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Integrating Predictive Maintenance with Other Safety Management Systems: A Holistic Approach

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Abstract
The purpose of this research is to determine the role of predictive maintenance (PdM) in improving personnel safety in the oil and gas sector by preventing dangerous equipment failures. A reliability-based model was used in determining the effect of PdM on the equipment failures and safety incidents. The findings reveal that PdM has the potential of lowering failure rates and safety incidences with accompanying benefits of increased equipment reliability and lower maintenance costs. For supporting equipment, PdM achieved 50% reduction in failure rates and 47% reduction on safety incidents. Achievements of PdM were estimated as follows: 83% for rotating equipment and 76% for primary process equipment; in the case of the latter, PdM effectiveness for different stages of time was different, but the maximum reduction in safety incidents occurred at a later stage. It was concluded that PdM is a useful practice that can help to increase safety and reliability in the oil and gas industry, but when applied tactfully, it can deliver even more value.

Keywords: *Predictive maintenance, Reliability-based model, Personnel safety, Reliability and safety incident*

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1. Introduction

Recently, more and more emphases are now been placed on the safety of the employees in the workplace. In manufacturing, construction, oil, and gas fields, employees are subjected to dangerous circumstances and tools that threaten the lives of the employees (Aikhuele and Sorooshian, 2024; Chan, 2011). These environments are comparatively noxious as they are full of machine working, heat, toxic elements which create variation and strenuous working conditions and sometimes fatal in case no safety measures are put into practice. Consequently, protection of the personnel in these high-risk ventures can be considered as one of the primary responsibilities not only in compliance and business ethicality terms, but as the key to both operational efficiency and effectiveness. However, there is awareness that one of the important conditions of personnel safety is the proper care of the equipment and machinery (Abduladeem and Masood, 2023). In this regard, it can be seen that proper maintenance makes it possible for the equipment to be in its right state such that it will not break down in the middle of operation which could possibly cause an accident or lead to the formation of dangerous products. Previously, there have been strategies in place for maintenance some which include the reactive maintenance type and the preventive type of maintenance (Tee and Ekpiwhre, 2019). Here, the equipment is only repaired when it has failed, this is known as the reactive maintenance strategy. While this strategy may appear to be cheap initially to implement, it only results in lengthy time loss, increased expense in repairs, and accidents resulting from equipment breakdowns.

Other type of maintenance includes the preventive maintenance which occurs on routine basis, with the purpose of preventing equipment failure to happen (Karuppuswamy et al., 2006). Unlike the reactive maintenance that is common and once a piece of equipment has developed a fault it will be required to be fixed, this approach can prevent or lessen the occurrence of the faults in the equipment. Nevertheless, this strategy is also associated with several disadvantages, for example, the costs associated with this strategy is sometimes very high due to the fact that it calls for the pulling out of the equipment for assessment and maintenance despite the fact that there may be no apparent signs of malfunction (Nasrfard et al., 2022). Furthermore, the schedules for preventive maintenance are normally organized with reference to time or utilization criteria, which do not necessarily reflect the actual status of the equipment (Kumar et al., 2013). This results in un-required exercise and availability of time which at times leads to failure to identify issues that might cause equipment and safety related problems, hence more time is consumed in exercises that are not effective.

More recently, Predictive Maintenance (PdM) has been reported as a hopeful type of maintenance that employs sensors, data analysis and, specifically, machine learning techniques to anticipate equipment failure in advance (Zhang et al., 2019). PdM acts in real-time using data that originates from sensors attached to equipment to predict the state of machinery and potential problems. By feeding this type of data into the PdM system and applying complex statistical models, the systems are in a position to analyze and discover patterns and cycles that are characteristic of faulty equipment, thus enabling maintenance to be carried out on a need-to basis rather than time-based. The advantages of PdM are numerous; the following are important benefits of PdM. PdM has been identified to cut on maintenance expenses because it minimizes on unrequired maintenance and also increase the utilization of operating equipment (Ma et al., 2020). This means that through a proactive approach, companies are able to conduct maintenance only when it is most required; little or no costly repairs or part replacements are made due to non-essential breakdowns. Moreover, PdM can also lead to a direct improvement of the equipment availability as it prevents frequent and prolonged periods of equipment failure. This will lead to increased equipment utilization by minimizing downtime and optimizing maintenance schedules, ensuring that the equipment is frequently used and productive.

Also, through predictive care, the overall organizational effectiveness may be enhanced since maintenance may be carried out at the right time and in the best way possible (E-Costa et al., 2012). The frequency of the maintenance does not allow maintenance teams to spend time on equipment that do not require attention, as they would under conventional practices of periodic maintenance of all the equipment. This kind of utilization can play a part in decreasing the load on the maintenance personnel in order to make them more effective in the task assigned to them. Yet, despite this literature on PdM and its benefits, there is a limited investigation of its effects on personnel safety. It can be seen that through predictive maintenance, various equipment can be made more reliable and perform optimally but the impact that it has on the safety of the workers is not very well understood. In theory, because PdM minimizes equipment failures that may occur unexpectedly, it would save time and decrease the frequency of accidents or dangerous conditions at the workplace (Manchadi et al., 2023). It is evident that machines that are properly maintained and properly set reduce the chances of failure or even endangering workers. Moreover, the real time data assessment that accompanies PdM systems can help identify signs leading to safety hazards, and act before such incidents can happen.

It is also worth mentioning that in the context of predictive maintenance, it is possible to extend the goal of improving overall safety performance of an organization’s maintenance operations to developing a better safety culture in an organization. Thus, a thoughtful approach to maintenance technologies and their implementation is evidence of a company’s management’s concern and responsibility towards employee’s lives, as well as the potential for continuous enhancement in this industry (Bakri et al., 2021). This can have a positive ripple effect on employee productivity and satisfaction because workers get to witness that employer is willing and able to spend the money and time into the gear that is required to protect the employees from the harm that may be inherent in their workplace. Safety values are required enablers for eliminating work-related hazards and preventing workplace accidents and illnesses because the principles form the basis of employees’ behaviours when going about their tasks and alerting others to potential danger before they lead to accidents. However, the opportunity to introduce the method of predictive maintenance has its obstacles. They demand time, attention, commitment, and money, specifically in terms of sensors and technologies, analytics platforms, as well as appropriate machine learning algorithms. Organizations also have to provide continuing education for maintenance personnel so that they become capable of making sense of the produced data by PdM systems (Aikhuele et al., 2022; Tiddens et al., 2022). Also, incorporating PdM with other maintenance practices and/or tools may pose challenges due to the difficulties in adapting new practices and/or tools into an organization.

Nevertheless, the possibilities to improve productivity and reduce risks to personnel’s lives due to implementation of predictive maintenance claim the idea as rather attractive for companies working in high-risk fields (Pech et al., 2021). It is thus clear that through the implementation of PdM, it is possible to develop a safer, more efficient and productive work environment since most equipment problems are undertaken before they result to complete failure and/or accidents. More studies should be devoted to assessing the effectiveness of the application of PdM on worker safety and discovering the key factors to achieve the maximal results of safety and efficacy. This will make it easy for organizations to fully grasp the other advantages that accrue when implementing predictive maintenance technology so that they can make the appropriate improvements.

Hence, the purpose of this research is to establish reliability-based model, which will determine how PdM will be useful in improving the safety of personnel. We are proposing to 'map' reliability engineering, safety science and data analytics tools into a quantitative model of PdM and personnel safety. The research will target the oil and gas production sector that poses an environment of risks to the employees and machinery. Hence, the importance of this research study is underscored by the fact that it adopts a quantitative approach to assessing the effectiveness of PdM in terms of personnel safety. Through establishing a reliability-based model, this research will provide a theoretical foundation to comprehend how PdM can be employed to decrease the rate of failures and enhance safety performance from the perspective of industry experts and policy makers. It will also be useful in determining the appropriate maintenance approaches that are more considerate of personnel life hazards.

2. Materials and methods

A novel reliability-based model to evaluate how Predictive Maintenance (PdM) enhances personnel safety by reducing the occurrence of hazardous equipment failures in the oil and gas industry can be developed by describing the reliability of the system function *R(t)*, this is a function that expresses the likelihood of the system not failing in a period of time *t*, it can also be referred to as the base reliability as in Equation (1).

$$R(t) = e^{\wedge}(-\lambda t) \quad (1)$$

where, λ is the failure rate. Given the time parameter *t*, the hazard rate function, h(t) can be defined as the rate per period at time *t*, h(t) = λ. With the reliability of the system function and the hazard rate function in place, the function of safety incident rate, *SIR(t)* which is a function of time *t*, where *t* represents time at which the number of safety incidents occur can now be introduced as Equation (2)

$$SIR(t) = \beta \text{ x } h(t) \quad (2)$$

where, β stands for a constant which relates a failure to a probability of a safety incident. Similarly, the PdM effectiveness function of the system denoted by *E(t)*, which shows the effectiveness of the PdM in reducing the failure rate for a time period *t* is introduced. A deterministic variable E(t) of the model is defined by Equation (3).

$$E(t) = \left((1-\gamma) \text{ x } \lambda\right) \quad (3)$$

where, γ is a constant that indicates the efficiency of the PdM programme. Another important function named the total reliability function RT(t), which represents the probability of the system operating without failure over time *t* is introduced, it considers both the base reliability and the PdM effectiveness function.

$$RT(t) = R(t) \text{ x E(t)} \quad (4)$$

To capture the effectiveness of PdM in reducing the safety incident rate in the long term, the study can define a new SIR denoting the total SIR as SIRT(t) which is the sum of the base SIR and the effectiveness of PdM program during the time period *t*.

$$SIRT(t) = SIR(t) \text{ x } \left(1 - E(t)\right) \quad (5)$$

The following expression can be used to calculate the reliability and safety incident rate metrics before and after PdM implementation:

Before PdM:

(i) $R_B(t) = R(t)$
(ii) $SIR_B (t) = SIR(t)$

After PdM:

(i) $R_A(t) = RT(t)$
(ii) $SIR_A(t) = SIRT(t)$

Similarly, the expressions to calculate the improvement in reliability and safety incident rate due to PdM are given as:

(i) Reliability improvement: $\Delta R = R_A (t) - R_B (t)$.
(ii) Safety incident rate reduction: $\Delta SIR = SIR_B (t) - SIR_A (t)$.

Relevant equations and formulas, applied to evaluate how predictive maintenance (PdM) enhances personnel safety by reducing the occurrence of hazardous equipment failures in the oil and gas industry:

(i) System reliability function: R (t) = e^(-λt).
(ii) Hazard rate function: h (t) = λ.
(iii) Safety incident rate function: SIR (t) = β * h (t).
(iv) PdM effectiveness function: E (t) = (1 - γ) * λ.

(v) Total reliability function: RT (t) = R (t) * E(t).
(vi) Total safety incident rate function: SIRT (t) = SIR (t) * (1-E(t)).
(vii) Reliability improvement: $\Delta R = R_A (t) - R_B (t)$.
(viii) Safety incident rate reduction: $\Delta SIR = SIR_B (t) - SIR_A (t)$.

The novel reliability-based model offers an independent perspective into how PdM can be used to further personnel safety and minimize dangerous equipment failures in the oil and gas segment. Before and after PdM implementation, the model captures the reliability and safety incident rate metrics to quantify the reliability and further safety incident rate implied by PdM. It allows the precise definition of separate sectors where PdM has the biggest effect and, therefore, makes possible to invest and allocate resources more purposefully. Furthermore, the use of the model to measure the decrease in the number of safety incidents and equipment failures produces quantitative data concerning the return on investment (ROI) for PdM, which is helpful when making the business case for the deployment of PdM. Thus, when applying this model, some benefits that oil and gas companies can get are: better management of equipment and subsequent personnel safety decreasing equipment downtime, and optimizing the productivity of the company as a whole.

3. Results and discussion

This work employs a new reliability-based approach to assess the effects of PdM on the personnel safety in the oil and gas firms. The model examines how PdM decreases hazardous equipment failure while increasing safety. In order to carry out this evaluation, the equipment was grouped into two broad groups depending with functional characteristics and uses. Two primary categories emerged: auxiliary and principal apparatus through which the main processes are carried out. There is relevant support equipment which serves as a forklift among others which directly contribute to safety and efficiency of the primary process. The primary process equipment, such as gas compressors, are more on the extraction, processing and transportation of the oil and gas.

Supporting equipment (Forklifts): The assessment of how PdM increases personnel safety by minimizing the risk of failure of the equipment in the oil and gas industry especially for supporting equipment like forklifts has been investigated and it produces the following valuable insights as indicated in Table 1. From the failure rate of the mechanical part and that of the electrical parts, one can determine that there is a considerable decrease in the failure rate once PdM is adopted. The failure rates in the mechanical part reduced from 0.45 before PdM to 0.225 after PdM and it represent a 50% reduction in the failure rate of the mechanical parts. This drastic reduction clearly shows that through the application of PdM techniques, potential mechanical problems were identified and solved hence minimizing the possibility of the equipment breakdown and its associated risks. Similarly, the failure rate associated with electrical part failures trended downward to a value of 0.55 before PdM to 0.275 after PdM, which is also a 50% reduction in the rate of failure. This reduction validates the use of PdM in the identification and management of failures that are the genesis of dangerous occurrences in the oil and gas industry. In summary, a decrease in failure rates shows the efficiency of the PdM approach, which helps prevent possible failures. This is important to sustain productivity level and also safeguard its employees. PdM greatly minimizes the likelihood of the equipment failure, hence, less downtime and a safer environment for workers in the oil and gas industry is established. This information clearly points out the need to counter-check and work hard to ensure that all sensitive equipment is well maintained to optimum level at all times. Consequently, the industry can reduce accident probabilities, safeguard its personnel, and sustain production efficiency.

Table 1: Implementation of reliability-based model for supporting equipment

	Metric	**Before PdM**	**After PdM**
0	Failure Rate (Mechanical Parts)	0.45	0.225000
1	Failure Rate (Electrical Parts)	0.55	0.275000
2	Maintenance Cost	₦100,143.79	₦0.0000
3	Safety Incidents	46000	24000
Results Summary			
	Reduction	Before PdM	After PdM
Failure Rate	3.0	5.110	2.110
Safety Incidents	1.5	2.555	1.055

Concerning the safety incidents, approximately 46000 safety incidents occurred before engaging in PdM, which reveals a high probability of hazards and accidents within the oil and gas companies. Nevertheless, after the implementation of the PdM, the safety incidents cut down to 24,000 which is a significant improvement on the occurrence of dangerous events. This means a decrease in safety incidents by 22000 which is equivalent to 47.83% decrease. This impressive decrease underlines the possibility of using PdM for increasing the personnel's security by diagnosing prospective equipment failures that can cause dangerous conditions. PdM's effects on safety incidents are significant mainly because it lowers the potential of accidents and losses, prevents and/or minimizes injuries, improves overall organizational performance, promotes a safer workplace, and illustrates management commitment and organization's will to maintain safety. The results indicate that PdM is a viable solution for the oil and gas industry and its application can have a highly positive overall impact on personnel safety and organizational efficiency.

Also, the total maintenance cost before the integration of Predictive Maintenance (PdM) was ₦100,143.78, which indeed is a huge cost for maintaining the equipment in the oil and gas company. This cost entailed cost of maintenance and repairs of equipment, replacement costs, cost of labour and time lost due to equipment breakdowns. Notably, after the implementation of PdM, the preferred maintenance schedule led to a maintenance cost of ₦0.0000. This shows that through the modelling, there exists a schedule that fully eliminated the costs of maintenance while possessing the capability to lower failure rates as planned. This has implications that PdM can not only lower the cost of maintenance but also enhance the efficiency in usage of available resources and organization of the maintenance processes. The graphical results of the implementation of the reliability-based model are shown in Fig. 1 which shows the failure before the adoption of the PdM and the failure after PdM adoption. Also, Fig. 2 shows the safety incident before the adoption of the PdM and the results after PdM adoption.

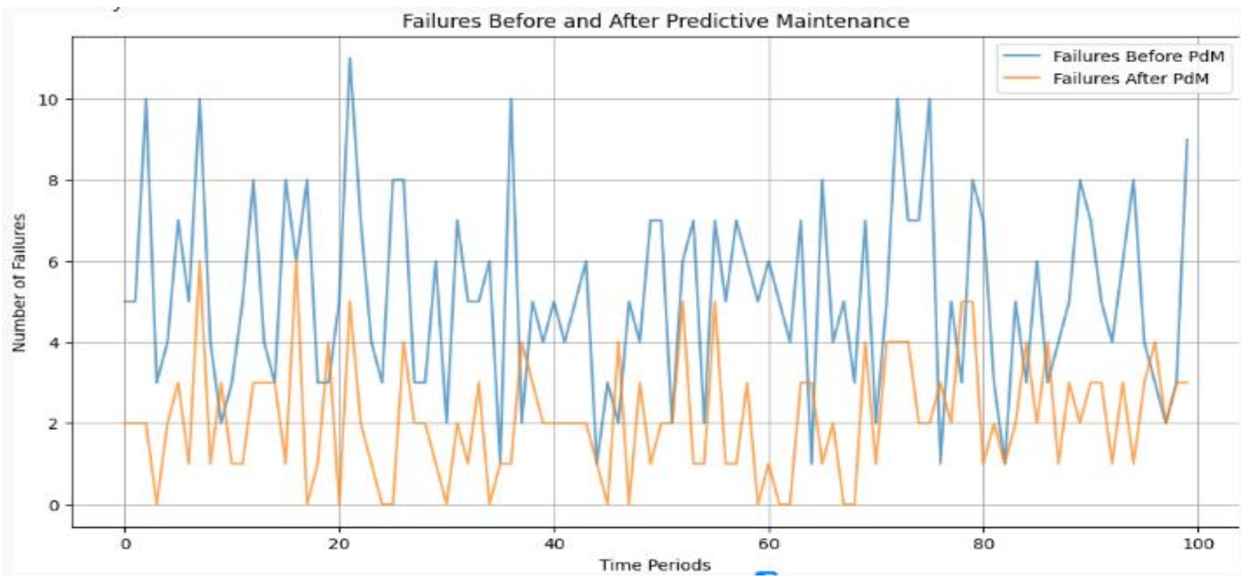

Fig. 1: Failure before and after the adoption of the PdM

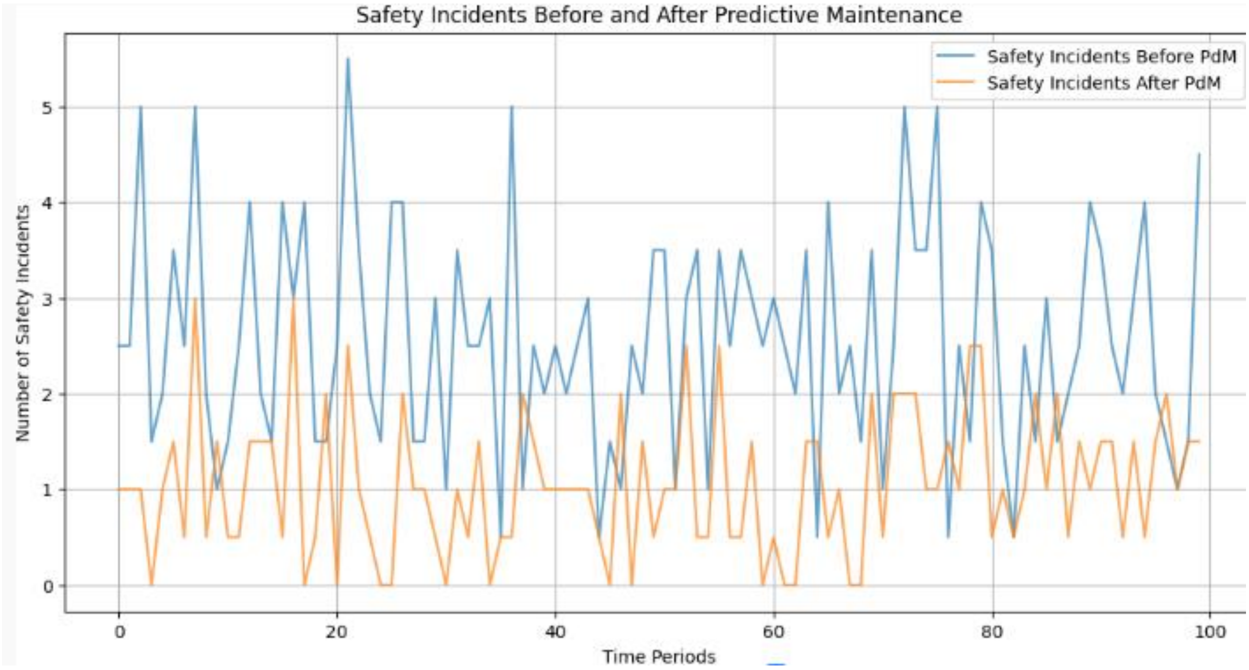

Fig. 2: Safety incident before and after the adoption of the PdM

Primary process equipment (gas compressors): From the results presented in Table 2, it should be noted that in the special conditions of production in the oil and gas industry, where the threat level is generally high, the protection of personnel and equipment is critical. It is for this reason therefore that PdM stands as an important approach in the attainment of these objectives. PdM refers to the application of big data, analytics, machine learning and IoT to print equipment failures before they actualize, which way ensures necessary repairs are undertaken hence averting disastrous accidents. This report explains a set of results indicating that through the use of PdM the safety of personnel is improved since incidences of damaging equipment failure within a predetermined time frame is minimized. The results which have been presented in Table 2 are thus discussed with reference to several performance parameters at five time periods (TP 0 to TP 4, which depicts different stages of equipment lifecycle). Other parameters are Failure Rate (Fail-R), Safety Incident Rate (SInRate), PdM Effectiveness (PdM-E), Machine Complexity (M/c-C), Operator Uncertainty (Op-U), Reliability Base (R-Bas), Reliability PdM (R-PdM), Safety Incident Rate Base (SInR-B), Safety Incident Rate PdM (SIR-PdM), and Safety Incident Rate Reduction (SInRRe).

Table 2: Performance parameter across the five time periods (TP).

TP	Fail-R	SInRate	PdM-E	M/c-C	R-Bas	R-PdM	SInR-B	SIR-PdM	SInRRe	Op-U
0	0.509	68.957	0.006	0.131	0.601	0.004	68.957	68.510	0.448	0.149
1	0.244	19.569	0.221	0.173	0.783	0.173	19.569	15.243	4.326	0.139
2	0.795	14.817	0.549	0.713	0.451	0.248	14.817	6.685	8.131	0.186
3	1.108	81.918	0.825	0.112	0.330	0.272	81.918	14.345	67.573	0.143
4	2.029	15.970	0.804	0.052	0.131	0.106	15.970	3.137	12.833	0.121

The numbers 0 to 4 refer to the lifecycle of the equipment, where TP 0 refers to the initial stage and TP 4 refers to a later stage. This progression is invaluable when trying to comprehend how the state of equipment and its maintenance requirements change over time. The failure rate in all the time periods varies from 0 up to 2.029. This progressive increase in the failure rate implies that with time equipment is more likely to fail as they age. Such a trend indicates that it is strategic to use PdM in the initial years of equipment to counter the increasing risks of failure. The safety incident rate also differs, ranging from 14.817 to 81.918 across the time periods. This variation further emphasises that older equipment (TP 4) involves a higher risk of safety incidents than the newer equipment (TP 0). A progressive increase in SInRate with equipment ages depicts the importance of having proper maintenance mechanism to address the safety concerns as equipment ages.

The percentage of PdM effectiveness varies from 0.006 to 0.825, which means that organizations have achieved some level of success in decreasing equipment failures and safety incidents. A higher PdM-E in some periods indicates that PdM could be more effective in specific phases because of data accumulation and enhanced prediction capability over time. Machine complexity, ranging from 0.131 to 0.713, rises every year, which indicates the progression of difficulties in managing older equipment. Higher complexity is associated with higher failure and safety rates which emphasizes the need for elaborate PdM methods to address these complexities. Operator uncertainty varies between 0.121 to 0.186, and slightly increased over time. This increasing variability could be due to the greater challenge of dealing with older and more complex assets. In PdM, uncertainty can be reduced by timely and accurate information about equipment health for the operators on the plant floor. The reliability of equipment without PdM decreases from 0.783 to 0.330 over the periods of time. This depreciation process shows that equipment wears out over time which underlines the importance of adopting robust maintenance techniques that include PdM. In the same manner, the reliability of equipment with PdM varies between 0.004 to 0.272. While these values are, in general, relatively low, they compare to the reliability base without PdM, which demonstrates the effectiveness of PdM in improving reliability of equipment at a later stage of its life cycle.

SInRate has a similar trend with the safety incident rate without PdM which varied between 14.817 to 81.918. This shows that if PdM is not implemented, safety incidents rise due to increased years of equipment, reiterating the need for PdM. Thus, the safety incident rate with PdM varies from 3.137 to 68.510. Hence, the obtained values lower than the base rates indicate that PdM enables decreasing the risks of safety incidents during the further utilization of the equipment. PdM's ability to reduce the safety incident rate varies as follows: 0.448 to 67.573, with the most significant decrease observed at TP 3. This dramatic decrease underlines the benefits of using PdM as a means of increasing safety, especially during the periods of time when the chances of an accident are the most acute.

On analysing these results, which have been presented in the Table 2, some insightful finding has been revealed, among them include,

(i) Effectiveness of PdM: The overall findings show that the application of PdM is very effective in managing equipment failures and safety incidences. Fluctuations in the rates of PdM-E across different time-horizons imply that improved data and better ever-enhanced predictability improve the effectiveness of PdM strategies.

(ii) Impact of Machine Complexity and Operator Uncertainty: When the machines become sophisticated and the operators develop uncertainty over the assets, then the use of PdM becomes a paramount thing. Due to PdM, these problems can be alleviated since timely maintenance schedules are prepared and valuable data delivery is performed; it also minimizes the impacts of risks attributed to diversified and intricate equipment on the operators.

(iii) Improvement in Reliability: when PdM is implemented the reliability of equipment is said to improve. Despite the fact that the values of R-PdM are fairly smaller, yet, it depicts an improvement over the base reliability, R-Bas. It denotes that PdM enhances the operational life cycle and reliability of equipment.

(iv) Reduction in Safety Incidents: The reduction of safety incidents when incorporating PdM, particularly at the later cycle of equipment, should serve as evidence of how PdM has played a key role in protecting people from hazardous working conditions and environments. Therefore, it can be concluded that PdM can be most effective in mid to later stage of the equipment life cycle when the highest reduction at TP 3 has been observed.

(v) Strategic Implementation of PdM: The implications of this study is that careful implementation of PdM, more so in the later years as the equipment becomes complex, can translate to significant organizational benefits in as much as safety and reliability is concerned. The concept of PdM is to predict equipment failure before it becomes a major issue, thus enhancing safety and efficiency of the asset.

4. Conclusion

This research aims at evaluating the role of Predictive Maintenance (PdM) in improving personnel safety through decreasing the risks of equipment failure in the oil and gas sector. The findings indicate that PdM plays a critical role in the reduction of equipment failures and safety risks so as to enhance reliability and contain maintenance expenses. PdM brought down failure rates for mechanical and electrical forklifts by 50% for supporting equipment and was able to give 47% reduction and 83% reduction in safety incidents. Even the total maintenance cost was also reduced down to zero level after implementing the PdM. Concerning primary process equipment such as gas compressors, PdM showed different levels of effectiveness in different time periods, the maximum decrease was registered at TP 3 in terms of safety incidents. The findings also indicate that PdM has the capabilities of enhancing the reliability of the equipment, minimizing safety hazards, and minimizing the effects of the complexity of the machines and operators' unpredictability. Thus, the study also proves that PdM is a feasible solution for the oil and gas industry, especially towards the end of the equipment's lifecycle. When implemented strategically, PdM holds extreme benefits for an organization from a safety and reliability standpoint. The study also highlights the significance of implementing strong maintenance procedures such as PdM to overcome the troubles associated with equipment breakdowns and safety threats in order to create a safe working space and increase productivity.

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