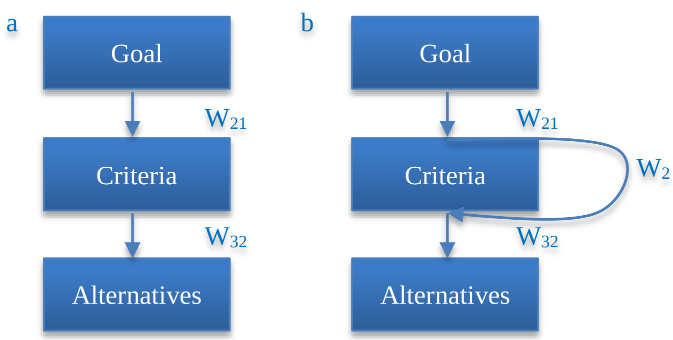

Fig. 1 Hierarchy approach links

Shahin's (2012) study explains how the decision-maker is asked to reply to a series of pairwise comparisons of two elements or clusters to evaluate their contribution to their upper-level criteria. In addition, interdependence among the elements of a cluster must also be examined pairwise, where a vector describes each element's effect on other elements. The relative significance values are determined based on Saaty's 1–9 scale. A score of 1 represents equal importance between the two elements, and a score of 9 indicates the extreme importance of one element compared to the other one. A common value is assigned to the inverse comparison, such as aij =1/aji, where aij denotes the significance of the ith element over the jth element. Like AHP, the pairwise comparison in ANP is performed in the framework of a matrix, and a local priority vector can be derived as an estimate of the relative importance associated with the elements (or clusters) being compared by solving Equation (1)

$$Aw = \lambda max w \tag{1}$$

Whereby:
A matrix of pairwise comparison
W = eigenvector
λmax = largest eigenvalue of A.

If A denotes a consistency matrix, then the eigenvector X can be determined using Equation (2):

$$(A - \lambda maxI)X = 0 \tag{2}$$

The CI and CR values can be defined in Equations (3) and (4):

$$cl = (\lambda max - n)/(n-1) \tag{3}$$

$$cR = CI/RI \tag{4}$$

Where:
I = identity matrix.
CI = consistency index (CI) and
CR = consistency ratio (CR)

Where 'n' is the number of elements and 'RI' denotes the average consistency index for numerous random entries of same-order reciprocal matrices. If CR ≤ 0.1, then the pairwise comparison matrix is consistent; otherwise, a new comparison matrix is solicited until CR ≤ 0.1. Using the Normalized Geometric Mean (NGM) method, the relative priorities of the elements being compared concerning their upper-level criteria are estimated from the pairwise comparison matrix. Hence, the priority vectors must be determined for all the comparison matrices. Acquiring the global priorities in a system with interdependent influences, the local priorities are entered into the proper columns. As a result, a supermatrix is created, which is a partitioned matrix, where each matrix segment represents a relationship between two clusters in a system. The local priority vectors are grouped and placed in suitable positions in a supermatrix based on the flow of influence from one cluster to another or from a cluster to itself, such as in a loop. In 1996, Saaty introduced the concept of a 'supermatrix' as a standard method for addressing the interdependent relationships between elements and components, as shown in Figure 2 (Wey, 2007). He proposed using the supermatrix to solve network structures (Wey, 2007). It is important to note that a matrix can be replaced by any zero value in the supermatrix, depending on the interrelationship of the elements within a cluster or between two clusters. However, there is normally interdependence among clusters in a network. Thus, the columns of a supermatrix may sum to more than one.

$$
\begin{array}{ccc}
 & & \begin{array}{cccc} c_1 & c_2 & \cdots & c_N \\ e_{11}e_{12}\cdots e_{1n_1} & e_{21}e_{22}\cdots e_{2n_2} & & e_{N1}e_{N2}\cdots e_{Nn_N} \end{array} \\
W = & \begin{array}{cc} & e_{11} \\ & e_{12} \\ & \vdots \\ & e_{1n_1} \\ c_1 & e_{21} \\ c_2 & e_{22} \\ \vdots & \vdots \\ & e_{2n_2} \\ c_N & \\ & e_{N1} \\ & e_{N2} \\ & \vdots \\ & e_{Nn_N} \end{array} & \begin{bmatrix} W_{11} & W_{12} & \cdots & W_{1N} \\ W_{21} & W_{22} & \cdots & W_{2N} \\ \vdots & \vdots & \cdots & \vdots \\ W_{N1} & W_{N2} & \cdots & W_{NN} \end{bmatrix}
\end{array}
$$

Fig. 2 Supermatrix (WEY, 2007)

Shahin (2012) and Thor J (2013) both explain how it is crucial to identify the interdependent relationships among criteria that exist practically in any decision-making process. However, it is important to note that the AHP model is considered restrictive to solving problems having a linear, unidirectional hierarchical relationship among criteria. The ANP does not require this strictly hierarchical structure; thus, it resolves problems with diverse inter-relationships among criteria (dependencies and feedback).

4. Research Methodology

4.1. Sasol Catalyst Preparation Unit Operation

The case study is mainly focussed on the critical electromechanical equipment utilized in the Sasol Synfuels catalyst preparation unit, which consists of:

1. Kiln
2. Conveyor belts
3. Arc Furnace
4. Casting Machine
5. Ball Mill

The Sasol Synfuels catalyst preparation unit consists of Kiln (X04KN-101A and B), which uses the RMS (raw mill scale) fed by the conveyor belts (X04CV-101A and B) to burn the RMS and produce OMS (Oxidized Mill Scale). The OMS is then stored in the Bin. From the Bin using conveyor belts, the OMS is fed into the Arc furnace (X04AF-141A and B), which uses Electrodes to burn the product with promotors so that it melts the OMS into a molten catalyst. The catalyst is fed into the crusher to crush the cooled catalyst to small quantities using jaws, using the casting machine (X04CM-141), and spraying water coolers. The catalyst is fed into the storage Hopper manually from the crusher, whereby conveyor belts are utilized to transport the catalyst into the rotating Ball mill (X04GM-141). The ball mill consists of steel balls to further reduce the size of the catalyst to a finer product according to the Sasol specification. Inside the ball mill is the classifier, better known as the vacuum pump, which extracts the unused catalyst and feeds it to the hopper to further crush the catalyst. The unreduced catalyst from the ball mill is fed into the Casting Bin using conveyor belts, where it will be stored until the demand for the reduced catalyst is needed. Eventually, the reduced catalyst is fed into the Reactors to create hydrocarbons. Meridium software was used to analyze the current maintenance strategy applied to the equipment. This software is used primarily in Sasol to populate the Failure Mode and Effects Analysis (FMEA) for each piece of equipment.

4.2. Multi-Objective Model Coupled with a Simulation Model

The literature study done by Shahin (2012) shows that the Multi-Criteria Decision-Making (MCDM) technique, known as the Analytic Hierarchy Process (AHP), has been used in many studies to select the optimum maintenance strategy. However, the process is incapable of comparing interdependency among the criteria and the strategies or alternatives. This is due to the framework criteria used for comparing maintenance strategies, which make the clusters interdependent. The Analytic Network Process (ANP) is also used as another MCDM technique and is suitable for solving the problem of interdependencies, as clusters can be linked dependently.

4.3. Limitations of Study

Due to the lack of interdependency comparisons that the AHP model has, both the AHP and ANP methods were used and compared to determine the optimal maintenance strategy. This also formed as validation to the obtained results from the super decision software used to simulate the results.

The study focused mainly on the electromechanical equipment within the Sasol Catalyst preparation unit; thus, the results pertained only correlate to the unit.

4.4. Analytical Network Process Application

According to Abedini (2016), the main steps of the ANP method are stated as follows:

Step : 1 Identification of elements and network clusters and their relationships.

Step : 2 Conduct pairwise comparisons on the elements and clusters and obtain priorities from the pairwise comparisons matrix. The pairwise comparison process in ANP is the same as in AHP, done through Saaty's nine-point scale. Each weight is, therefore, determined by the eigenvector method elaborated in Chapter 2.

Step : 3 Establish the unweighted supermatrix. The obtained weights from the pairwise comparison matrices are placed in the unweighted supermatrix.

Similarly, to the Shahin (2012) and Abedini (2016) studies, the methodology applied with the conjunction of the super decision software is as follows.

4.4.1. Model Construction and Problem Structuring

The first and fundamental steps in using ANP were making the problem structure a framework network and clearly defining the problem and problem dimensions. In this research, the problem structure is created by brainstorming based on previous studies and incorporating the identified problematic areas in the unit.

From the evaluation stage and theoretical distribution obtained through brainstorming with the maintenance manager of the unit and the Reliability Engineer, it was realized that the availability, maintenance cost due to downtime, Mean Time to Repair (MTTR), and safety form part of the most crucial elements to maintenance optimization at the catalyst preparation unit. With the criteria identified, a framework model was formed for the optimization of maintenance.

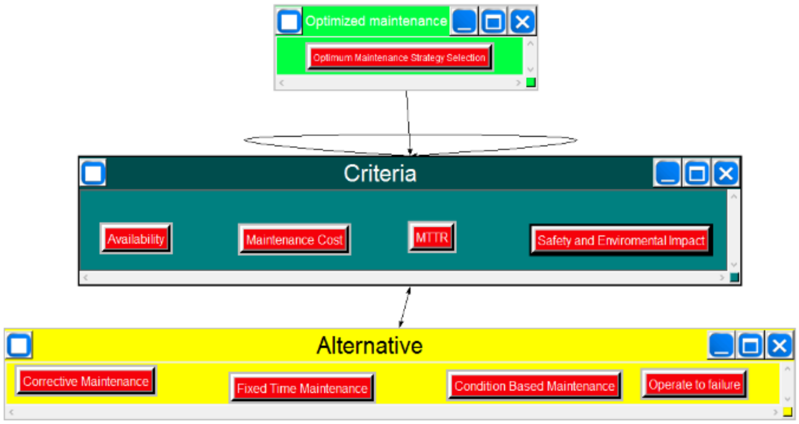

Fig. 3 Analytical network framework from the super decision software

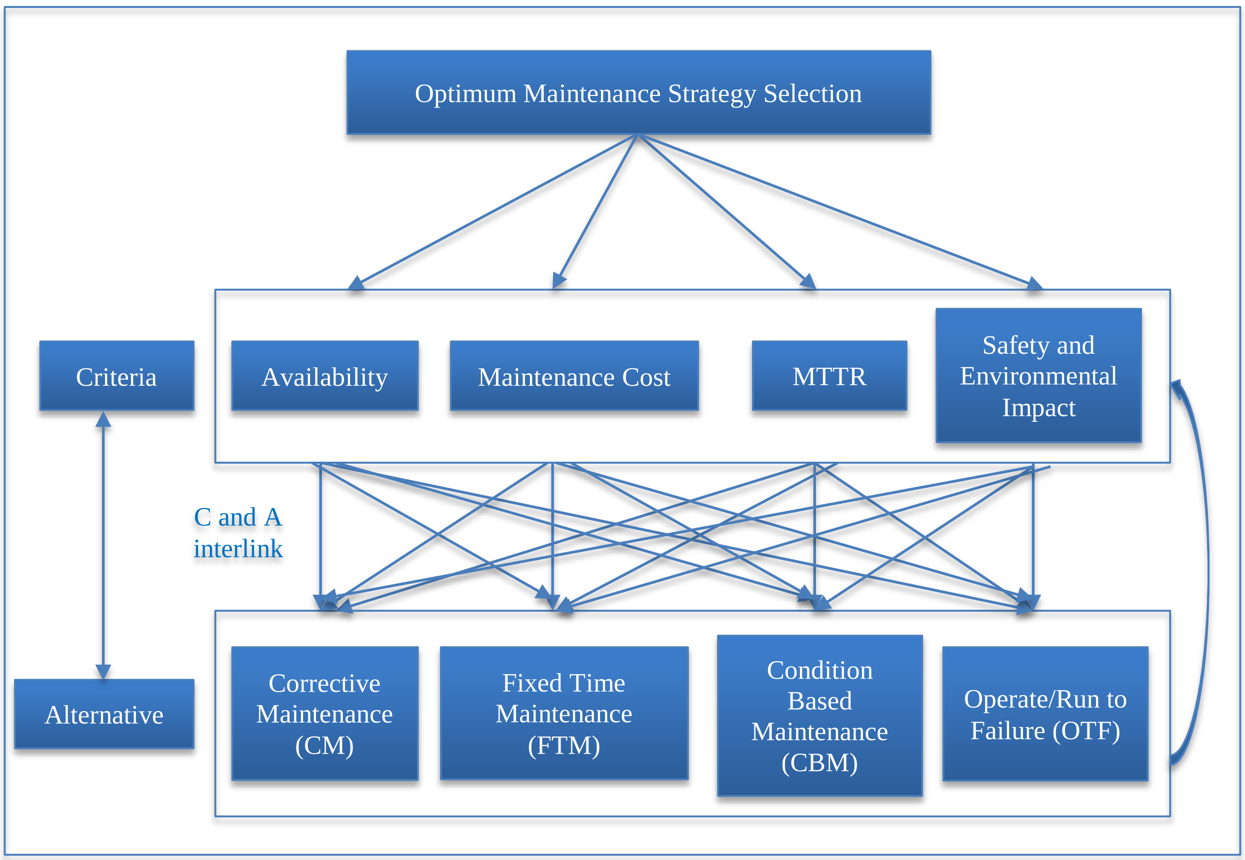

Fig. 4 Analytical network of maintenance strategy 5

From Figure 3, the goal is the optimization of the maintenance strategy, and the criteria, as discussed, are the four elements identified; lastly, the alternatives are the different maintenance strategies applied in Sasol Synfuels.

Both dependant and interdependent links were made between the goal, criteria, and alternatives. This framework was populated in the super decision software, as shown in Figure 4.

4.4.2. Pairwise Comparison Matrices and Priority Vectors

In this step, a paired comparison of criteria considering the goal is made whereby each criterion's importance regarding the issue of selecting the maintenance strategy is specified by a paired comparison matrix. A discussion was made with the maintenance manager of the unit and the Reliability Engineer, and the following were posed questions such:

1. How much is the importance of availability compared to maintenance cost for obtaining the optimal maintenance strategy?
2. How much is the importance of safety and the environment compared to maintenance cost for obtaining the optimal maintenance strategy?

The importance of each criterion has resulted from the problem. The ranking compared importance from 9 to 1. with 9 being extremely important and 1 is equally important. This judgment is further explained in Appendix Table 6. The criteria are drawn from the study by Bosco (2017), which is also used in the super decision ANP/ AHP simulation model, as seen in Figure 5. Using the Super decision simulation model and inputs obtained from the experts, the results are addressed.

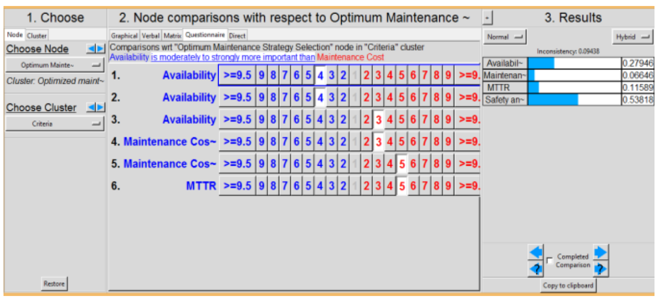

Fig. 5 Node comparison from super decision software

4.4.3. Paired Comparison of Criteria Considering Criteria

The criteria nodes (availability, maintenance cost, MTTR, and safety /environmental impact) influence in such a way that an improvement of each criterion directly impacts other criteria. In this step, the quantity of interdependency among criteria, or rather impact on each other regarding the electromechanical equipment, is measured with attention to this characteristic. The importance of the criteria for each other is weighed using the comparison matrix, as shown in Appendix Table 6. The results are calculated by asking questions such as,

1. How much does availability impact MTTR?
2. How much does MTTR impact Maintenance cost?

4.4.4. Paired Comparison of Criteria Considering Alternatives

Availability, Maintenance cost, MTTR, Safety, and environmental impact (AMMS) criteria have been linked and are thus dependent on each other. Hence, an increase in the importance of each criterion directly impacts other criteria. Therefore, in this step, the impact of interdependency among criteria regarding each other for the electromechanical equipment is weighted. Similarly, with the previous step, as in Figure 4, the importance of alternatives concerning each criterion to each other is ranked in Table 6, Appendix, by posing the following questions:

How much is the importance of condition-based maintenance compared to corrective maintenance for optimal equipment availability?

1. How much is the importance of condition-based maintenance compared to corrective maintenance for minimal MTTR equipment?
2. 3.3.5 Paired comparisons of alternatives related to criteria.

Figure 6 illustrates how, in this step, the importance of the strategies related to the criteria was measured by establishing the effects of employing the condition-based maintenance strategy on availability compared with equipment maintenance cost and other alternatives. Ranking each index between the alternative and criteria is done through ranking, similarly to the steps in the preceding section. The weights of the maintenance strategies against the criteria cluster are presented in the results section.

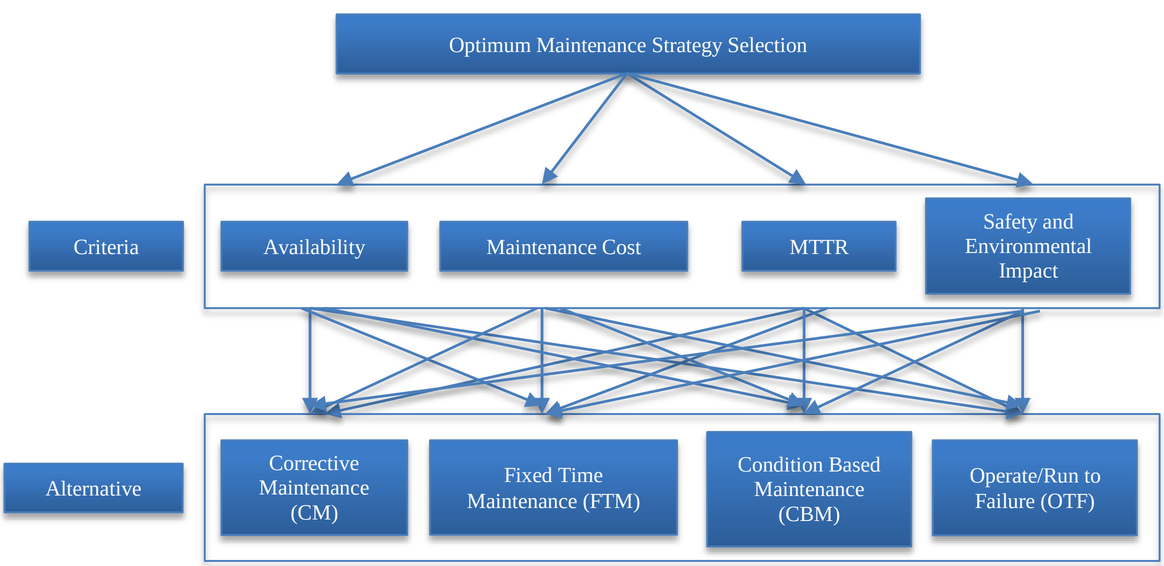

Fig. 6 Analytical hierarchy of maintenance strategy

4.4.5. Supermatrix Formation

The supermatrix is considered a major part of the ANP process as it comprises the importance weights of the criteria and strategies obtained by paired comparisons. The supermatrix in ANP has five main parts. The super-matrix framework structure depends on the type of problem and dependencies existing in the problem framework structure among criteria and strategies derived in the first step. In this research, the interdependency among the strategies alternative node is considered as a dependant. The resulting weights of criteria and strategies determined through paired comparisons in the previous are entered in the super-matrix columns as in the results.

4.4.6. Selection of the Best Alternative

In this final step, the criteria nodes and alternative nodes are ranked by solving the super-matrix, which was created in the previous step with the aid of super-decision software. Based on the calculations obtained, the priority weights of criteria and alternative nodes are obtained in the super decision model. Thus, the results thereof are published in the results.

$$W_{criteria} = W_{availability},\ W_{maintenance\ cost},\ W_{MTTR},\ W_{safety,\ and\ environmental\ impact} \quad (6)$$

$$W_{alternative} = W_{corrective\ maintenance},\ W_{fixed\ maintenance},\ W_{Condition\text{-}based\ maintenance},\ W_{operate\ to\ failure} \quad (7)$$

4.5. Analytical Hierarchy Process Application

4.5.1. Model Construction and Problem Structuring

As in the ANP method, the AHP method follows the same principle. However, the differences between the AHP and the ANP are due to the AHP method, which evaluates the criteria based on the level of importance whilst not considering the interdependencies among the alternative and criteria elements.

As illustrated in Figure 6, there are no criteria or alternative interlinks, unlike in Figure 3. This model is, therefore, seen as impractical, as in most real-world problems, the criteria and alternative nodes have interdependencies with each other. The AHP model is presented in Figure 6. This framework was then modeled in the super decision software, as in Figure 7.

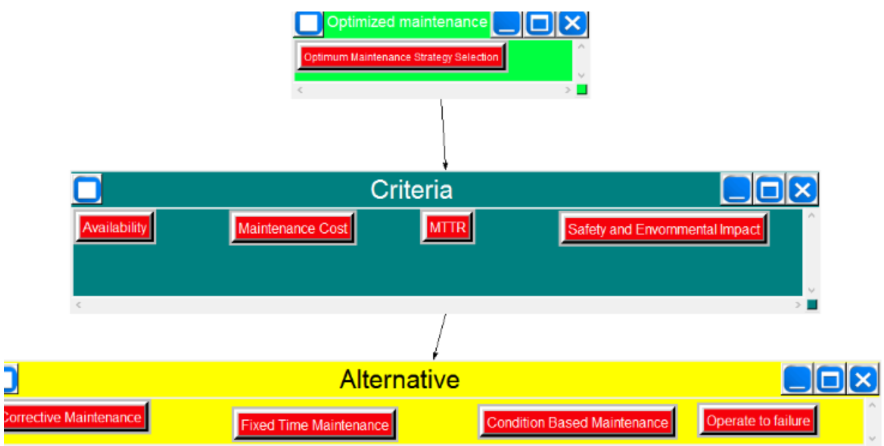

Fig. 7 Analytical hierarchy framework from super decision software

4.5.2. Pairwise Comparison Matrices and Priority Vectors

Similar to the step on the ANP method, the Pairwise comparison matrices and priority considering the goal were considered. The importance and ranking of each criterion regarding selecting the optimal maintenance strategy are specified by a paired comparison matrix. Thus, the comparison results similar to the ANP are presented in Table 1 of the results.

4.5.3. Paired Comparison of Criteria Considering Alternatives

Like the ANP methodology, the availability, maintenance cost due to downtime, mean time to repair, and safety criteria nodes have a relationship and dependency with the alternative nodes. The importance of alternatives concerning each criterion is calculated by establishing the importance of each alternative based on each criterion. Thus, the criteria weights are the same as those addressed in the ANP, as displayed in Table 2 in the section on results.

4.5.4. Supermatrix Formation

Unlike the ANP method, the Paired comparisons of alternatives related to criteria are not made as there is no link within the clusters due to the hierarchy model. However, the Super matrix formation was completed through the hierarchy framework. The Super matrix is formed by the importance weights of the criteria and alternatives obtained by paired comparisons. Similarly to the ANP process, the Super matrix is a major part of the AHP approach. It also consists of 5 main parts. However, the super-matrix structure and completing sections depend on the problem framework and dependencies amongst the criteria and alternatives. Thus, the obtained weights of criteria and alternatives differ from the ANP approach as the determined through paired comparisons in the previous steps were entered the super-matrix columns shown in Table 5 (Appendix) of the results section.

4.5.5. Selection of the Best Alternative

Likewise, for the ANP model, the ultimate step was the formulation of the super-matrix. With the aid of super decision software, the criteria and alternatives considered are ranked. The final superiority of each criterion and the alternative was obtained and weighted with formulae 6.

5. Results and Discussion Results

In this final section. The optimal maintenance strategy for catalyst preparation is discussed. Using two multi-objective methodologies, namely the Analytical Network Approach (ANP) and the Analytical Hierarchy Approach (AHP). The simulation model used for both methodologies is the super-decision matrix model, and both qualitative and quantitative methods were used.

5.1. Analytical Network Approach

5.1.1. Pairwise Comparison Matrices and Priority Vectors Results

The first step was to obtain the node comparison of the criteria to the goal of maintenance optimisation. From Table 1, both the normalized and idealized results suggest that availability is the most important criterion for achieving optimum maintenance in catalyst preparation units for both east and west unit sections. The least important criterion in catalyst preparation in terms of maintenance optimisation is the maintenance cost. This parameter is then followed by reducing the risk to safety and the environment by placing more safety devices. This practice ensures that product containment risk is minimized, thus reducing the safety risk to personnel and the environment. The third most important criterion is the MTTR ratio. MTTR is indirectly proportional to availability; thus, when the availability of equipment increases, there is a decrease in the MTTR rate and vice versa.

Table 1. Node comparison concerning optimum maintenance results

Criteria	Normalized Results	Idealized Results
Availability	0.27946	0.51927
Maintenance cost	0.06646	012349
MTTR	0.11589	0.21534
Safety and Environmental Impact	0.53818	1.0

5.1.2. Paired Comparison of Criteria Considering Criteria

The criteria vector is compared to each criteria node. Availability, MTTR, Maintenance cost and safety, and environmental impact criteria have connections and dependency; thus, increased weight on one criterion impacts another criteria node.

Therefore, this is expressed as the same results obtained in Table 1, resulting in availability being the most weighed alternative mode, followed by MTTR and safety and environmental impact.

5.1.3. Paired Comparison of Criteria Nodes Considering Alternative Nodes Results

In this step, the alternative nodes developed in the framework project in the previous method section are compared to the criteria nodes. Table 2 results proved that availability safety and environmental impact are weighed more than maintenance cost and MTTR for condition-based maintenance and fixed-time maintenance strategy to be effectively implemented.

However, the effectiveness of corrective maintenance and operate-to-failure strategies are prioritized through safety and environmental impact. The least weighted priority vector is the maintenance cost for corrective maintenance and availability for operating to failure.

5.1.4 Paired Comparison of Alternative Nodes Considering Criteria Nodes Results

The alternative nodes can determine the availability, maintenance cost, MTTR, safety, and environmental impact (AMMS) criteria dependency. This relationship in Table 3 reveals the results obtained from the criteria comparison. It is important to apply more condition-based maintenance and less corrective maintenance to achieve optimal availability of the equipment in the catalyst preparation unit.

Likewise, corrective maintenance is the least weighed maintenance strategy applied to optimize the maintenance cost, MTTR, and safety and environmental impact. The optimal maintenance cost, safety, and environmental impact are detrimental to applying more condition-based maintenance. It is proven that condition-based maintenance is more weighed compared to the three other maintenance strategies. However, for reduced MTTR, both condition-based maintenance and fixed-time maintenance weigh the same rating.

Table 2. Maintenance strategies weight with the AMMS

	Condition Based Maintenance	Corrective Maintenance	Fixed Time Maintenance	Operate to Failure
Availability	0.34969	0.32573	0.34969	0.14378
Maintenance cost	0.21670	0.12426	0.11215	0.16129
MTTR	0.11215	0.19358	0.21570	0.27007
Safety and Environmental Impact	0.32246	0.35644	0.32246	0.42486

Table 3. AMMS weight with the different maintenance strategies

	Availability	Maintenance Cost	MTTR	Safety and Environmental Impact
Condition Based Maintenance	0.57367	0.42646	0.36789	0.54021
Corrective Maintenance	0.06622	0.07006	0.09557	0.06841
Fixed Time Maintenance	0.26392	0.37993	0.36790	0.24714
Operate to Failure	0.09619	0.12354	0.16864	0.14424

5.1.5. Unweighted Super Matrix

The obtained weights of criteria and strategies determined through paired comparisons in the previous steps were entered in the super-matrix columns as in Table 4 (Appendix). The criterion's weight against the goal function determining the optimal maintenance strategy is entered into the matrix, representing the goal. The 0 indices in the super-matrix show the interdependency among the variables in the rows and columns.

In the final steps, by solving the super-matrix created from Table 4 (Appendix), with the aid of a super decision software tool, a ranking of the criteria and alternatives was obtained. The final superiority of each criterion and strategy is addressed in equation 8. According to the calculations, the priorities of criteria and alternatives include.

$$W_{criteria} = W_{availability}, W\ maintenance_{cost}, W_{MTTR}, W_{safety,\ and\ environmental\ impact} = (0.3213, 0.17140, 0.16911, 0.33817) \tag{8}$$

$$W_{alternative} = W_{corrective\ maintenance}, W_{fixed\ maintenance,\ Condition\text{-}based\ maintenance}, W_{operate\ to\ failure} = (0.07258, 0.29572, 0.50232, 0.12938) \tag{9}$$

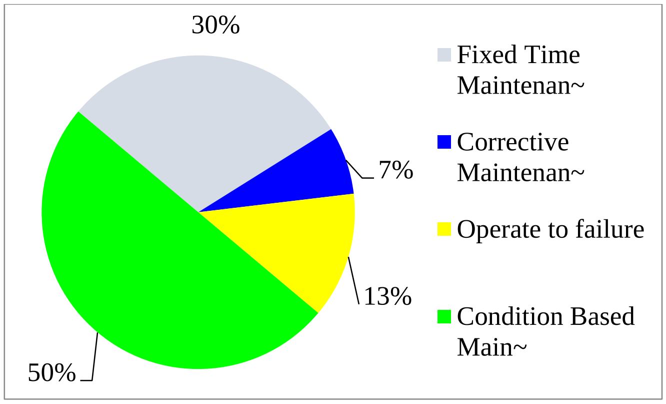

Fig. 8 ANP optimal maintenance strategy pie chart

The results indicate that for criteria nodes, safety and environmental impact have more weight with a factor of 0.34 and availability with a factor of 0.32. the least weighed criteria are the maintenance cost and MTTR, which have a factor of 0.17. Respectively, for the evaluated critical equipment, similar to the Abedini (2016) study, condition-based and fixed-time maintenance strategies are preferable based on the evaluator's point of view and simulated results thereof, as presented in Figure 8, the aforementioned calculated weights. The condition-based maintenance strategy is most weighted at 50%, followed by the fixed-time maintenance of 30%. Operate to failure maintenance is weighed at 13%, and lastly, the corrective maintenance strategy is the least weighed at a percentage rank of 7%

5.2. Analytical Hierarchy Approach

In this approach, a hierarchy framework is used, as in Figure 5. It assumes the network flows from the objective to the criteria and alternative nodes. The difference between the network and hierarchy approach is that the nodes are not interlinked.

5.2.1. Unweighted Super Matrix

With that considered, the same steps as in analytic network analysis were followed, except that the paired comparison of criteria considering criteria was not made. Thus, Tables 1, 2, and 3 had the same results. From the simulated results, the unweighted supermatrix, as in Table 5 (Appendix), was drawn.

From Table 5 (Appendix), the criteria nodes have no values because the comparison of criteria to criteria nodes was not considered. Therefore, it is concluded as in the ANP approach by solving the super-matrix created in the last step with the aid of super decision software. The criteria and alternatives considered were ranked as in equation 9. According to the calculations, the priorities of criteria and strategies are obtained in equation 9.

$$W_{alternative} = W_{corrective\ maintenance}, W_{fixed\ maintenance}, W_{condition\ based\ maintenance}, W_{operate\ to\ failure} = (0.071056, 0.274652, 0.522030, 0.132262) \tag{9}$$

This concludes similarly to the analytical network approach, condition-based maintenance is weighed the most with the same percentage of 50%, followed by fixed time maintenance at 30%. Operate to failure is weighed 13% more than corrective maintenance, which is 7% because corrective maintenance is the least applied for optimal maintenance. This is also evident in the analytical network process.

5.3. Optimal Maintenance Strategy

Though the ANP and AHP approaches have different problem identification frameworks and cluster dependencies, both portray more or less similar results. From both equations 8 and 9, the optimal maintenance strategy is highly dependent on the condition-based maintenance applied. Figure 8 indicates that optimal maintenance is to be achieved, the condition-based maintenance strategy is weighed the highest with 50%.

The least weighted alternative node is corrective maintenance, weighed at 7%. This is true as corrective maintenance is applied once a breakdown has occurred, intending to avoid unforeseen breakdowns. Fixed-time maintenance is the second most weighted maintenance strategy, with 30%, followed by the operate-to-failure strategy, which is 13%. Considering that the operation to failure maintenance strategy is applied based on the consequence of failure and maintenance cost as well MTTR, this is then concluded as practical as RCM priorities predictive and preventative strategies to be employed.

For criteria nodes, it is drawn from both the ANP approach that environmental safety impact is considered the most critical criteria rating at 0.33 (from equation 7), followed by availability with a factor of 0.32. The least weighed criteria nodes are then the maintenance cost and MTTR, both with a factor of 0.17.

However, the AHP approach structure does not consider interdependencies through the criteria and alternative clusters, so the alternative weight cannot be defined. The results obtained from the ANP approach proved practical, considering that the petrochemical industry is considered a high-risk industry due to the hazardous chemicals used in the systems process.

The electromechanical equipment utilized in the catalyst preparation unit contains and processes the catalyst, which is raw and melted at high temperatures. Furthermore, the catalyst is classified as flammable and toxic. Hence, the loss of product containment may lead to catastrophic damage.

Availability is also weighted more as it is indirectly proportional to MTTR, and the availability of equipment increases as the MTTR ratio decreases. Maintenance cost is considered the least weighed criteria node. However, this criterion is also impacted by the MTTR ratio. Though the maintenance cost is the least important factor for optimal maintenance in the catalyst preparation unit, this may vary for other units.

6. Conclusion of Results

The analytical network and hierarchy framework were populated based on all equipment within the case study. With the use of the super decision simulation approach and qualitative information gathered, the optimal maintenance strategy was obtained. An unweighted supermatrix was obtained from the pairwise comparison of the criteria nodes and alternatives. The most weighed alternative solution resulted in condition-based maintenance as the optimal maintenance strategy to be applied at a ranking of 50%.

This is followed by a fixed-time maintenance strategy with a 30% ranking, then operating to failure of 13% and corrective maintenance with 7%. Though the ANP and AHP have different methods regarding the correlation and interdependencies of the network structure, both approaches reach the same outcome of the type of maintenance strategy to apply to obtain optimized maintenance.

Using the ANP approach, the pairwise comparison of the criteria concluded that the nodes that should be focussed on to reach the optimal maintenance strategy have an environmental safety rating of 0.33 from equation (8) followed by availability with a factor of 0.32.

The least weighed criteria nodes are then the maintenance cost and MTTR, both with a factor of 0.17. The AHP network structure, however, does not consider the interdependencies between the criteria and alternative nodes. Thus, the alternative weight was not obtained in this regard. In conclusion, it is seen that it is not the amount of maintenance strategy employed on the equipment that is the problem but rather the actual maintenance action stipulated by FMEA. All the types of equipment identified apply, on average, above 50% of condition-based maintenance. In this regard, the proposed use of the ANP and AHP multi-objective approach allows the decision-makers to consider multiple and conflicting criteria in the decision-making process. Hence, the research makes a unique contribution by proposing a multi-criteria decision approach based on ANP and AHP to select optimum maintenance strategies in the synfuels catalyst preparation unit.

6.1. Recommendation

1. The ANP and AHP model is mostly based on qualitative inputs, which rely mostly on the decision-maker's inputs, and correct and precise information should be gathered. With the use of fuzzy and TOPSIS software, the uncertainties of the decision-making can be eliminated, which provides a baseline for future work.
2. The lack and quality of historical data will always be a constraint. In the strongest viable way, this research recommends performing a robust FMECA, using sensors to collect data using continuous variables frequently, and an online system to store, analyze, and manage the data. If any of these are missing, the organization will be forced to make broad decisions based on limited data and inaccurate analysis.
3. The ANP and AHP framework can be extended by adding the risk and opportunity control hierarchies, and at the

same time, it can be developed by using the limiting priorities as input in the mathematical program techniques.

4. This research mainly focused on the broad perception of the unit rather than each piece of equipment. Future research can apply the framework to each piece of equipment whilst broadening the criteria and alternative modes to include other factors such as quality assurance and opportunity-based maintenance.
5. Taking into consideration the current maintenance employed on the electromechanical equipment and the results obtained from both ANP and AHP approaches, it is therefore concluded that FMEA utilized for the development of the strategies is to be reviewed. All the equipment employs a condition-based maintenance strategy above the 50% average. Thus, further simulation-based optimization methods must be considered to verify the current maintenance strategies employed on electromechanical equipment in the Sasol Synfuels Catalyst preparation unit.
6. This study focused on using ANP and AHP maintenance optimizing tools; however, a comparative study with the result obtained from other maintenance optimization strategies can be further explored.

List of Abbreviations

ANP : Analytical Network Process
AHP : Analytical Hierarchy Process
CBM : Condition-Based Maintenance
CM : Corrective Maintenance
EMS : Equipment Maintenance Strategy
FANP : Fuzzy Analytical Network Process
FAHP : Fuzzy Analytical Hierarchy Process
FFM : Fault-Finding Maintenance
FMEA : Failure Mode and Effects Analysis
FMECA : Failure Mode and Effects Criticality Analysis
FTM : Fixed Time Maintenance
MCDM : Multiple Criteria Decision-Making Method
NGM : Normalised Geometric Mean
OMS : Oxidized Mill Scale
OTF : Operate to Failure
PdM : Predictive Maintenance
PM : Performance-based Maintenance
RBI : Risk-Based Inspection
RCM : Reliability-Centered Maintenance
SAS : Sasol Advanced Synthol

Funding

This research has been funded by Mangosuthu University of Technology, Department of Mechanical Engineering, and Walter Sisulu University of Technology, Department of Mechanical Engineering.

Acknowledgements

This research has been funded by Mangosuthu University of Technology, Department of Mechanical Engineering, and Walter Sisulu University of Technology, Department of Mechanical Engineering. Sasol Synfuels is acknowledged for allowing the case study to be conducted in the Sasol Catalyst Preparation Unit.

References

[1] Malek Tajadod et al., "A Comparison of Multi-criteria Decision-making Approaches for Maintenance Strategy Selection," *International Journal of Strategic Decision Sciences*, vol. 7, no. 3, pp. 51-54, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[2] Ling Wang, Jian Chu, and Jun Wu, "Selection of Optimum Maintenance Strategies based on a Fuzzy Analytic Hierarchy Process," *International Journal of Production Economics*, vol. 107, no. 1, pp. 151-163, 2007. [CrossRef] [Google Scholar] [Publisher Link]

[3] Maurizio Bevilacqua et al., "Development of Innovative Criticality Index for Turnaround Management in an Oil Refinery," *International Journal of Productivity and Quality Management*, vol. 9, no. 4, pp. 519-543, 2012. [CrossRef] [Google Scholar] [Publisher Link]

[4] Gregory Michael Bosco, "*Practical Methods for Optimizing Equipment Maintenance Strategies Using an Analytic Hierarchy Process and Prognostic Algorithms*," Thesis, Tennessee: TRACE: Tennessee Research and Creative Exchange, pp. 1-183, 2017. [Google Scholar] [Publisher Link]

[5] Roman Denysuik et al., "Multi-Objective Optimization of Maintenance Scheduling: Application to Slopes and Retaining Walls," *Procedia Engineering*, vol. 143, pp. 666-673, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[6] "*Department of Alternative Energy Development and Efficiency (DEDE)*," Thailand Energy Situation, Report, Ministry of Energy, Thailand, pp. 1-41, 2009. [Google Scholar] [Publisher Link]

[7] Gustav Fredriksson, and Hanna Larsson, "*An Analysis of Maintenance Strategies and Development of a Model for Strategy Formulation-A Case Study*," Master Thesis, Sweden: Chalmers University of Technology, pp. 1-156, 2012. [Google Scholar] [Publisher Link]

[8] Devarun Ghosh, and Sandip Roy, "A Decision-Making Framework for Process Plant Maintenance," *European Journal of Industrial Engineering*, vol. 4, no. 1, pp. 78-98, 2009. [CrossRef] [Google Scholar] [Publisher Link]

[9] Patrik Hilber, "*Maintenance Optimization for Power Distribution Systems*," Ph.D. Thesis, Department of Electrical Power Engineering, KTH, Stockholm, 2008. [Google Scholar]

[10] Fereshteh Jaderi, Zelina Z. Ibrahim, and Mohammad Reza Zahiri, "Criticality Analysis of Petrochemical Assets Using Risk-Based," *Process Safety and Environmental Protection*, vol. 121, pp. 312-325, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[11] Shalu Kaushik et al., “A Review Based on Various Applications to Find a Consistent Pairwise Comparison Matrix,” *Journal of Reliability and Statistical Studies*, vol. 17, no. 1, pp. 45-76, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[12] Mobius Institute, “Vibration Analysis Training Manual: Version 4.1, Victoria: Mobius Institute,” 2016.

[13] Charles M.M. Ondieki, “*Training Manual for ITEC 236: Terotechnology*,” Faculty of Engineering and Technology, Department of Industrial and Energy Engineering, Report, Egerton University Njoro, Kenya, pp. 1-77, 2007. [Publisher Link]

[14] Youssef Sadraoui et al., “Optimization of Quality Process Control and Preventive Maintenance Strategy: A Case Study,” *Operations Research Forum*, vol. 5, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[15] SASOL, Sustainable Development Report, pp. 1-56, 2012. [Online]. Available: https://www.sasol.com/sites/default/files/2022-04/Sustainable%20development%20report%20-%202012.pdf

[16] Mahmood Shafiee, and John Dalsgaard Sorensen, “Maintenance Optimization and Inspection Planning of Wind Energy Assets: Models, Methods, and Strategies,” *Reliability Engineering and System Safety*, vol. 192, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[17] Arash Shahin, Ehsan Pourjavad, and Hadi Shirouyehzad, “Selecting Optimum Maintenance Strategy by Analytic Network Process with a Case Study in the Mining Industry,” *Productivity and Quality Management*, vol. 10, no. 4, pp. 465-483, 2012. [CrossRef] [Google Scholar] [Publisher Link]

[18] E. Shayesteh, J. Yu, and P. Hilber, “Maintenance Optimization of Power Systems with Renewable Energy Sources Integrated,” *Energy*, vol. 149, pp. 577-586, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[19] M. Sondalini, Lifetime Reliability Solutions, 2018. [Online]. Available: www.lifetime-reliability.com/cms/faqs/reliability-improvement/faq-pragmatic-maintenance-strategy/

[20] Jureen Thor, Siew-Hong Ding, and Shahrul Kamaruddin, “Comparison of Multi-Criteria Decision-Making Methods from the Maintenance Alternative Selection Perspective,” *The International Journal of Engineering and Science*, vol. 2, no. 6, pp. 27-34, 2013. [Google Scholar] [Publisher Link]

[21] Wann-Ming Wey, and Kuei-Yang Wu, “Using ANP Priorities with Goal Programming in Resource Allocation in Transportation,” *Mathematical and Computer Modelling*, vol. 46, no. 7-8, pp. 985-1000, 2007. [CrossRef] [Google Scholar] [Publisher Link]

Appendix 1

Table 4. ANP unweighted super matrix

Cluster Node Labels		Alternatives				Criteria				Optimized Maintenance
		CBM	**Corrective Maintenance**	**FTM**	**Operate to Failure**	**Availability**	**Maintenance Cost**	**MTTR**	**Safety and Environment**	**Optimum Maintenance Strategy**
Alternative	CBM	0.000000	0.000000	0.000000	0.000000	0.573667	0.426464	0.367895	0.540210	0.000000
	Corrective maintenance	0.000000	0.000000	0.000000	0.000000	0.066224	0.070064	0.095570	0.068408	0.000000
	FTM	0.000000	0.000000	0.000000	0.000000	0.263923	0.379934	0.367895	0.247142	0.000000
	OTF	0.000000	0.000000	0.000000	0.000000	0.096186	0.123537	0.168640	0.144239	0.000000
Criteria	Availability	0.349691	0.325727	0.349691	0.143784	0.000000	0.000000	0.000000	0.000000	0.279463
	Maintenance Cost	0.215699	0.124257	0.112154	0.161286	0.000000	0.000000	0.000000	0.000000	0.066462
	MTTR	0.112154	0.193576	0.215699	0.270066	0.000000	0.000000	0.000000	0.000000	0.115894
	Safety and Environment	0.322456	0.356440	0.322456	0.424863	0.000000	0.000000	0.000000	0.000000	0.538181
Optimized Maintenance	Optimum Maintenance Strategy	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000

Table 5. AHP unweighted super matrix

Cluster Node Labels		Alternatives				Criteria				Optimized Maintenance
		CBM	**Corrective Maintenance**	**FTM**	**Operate to Failure**	**Availability**	**Maintenance Cost**	**MTTR**	**Safety and Environment**	**Optimum Maintenance Strategy**
Alternative	CBM	0.000000	0.000000	0.000000	0.000000	0.573667	0.426464	0.367895	0.540210	0.000000
	Corrective Maintenance	0.000000	0.000000	0.000000	0.000000	0.066224	0.070064	0.095570	0.068408	0.000000
	FTM	0.000000	0.000000	0.000000	0.000000	0.263923	0.379934	0.367895	0.247142	0.000000
	OTF	0.000000	0.000000	0.000000	0.000000	0.096186	0.123537	0.168640	0.144239	0.000000
Criteria	Availability	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.279463
	Maintenance Cost	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.066462
	MTTR	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.115894
	Safety and Environment	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.538181
Optimized Maintenance	Optimum Maintenance Strategy	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000

Table 6. ANP and AHP demonstration-judgement score matrix (BOSCO, 2017)

Judgment	Explanation	Score
Equally	Two activities contribute equally to the objective. Higher than equal	1 2
Moderately	Experience and judgment slightly favor one activity over another. Another Higher than moderately	3 4
Strongly	Experience and judgment strongly favor one activity over another. Another Higher than strongly	5 6
Very Strongly	Activity is strongly favored, and its dominance is demonstrated. Higher than very strongly	7 8
Extremely	Evidence favoring one activity is the highest possible order of affirmation	9