We are IntechOpen, the world's leading publisher of Open Access books
Built by scientists, for scientists

4,500
Open access books available

118,000
International authors and editors

130M
Downloads

154
Countries delivered to

Our authors are among the

TOP 1%
most cited scientists

12.2%
Contributors from top 500 universities

CLARIVATE ANALYTICS
BOOK CITATION INDEX
INDEXED

WEB OF SCIENCE™

Selection of our books indexed in the Book Citation Index
in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?
Contact book.department@intechopen.com

Numbers displayed above are based on latest data collected.
For more information visit www.intechopen.com

Sustainable Maintenance Practices and Skills for Competitive Production System

Adeyeri Michael Kanisuru

Additional information is available at the end of the chapter

Abstract

Many industries are becoming moribund, while those who are in operatives are producing at low efficiency which are not commensurate to the resources invested. These imbalances and poor performance attest to the fact that the maintenance practices adopted were unskilfully implemented and are not sustainable. Therefore, this chapter discusses the maintenance strategies and skills needed in establishing a sustainable maintenance technology for the manufacturing industries by the formulation of sustainable maintenance framework practices for competitive production systems and translation of the formulated framework to iconic and equation models. The expected outcome showed that maintenance sustainable practices cannot be undermined if production set goals and overall equipment effectiveness are to be achieved. Successful implementation of this instructive methodology will reduce wastages, eliminate machine downtime, increase machines performance with improved functionality of parts thereby providing maximum usability and reusability of parts/components and thus increase the machine optimal functionality and efficiency.

Keywords: sustainability, maintenance skills and practices, competition, production systems, models

1. Introduction

Production losses are incurred when machinery failures and breakdowns become erratic and unattended to as required and expected. Man-hour and production time are no longer optimized and maximized as mean time between failure and mean time to repair decreases and increases, respectively. The consequence of this frequent failure has not only led to losses but also affected compromise of standards, product dimensions and products' integrity.

In general, the goal of maintenance is to eliminate or to avoid unnecessary or unplanned downtime due to failure. Maintenance activities can influence the entire manufacturing/production operation, from product quality to on-time delivery records and its effect on the environment. Good maintenance practices can cut production costs immensely, whereas poor maintenance procedures can cost a company millions of dollars to effect repairs and correct poor quality and production lost. In the bid to correct and reduce this menace, a good sustainable maintenance strategy and practice needs to be adopted. This assertion may lead to the question of asking 'why sustainable maintenance practices and not just maintenance practice?'

According to Jawahir [1], Sustainability is '*meeting the needs of present without compromising the ability of future generations to meet their own needs*'. In a more elaborate form, by application and implication, *sustainable maintenance practices are practices of high quality aimed at increasing machines performance with improved/enhanced functionality of parts using safe, secure technologies and methods utilizing optimal resources by reducing or eliminating machine downtime, mean time to repair* (MTTR) *and products' wastes thereby providing maximum usability and reusability of parts/components, enhanced production benefits, economic impact and making the enterprise to stand competitively*. No maintenance method will work better for any manufacturing sector if such manufacturing set-up has not been fully studied and analysed. It is beyond being a formula, but rather, it calls for relationship in knowing what is required for respective industries.

Having established the definition of sustainable maintenance, there is need to discuss the elements of sustainable maintenance practices, skills and strategies (and this is showcased in Section 1.1). Section 1.2 discusses the various maintenance strategies that are practicable, whereas selection guidelines for sustainable monitoring programme for machinery are discussed in Section 1.3. Maintenance model formulation for different manufacturing methods at varying competitive environment is being addressed in Section 1.4. Sections 1.5–1.7 explain the steps for improving sustainable maintenance plan, the skills required by 'maintenance engineer to be' in maintaining sustainability objectives and conclusion, respectively.
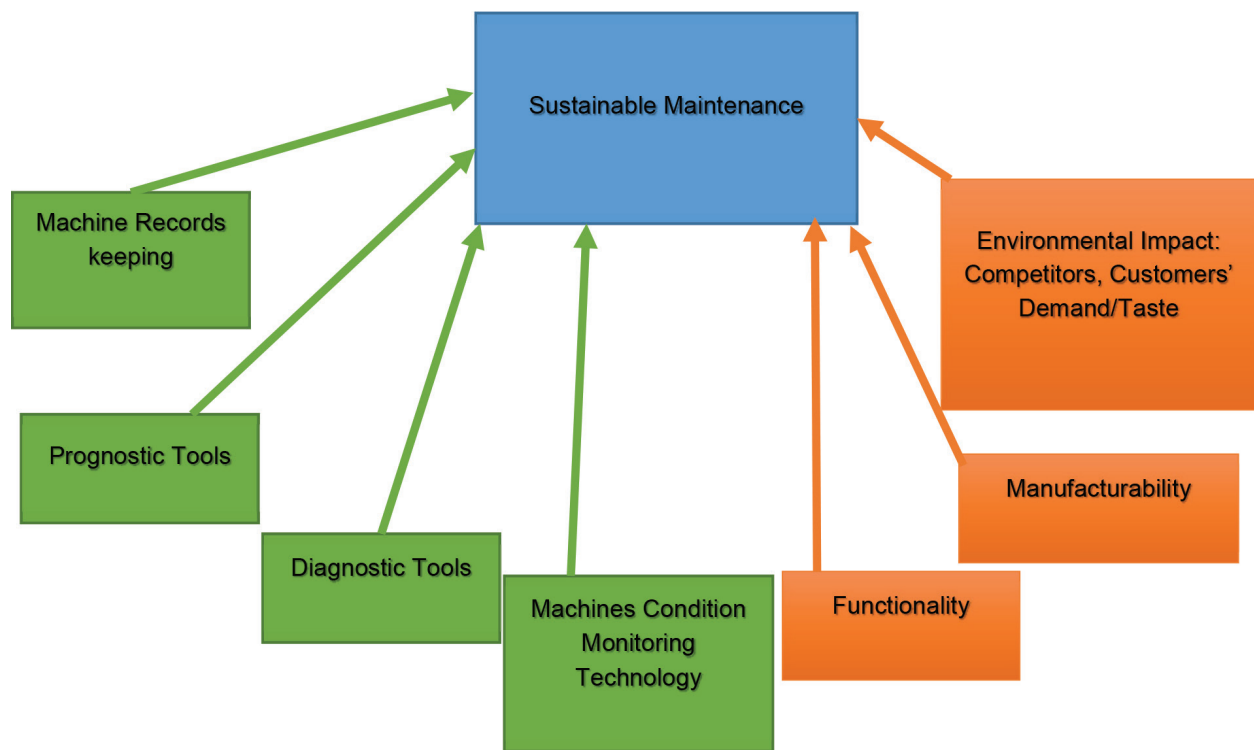
1.1. Elements of sustainable maintenance practices

The elements of sustainable maintenance practices are shown in **Figure 1**. They are divided into two groups. The four factors painted in green colour, namely: machine records keeping; diagnostic techniques; prognostic techniques; and machine condition monitoring techniques are the tooling dependent factors. Whereas the three factors painted in orange colour, namely: environmental impact; machines functionality; and manufacturability are the informative factors whose parameters and information are needed by dependent factors to provide decision and direction on actions needed to be taken on machinery to effect maintenance activity.

Mathematically, if sustainable maintenance practice is tagged with acronym (SMP), then the connecting equation expressing the SMP is given in Eq. (1)

$$SMP = F(M, D, P, C, F, M, E) \tag{1}$$

where M is the machine records keeping, D is diagnostic technique, P stands for prognostic technique and C is the machine condition monitoring technology. F, M and E are acronyms

Figure 1. The elements of sustainable maintenance practices.

for machines functionality, manufacturability and environmental impact, respectively. These factors are as explained in the preceding subheadings. The four factors in green boxes are inherent and internal factors associated with data keeping, whereas the other three factors in orange boxes are external factors imposed on the machines due to demand pressure and rivalry competitions that may arise in the course of production which will in one way or the other affect the machinery functionalities.

Machine records keeping: This is a sine qua non to sustainable maintenance practices. The documentation of every activity on machinery and their components will form the knowledge base to determine the performance behaviour, prediction of machine signature and other necessary attentions that are ought to be given to them.

The three machine records keeping approaches to look at in this chapter are preventive maintenance visit check time schedule; maintenance log book and repair report. These three samples, which are explicit to understand, are shown in **Tables 1**, **2** and **3**, respectively.

Prognostic tools: These are the tools meant to predict the future performance of components by assessing the extent of deviation or degradation of a system from its expected normal operating conditions. Its principle is based on the analysis of failure modes, detection of early signs of wear and ageing and fault conditions. It is more effective if the knowledge of the failure pattern that leads to system deterioration is trended. The prognostic approaches are model based built on collected or retrieved data from machines at both good and deteriorated condition. Its formulation is characterized by: varying of loading conditions in haphazard manner and monitoring of machine faults through preset time for defining its behavioural path. The concept in general aids in the estimation of remaining useful life (RUL) of the machine [3].

Name of components	Periods of activities carried out (weeks)								
	1	2	3	4	5	6	7	8	9
Electric Motor-1	ABL	ABL	ABCL	ABL	ABL	ABCL	ABL	ABL	ABCL
Belt 1	A	A	A	A	A	A	A	A	A
Belt 2	A	A	A	A	A	A	A	A	A
Gearbox-1	ABL	ABDL	ABL	ABL	ABDL	ABL	ABL	ABDL	ABL
Bearings	AB	AB	AB	AB	AB	AB	AB	AB	AB
Crusher plates	AW	ABW	AB	ABCW	ABC	ABC	ABC	ABC	AB

A = visual check, D = lubrication analysis, B = temperature check, L = lubrication check only, C = vibration check, W = wear check.

Table 1. Example of a simple preventive maintenance schedule.

GEAR DRIVE MAINTENANCE LOG

Location:	Ground floor						Machine:	Milling Machine I		
Gear drive type:	Reducer 1:10						Serial no.:	xxxxxxxxxxx		
Date of putting in operation: 20/4/2015							Manufacturer:	Tokyo		
Special maintenance requirements: Oil Grade 05							Auxiliary drives:			
							☐ Belts _____			
							☐ Chain _____			
							☒ Coupling **Flexible Coupling**			
							☐ Others _____			
Date of Activities	Levels of Activities									
	Add Oil	Change Oil	Temp. Check	Vibr. Check	Lubri Analy-Sis	Load Check	Aux. Drive Check	Change Seal	Change Bearing	Complete Overhaul	Remark/ Recommendation
1/6/16	Yes	No	86 ºC	No	No	46 A	Yes	No	No	No	Gear belt was Tensioned
12/6/16	No	NO	89 ºC	No	Yes	48 A	Yes	No	No	No	Oil is due for changing next week
19/6/16	No	Yes	92 ºC	No	No	50 A	Yes	No	No	No	Gear box oil was changed with Grade 05
26/6/16	No	No	85 ºC	510	No	45 A	Yes	No	No	No	Perfect

Source: [2].

Table 2. Example of simple 'Maintenance Log'.

GEAR DRIVE REPAIR REPORT					
Location:	Building 345, Ground Floor		Machine:	Textile mill # 4	
Gear drive type:	Reducer 1:10		Serial no.:	xxxxxxxxxx	
Date of putting in operation: 5/21/2004			Manufacturer:	Japan	
Date of Repair:	5/26/2008		Auxiliary drives:		
Special maintenance requirements:			☐ Belts _____		
Oil Grade 05			☐ Chain _____		
			☒ Coupling Flexible Coupling		
			☐ Others _____		
Part	**Failure Description**	**Mark**	**Part**	**Failure Description**	**Mark**
Auxiliary Drive	Chain or belt broken		Gears	Seal worn out	+
	Sprocket/Pulley worn out			Broken teeth	
	Keyway problem	+		Worn out teeth	+
	Drive shaft bent			Others	
	Coupling damaged		Lubrication	No oil	
	Coupling rubber broken	+		Little oil	+
	Others			Dirty oil	
Sealing	Lip seal defective	+		Water in oil	+
	Housing seal defective	+		Breather defective	
	Others			Others	
Shaft	Seat of bearing worn out		Housing	Cracked	
	Seat of Lip seal worn out	+		Problem with bolt connection	+
	Bent or broken			Problem with pin connection	+
	Others			Others	
Bearings	Worn out	+	Base Plate	Loose, weak	+
	Excessive damaged			Problem with bolt connection	
	Others			Problem with foundation	+

Source: [2].

Table 3. Example of simple 'Repair Report'.

Diagnostic tools: Diagnostics is required when fault prediction of prognostics fails and a fault occurs. It addresses fault detection, isolation and its identification when it occurs. To detect faulty components or machines, it calls for knowing what is going wrong in the monitored system; fault isolation is a task to locate the component that is faulty; and fault identification is a task that helps in the determining the nature of the fault when it is detected [4]. Diagnostic activities are posterior event analysis, whereas prognostic are prior event analysis.

The basic maintenance diagnostic tools based on the signal time series and time series analysis theory are machinery data acquisition, data processing, maintenance decision making, pseudo-phase portrait, singular spectrum analysis, wavelet transform and correlation dimension [4].

Machines condition monitoring technology: A condition monitoring program can be used to do diagnostics or prognostics, or both. The condition monitoring technology employs data acquisition on machinery vibration, its acoustic, oil analysis and temperature, pressure, moisture, humidity, weather or environment through the use of versatile sensor-liked equipment attached to the observed components [4]. The detailed description of these condition monitoring tools are as follows:

 i. Lubrication monitoring

Lubrication monitoring is a tool for condition monitoring meant to reduce friction and wear between machine component parts with relative motion. Such component parts include gears,

bearing and hydraulic systems. The substance used in achieving this is called the lubricant. The use of appropriate or recommended lubricant either by manufacturer or maintenance experts plays a vital role in machinery sustenance. The choice of right lubricant will not only reduce wear from the machine but also convey off wear debris from the component parts if and when it occurs.

ii. Vibration monitoring

This deals with the measurement of vibrations generated in machinery by its dynamic components. On a general note, rotating machinery is characterized by vibration pattern in a repeated manner intermittently. The intermittent or periodic pattern of signal from the machine forms the basis for monitoring because examination can be done on either at off-load or on-load. Therefore, the outcome from the vibration analysis will form or give basic information about the mechanical condition of the machine being monitored.

iii. Thermal monitoring

The need for thermal monitoring arises due to increased temperature that machines do experience at their surface. According to Okah-Avae [5], there are associated faults or flaws that are linked to temperature rise in machinery. Hence, the need for its monitoring. Thermal monitoring technique helps in determining the health and performance probity of machinery. Its measurement and analysis techniques include the use of thermal imaging camera; surface contact sensors (thermistors or thermocouple sensors); radiation sensors (radiation pyrometers) and surface temperature indicators. When suitable sensor is used at either on-load or off-load on the equipment or machine to be monitored, there will be corresponding temperature read out indicating the thermal signature of temperature distribution of the equipment. This outcome will form based on which inference can be drawn about the behaviour of the equipment.

iv. Visual inspection

This is critical appraisal or examination of equipment or machinery either in use or not in use visually. When machines are being used, there is possibility that incipient fault (fault that is not temperature or vibration based) may arise calling for its immediate attention and rectification. Through visual inspection, such faults are being addressed. Example of visual inspection includes routine check-up, machine examination before being used, just to mention a few.

v. Operational dynamics analysis

This is similar to visual inspection, but it is majorly meant to ascertain if design specification matches with equipment supplied or received at the shop floor.

vi. Electrical monitoring

This entails regular checking of electrical parts and components such as main cable of power supply of the machine (to guard against disconnection or partial contact); switches; electric motor (checking against motor flux leakage) and input voltage (confirming if it is in line with recommended voltage), so as ensure operational probity. Other critical issues aimed at correcting under electrical monitoring are identification of poor connection, isolation of faulty isolators and guarding against overloading.

vii. Failure analysis

The underlying principle of machine condition monitoring tools lies on failure determination and how it can be avoided. Failure analysis is based on the processed retrieved data through the use of model and submodel criteria trained to establish why, when and how failed components could be corrected and avoided in the future.

Environmental impact: This is also a factor to be considered when aiming at perfect sustainable maintenance in the midst of competitors. At production, the quantity of product to be produced as output is a function of the number of competitors producing that same singular product as well as the quantity demanded provided the quality of the product produced is constant. As quantity demanded increases, the industry will intend to produce more to meet up with the increasing demand thereby subjecting the machines to more usage. In order for the industry not to lose customers as well as not compromising product's quality, there is need for the machines used for production to be maintained through the use of sustainable maintenance strategy suitable for profit maximization. Therefore, this factor is very significant to machines maintenance sustainability [6].

Manufacturability: This presents about the various approaches by which manufacturing of products can be achieved. Parts of these approaches are lean manufacturing, just in-time manufacturing approach, conventional approach, automated processes, just to mention a few. Once there is need to formulate maintenance strategy or approach, this factor cannot but be considered. The effect of this factor will be demonstrated in Section 1.4.

Functionality: Functionality is based on the condition at which the product to be produced is required. Some products require high precision, accuracy and uncompromised quality. If machines meant to produce such products are not fully sustained and maintained, then the aim for producing such products will be jeopardized as they will not be able to meet their functionalities in the intended field of operations. In other words, for maintenance strategy to be proposed for such set of machines, the maintenance manager must put this factor into consideration.

The technical know-how of any maintenance manager on the above factors will assist in his choice of maintenance strategy formulation in proffering the most sustaining practice. Various maintenance strategies are being discussed in Section 1.2.

1.2. Maintenance strategies

Maintenance strategies can be categorized into four major types:

  i. Reactive/corrective/breakdown maintenance

 ii. Preventive maintenance

iii. Improvement or design-out maintenance and

 iv. Terotechnology maintenance strategy

Preventive maintenance can be subdivided into two major types, namely:

  i. Periodic maintenance

 **ii.** Predictive maintenance

These periodic and predictive maintenance are well subdivided into two types each as shown in **Figure 1**. The periodic maintenance is divided into routine and scheduled maintenance, whereas the predictive maintenance is divided into condition monitor maintenance and condition-based preventive maintenance [5].

Figure 2 shows the three broad categories plus terotechnology, which is the latest development in maintenance engineering. Preventive maintenance is being split into two subcategories. All the seven categories have been arranged in progressive order of effectiveness in terms of scientific value, colour coding and cost of such a maintenance programme. Although design-out maintenance and terotechnology maintenance strategies have (same) green colour, it is an indication that the practice is efficient, safe and mostly equal in its service delivery to the upkeep of plant. These strategies shall be briefly discussed in the order at which they are spelt out in **Figure 2**.

1.2.1. Reactive maintenance

This is also termed to be **run to failure maintenance or c**orrective maintenance or **b**reakdown maintenance. These are operations carried out to restore a machine to operative condition after a breakdown, accident, wear, etc. Since these activities are generally not known in advance and therefore cannot be scheduled, they are often referred to as unscheduled, emergency or
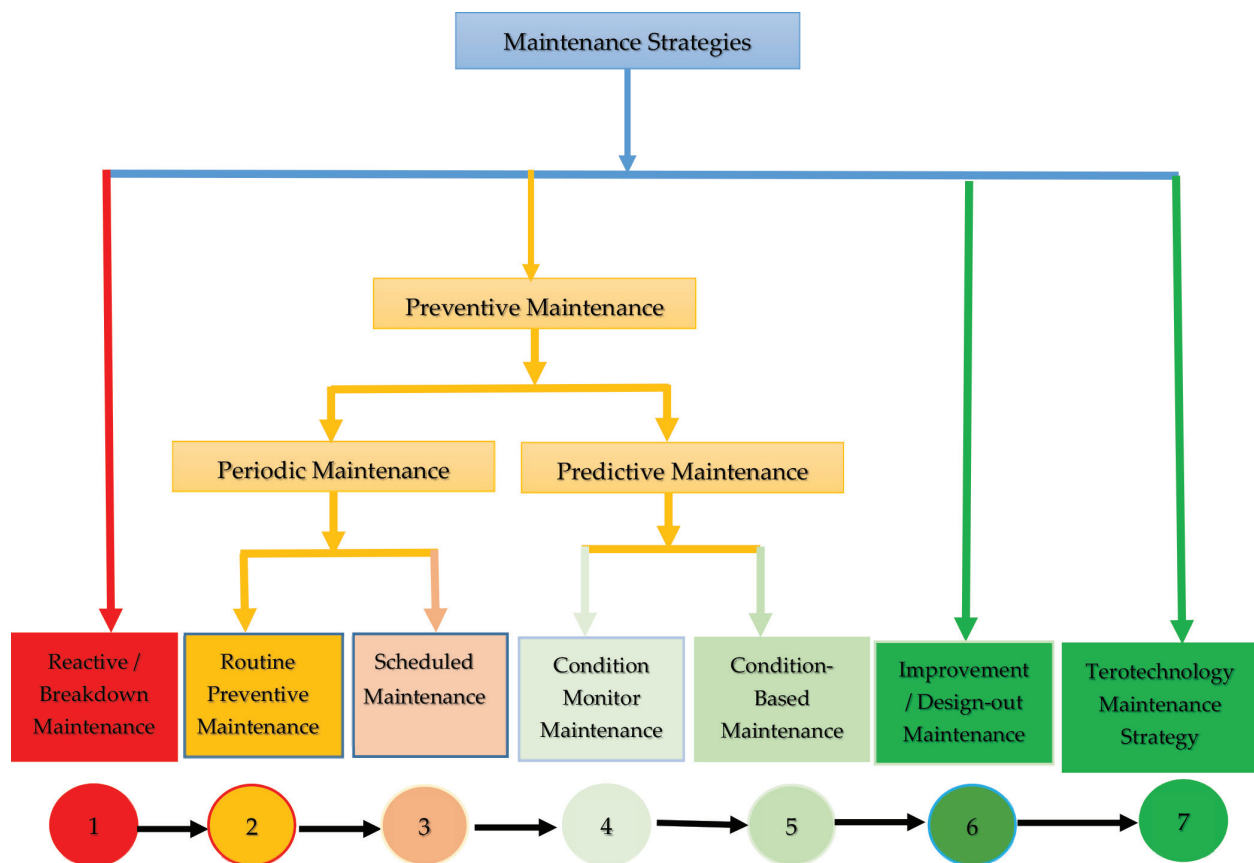
Figure 2. Modified maintenance strategies indicating ascending order of technology effectiveness [5].

repair maintenance. In this type of maintenance, there is no routine maintenance task performed on the equipment until after it has suffered a failure. In other words, machines are repaired or replaced upon failure. It is the simplest approach to maintenance and equally the least effective. It can only be practiced in an industry or applied to equipments that are inexpensive, largely duplicated and easy to repair or replace.

1.2.2. Preventive maintenance

Preventive maintenance is hinged on activities put in-place prior to machinery breakdown or failure of its component parts. It is aimed at ensuring smooth production/machine running that will lead to high product quality and minimal or zero (0) % materials wastage. Production systems repaired or maintenance are scheduled or planned regularly at set interval of time. It uses the tools of condition monitoring where critical component parts are being monitored [7].

Preventive maintenance can be subdivided into periodic and predictive maintenance. These subgroups can be further subdivided into routine and scheduled maintenance and condition monitor (or condition monitoring) and on-condition maintenance, respectively.

Routine preventive maintenance: These are maintenance operations, not involving disassembly or replacement of components and comprising mainly of cleaning and adjustments, which are carried out regularly such as every hour, every day, or every week.

Scheduled maintenance: This is maintenance in which preventive activities are scheduled for fixed intervals that are much longer than routine intervals. Moreover, these activities include oiling, greasing, adjustments, replacement of parts, etc. This type of maintenance may be due to government regulations, scheduling of downtime around production operations, availability of special personnel or simply the need for a finite standard that can be understood by everyone involved (e.g. oil changes).

1.2.3. Predictive maintenance

Predictive maintenance is a maintenance practice aimed at predicting the performance behaviour of machinery and their component parts in order to take necessary steps in averting the occurrence of intending and incipient failures and breakdown and its consequences. It uses prognosis tools principle as basis for its operation which is based on monitoring the equipment's condition.

Predictive maintenance allows failures to be forecasted through analysis of the equipment's condition. Thus, it ensures high service. Its analysis is generally conducted through some forms of trending on parameters like vibration, temperature, noise/acoustic sound and lubricant/oil flow in the machinery.

1.2.4. Condition monitor maintenance

Condition monitor maintenance is a self-scheduled, machine-cued predictive maintenance that is based on the periodic, and sometimes continuous, measurement of one or several

parameters of condition in an equipment such that a significant change is indicative of a developing failure. Examples are measurement of the viscosity of engine oil in a working machine or the amplitude of vibration of rotating machinery. The evolution of these parameters is considered to be representative of the actual condition of the machine. However, a deviation from a reference value (e.g. temperature, viscosity or vibration amplitude) must occur to identify impending damages. In failure detection, the emphasis is on inspection and test because that is the best way to determine whether warning signs of impending failure are occurring. In order for condition monitoring to be effective, the failure must not be catastrophic. The pay-off from inspection is best with a slow wear-out situation

1.2.5. Condition-based maintenance

Maintenance carried out in response to a significant deterioration in a plant unit as indicated by a change in a monitored parameter of the unit condition or performance is called condition-based maintenance. It uses the machine condition monitoring tools discussed in Section 1.1. vis-à-vis: vibration monitoring tools, thermal monitoring tools, sound monitoring tools, acoustic emission monitoring tool, shock pulse monitoring tools, strain load monitoring tool, lubricant monitoring tools, corrosion monitoring tools, crack detection tools, ultrasonic tools and flux monitoring tools. All these aimed at giving: good indication whenever machine is running smoothly and efficiently or otherwise for failed condition; giving early sign of warning when fault is noticed and providing diagnoses for developed faults.

1.2.6. Design-out (improvement) maintenance

Considering scientific values and overall cost implication, design-out maintenance is the most effective maintenance strategy to be embarked on. It aims at eliminating the effect of failure. The design-out maintenance approach initiates learning system, which collects and provides information on maintenance problems as a feedback loop to design.

Design-out maintenance is usually a phenomenon for areas of high maintenance cost resulting from poor design or operating outside initial design specifications. In a nut-shell, design-out maintenance is to pre-act to eliminate failure instead of reacting to failure [5].

1.2.7. Terotechnology

Terotechnology is the technology of installation, commissioning, operation, maintenance and feedback to design of plan, machinery and installation. **Figure 3** shows various stages of an equipment life cycle and the role of terotechnology.

At design stage, terotechnology concentrates on reliability and maintainability factors, which should be considered in relation to equipment performance, capital, running costs and environmental influence. At manufacture, it concentrates on quality control and design fault detection. While at installation, it focuses on maintainability as the multi-dimensional nature of most of the anticipated maintenance problems (mainly on logistics) begin to clarify. During operation of machines, the technology establishes a learning system, which is to collect and
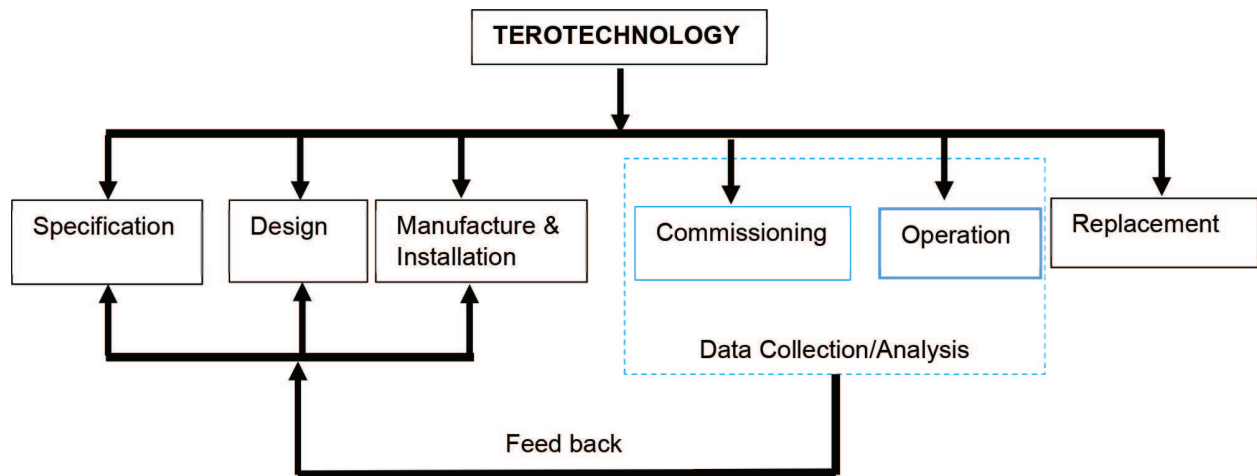
Figure 3. Adapted role of terotechnology in equipment life cycle [5].

provide information on maintenance problems with a view to improving the design to elimi-nate or reduce maintenance cost.

1.3. Selection guidelines for sustainable monitoring programme for machinery

In order to aid the readers/maintenance engineers understanding on how to know the suit-able maintenance practice to adopt for any given machinery, a broad category of machinery classification is made as critical, major support and minor support. Possible failure results associated with these machineries are proposed with possible parameters to use in monitor-ing their behaviour. Also, the level of monitoring programmes that are needed to be put in place for their sustainability is proffered as contained in **Figure 4**.

For example, critical machinery with 100% production loss can be maintained by observing and monitoring the following parameters: vibration, oil lubricant, thermal behaviour or any specialized method using permanent on-line monitoring technique, spectral analysis, trend monitoring and computerized analysis, whereas minor support machinery with no produc-tion loss would not call for any condition monitoring attention. If it is called, it is an indication that the manufacturing enterprise is at the verge of incurring resources waste, which will no more be classified as sustainable manufacturing and maintenance practice.

Another comprehensive approach to matching of maintenance strategies based on manufac-turing functionality is given in **Table 4**. Here, some manufacturing methods are highlighted with their appropriate suggested maintenance strategies.

1.4. Maintenance model formulation for different manufacturing methods at varying competitive environment

This subsection discusses modelling as part of tools that serve as indicator that could help indicating what is required to be done. Briefly, two scenarios in the use of models shall be looked into by considering some parameters on environmental impact such as demand, com-petition, cost and age-based policy on single component.
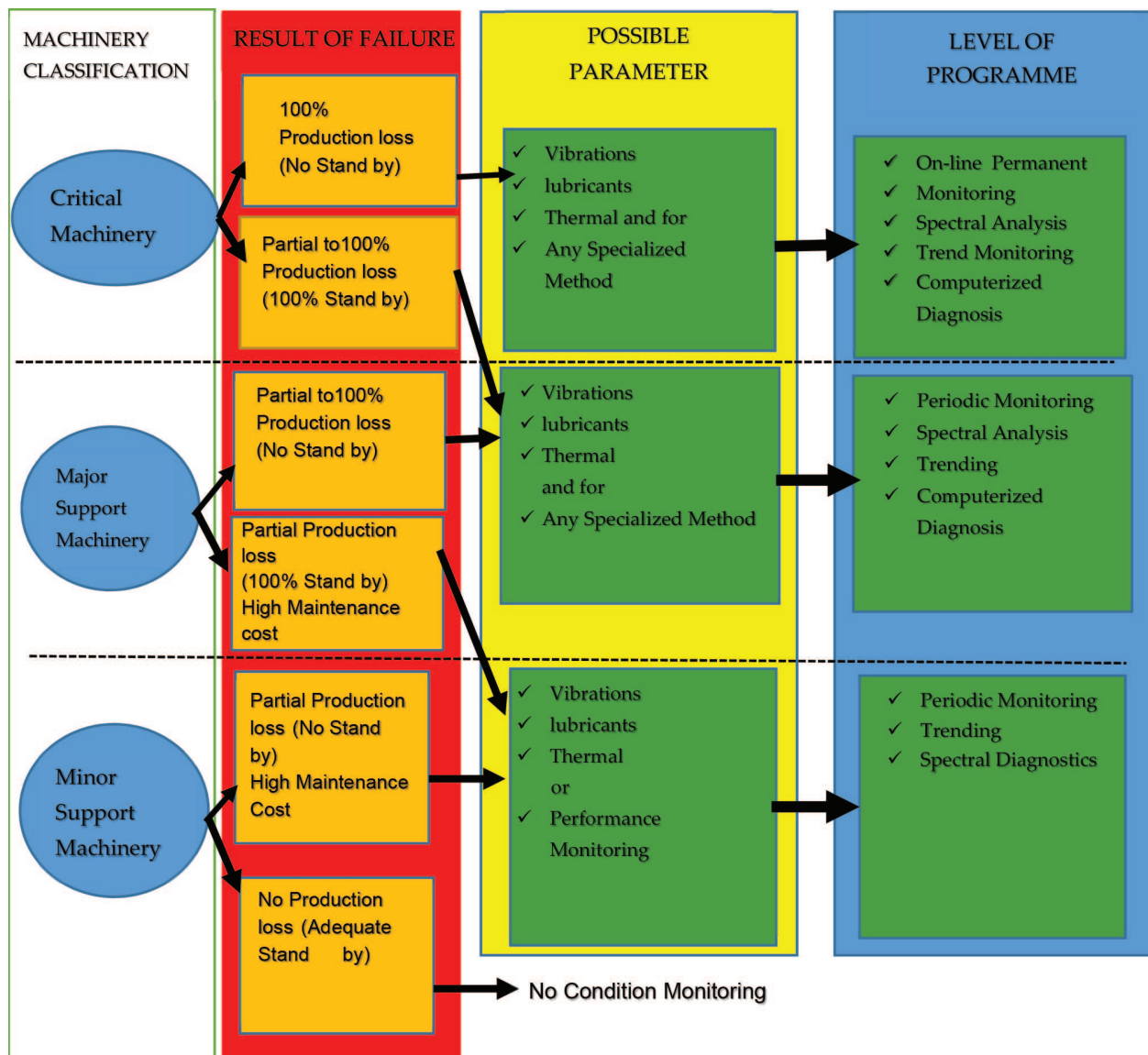
Figure 4. Re-modified application guide model for machinery condition monitoring [5].

1.4.1. Maintenance model for varying products demand and competitive environment

Adeyeri et al. [14] and Adeyeri and Kareem [6] formulated models that could assist in industrial decision making by considering the competitiveness of products and the number of manufacturers involved in producing such product(s). The model formulated is vast in predicting and matching the type of manufacturing to use at varying demand levels of product and as well as establishing the maintenance practice to adopt in order to minimize resource wastage and inventory cost. Based on this, **Table 5** gives the guide to how the prominent manufacturing practices, namely automated processes (AUTO), conventional process (CON) and just in-time manufacturing (JIT), can be married to the right maintenance activities under a varying market condition range of severity. The range of severity is a factor that determines whether to carry-out preventive, breakdown and predictive maintenance, or their combination in group or not.

S/N	Manufacturing functionality/ description	Maintenance practice description	References for explicit study
1.	• Mainly industry 4.0 manufacturing settings • Autonomic manufacturing systems • Integrated manufacturing system	• S-maintenance management system • Intelligent maintenance system • Use of domain expert knowledge	[8]
2.	• Flexible manufacturing system • Flexible manufacturing cell • E-manufacturing	• E-maintenance management system • Use of Information Communication Technology (ICT) and real-time monitoring sensors strategy	[9]
3.	• Competitive manufacturing environment	• Dynamic maintenance • customer-demand induced maintenance planning technique	[6]
4	• Quality oriented manufacturing system	• Total quality maintenance • Use of intensive real-time data acquisition and analysis to detect causes behind deviation in product quality • Use of overall process effectiveness (OPE) strategy	[10]
5	• Distributed stream manufacturing (processing) system	• Predictive failure management system • Online failure prediction to achieve selective, just in-time and informed failure prevention • It uses light weight stream classifiers to achieve online failure prediction which continuously classifies received feature samples into three states: normal, alert and failure • The classifier raises failure alerts when the component state falls into the alert or failure state. The classifier is continuously updated using labelled measurement data	[11]
6	• General purpose machinery	• Maintenance management application based on artificial intelligence and knowledge-based principles	[12]
7	• Multi-component system in continuous manufacturing units (Petrol Chemical Plant)	• Opportunistic maintenance policy • Combined algorithm for preventive corrective and opportunistic maintenance plan	[13]

Table 4. Suggested sustainable maintenance approaches based on manufacturing functionality.

1.4.2. Maintenance model formulation for age-based single component

Laggoune et al. [13] is known that if the corrective and preventive maintenance costs for a component i and its failure distribution established, the expected cost per unit time is expressed as the sum of the expected corrective and preventive costs divided by the expected cycle length.

Parameter definition on manufacturing production target setup, product demand and range of severity	The suggested/preferred suitable maintenance practice to adopt	Preferred production method
Production output is less than demand with range of severity less than 0.5	Breakdown maintenance coupled with opportunistic maintenance practices	Automation manufacturing is more appropriate
Production output is less than demand with range of severity greater than 0.5	Preventive and dynamic maintenance are preferred	Automation manufacturing is preferred
Production output is greater than demand with range of severity less than 0.5	Breakdown maintenance integrated with static grouping is preferred	Conventional approach to manufacturing
Production output is greater than demand with range of severity greater than 0.5	Preventive and predictive maintenance are recommended	Conventional approach to manufacturing
Production output equals to demand with range of severity less than 0.5	Dynamic maintenance with opportunistic approach will do better	Just in-time approach is recommended
Production output equals to demand with range of severity greater than 0.5	Opportunistic or static maintenance strategy is preferred	Just in-time approach is recommended

Table 5. Suggested sustainable maintenance approaches based on production target setup and production approach.

$$C_i(\tau_i) = \frac{C_i^c F_i(\tau_i) + C_i^p(1 - F_i(\tau_i))}{\int_0^{\tau_i}(1 - F_i(t)dt} \tag{2}$$

Where $C_i(\tau_i)$ is the cost rate component i (objective function of the mono-component policy), C_i^c is the specific corrective cost, to be paid at each replacement upon failure of component i, τ_i is the time (age) for the preventive replacement of component i and $F_i(\tau_i)$ is failure probability distribution, it represents the cumulative distribution function (CDF) of the random variable 'time to failure' and can be obtained from historical failure data.

1.4.3. Equivalent mono-component approach

The mono-component approach entails modelling failed components together according to their failure pattern and time. It gives precedence to their failure time knowing fully well that once a component fails it leads to the complete shutdown of the system. Equation (3) expresses the system replacement cycle to be [13]:

$$\int_0^{\tau} \prod_{i=0}^{q} (1 - F_i(t))dt \tag{3}$$

which makes the system total cost per time unit to be expressed as:

$$C_{mono}(\tau) = \frac{\left(C_0^c + \sum_{i=1}^{q} C_i^c\right) F_{sys}(\tau) + \left(C_0^p + \sum_{i=1}^{q} C_i^p [1 - F_{sys}(\tau)]\right)}{\int_0^{\tau} \prod_{i=1}^{q} [1 - F_i]} \tag{4}$$

Where $F_{sys}(\tau) = 1 - r_{sys}(\tau) = 1 - \prod_{i=1}^{q} [1 - F_i(\tau)]$ is the failure probability of the overall system and $R_{sys}(\tau)$ is the system reliability.

This maintenance plan seems to be sustainable if and only if the systems of same components with similar lifetime distribution [13].

1.4.4. Flowchart model on choice of maintenance for manufacturing system based on sustainable development perspective

Manufacturing system on the basis of developmental growth was classified as mass manufacturing system, lean manufacturing, green manufacturing and sustainable manufacturing system [15]. They are characterized and identified by cost reduction policy; waste reduction strategies; environmental friendly encapsulated by reuse, reduce and recycle principles and innovative product phenomenon wrapped in remanufacturing, redesign, recover, recycle, reuse and reduce concepts [16]. A flowchart for choosing the best production system as well as the maintenance strategy sustainable by the chosen manufacturing system based on the consideration of set goals and parameters at which the manufacturer decides on is presented in **Figure 5**. On the basis of the flowchart explanation, assuming a manufacture has it in mind of having a manufacturing system that is environmentally inclined and can as well support the reuse, reduce and recycle (3R) principles, as the flowchart is initiated, the flowchart will suggest that the best manufacturing system suitable for the set goals is 'green manufacturing matched with green maintenance practices'. After this, it will still be interested in knowing the outcome of the choice if indeed it is sustainably satisfactory after it has been implemented.

1.5. Steps for improving sustainable maintenance plan

Having done all necessary activities in putting up a sustainable maintenance practice for any category of machineries, it is as well expedient to see the improvement of these maintenance plans. In view of this, **Figure 6** shows the nine steps for improving any maintenance plan. The first three steps are referred to as the data acquisition cycle where process history and overall equipment effectiveness are being measured. The next four steps describe the equipment status cycle where critical assessment, appraisal of set out condition and refurbishment are being carried out. The last two steps centered on proactive measure cycle.

1.6. The required skills for maintenance sustainability paradigm frontiers

Skill is the safe technical know-how or hands-on ability to appropriate available technology in solving challenges within the limited available resources at zero level of materials and resources waste. The man behind the scene who will be able to appropriate all the aforementioned practices in this chapter must possess all the following skills and virtues. If any of these skills is missing, the sustainability goals will not be achieved.

i. **Knowledge competence of the field**: The basic requirement for potential maintenance engineers lies on the acquired knowledge skills competence which is got through formal education and training on specialized fields of study. It involves training on machine learning; machines and systems dynamics; hydraulic system and its principles of operations; machine modelling and its kinetics, just to mention a few. Acquiring this knowledge will accelerate the performance rating of the maintenance engineers to be.

ii. **Scientific knowledge**: In addition to knowledge competence, the scientific knowledge encompasses the general knowledge of applied principles and methods in the mechanical, electrical electronics, mechatronics and systems engineering. A maintenance engineer should be able to distinguish between single phase or three-phase power and what type of load they are meant to be used for. In distinguishing between them lies on the scientific knowledge understand of the engineer.

iii. **Design creative skills**: In engineering world, the medium of expression is through drawing design. Therefore, for every idea or concept conceived by the maintenance engineer, he or she should be able to communicate this in drawing. To go further, such an idea when communicated in drawings can be simulated to see the reality of how the concept improves the production facilities setup.

iv. **Interpretation of engineering drawing and symbols**: The ability to read and interpret design drawings and symbols from manuals provided on equipment or machines is required from the 'to be maintenance engineer'. If these drawings are wrongly interpreted, it will result to resource wastage as damages may occur in the course of the process. When damages are incurred, the principle of sustainability has been violated. Therefore, dreading and interpretation of drawings importance cannot be overlooked.

v. **Proactive instinct of thinking and analytical minds in decision making**: A good maintenance engineer must be proactive in decision making. Whenever it comes to decision on machines maintenance actions, he should be able to project above reactive thinking to solution provision on critical components, rather, he should give suggestion that will prevent the occurrence of the failure which is being addressed.

vi. **Good listening ability and skills to distinguish between sounds and acoustic output by matching them with probable cause roots of faults and failure**: When machinery is in use, inherent noise and sound are associated with machines as a result of vibration effect and motion-related issues. The recognition of sound produced above the required threshold frequency because of compromise in the machine's integrity as a result of change in its attenuation will help in knowing the decision to take. Therefore, exhibiting this ability will help in detecting the onset of failure and thus prevent further degradation of the components and machine as a whole.

vii. **Ability to match the best maintenance strategy with any production setup and its machines**: Knowing the various maintenance strategies is not enough, but the ability to marry or match the required strategy with the manufacturing setup will be more beneficial. This chapter has moved further by giving blue print scenario of cases and guidance on how maintenance could be matched with appropriate manufacturing setup.

viii. **Trouble shooting and diagnostic skills**: He or she must be able to run a series of analytical questions and tests that will lead to the detection, isolation and identification of probable faulty component parts.

ix. **Good in record keeping**: Information on machinery behaviour can only be made known through the processed data retrieved from the machines. It is imperative that any prospective maintenance engineer must have good record keeping habit.

x. **Good team spirit**: There are some repairs or faults that will require the expertize of others in the area where the incumbent maintenance engineer's knowledge is limited; in such a situation, there is need to collaborate for assistance so as to minimize time wastage in repairing the fault.
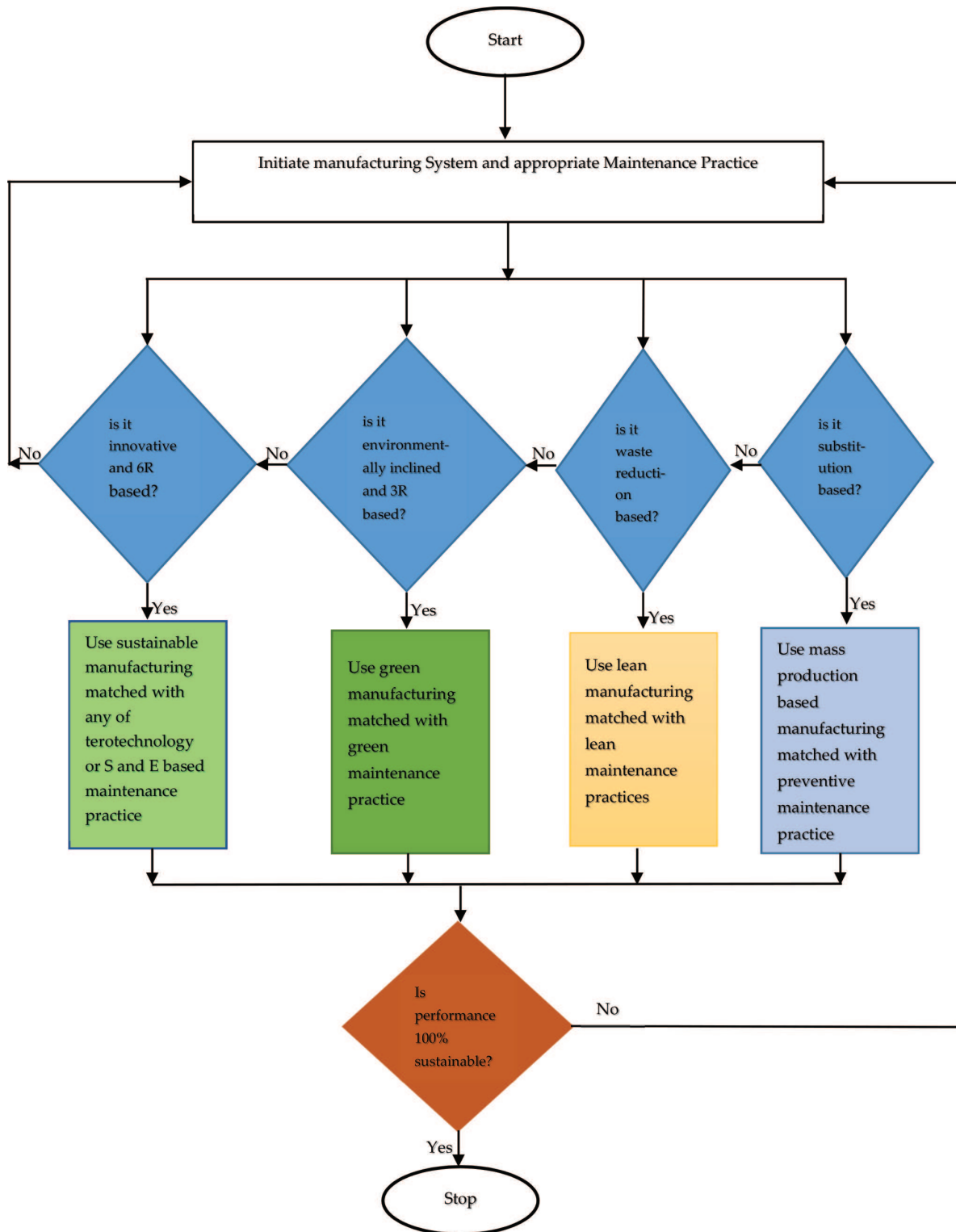

Figure 5. Flowchart for matching manufacturing system with maintenance strategy.

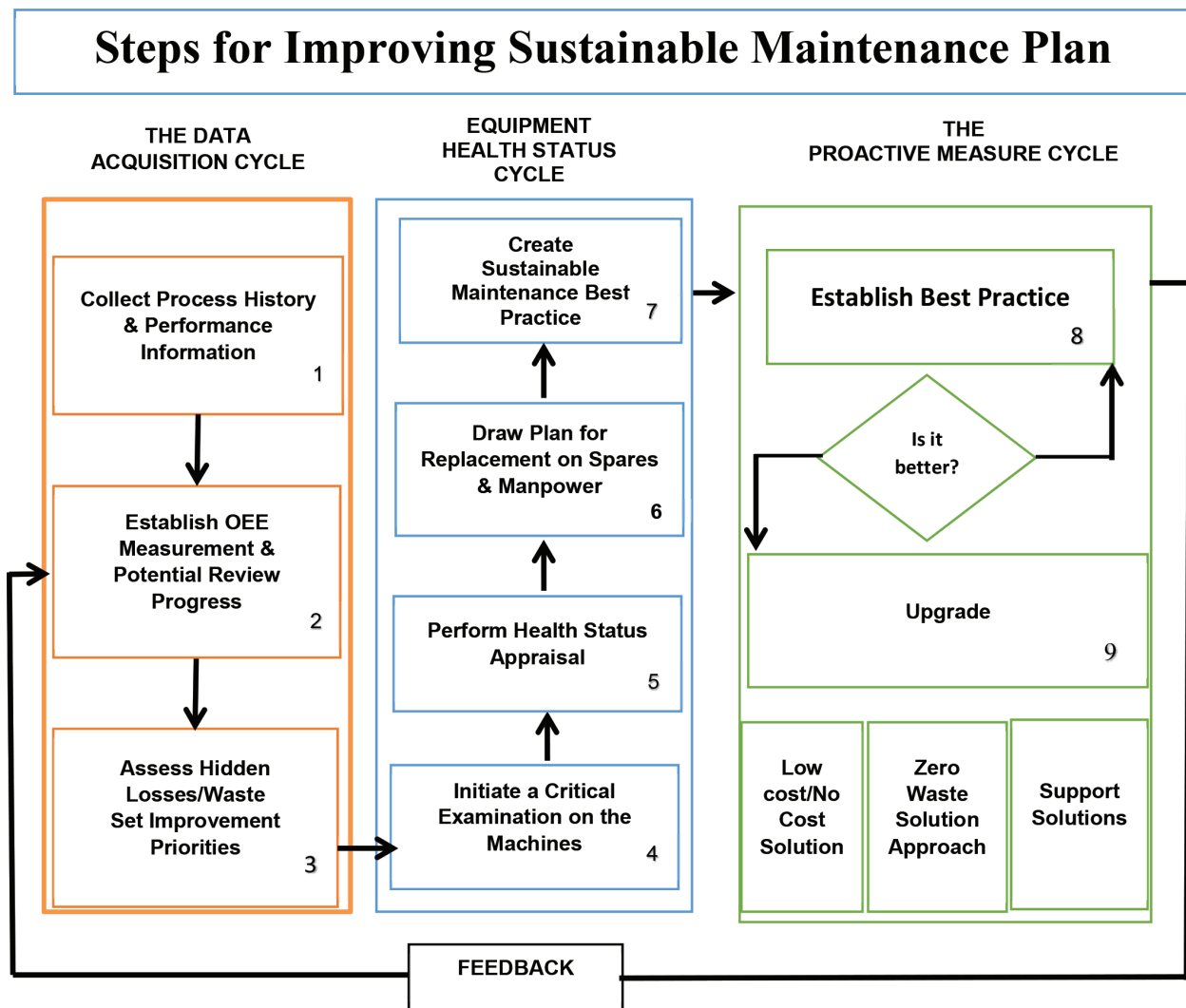## Steps for Improving Sustainable Maintenance Plan

Figure 6. Steps for improving sustainable maintenance plan [17].

1.7. Conclusion

The chapter has established the major ingredients of sustainable maintenance practice, which is indeed novel, and as well established different groupings at which various manufacturing strategies could be matched with the best maintenance practice depending on the factor being considered. Also, the proposed sustainable maintenance prediction algorithm plan has richly provided the platform on which the best maintenance strategy could be practiced at minimal cost and reduced waste level under a competitive business world. The chapter has also assisted in viewing sustainable manufacturing practices from the angle of manufacturing functionality machinery classification and the industrial growth perspective. All these three categories of production or manufacturing strategies were all matched with the best sustainable maintenance practices. The system component policy models have laid foundation for robust replacement plan and holistic maintenance practice. Therefore, the maintenance plan if followed dogmatically with high sense of expertize has the potential for substantially reducing the operating costs and for increasing corporate profit by increasing availability and production.

In addition, successful implementation of this instructive methodology will reduce wastages, eliminate machine downtime, increase machines performance with improved functionality of parts thereby providing maximum usability and reusability of parts/components and thus increase the machine optimal functionality and efficiency.

Author details

Adeyeri Michael Kanisuru

Address all correspondence to: adeyerimichaeltut@gmail.com

Department of Mechanical Engineering, The Federal University of Technology, Akure, Ondo State, Nigeria

References

[1] Jawahir IS. Beyond the 3R's: 6R Concepts for Next Generation Manufacturing: Recent Trends and Case Studies. Symposium on Sustainability and Product Development IIT. Research Institute for Sustainability of Engineering, College of Engineering, Lexington, USA. 2008. pp. 1-110.

[2] https://www.giz.de/expertise/downloads/Fachexpertise/en-maintenance-and-repair-module-1.pdf, 2017.

[3] Lee J, Ni J, Djurdjanovic D, Qiu H, Liao H. Intelligent prognostics tools and e-maintenance. Computers in Industry. 2006;**57**:476-489

[4] Jardine AKS, Lin D, Banjevic D. A review on machinery diagnostics and prognostics implementing condition-based maintenance. Mechanical Systems and Signal Processing. 2006;**20**:1483-1510

[5] Okah-Avae BE. The Science of Industrial Machinery and Systems Maintenance. Ibadan: Spectrum Books Limited; 1995. pp. 19-28

[6] Adeyeri MK, Kareem B. Maintenance dynamics, tools for machines functionality in a competitive environment. Industrial Engineering Letters. 2012;**2**(7):12-19

[7] Lee H. A cost/benefit model for investments in inventory and preventive maintenance in an imperfect production system. Computers and Industrial Engineering. 2005;**48**(1):55

[8] Rasovska I, Chebel-Morello B, Zerhouni N. Process of s-maintenance: decision support system for maintenance intervention. Proceedings of the 10th IEEE Conference on Emerging Technologies and Factory Automation; Vol. 2; Catania, Italy. 26-29 July, IEE published in "9th IEEE International Conference on Industrial Informatics, INDIN'11., Caparica, Lisbon: Portugal (2011). 2005. pp. 679-686

[9]   Mullera A, Marquezb AC, Iunga B. On the concept of e-maintenance: Review and current research. Reliability Engineering and System Safety. 2008;**93**:1165-1187

[10]   Al-Najjar B, Alsyouf I. Selecting the most efficient maintenance approach using fuzzy multiple criteria decision making. International Journal of Production Economics 2003;**84**:85-100

[11]   Niu G, Yang B-S, Pecht M. Development of an optimized condition-based maintenance system by data fusion and reliability-centered maintenance Reliability Engineering and System Safety 95 (2010);786-796

[12]   Nadakatti M, Ramachandra A, Santosh Kumar AN. Artificial intelligence-based condition monitoring for plant maintenance. Assembly Automation. 2008;**28**(2):143-150

[13]   Laggoune R, Chateauneuf A, Aissani D. Opportunistic policy for optimal preventive maintenance of a multi-component system in continuous operating units. Computers and Chemical Engineering. 2009;**33**:1499-1510

[14]   Adeyeri MK, Mpofu K, Kareem B. Modelling of product demand as a pointer tool for choice of maintenance strategy. African Journal of Science, Technology, Innovation and Development. 2015;**7**(2):44-150

[15]   Vladimir SV, Jasiulewicz-Kaczmarek M. Maintenance in sustainable manufacturing. LogForum 2014;**10**(3):274-284

[16]   Jayal AD, Badurdeen F, Dillon OW, Jr., Jawahir IS. Sustainable manufacturing: Modeling and optimization challenges at the product, process and system levels. CIRP Journal of Manufacturing Science and Technology. 2010;**2**:144-152

[17]   Willmott P. Implementing sustainable maintenance best practice: Some myths and realities. MEETA Annual Conference, 2008. https://www.engineersireland.ie/EngineersIreland/media/SiteMedia/groups/societies/meeta/Implementing_Sustainable_Maintenance_Best_Practice.pdf?ext=.pdf