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Review Article

Maintenance Overview on the Electromechanical Equipment in Sasol Synfuels Catalyst Preparation Unit: A Review

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Abstract *- Each industry and equipment is unique as the product streams differ, as well as layouts and operation variables, to name a few. However, Turn-around management is the most used strategy in petrochemical industries. Equipment downtime remains the biggest challenge; thus, the purpose of the study was to understand the different maintenance practices and evaluate the current maintenance strategy applied within the unit to optimize the maintenance strategy employed.*

Keywords *- Maintenance strategy, Electromechanical equipment, Petrochemical industry, Reliability Centred Maintenance (RCM), Condition based maintenance, Corrective maintenance, Proactive maintenance.*

1. Introduction

1.1. Petrochemical Industry Overview

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 differs from the refinery industry. The products thereof produced include plastics resins, synthetic fibres, synthetic rubbers, surface coating materials, and various types of adhesives, as reported by the Department of Alternative Energy Development and Efficiency, 2006. Some of the industry products can be classified into two groups, namely Primary and Secondary products. Primary products consist of methanol, ethylene, toluene, and propylene. In contrast, secondary or derivative products (the primary products) include vinyl acetate for paint, vinyl chloride for PVC, and styrene for rubber and plastics. (Oluwasina, 2011). Plant configuration and size are dependent on the end products produced. A large amount of landscape is utilized mainly due to the extensive pipeline network, furnaces, vessels, heat exchangers, cooling towers, tanks, and rotating equipment. The petrochemical industry is divided into three groups. The first is the Upstream Petrochemical industry. This is the baseline and supplier to the further production of the other petrochemical products, of which it aims to produce primary feedstock for the next group of products. Second is the intermediate petrochemical industry, which utilizes the products proceeding from the upstream to provide feedstock to downstream production, the last main group. The downstream petrochemical industry utilizes products from both the upstream and intermediate to produce the end products, such as synthetic plastic, rubber, etc. A study by Majozi (2015) explored how the petrochemical industry in South Africa compromises about 55 percent of all chemicals produced, thus requiring high energy consumption. Energy conservation is a factor due to its direct impact on production costs, as reported by the Department of Alternative Energy Development and Efficiency (2006). The study highlighted that the problems in energy conversion consist of energy management, technology, economy, and human resources. One of the contributing factors is the high cost of machines, technology, and maintenance.

However, in the era of global competition, the majority of power, processing, and manufacturing sectors are required to reduce their overall cost while maintaining the value and reliability of their sectors (Bevilacqua, 2012). Hilber's (2008) study states that finding the optimal maintenance solution is not new. However, the relationship between maintenance, reliability, and costs is not entirely solved. Furthermore, the requirements from owners, authorities, and customers create needs and incentives for newer methods to handle maintenance effectively and efficiently. Numerous studies have been conducted on maintenance strategies and development. Some research work that has been conducted focuses on maintenance strategies through turn-around management and implementation within the Petrochemical industry. (Bevilacqua, 2012) Very few studies have focussed on maintaining electromechanical equipment used in a petrochemical plant. Hence, this article aims to review the maintenance strategies that can be applied in Petrochemical industries such as Sasol. It is also important to obtain tools to review the current maintenance employed in this industry to evaluate the effectiveness of the maintenance strategies applied.

1.2. Introduction to Sasol Catalyst Preparation Unit

Majozi, (2015) explains in his journal how South Africa's petrochemical industry started in the 1950s after George Williams Stow discovered coal near the Vereeniging on the banks of the Vaal River in 1878. The first coal-to-liquids plant was built at Sasolburg. After that, Sasol built two large Coals to Liquid plants. Furthermore, the Synfuels sector now serves as a source of energy and is the country's primary source of chemical feedstocks and their intermediate products as stipulated by (Majozi, 2015). According to the article, almost 160,000 barrels of liquid fuels are produced by Sasol per day, serving 40% of the South African market.

Sasol uses the Fisher-Tropsh process to produce liquids derived from coal, liquids such as synthetic rubber, fertilizers, and secondary chemicals such as ethanol, butanol, ethyl acetate, acrylic acid, and butyl acrylate, including diesel fuel. Through continuous improvement and development, the Sasol Advanced process (SAS) was introduced, and seven new SAS reactors were introduced in 1999, as illustrated in Figure 1.

The whole process has a series of connections, as illustrated in Figure 2. This means that every unit depends on the other to provide the products needed; however small the unit might be, it is crucial to provide the output product. In other simple terms, the system's successful operation depends on the proper operation of all the components. Hence, if one of these components fails, the system fails. This type of setup is a disadvantage not only to the operation side of the plant but also to maintenance. Since every unit depends on the other, anytime maintenance activities are rarely used. Most maintenance schedules depend on the unit, plant, or factory shutdown, also known as turn-around maintenance.

In terms of survival, the system can be no better than a component with the lowest probability of survival. Figure 2 illustrates the concept of series connection is shown. The catalyst is provided through U04/204, the catalyst preparation unit. It plays an important role in providing the catalyst needed for the SAS reactors, as illustrated in Figure 3. The catalyst is fed through process lines, which assist in creating hydrocarbons needed in downstream units. The main unique nature of the catalyst preparation unit is its ability to store products for future use. Thus, unlike most units, this unit isolates some of the equipment for maintenance for a period without affecting the factory production rate. Hence, it is called a batch plant.

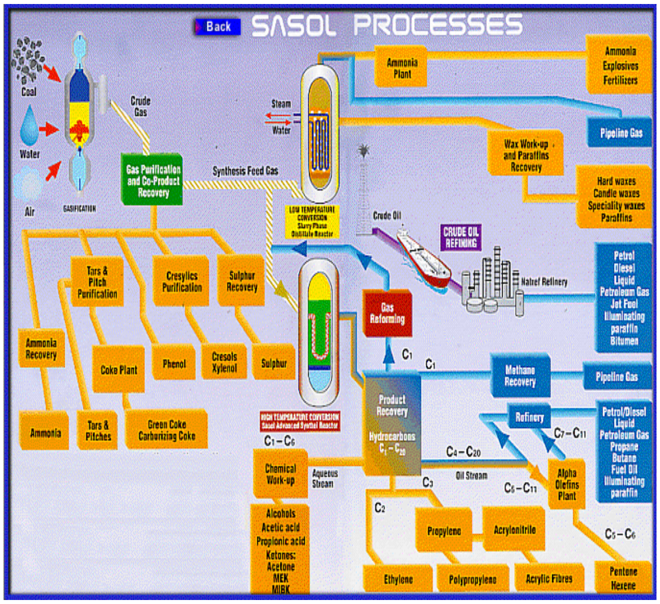


Fig. 1 Sasol process (2012)

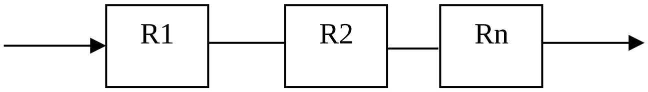


Fig. 2 System with components in series (Ondieki, 2007)

1.3. Production of Catalyst for Use in Synthol Reactors

Raw Mill Scale (RMS) is the raw material used to make catalysts, which is iron waste from ironwork factories. RMS is fed into the rotary Kiln, where oily contaminants are burned off, and the oxide levels of the RMS are increased by the reaction shown in Equation (1).

$$6FeO+O_2 \rightarrow 2Fe_3O_4 \qquad (1)$$

The reaction (Ferrous oxide) occurs at a temperature of 1100^{O}C. This is done to increase the mole ratio of the catalyst to a ratio of 1. The mole ratio represents the amount of pure Fe_3O_4 in the mixture and measures the amount of oxide content in the mill scale. After cooling down and exiting the Kiln, the Oxidized Mill Scale (OMS) is sent to the storage hopper or the ground, if not of standard quality, better known as off-specification.

The OMS in the storage hopper is unloaded into a secondary hopper, where it is weighed to ensure the correct load is ready for the Arc furnace. The weighted number of OMS is then fed onto a conveyor belt. The belt passes underneath four other weight hoppers, each weighing and unloading the required number of promoters. The mixture is fed into the furnace, melted, and mixed, ensuring even promoter distribution, and then the promoters are fused with the catalyst.

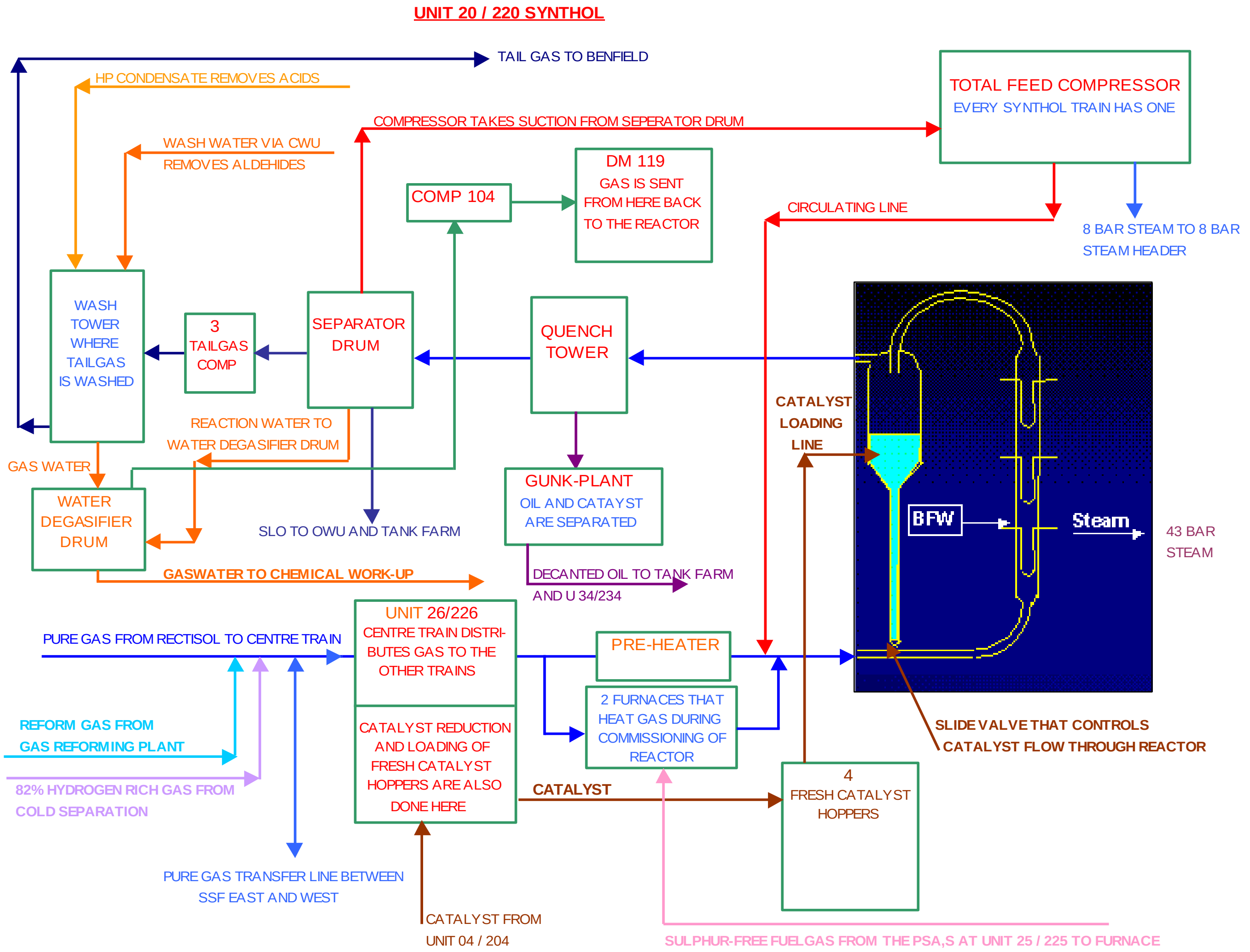


Fig. 3 Synthol process (2012)

The molten catalyst (now called fused cat) is then tapped from the furnace into metal casting pans for cooling. After cooling, the catalyst is fed into jaw crushers, reducing the particle size to 50 mm. These particles are fed into the ball mill milled to the required size, known as a milled catalyst. The milled catalyst is loaded into storage hoppers, which can then be loaded into the reduction reactors at unit 26. In the reduction reactor, hydrogen gas is used as the process gas. The hydrogen gas is forced through the system by a compressor. The gas passes through pre-heaters and a furnace, where it is heated to a temperature of 420^{O}C before entering the reactor.

The upward flow of hydrogen gas through the reactor fluidizes the catalyst bed, increasing the reaction area within the bed. The hydrogen gas reacts with the oxygen gas in the presence of iron, thereby removing the Oxygen gas increases the porosity of the catalyst and activates the catalyst for the Fischer-Tropsch reaction. The reduction percentage is calculated by measuring the amount of water produced in the separator, as water is a product of hydrogen reacting with oxygen gas. After the catalyst is reduced to the desired levels, the reduction train is cooled off using nitrogen gas. The cooled-down reduced catalyst is then unloaded to the fresh catalyst hoppers for storage until it is used.

1.4. Maintenance Defined

Maintenance is defined by Fredriksson (2012) as the combination of all technical, administrative, and managerial actions on an equipment's life cycle. Maintenance intends to retain or restore the equipment to a state where it can perform the required function. In other words, maintenance is an action performed to prevent a device or component from failing either from normal equipment degradation or breakdown. A study by Manickam (2012) argues that the maintenance objective is to retain or restore the systems to carry out a perfect production function. Whilst Fredriksson's (2012) research work concluded that a maintenance organization’s primary objective is to ensure that all equipment and systems are constantly in good operating condition and online, in other words, to reduce disturbances.

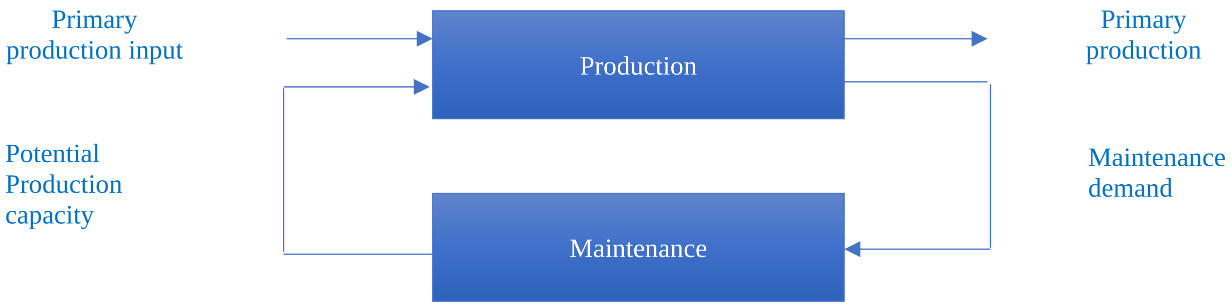


Fig. 4 Relationship between production and maintenance (Manickham, 2012)

All these arguments have one similar objective: maintenance has two essential objectives, the first being a high availability of production equipment and the second being low maintenance costs (Vishnu, 2016). Maintenance is considered support for the production process, whereas the production input is derived into specified production output, as in Figure 4. Industrial maintenance is a secondary process that must contribute to obtaining production objectives (Manickham, 2012). The same study by Fredriksson (2012) defined Production disturbances as discrete or decreasing, unplanned or planned change or disruption during production time. The disturbance in production may influence the operational performance, availability, product quality, work conditions, safety, environment, etc.

Maintenance must retain or restore the systems to carry out a perfect production function and avoid production losses (Manickham, 2012). According to Fredriksson (2012), the production sector did not have a high mechanical level before the Second World War (SWW) due to the over-design and simplicity of the equipment, which led to most industries relying on a run-to-failure strategy. After the Second World War (SWW), the industry shifted dramatically towards more preventative actions due to high product demand, which led to reliability. Availability and maintainability are the key elements of an effective maintenance practice (Frediksson, 2012). Ondieki (2007) defines reliability as the probability that an asset will perform its function with no disturbances for the specified time interval subject to its operation according to the design.

Meanwhile, maintainability is the action taken during the design and development of assets to ensure that maintenance tasks can be performed easily and effectively. The study further defines availability as the probability that a system or equipment will be ready for use. For the assets to be ready for use, a system must either have no failure. If a failure has occurred, then a repair must have been done. Thus, availability includes both maintainability and reliability. Maintenance has traditionally been considered a daunting task, but it is, in fact, rather a centre of profit than just an unavoidable and unpredictable expense (Fredriksson, 2012). If effective maintenance policies are used, most failures can thus be reduced to a minimum level, resulting in cost savings (Fredriksson, 2012).

1.5. Maintenance Approaches

Several different maintenance approaches, better known as strategies, are available for application in all production methods. (Mingani, 2013). They consist of reactive repairs and replacement activities employed through failures as well as planned and predictive tasks such as preventive replacements, inspections, scheduled repairs, etc. (Wakiru, 2018). Shafiee's (2017) study further explains how an effective maintenance strategy aims to reduce the frequency of asset downtime and avoid such interruptions. More so, over-maintenance can increase maintenance costs, and subsequently, less maintenance may bring undesirable failures and interruptions. Thus, the integration of an optimal maintenance strategy is important. Another study by Abedini (2016) explained how, in recent years, the importance of maintenance strategy selection has increased due to its critical role in increasing availability, mean time to failures, and safety and environment.

Other maintenance benefits reported were improved system reliability and product quality, reduced factory shutdown interval, and prevented insignificant investments. Maintenance strategies are created to meet the objectives of maximum availability and reliability, more so to obtain a thorough knowledge of the technical systems with a practical and easy-to-use structure approach (Fredriksson, 2012). This clearly shows how availability, reliability, and maintainability are the key factors to an optimized maintenance strategy. The maintenance strategy fundamentals are similar, but the focus is different.(Mingani, 2013). Fredriksson (2012) discusses how diverse maintenance optimization should be customized to suit the company's customs, operation, and culture due to its unique strategy. Hence, maintenance strategies are unique to each company. The merging of all departments involved in maintenance is considered an important role in maintenance optimization. This needs to be directed to the development of three maintenance approaches and integration, namely, Reliability-Centred Maintenance (RCM), Total Productive Maintenance (TPM), and Business-Centred Maintenance (BCM).

- Reliability-centred maintenance (RCM) is a method initially developed by the Airline Industry in the late 1960s that aims at preventing failures whose consequences are most likely to be serious, as reported by the International Atomic Energy Agency, 2008. Its focus is on equipment reliability (Mingani, 2013). RCM analysis is a systematic evaluation approach for developing or optimizing a maintenance program. The International Atomic Energy Agency 2008 stated that RCM incorporates a decision logic tree to obtain equipment maintenance requirements. This is done based on each failure's safety and operational consequences and the degradation mechanism responsible for the specific failures. Mingani (2013) further explains how preventive action is employed if the consequences of failure are safety-related or hidden from the operators. The RCM process results in a life plan for each system asset, consisting of a list of preventive tasks (scheduled run-to-failure tasks, scheduled restoration tasks, or on-condition tasks). International Atomic Energy Agency (2008) explains how the outcomes of an RCM analysis may result in existing preventive maintenance task changes and the use of condition monitoring. Other changes include inspections and functional testing or adding or eliminating such tasks. Figure 5 shows the structure of RCM maintenance. When used effectively, it can improve the safety and reliability of plants and equipment and, ultimately, the optimization of maintenance activities and operations.

- Pradhan, (2006) study defines Total Productive Maintenance (TPM) as a lifecycle and employee involvement method maintenance management uses to maximize overall equipment effectiveness and efficiency. It developed a preventive maintenance program for the equipment's lifecycle and used team-based concepts. Further, the approach Involves operators in maintaining the equipment and uses motivational management to promote preventive maintenance. According to Mingani's (2013) work, TPM originated in the line industry, which focuses on improving the quality of people and processes. Further, Fredriksson's (2012) study explains that TPM aims to maximize the overall equipment efficiency, thus creating a disturbance-free system. By focusing on preventive techniques and operators' involvement, downtime can be minimized, and equipment efficiency can be increased. (Fredriksson, 2012). This TPM system focuses mainly on equipment performance by monitoring defects, breakdowns, and accidents, which can be a narrow approach. However, the TPM system considers factors such as ergonomics and workmanship, which do have, according to (Oluwasina, 2011), a factor not often considered with the speed at which maintenance is carried out. TPM consists of three basic goals, namely, Zero product defects, Zero breakdowns, and Zero Accidents. Furthermore, the TPM method contains 12 activities coupled with the basic goals as in Figure 6 (Fredriksson, 2012).

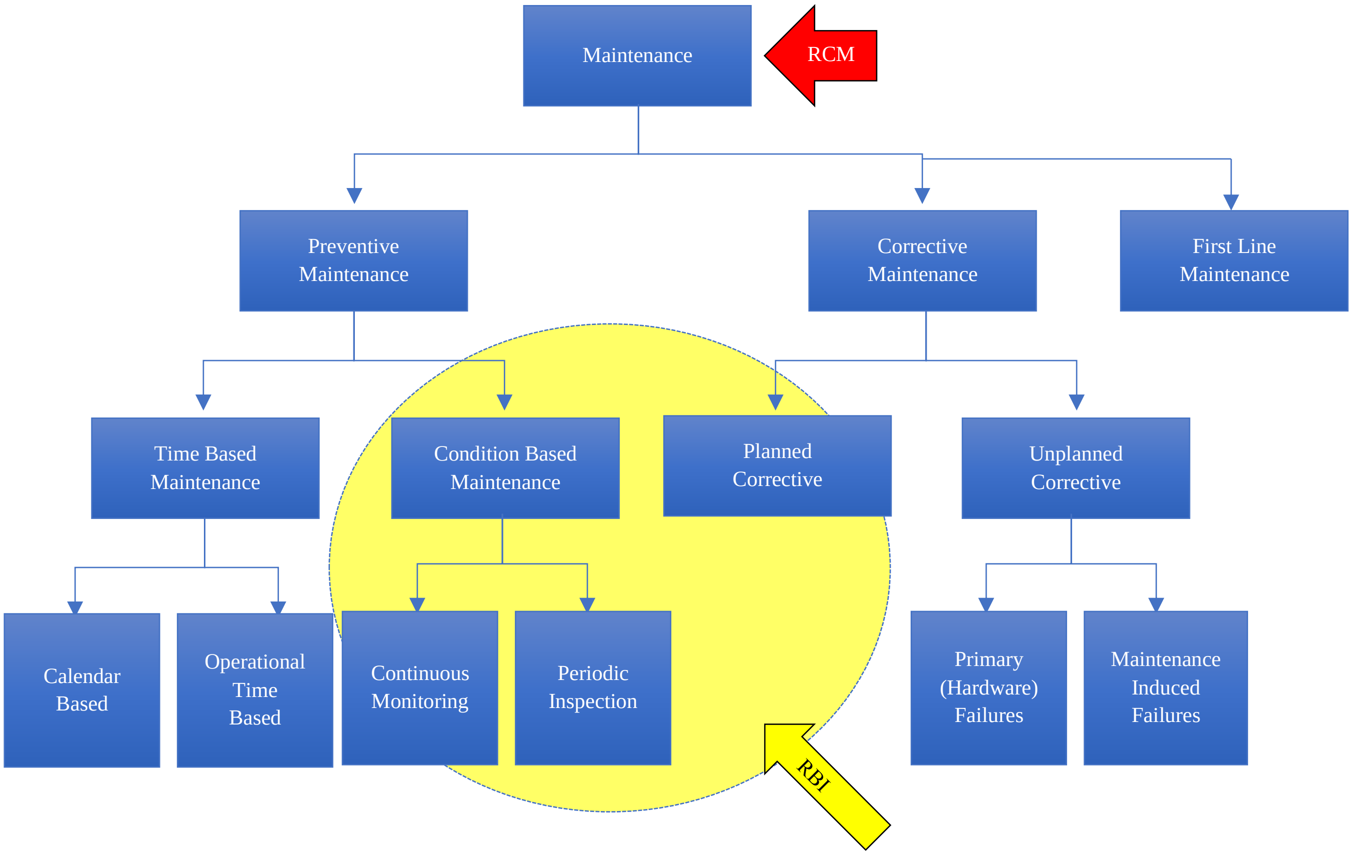
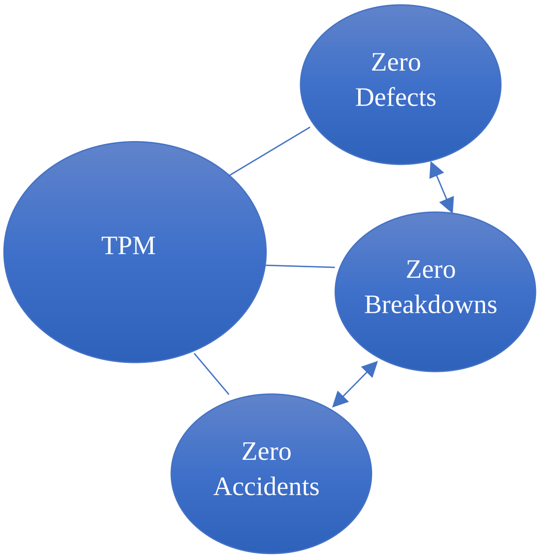


Fig. 5 Maintenance structure (2008)



Management information
Education and information
Design a TPM organization
Establishment of clear and structured policies and goals

Activities and main plan
Kick-off
Improve equipment efficiency
Design an integrated maintenance

Develop quality maintenance
Competence for production personnel and maintenance personnel
Maintenance prevention
Aim for higher goals

Fig. 6 TPM objective (Fredriksson, 2012)

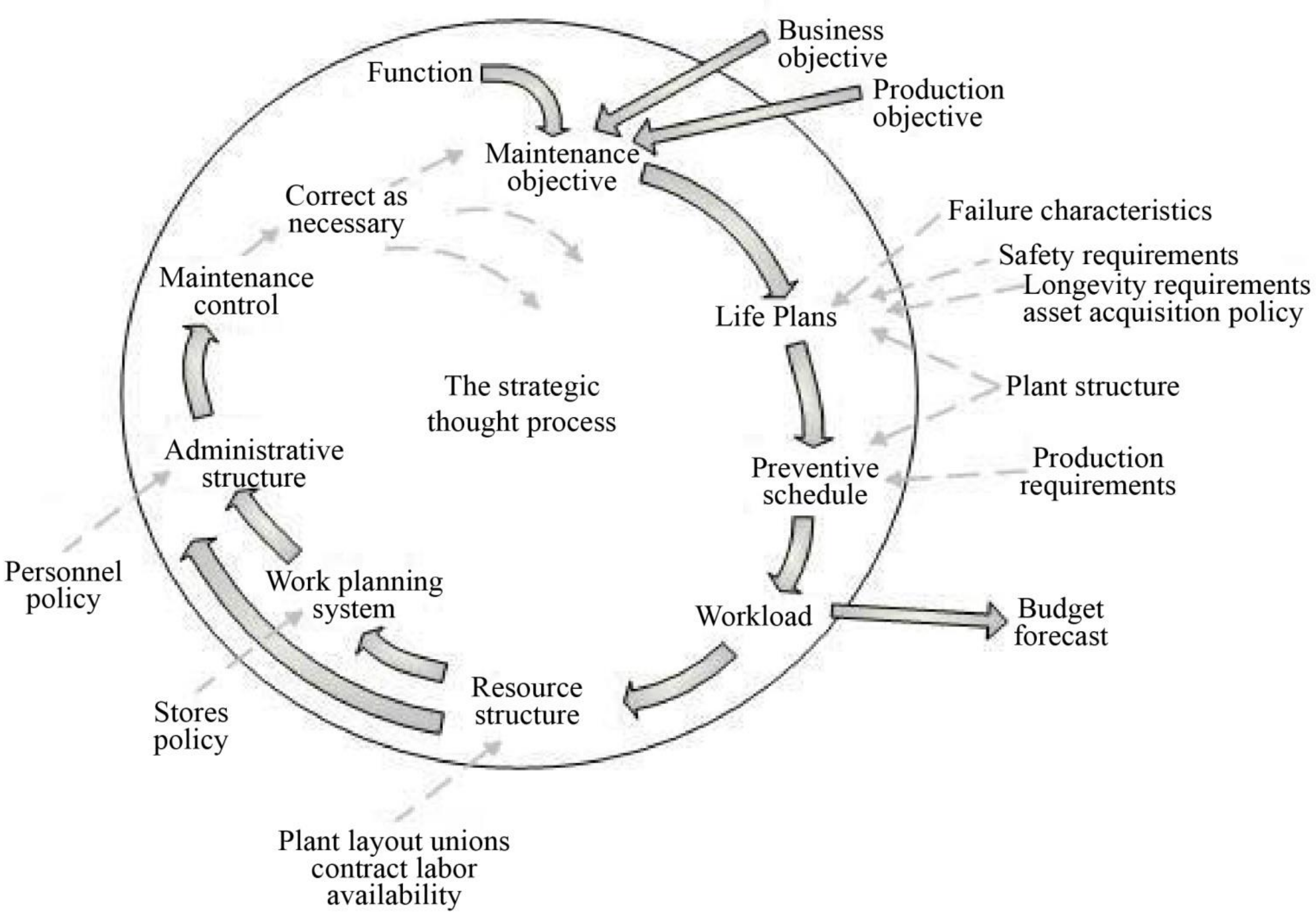


Fig. 7 Business-Centred Model (BCM) for the formulation of a maintenance strategy (Fredriksson, 2012)

- Lastly, Business-Centred Maintenance (BCM) originated in the process industry. The prime driver is the business objectives identification, which is translated into maintenance objectives and the support formulation of the maintenance strategy (Fredriksson, 2012). Moreover, Mingani, (2013) study elaborates on how BCM is a generic method used in most manufacturing production systems or service systems, including chemical process plants, power stations, fleet-type systems, or communication networks. Yet Frediksson, (2012) study points out how crucial it is when formulating a maintenance strategy through this approach. It is essential to understand the plant operation, the connection between the plant and its market, and the maintenance function within the business. This approach can be rather diverse and complex; thus, its success requires extensive data collection, as illustrated in Figure 7. Hence, the approach may be rather tricky, especially in big industries such as petrochemical industries. Table 1 shows the different advantages and disadvantages of each maintenance objective each business will use per their objective.

Table. 1 Advantages and disadvantages of maintenance approaches (Mingani, 2013)

RCM	BCM	TPM
ADVANTAGES		
Traceability Cost saving Rationalization Operator & maintenance involvement Plant reliability improvement	Accuracy Business-centered Integrated auditing possibility	Productivity improvement Quality improvement Cost reduction Operator involvement
DISADVANTAGES		
Complexity Extensive need for data Reliability-centred Does not focus on economic problem	Complexity Extensive need for data	Not a true maintenance concept Lacks decision rules on maintenance policies Does not focus on economic problem

According to MINGANI (2013) study, RCM is focused on asset reliability. It is most suited for high-risk systems, whereas TPM is focused on people factors and organizational culture and is most suited for assembly-type industries. However, it has also been applied in the continuous process industry. On the other hand, BCM is aimed at aligning the maintenance function with organizational or business objectives. Most industries have integrated the RCM approach due to its integration of Preventive Maintenance (PM), Predictive Maintenance (PdM), Corrective, and Proactive Maintenance. This integration does increase the likelihood that equipment will operate as required over its design lifecycle with a minimum amount of downtime and maintenance. (Frediksson, 2012). The maintenance strategies are optimally integrated to incorporate their respective strengths and ensure maximum reliability and availability of equipment while minimizing the equipment lifecycle costs. (Frediksson, 2012). This is seen through many recommendations given by researchers' studies, such as Mingani (2013), Odeyinde (2008), and Borjalilu (2018), just to name a few.

1.6. Maintenance Strategies

Several strategies are adopted in maintaining process equipment and their complexities considering the size of the Petro-chemical plant. Every plant requires a unique maintenance structure, which is affected the majority by the size of the plant. (Fredriksson, 2012). Most industry's maintenance methodology employs an integrated strategy where they incorporate the activities of both the planned and unplanned actions. According to Oluwasina (2011), a Petrochemical plant may be shut down based on routine or planned maintenance. The speed at which the plant is brought back online often depends on the nature or complexity of the failure, tools or machinery required, and availability. Other dependencies are parts availability, Skills or expertise required, Maintenance personnel availability, Maintenance management system operational in the plant, needed technical support, etc.

Mingani (2013) reported three major maintenance objectives that incorporate both planned and unplanned maintenance, as shown in Figure 8. Another study by Akinyemi (2010) defines unplanned maintenance as a practice carried out at equipment breakdowns. It involves an Unplanned Corrective Maintenance (UCM) or Operates to Failure (OTF) Strategy due to equipment breakdown. With preventive maintenance, equipment is routinely inspected and serviced to prevent breakdowns from occurring. There are three main maintenance strategies as derived by Mingani's (2013) work, namely: Preventive Maintenance (PM), which consists of condition and scheduled maintenance; second improvement, better known as design out maintenance; and lastly, corrective maintenance. The seven maintenance strategies developed throughout the years as maintenance activities that broadened tremendously through equipment optimization are reviewed under the following subheadings.

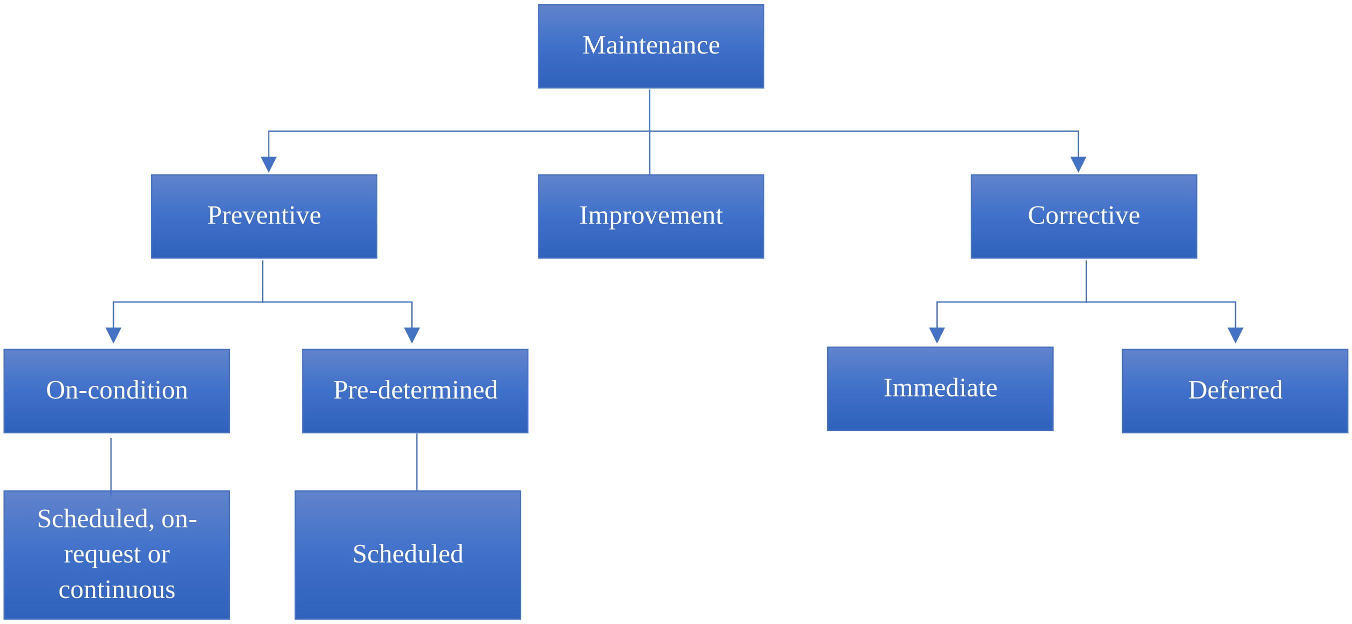


Fig. 8 Major maintenance types or tactics (Mingani, 2013)

1.6.1. Corrective Maintenance

The definition of Corrective Maintenance (CM) according to the standard prEN13306 1998 states that corrective maintenance is the maintenance employed after fault recognition and is aimed to put an asset into a state in which it can perform a required function (Fredіksson, 2012).

The strategy is simple in its operation based on fixing the equipment when it breaks; thus, it is also known as failure-based maintenance. It is mainly accompanied by other strategies to avoid the sole use of this strategy. Ondieki's (2007) book states two types of corrective maintenance. The first type is primary maintenance, replacing a failed part with a good one. The second type of corrective maintenance is called secondary maintenance. This type of maintenance usually consists of the follow-up repair when the initial replacement has failed. Corrective maintenance is utilized when the risk of failure is low and the failure rate cannot be determined.

1.6.2. Proactive Maintenance

Oluwasina (2011) states that this strategy uses a different technology to extend machines' operating lives and remove reactive maintenance. The strategy embraces what is known as 'predictive' and 'preventive' maintenance. (Fredriksson, 2012). Proactive maintenance is based on theoretical risk analysis and root cause failure analysis, whereby failures are analyzed, and preventive measures are taken to avoid unplanned downtime. Similarly, the Sasol Equipment Maintenance Strategy (EMS) defines proactive maintenance as a strategy utilized to ensure no unplanned repairs are done on equipment. The equipment runs and is proactively maintained before any functional failure occurs, as shown in Figure 9.

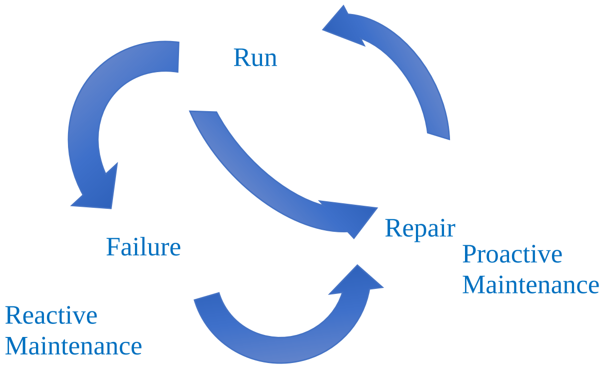


Fig. 9 Reactive and proactive maintenance cycles defined by SASOL EMS

1.6.3. Preventive Maintenance

Frediksson (2012) defines preventive tasks as replacing or overhauling items at fixed intervals. The objective of the strategy is to prevent unscheduled downtime. Oluwasina's (2011) study explains that the actions are performed on a given period, or the equipment is run based on a schedule that detects, precludes, or mitigates the degradation of a component or system. This aims to sustain or extend the useful life of machinery by controlling degradation to an acceptable level. Preventive Maintenance (PM) is divided into three activities briefly described hereunder. (Fredriksson, 2012).

- Scheduled Maintenance

Preventive maintenance is employed under a specific schedule or established number of units of use. (Fredriksson, 2012). Abedini (2016) elaborates on how this method is time-based maintenance. The periodic times are often optimised to minimise costs since the maintenance is performed at specific intervals, regardless of the equipment's condition. However, EMS describes this maintenance strategy as Fixed-Time Maintenance (FTM). The maintenance strategy is mainly applied when failure prediction can be predetermined using the condition versus time graph. Besides, the routine maintenance frequency is dependent on the equipment life cycle. This analogy is based on SASOL's EMS process. Ondieki's (2007) study, though similar to the SASOL EMS process, states two conditions to consider when applying this strategy. The first condition is when the component in question has an increasing failure rate. Whereas the second condition is the overall cost of the time-based preventive maintenance action, which should be less than the overall cost of corrective action. In conclusion, it is worth noting that the FTM method is applied whenever the failure characteristic curve resembles that of Figure 10

- Predetermined Maintenance

Borjalilu (2018) stated that predictive maintenance is a strategy that could detect or establish degradation of the temporary performance trend and establish faults occurring in machines through analysing the data related to the observed parameters.

- Condition-Based Maintenance (CBM)

According to Abedini (2016), Condition-Based Maintenance (CBM) was established in the 1970s based on the development of machine diagnostic techniques. It is a form of preventive maintenance technique that entails performance, parameter monitoring, and subsequent actions. Fredriksson (2012) states that the performance and parameter monitoring of the asset may either be scheduled, on request or continuously. This maintenance approach is based on real-time assessments of equipment conditions, which are obtained from online sensors or external monitoring tools and measurements taken by portable equipment(Oluwasina, 2011). Borjalilu, (2018) study further explains the different methods used, such as vibration monitoring, oil analysis, and ultrasonic testing.

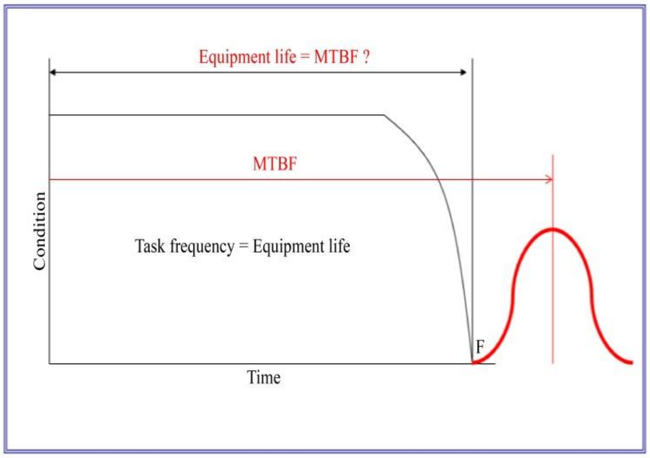


Fig. 10 Failure characteristics of equipment to apply FTM (SWART, 2015)

More so, preventive repairs or replacements are then taken when the measurements reach a certain threshold (Shafiee, 2017). The objectives of Condition-based maintenance are to detect failures before they occur, carry out maintenance only when required, and reduce maintenance and downtime costs (Ondieki, 2007). According to SASOL's EMS process, the CBM strategy can only be applied on equipment where the condition versus time graph can be plotted, and the P-F interval can be obtained as shown in Figure 11. The P-F curve illustrates how a failure starts and deteriorates to the point at which it can be detected (the potential failure point "P").

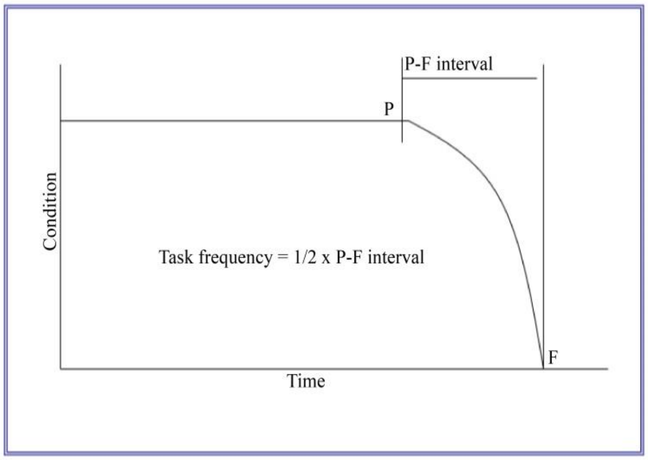


Fig. 11 Failure characteristics of equipment to apply CBM (SWART, 2015)

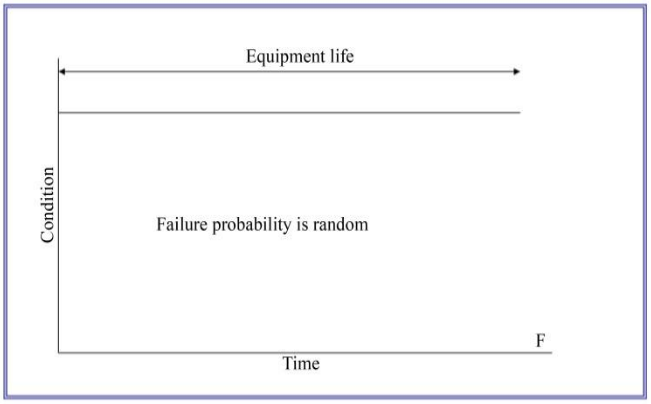
If the failure is not detected and corrected, it continues to deteriorate at an accelerated rate until it reaches the point of functional failure ('F') (Joshi, 2004). The frequency at which maintenance is applied to equipment is thus dependent on the P-F interval, as the basic measurement is half of the P-F interval.

1.6.4. Predictive Maintenance

Shafiee (2017) defines predictive maintenance strategy and condition-based maintenance as similar as they use modern measurements and signal processing methods to directly predict and diagnose system conditions during operation. It aims to optimize the maintenance activities done on equipment by possibly finding the failures before they occur and proactively acting before the failure occurs. A predictive maintenance management program that effectively uses a combination of the most cost-effective techniques to obtain the condition of critical equipment(Fredriksson, 2012). The maintenance task is scheduled and planned based on the data obtained, which results in a reduced maintenance cost. It also provides the ability to optimize the equipment availability (Fredriksson, 2012).

1.6.5. Overhauling

Under the strategy, a major overhaul (including re-design and or replacement of critical equipment) is done after a long period (Shafiee, 2017). This strategy plays a major role in the Petrochemical industry through major shutdowns or turnarounds. For instance, a unit phase or train is shut down for a certain period. In this process, critical equipment is overhauled and refurbished to extend the life span of the equipment. Intensive scheduling and planning are crucial to ensure that the equipment is restored in the specific period due to downtime costs linked to loss of production and maintenance. According to Ondieki's (2007) study, this maintenance can only be carried out when the plant or unit is not in use (off-line maintenance); thus, this form of either preventive or corrective maintenance.



Note: The failure must have low impact
(consequences) before OTF can be specified.

Fig. 12 Failure characteristics of equipment to apply OTF (SWART, 2015)

1.6.6. Run-to-Failure

Research by Mingani (2013) defines a run-to-failure maintenance strategy as corrective or reactive maintenance. In this method, the equipment is operated until a failure occurs. Thereafter, a replacement is usually performed. According to the author, this tactic is often the cheapest since the full design life of the component is utilized. Nonetheless, it is not considered a good practice when the consequence of failure is severe, such as loss of life or a major release of harmful substances. Ondieki (2007) describes this maintenance strategy as a replacement instead of maintenance, as the failed equipment is replaced instead of repaired. This strategy can be planned or unplanned.

In SASOL's EMS process, the strategy is called Operate To Failure (OTF). This strategy is only applied if the potential point of failure cannot be predetermined, as illustrated in Figure 12. It is also considered when the consequence of failure has a low impact on safety and maintenance costs.

1.6.7. Risk-based Maintenance (RBM)

In recent years, the process and power plant industries have used various methods to assess risks and safety hazards. (Chemweno, 2018). Chemweno (2018) study explains that in the maintenance decision-making activities, risk assessments are performed to identify, analyze, evaluate, and mitigate failure risks in assets. Shafiee, (2017) study of maintenance optimization defines RBM's aim to reduce the overall risks associated with unexpected failures. The author studied the behaviour of wind turbines. Among the commonly used methods in this context include Failure Mode and Effect Analysis (FMEA), Fault Tree Analysis (FTA), and Bayesian Network (BN) (Chemweno, 2018). These methods will be elaborated further in the subsequent sections.

2. Evaluation of Maintenance Strategies

Industrial systems are subject to degradation due to using hazardous chemicals and exposure to such environmental factors. Every industry is thus unique with regard to the operation and design thereof. Thus, choosing the best maintenance approach for the specific working environment will be both practical and cost-effective considering the industry operations. Abedini's (2016) study on manufacturing companies compares the corrective, predictive, and preventive maintenance strategies.

The study used the Analytic Network Process (ANP) method, Analytic Hierarchy Process (AHP), Fuzzy Analytic Hierarchy Process (FAHP), and Fuzzy Analytic Network Process (FANP) methods to measure the weight and ranking according to their desired criteria. The criteria used in this study considered the effects of quality, efficiency, cost, time, availability, and lastly, feasibility and reliability. The presented results proved why predictive maintenance was selected as the most appropriate strategy in the case company since the preventive strategies outperformed the corrective strategies.

Table. 2 Decision factors for maintenance optimization

Decision Factor	Description
Interval	Optimal maintenance and/or replacement and/or inspection interval, for example, based on failure statistics.
Delay-time	Related to "Interval" but based on the time from a measurable indication of failure to actual failure.
Spare part	Identifies the allocation and number of spare parts.
Opportunity	For equipment that is costly to interrupt or hard to access, opportunity optimization produces schedules for what should be done during planned and unplanned interruptions/access to the equipment.
Manpower	Identifies optimal maintenance workforce manning, for example, how several utilities should be manned.
Redundancy	Identifies where it is most profitable (from a reliability viewpoint) to place redundant components.

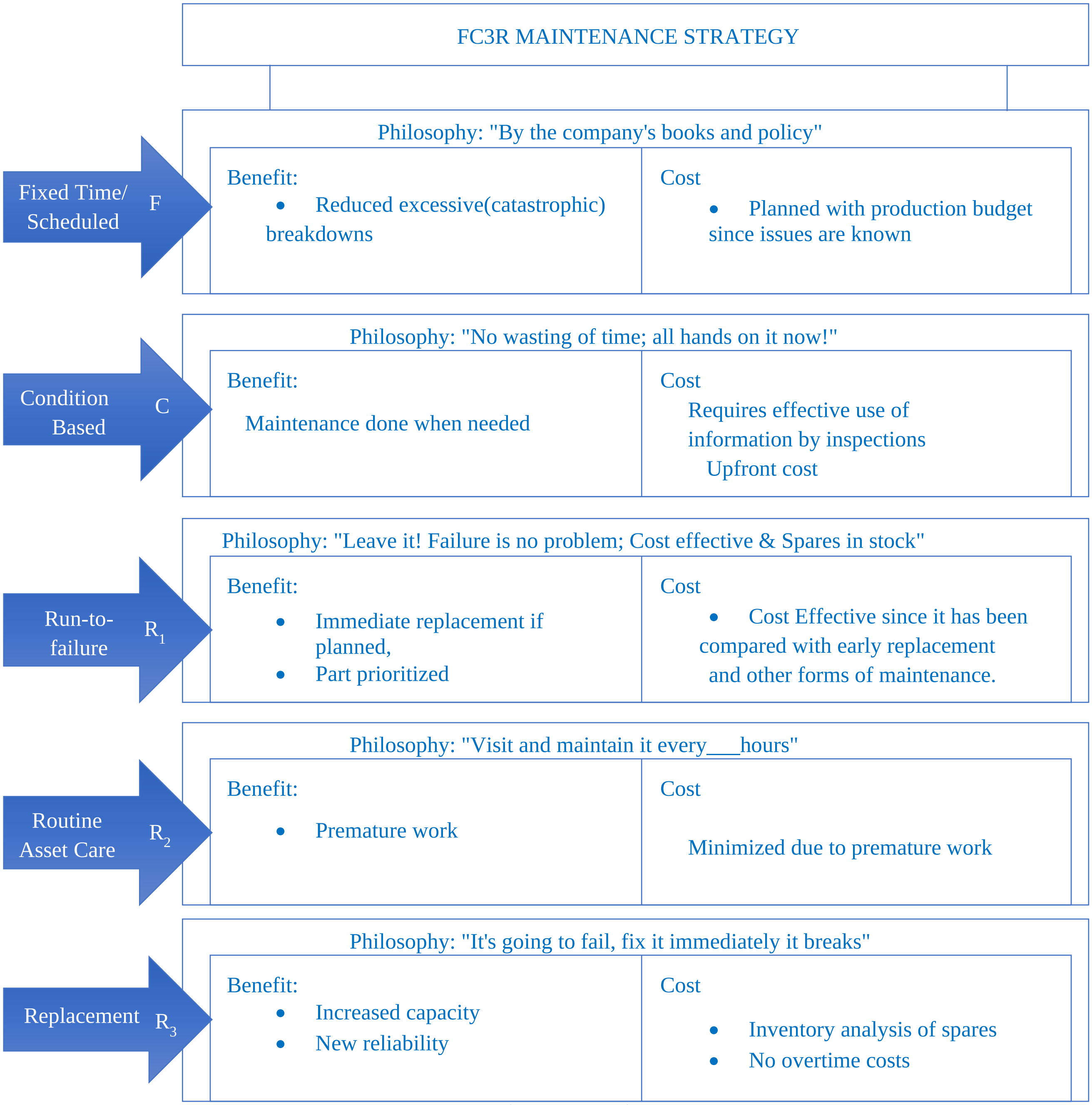


Fig. 13 Maintenance strategy benefit versus cost of maintenance (Akinyemi, 2010)

Their results were subsequently validated and similar to those of Pariazar (2008) and Azizi (2014) studies. Subsequently, the FC3r maintenance strategy also addressed the benefits of using predictive and preventative maintenance strategies compared to run-to-failure, routine asset care, and replacement, as illustrated in Figure 13. Akinyemi's (2010) study presents a breakdown of benefits versus the cost of maintenance, which is a link to obtaining high equipment availability. High equipment availability leads to increased productivity and reduced excessive expenses (such as overtime costs). It furthermore aided technological improvements and provided reliability and stability when the sole aim of minimizing downtime was achieved.

The main challenge of evaluating maintenance strategy lies in choosing a maintenance strategy best suited for the petrochemical industry. Turn-around maintenance is greatly used in the petrochemical industry. The equipment is arranged in a serial connection. The availability of equipment to be maintained on a shutdown basis is reduced. However, this principle can be costly if not properly planned; hence, predictive maintenance is preferred for optimal maintenance.

Hilber's (2008) study explains how several decision factors for maintenance optimization are to be considered for maintenance optimization, as presented in Table 2. The decision factors will never be complete, but the most common factors are captured in the table. The decision factors depend on available data and the aspects of the organization's activities that impact its objective. Before the optimization of any system, there is a need to study the system as is and study its effectiveness. Mbohwa, (2016) study investigates machinery breakdowns and the effect thereof through the determination of plant utilization and availability as well as the evaluation of the sales lost due to downtime. A robust solution was obtained for an effective Reliability - Centered Maintenance (RCM) decision diagram using qualitative and quantitative approaches. Within the evaluation stage, Mbohwa (2016) used a key performance approach whereby a selection of maintenance Key Performance Indicators (KPI) is chosen to measure the machines' performance based on them. Figure 14 illustrates the KPI for the effective maintenance strategy proposed by Mbohwa (2016). Similarly, Frediksson, (2012) study also explains how key performance indicators are to be utilized as indicators for obtaining critical assets. They are used to yield as an assessment and thus to indicate the subject maintenance performance. Furthermore, indicators such as overall equipment efficiency, labor and material costs, and the ratio between scheduled and unscheduled maintenance work are tracked within the maintenance department. Thus, the indicators also support the organization's operational control.

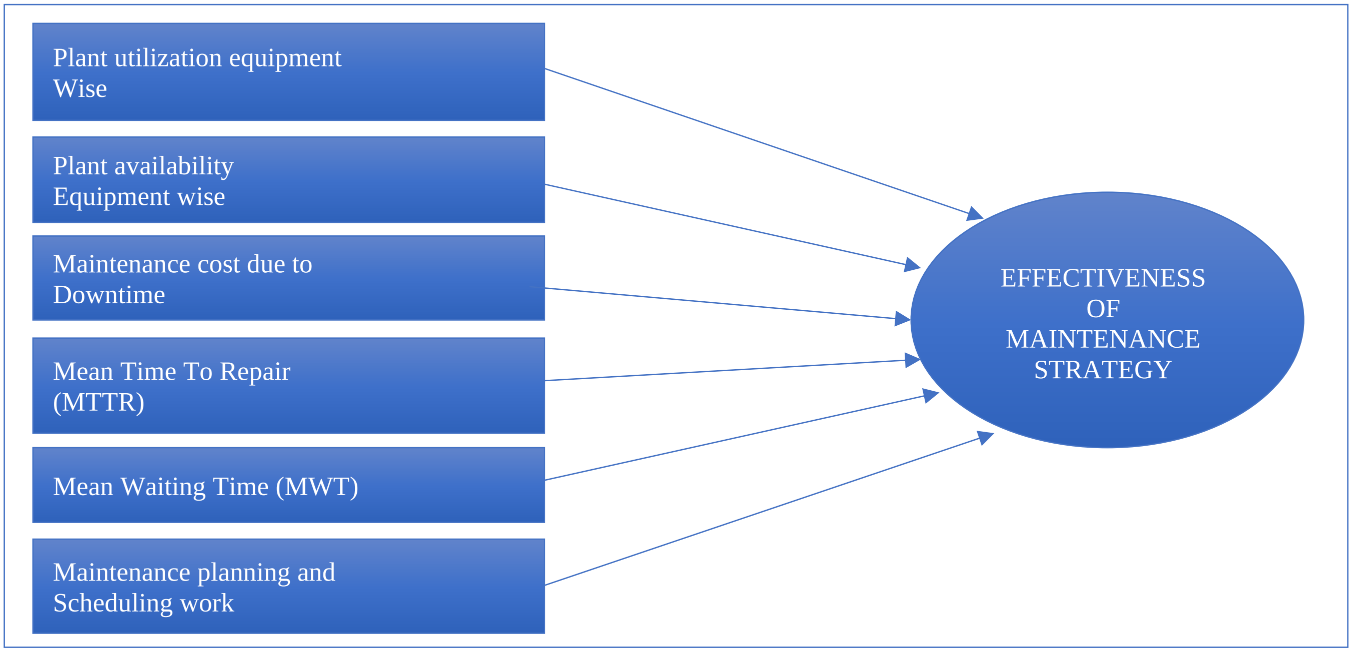


Fig. 14 Conceptual framework (Mbohwa, 2016)

Similarly, Vishnu's (2016) study states that the performance of an employed maintenance strategy can be analyzed by means of different maintenance indicators such as Mean Time Between Failures (MTBF), Mean Time to Repair (MTTR), productivity, maintenance cost, availability of assets, to name a few. As such, Afefy (2010) study of the RCM implementation in a steam processing plant explains how the factors that influence the selection of critical systems are the same as those stated by Vishnu's (2016) study, excluding productivity.

2.1. Availability

According to Ondieki (2007), study availability is the probability that a stated percentage of equipment will have no downtime above *t* in the mission time, *T*. This definition means that good maintainability can offset poor reliability. The higher the plant availability, the more effective the maintenance strategy is, and vice versa. (Mbohwa, 2016)

There are three types of availability parameters, namely inherent availability, achieved availability, and Operational availability depending on the time, as stated by Ondieki (2007) study:

- Inherent availability is the probability that a system or equipment is used in an ideal support environment. The tools, spares, and maintenance personnel are readily available and will operate satisfactorily at any point in time as required. It, however, does not consider the preventive or planned maintenance actions and logistics delays. This is expressed as (2):

$$Ai = \frac{MTBF}{(MTBF+MTTR} \qquad (2)$$

Whereby MTBF is the mean time between failure, and MTTR is the meantime to repair.

- Achieved availability is the probability that a system of equipment will operate satisfactorily at any point in time, similarly to the inherent availability when used under stated ideal conditions. This, however, incorporates the preventive or planned maintenance actions. It also excludes logistic delay time. It is therefore expressed as (3):

$$Aa=\frac{MTBM}{(MTBM+M)} \qquad (3)$$

Whereas MTBM is the mean time between maintenance and M is the mean active maintenance time

- Operational availability is the probability that a system or equipment, when used under an actual operational environment, will operate satisfactorily when called upon. It is expressed as (4):

$$Ao=\frac{MTBM}{(MTBM+MDT)} \qquad (4)$$

Of which MDT is the mean downtime. However, there are many expressions of availability. Manza, (2015) study states availability considers downtime loss, which includes all events that caused a planned production to discontinue. It is, therefore, presented as (5):

$$\text{Availability}=\frac{total\ time-total\ downtime}{total\ time}x100 \qquad (5)$$

Furthermore, Infralet (2016) defines availability as the percentage of time a system can perform its required functions at a stated instant or over a stated period.

The faster the system can be repaired after a failure, the greater the availability; thus, it is expressed as inherited availability, as expressed in Equation 2.

The difference is that Infralet (2016) defines this availability as operation availability. For this study, the inherent availability Equation 2 is utilized for the evaluation.

2.2. Meantime Time to Repair (MTTR)

The Mean Time to Repair (MTTR) simply considers the total time for the repair to be done. Many influences extend the repair time, such as access time, diagnosis time, and spare part procurement, as stated in the Ondieki (2007) study. Thus, each of the recovery activities will be obtained as in Equation (6):

$$\frac{Ta}{f}; \qquad (6)$$

Where T_a failure time over the number of failures f Apart from the MTTR, the failure rate λ will be determined in Equation (7):

$$\lambda=\frac{f}{T}; \text{ Where T is the total time of operation} \qquad (7)$$

Infralet (2016), similarly to the study Ondieki (2007), states how the Mean Time Between Failures (MTBF) can be obtained using the inverse of the failure rate as in Equation (8):

$$MTBF=\frac{Total\ Operative\ time}{Total\ Number\ of\ Failure}$$

$$MTBF=1/\lambda \qquad (8)$$

2.3. MDT = Mean Maintenance Downtime

MDT includes active maintenance time (M), logistic delay time, and administrative delay time.

2.4. Maintenance Cost Due to Downtime

One of the main criteria for optimal maintenance is decreased maintenance cost due to downtime. Thus, it is evident that the lower the maintenance cost due to downtime, the more the maintenance strategy employed is deemed as effective as the maintenance strategy.

3. Conclusion

Maintenance plays a major role in the industry's performance; thus, an optimal maintenance strategy is key to deter unexpected equipment downtime. Several industries have employed the Reliability-based Maintenance Strategy (RCM). The RCM incorporates different maintenance methods, such as corrective, proactive, preventive, and predictive, to name a few. While that may be beneficial, it is more important to focus on how the specific industry operates, whether through parallel or series systems. Each industry is different in operation and production; hence, an umbrella method for all industries cannot be applied. The Sasol catalyst preparation unit is a portion within the Sasol whereby it is connected to an upstream and downstream supply. It is considered a batch plant since there is capacity for storing produce; thus, it works differently from other units that cannot cater to storage. Using the mentioned indices, such as availability, mean time to repair, mean maintenance downtime, and maintenance cost for each electromechanical equipment within the unit, an evaluation of the current maintenance strategy applied can be made to obtain an optimal maintenance strategy. These parameters play a key role in evaluating the current maintenance strategy employed in an industry.

Data Availability

The data used to support the findings of this study are included in the article.

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