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Optimization of condition-based maintenance strategy prediction for aging automotive industrial equipment using FMEA

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Abstract

Maintenance plays a highly important role in achieving production targets and system performance. Electromechanical equipment and facility infrastructure within motor manufacturing industries are expected to perform at optimal efficiency during the operational phase of production. A major problem in the automotive production plan from motor industry statistics is associated with unexpected downtime, which is largely linked to aging equipment. During production downtime, much time is lost to fault finding, repairs, and replacement of faulty components within production lines. This transforms into low throughput in production, and performance gradually declines during the operational life cycle of the equipment. This paper presents an approach taken to prevent such instances in the automotive manufacturing industry, which considers an optimized condition-based maintenance approach to predict the condition of each component and assembly line using Failure-Mode-and-Effect-Analysis (FMEA). The condition-based performance level prediction is designed to help in formulating maintenance schedules and strategies that eliminate unplanned downtimes.

Keywords: FMEA; dynamic maintenance optimization; lifecycle; automotive

1. Background

Motor manufacturing industries are confronted with challenges which pressurize them to deal with high costs associated with maintenance, investments, and operations of the industrial systems [1]. This myriad of challenges is

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contributed by factors such as aging infrastructure, poor systems reliability, uncertainties, and changes in the regulatory requirements of the automotive sector [2-3].

In this regard, maintenance management plays an important role in constituting a major source of competitive advantage for industries. Rapid changes in globalization, short life cycles of equipment and products, new economic models, and technology integration are perceived to disrupt many spheres of the current industrial operations [4]. Globalization has rendered organizational processes more intricate. Institutions over the world are now compelled to adopt advanced management techniques that can facilitate faster and better performance output.

One of the major challenges experienced in automotive manufacturing industries is the aging infrastructure that encounters unplanned failures, leading to high operational costs and negatively influencing the production throughput. System maintenance was found to be the most costly in the Operational Expenditure (Opex) to guarantee the reliability of manufacturing machinery, and the desirable limits due to multiple aging infrastructures [5]. In Europe, an estimated amount of approximately 150 billion Euros is expended annually for industrial maintenance [6]. In other industries, approximately one-third of the maintenance budget is lost to unnecessary unplanned maintenance activities due to improper maintenance plans [1].

This research paper focuses on communicating a veritable approach for optimizing the reliability of manufacturing systems and equipment by deploying condition-based maintenance, which has the potential of predicting the condition of aging manufacturing infrastructure using Failure Mode and Effect Analysis (FMEA) to reduce failure frequency, the severity of failures, and improving manufacturing systems reliability to enhance performance. The optimized condition-based maintenance strategy considering the equipment health prediction method using FMEA will reduce unplanned outages and improve the reliability of manufacturing systems.

Nomenclature

A	Dynamic maintenance

2. Review of literature

The automotive industries experience unplanned system outages that require corrective maintenance approach and short time planned preventive maintenance to keep production run at optimal efficiency. According to Adeyeri et al.[9], the maintenance of a system can extend a system's life and reduce the number of failures, which in return, reduce the total cost of maintenance. Maintenance has been associated with costs and stoppages and has, for this reason, acquired a connotation of being something necessary evil. Currently, availability, reliability, and safety in the production plants are more emphasized. An increasing number of companies have seen the need to replace their reactive, fire-fighting maintenance strategy with proactive strategies such as predictive maintenance. Predictive asset maintenance can save over 12% in scheduled repair costs as observed from industry reports [3]. It has the potential of reducing the overall maintenance costs by up to 30% and as much as achieving 70% fewer breakdowns. Preventive maintenance strategies together with aggressive Total Productive Maintenance(TPM) has the inherent potential of achieving world-class performance [3]

The impact of maintenance activities on asset availability is measured through minimal downtime. This includes both scheduled and unscheduled maintenance-related downtime. The key objective of proactive maintenance is to identify potential failures with sufficient lead-time to plan and schedule the corrective work before the actual failure occurs using Failure Mode and Effect Analysis (FMEA). If the Preventive maintenance is done properly according to condition-based planning, there will be less likelihood of occurrence of system outages (downtime) and unscheduled maintenance related to downtime would reduce. It is important to measure failure statistics of equipment using FMEA to identify the gaps in equipment or system reliability. The work identification element of the maintenance process strives to eliminate unnecessary corrective maintenance by focusing on only performing the 'right work at the right time' [4].

Embedded diagnostics together with the aid of equipment health level prediction using FMEA can help reduce unexpected machine downtime, lower the meantime to repair, and detect defective systems or equipment components before failure occurs. Today's machines often provide little detail as to what is wrong or what specifically needs to be repaired. Advanced diagnostics technology together with inspection rubrics can ensure quicker diagnostic of problems, and identification of exactly what to repair before machines fail. Ideally, this technology is used for predictive diagnostics to help identify potential problems before deteriorating to a point of resulting in a downtime event. This would allow maintenance personnel to rectify issues and determine the health level of equipment before planned maintenance downtime [5].

Today's automotive manufacturers are required to operate an open operating system. In such systems, advanced operational manufacturing technologies are blended with modern information systems to integrate and coordinate operational resources, processes, and activities, in order to generate a stream of value-added operations aimed at achieving competitive advantage. With the increasing complexity of equipment within the production line, a condition-based maintenance approach using FMEA for health level prediction of these technologies is becoming increasingly important as a determinant of competitiveness [6].

2.1. Failure source: Causes of aging equipment failure

Manufacturing machinery and systems are interrupted by both system faults, natural breakdowns, and external factors. The factors that contribute to system downtime are mainly equipment or hardware failures, vandalism, natural events, operating errors, third party collisions, and other unsubstantiated causes [7].

In reliability analysis, failure describes the state or condition of a system not satisfying its intended objective [8]. In complex engineering set-ups and equipment like automobile plants, a resulting system failure may be caused by multi-level causality of latent failures. Although Adeyeri considered customers' demand and usage of machines for formulating condition-based maintenance policy [9], Wang et al. argued that preventive maintenance is not able to completely remove failures of systems and that corrective maintenance remains widely adopted in engineering practice [9-10].

2.2. Factors contributing to equipment aging

During the operational phase of any system, the physical, mechanical, and electrical strength deteriorates gradually, leading to system failure. This failure of infrastructure or equipment due to components deterioration is a sign of the system's grave. According to Willis and Schrieber, the aging of the power systems process can be categorized into four types [11]. Table 1 below shows four categories of aging equipment and their outcomes:

Table 1: Categories of aging equipment [2-12]

Category	**Outcomes**
Equipment / Infrastructure Age	The age is based on the day system was commissioned to its entire service. An increase in system age is associated with components deterioration leading to Failure.
Cumulative service stress (CSS)	The time the system has been commissioned and the load it had served in the period
Abnormal Events Stress (AES)	Events that severely influencing the power system operations. This includes natural causes, vandalism, accidents, etc.
Technical Obsolescence (OT)	This is generally associated with the error in operations and maintenance. This lead to damage equipment or harm to people

Table 2: Factor indicating the deteriorations of infrastructure

Sign of deterioration	Causes			Comments
	CA	AES	CSS	
Corrosion	X	X	X	This is chemical decomposition until material loses its required quantities, mechanical and electric strengths.
Loss on Dielectric strength	X	X	X	Loss of electrical withstands by various mechanisms.
Tear and Wear		X	X	Breaking. Mechanical components lose tolerance and bind
Moisture retention	X			Water absorption by the equipment or material degrading its electrical or mechanical strength
Shrinkage	X		X	Paper/rubber shrinking with age. This leads to a loss of ability to keep moisture out and contain pressure.
Hardening	X		X	Wear and tearing of plastics, seals hardening with age. This leads to a loss of ability to keep moisture out and contain pressure.

2.3. Causes of equipment failure

The manufacturing system is a combination of different equipment and hardware interdependent on one another to achieve line system objectives. Equipment failure occurs when any part or component of the system malfunction or failure which results in a stoppage. The major problem that leads to equipment failure is sub-standardized equipment, improper installation, aged equipment, and any other part of the system that exceeded its life span [13]. The causes of equipment failure can be visually identified or require technological diagnostic instruments. On the occurrence of equipment failure, it requires components or entire equipment replacement. The duration taken for repair nor replacement, have a high impact on production interruption, which lead to poor reliability to service delivery.

When the equipment becomes old, the following need to be taken into consideration [2]:

- The likelihood of failure increases.
- Higher maintenance cost.
- Replacement parts are difficult to obtain sometimes due to phase out of such components.
- Old equipment become technologically outdated.
- Failure rate of equipment increases.

2.4. Modeling failure rate of the aging process of equipment

The aging process of infrastructure or equipment is validated by the frequency of failure and the likelihood of failure. The aging process of any equipment or machinery is usually measured by the relationship between the frequency of failure and time utilized. In many types of research, Bathtub was used to demonstrate the life span process of equipment/ systems or infrastructure from the development or commissioning stage to the end of life [14]. Figure 1 below shows the Bathtub curve.

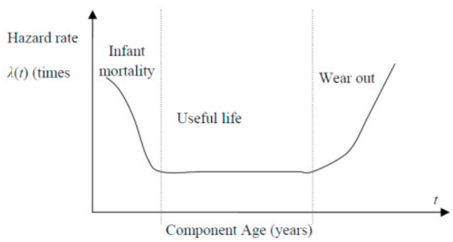

Figure 1: Bathtub curve of any equipment

The infant mortality stage has decreased failure rate as part of the early life cycle, followed by a useful life stage of constant failure rate and wear out stage of increasing failure rate [15].

The exponential distribution is used to measure the probability of failure time and/or constant failure rate during a useful life span [2]. The equipment reliability model mostly uses the useful life period due to the constant failure rate.

The failure rate (λ) or hazard rate during the useful period is mathematically represented by the exponential distribution model calculated using equation [16].

$$f(T) = \lambda e^{-\lambda T}, \; T > 0 \quad \ldots\ldots (1)$$

Annual component or equipment failure rate and repair time are mathematically expressed by the formula:

$$\lambda = \frac{Number\ of\ failures}{Number\ of\ components\ considered * Period\ of\ recorded\ data} \quad \ldots\ldots (2)$$

In the infant mortality and/ or wear out period, Weibull frequency is used to model the nonlinear failure rate. The infant mortality and wear out are mathematically calculated using the formula:

$$f(T) = \alpha\beta T^{\beta-1} e^{\alpha T^{\beta}} \quad \ldots\ldots (3)$$

The piecewise linear failure rate is used to represent the nonlinear failure rate in mimicking the bathtub function [21].

$$\lambda(t) = \begin{cases} C_0 - C_t t + \lambda, & 0 \le t \le C_0/C_1 \\ \lambda, & C_0/C_1 < t < t_0 \\ C_2(t - t_0) + \lambda, & t_0 < t \end{cases} \quad \ldots\ldots (4)$$

The time to failure is mathematically expressed as:

$$f(t) = \begin{cases} Exp - \left\{(c_0 + \lambda)t - c_1\left(\frac{t^2}{2}\right)\right\}, & 0 \le t \le C_0/C_1 \\ Exp - \left\{\left(\lambda t + \frac{c_0^2}{2c_1}\right\}\right., & C_0/C_1 < t < t_0 \\ Exp - \left\{\left(\frac{c_2}{2}\right)(t - t_0)^2 + \lambda t + \frac{c_0^2}{2c_1}\right\}, & t_0 < t \end{cases} \quad \ldots\ldots (5)$$

3. Modeling maintenance systems

3.1. Health condition prediction in equipment

In 2013, Wu used Artificial Neural Network (ANN) based methods in predicting the health condition of equipment [17]. The health condition of equipment or machinery is inversely proportional to the number of system interruptions and /or failure rates. Frequent system outages are a sign of an unstable health condition of the equipment. Frequent failures are caused by factors such as inadequate maintenance, aging value, operating conditions, and environmental factors. In this research paper, FMEA is used in predicting the health condition of the substation with aging equipment, in order to optimize the reliability of power systems.

3.2. Equipment health prediction

Defect prediction is an action taken based on the periodic inspection, diagnostic tests, and/ or any other means of monitoring the condition of equipment or system. The prediction strategy is carried out only if it is necessary to compare the outcome with other maintenance strategies. The time for execution of this maintenance is not predefined but depends on the failure risk of the system. The preventive maintenance strategy will only be implemented when needed, other than some of the routine maintenance. The equipment health prediction is divided into inspection and condition monitoring.

The inspection involves identifying the defects or defective components on equipment or system. This process includes both visual inspection and diagnostic tests using technological measuring units or systems. During the inspection and diagnosis process, defects associated with equipment failure or risk to failure will be identified.

Condition monitoring involves the periodic inspection of a system or equipment to determine if maintenance is required and ensuring good operation of such equipment or system without any risks associated with failure. The type of defects and system conditions guide maintenance engineers and technicians on where, when, how, and why: to execute maintenance of the system or equipment. Frequent inspection of the system or equipment gives greater control of systems defects and contributes to decision-making by selecting the appropriate maintenance approach [18]. In a continuous monitoring period, equipment, or system life deterioration can be seen beforehand.

3.3. Remaining Useful Life (RUL) estimate

Remaining Useful Life (RUL) estimate is a prediction method for forecasting equipment life. RUL is also referred to as Remaining Service Life (RSL) as it indicates the time left before a system or equipment undergoes a failure. In 2010, Tian et al. used the multi-components Condition Based Maintenance (CBM) policy in predicting the RUL using FMEA methodology [19]. This prognostic RUL method is used in predicting the useful life of physical assets based on the current equipment condition and/or previous operation information. This methodology permits the assessment of equipment deterioration of the multi-component systems using FMEA methods for predicting RSL [19-20]. The FMEA inputs includes the equipment / system / components age value and condition monitoring indices and/or measurement units at both current and past inspections point [17]. The challenge with RUL is associated with the uncertainties of operating under load restrictions [17]. The RSL prediction uncertainties are estimated based on lifetime forecast errors [19].

Table 3 below shows a comparison of different maintenance levels of machinery or equipment and their characteristics [21].

Table 3: Comparison of different maintenance levels

Class /Level	**Responsible person**	**Content**	**Impact and effect of equipment**
Inspection	Operating and/or maintenance technicians often carry out this task using condition monitoring/ diagnosing instruments and any visual methods	The technicians responsible for these tasks continuously do a site visit to identify defects in power equipment	The cost of an inspection is very small compared to that of maintenance. Inspection can only bring the idea of action to be taken to avoid dangers or risks associated with system failure.
Minor Maintenance	This task is specifically dedicated to maintenance technicians. This includes repair and replacement with minimum Mean Repair Time.	This type of maintenance includes replacement/repair or cleaning up of system components/ removal of the system itself.	In some instances, minor maintenance requires switching off the systems, which will interrupt electricity supply to customers. The duration and cost of maintenance are lower compared to that of major maintenance.
Major Maintenance	Manufacturers, professional personnel, or contractors specializing in that task or maintenance specialist usually carry these tasks.	This may include factors such as refurbishment, repair of multiple systems & major replacements	Major maintenance of the system effectively improves its performance and extend its life span. The challenge with this maintenance strategy is higher cost and complexity

To illustrate the failure mechanism described in latent failures, a system in figure 2 represents the example of propagation from the presumed cause of failure to consequent failure.

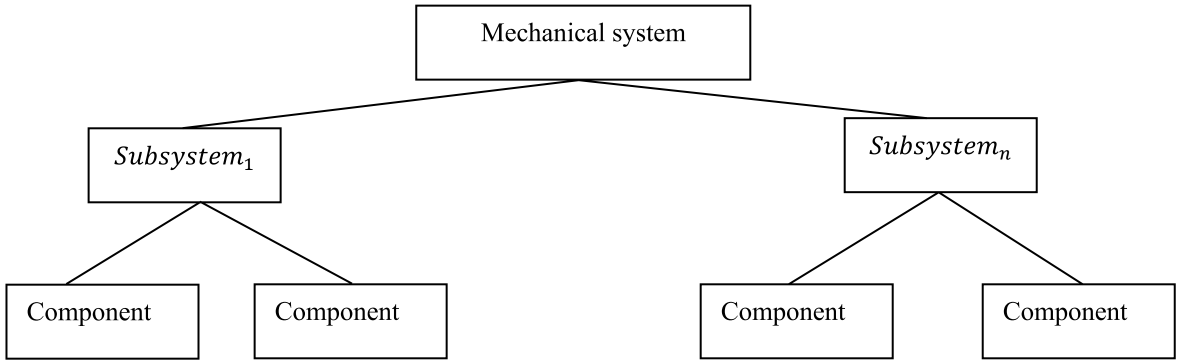

Figure 2: Example of propagation from a presumed cause of failure consequent.

Figure 1: BOM of system

As illustrated in figure 3 below, a resulting failure of a mechanical system Y can be caused by several single failures of individual components or concurrent causes in modularised sub-systems or. As the failure propagates to upper system levels, the failure propagation model (FPM) can be used to describe the propagation phenomenon in Figure 3 and be expressed mathematically by equation 6. In equation 6, the probability that that failure Y is caused by all causes of failure will sum to 1 and it implies that the failure causing leading to Y are mutually exclusive.

$$\sum_{i=1}^{l} \mathrm{Percent}_{\wedge_i \to Y} + \sum_{j=1}^{j} \mathrm{Percent}_{\wedge_j \to Y} = 1 \qquad (6)$$

In equation 6; I and J are the respective total number of concurrent causes of failure and single cause of failure Y.

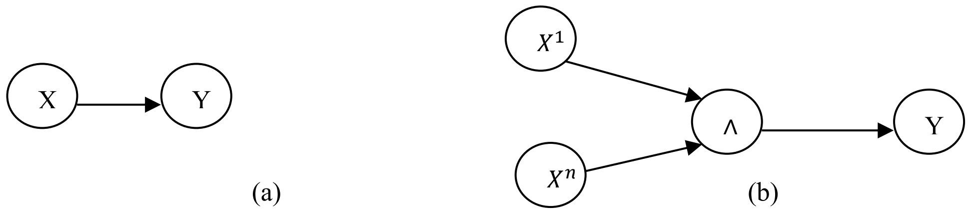

Figure 3: Failure propagation model (a) single cause and (b) concurrent cause

In the FPM of figure 3 and eq (6); the edge with the arrow indicates the failure propagation direction and the percent is the probability that the consequent failure is caused by single failure X or concurrent failures X^1,....X^n [9].

3.4. The importance of condition-based maintenance approach in Automobile manufacturing

Maintenance improves the efficiency and extent the life cycle of equipment. If the manufacturing facilities are not maintained, it will results in more frequent down time caused by system faults. The performance of the machinery deteriorates due to operational wear cycle and results in lower manufacturing efficiency of automobiles. When the demand from customers varies and can sometimes be very high, management needs to come up with cost effective ways of maintaining the plant systems.

The deployment of suitable maintenance strategy will lead to improve the reliability and availability of machine and engineering equipment. Most of manufacturing companies spend between 4-6% of their annual turnover on the maintenance [22]. The limitation is that, maintenance can minimize the likelihood of equipment failure, but does not mean end of failure. In the automobile manufacturing sector, we will give importance to three consecutive steps which are: Audit inspections, resource allocation and rating of maintenance approaches commonly used (preventive/predictive/opportunistic and corrective) to develop a questionnaire that satisfies a required dynamic maintenance strategy.

3.5. Conditioned based maintenance strategies

The functional hierarchy level of dynamic maintenance is the series pattern of decision that is to be taken by motor manufacturing industries to formulate the dynamic maintenance strategy. This maintenance strategy needs to be linked with manufacturing and business goals, but the research in the North East of England suggested that only a few companies [14].

The equation P_actual=P_t-P_(i)is used to strategize for actual production as a function of demand and maintenance activity. P_t Is total output or expected output, P_(i) is a total loss due to maintenance and spare part inventory is necessary when $\mu \geqslant 0.5$ [1]. If P_(actual)= Demand, $\mu \geqslant 0.5$ dynamic maintenance approach is used.

3.6. Application of maintenance process

The maintenance managers need to develop and improve their maintenance strategies and plan to meet the overall objective [23]. When drafting the condition-based maintenance plan of Automobile manufacturing the following need to be considered:

- First the is a need to set a maintenance goal
- Calculate and measure the Production demand
- Capacity of manufacturing facilities available
- Identify the faults or defective parts of machinery or system
- Derive the scope of work, Material/components acquisition
- Allocation of resources based on the specializations
- Set the maintenance date based on the volume of customers' products demand and carry out the maintenance.

After the maintenance is done on the automobile manufacturing plant, it is very important to measure the production outputs, conduct the maintenance audits, and measure the reliability of manufacturing facilities. After creating the maintenance strategy, the next step is executing the maintenance plan. The diagram below in figure 4 bringing the formulation and execution phases of developing a functional maintenance strategy [24].

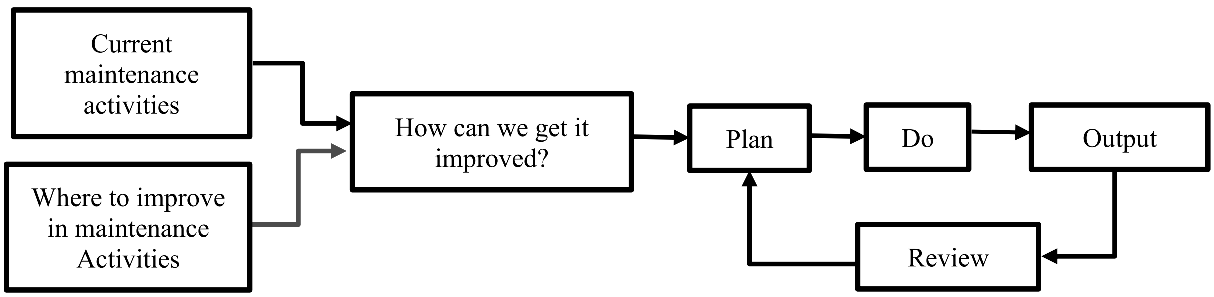

Figure 4: Maintenance strategy process

3.7. Auditing health condition of equipment using condition-based approach in automobile manufacturing

It is very important to identify the gaps in the maintenance of systems, In order to come up with a cost-effective way to improve maintenance strategy. Audits are very important source to identify the gaps between the current state and the desired state of maintenance. The audit results provide management with guidelines on where the organization lacks and what strategies to put in place in order to achieve the desired target state of the organization. In conducting audits, questionnaires are used as a method to collect information and opinions from people involved in operations and their responses are then used as data which helps make decisions and improvements. In this paper, we make use of a questionnaire to define dynamic maintenance as an approach for the automobile manufacturing sector. According to [18], questionnaires are sets of questions, printed on paper or created through an online tool, which are used for both qualitative and quantitative research.

The objectives of the maintenance oriented questionnaire in this survey is to assess the organisation's performance drivers; so as to identify where the weakness and strengths are and leverage improvements activities and opportunities to correct irregularities. For identifying the operational dynamics of the automobile plants, some open-ended questions were asked to experts, which were:

"What are the financial and non-financial performance parameters used in their organization?"

"What are the factors of performance related to 'situation' and 'processes'?"

The questions have objectives to determine what drivers would significantly improve the financial performance of the organisation in terms of profitability, revenue growth and market share. The list of strategic factors related to enterprise performance perspectives is as follows (PE denotes strategic factors related to enterprise perspective):

Situation:
PE1: Technological transformations

Is the effectiveness of maintenance strategy in automobile manufacturing adequate?
Is the maintenance group meeting or exceeding their targets?
Are the maintenance objectives clearly linked to the manufacturing strategy of the Automobile plant?
Are the maintenance objectives, specific, measurable, achievable, realistic and timely (SMART)?
Are all stakeholders getting involved in developing the maintenance strategy?
Is there any contribution the maintenance has improved in the manufacturing?

PE2: Changing customer demands
Is there any documented objectives agreed between manufacturing and customer's base on demand?
What is the current state of operation and the maintenance objectives?

Process:
PE6: Process innovation

Are the maintenance objectives clearly linked to the manufacturing strategy of the Automobile plant?
Is there any joint consultation between the manufacturing and maintenance department (operators) in establishing the maintenance objectives

PE7: New process development
Are the Key performance indicators (KPIs) used in developing the maintenance plan?
Have all the key stakeholders agreed on the action plan?
Are the maintenance team implement the action plan in the right work location
Is there monitoring of the status of action list?

4. Conclusion

This study empirically corroborates various manufacturing equipment that contributes to system and subsystems functionality in the automobile assembly line, and how the maintenance process can be dynamically integrated to improve the maintenance policy, and subsequently increase the overall performance. Although assumptions are made that common system failure are caused by mutually exclusive factors; it should be noted that some consequent failure might propagate simultaneously and cause multiple failures. Compared with the traditional fixed maintenance cycle designed with nominal process information, this approach considers condition-based process information of elements in the automobile assembly plant to develop a questionnaire that will subsequently help generate appropriate maintenance strategy and provide an insight to end of life management of vehicle. It can be seen that the right equipment or machinery maintenance strategies improve the reliability, which results in higher output and efficiency in the automotive sector.

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