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Scientific Model Development for Machinery Safety using Machine Reliability, Integrity and Availability

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Abstract

Introduction: Machines are equipment that increases productivity and efficiency in a workplace. Machine reliability, integrity, and availability are the most critical factors to ensure machinery safety in a workplace.

Methods: Throughout this study, a series of reviews of previous literature are described in relation to the elements of reliability, integrity, and availability. This study examines the methods used to investigate the levels of each element as well as the results of performing the analysis. Each review is chosen from the aspect of the safety feature that can be interpreted from the research study. A scientific model that utilizes an improved bottom-up approach is proposed to further improve the worker's safety and enhance the productivity of an industry.

Results: Research shows that the chosen reviews have positive and negative changes towards the level of machinery safety and a more substantial approach is needed to further strengthen the issue. The proposed model combines the effort of employees and various management organizations as a team. The model is validated using Bias-Variance trade-off method that analyses the proposed model in a 27MW power plant with a selection of employees and management.

Conclusion: Model validation proves that the proposed model is an effective method to increase machinery reliability, integrity, and availability in a workplace. The scientific methodology provided will help management as a team to avert mechanical accidents from occurring at an initial stage.

Key words: Work, occupational health, equipment safety, safety management, health and safety.

Introduction

Machines are devices that can help perform a task and enhance the production efficiency in a workplace as the demand for a particular product increase in the market requires adopting machine processing to meet the market requirements.[1] Today, just about every industry is expanding into other countries through franchising.[2] Whether it is a local industry or international industry, machinery is used to speed up the process to meet the market demand. As there is an increase in machinery use, it is quite necessary to make machinery safe for the employees. The moving parts of machines, hot surfaces, and sharp edges can cause severe injuries like burns, cuts, crushed hands/figures, and blindness. So, health and safety are the first priority and essential for the workers.[3,4] According to Wenying Chen in 2014, there are several hazards while working with machines or near the machines, which cause occupational injury such as stabbing, friction, abrasion, crushing, impacting, puncturing, and cutting.[5] Simultaneously, there are other reasons for occupational injuries while working with or near a machine, such as thermal energy and electrical energy, noise, radiation, vibrations, and fluid pressure.[6]

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There are several factors that affect machinery safety in a workplace. For this study, three main factors were chosen which are reliability, availability, and integrity. These three factors are the major contributors to the increase of machinery accidents in a workplace, especially in safety-critical workplaces such as power plants.[7] Every machinery has a particular function, and the duration that a machine can perform is known as reliability which indicates the performance of the machinery. The procedure to measure the impact of a failure is by enhancing machinery reliability.[8] There is another term called 'Machine Integrity,' which is to recuperate the system from the initial condition after the breakdown (unplanned downtime). The reliability depends on the integrity of a system whereby it can be subsequently increased by improving the maintenance. If a system goes for an unplanned breakdown and if the degree of recovery from the breakdown is satisfactory, the system's ability to perform a particular task will also improve.[9] Availability is the actual time in which the machinery or equipment is available to perform the assigned tasks. In order to find out the availability of machinery, it is necessary to look at its uptime. Although many studies have been conducted on machine reliability, integrity, and availability in the past, these studies do not emphasize the fundamental measures of machinery safety. Thus, this study has examined three elements of machinery safety through mathematical and past research theoretical representations and inculcates the safety element of the research study to form a scientific model that would be able to curb machinery accidents due to these factors. This study will be able to provide a framework for all workplaces to specify machinery safety in the process and would not generalize the elements as requirements only. The scientific model proposed can also help the management and the employees to work together as a team to curb machinery accidents from an early point.

Methods

The framework of the methodology is shown in Figure 1. Various research on machine reliability, integrity, and availability are investigated and studied as the materials under the literature review of this study. Machinery analysis methods on various workplaces with variations are selected and compared to find out the effects of machinery safety analysis towards the reliability, integrity, and availability of machines. Combinational analysis reviews are also taken into account to contrast the results with the current practice of the selected workplace. A summary of all the reviews will be shown at the end of the review.

Upon analyzing the impact of machine reliability, integrity, and availability from the research, a scientific model that comprises of the team formation of employees and management are proposed, which will be shown in the discussion section. Vigoroso et al. in 2020 explained that a Bottom-up approach can provide positive changes to the workplace safety level, provided that a flow of the process is proposed by hand.[10] Therefore, a Bottom-up model will be designed and proposed to be part of the research study in this paper.

The structure of the model is divided into two parts, particularly the employee and the management. The employees would be selected from the area of workplace that is connected to machinery handling and maintenance of either manual equipment or safety-critical equipment. Employees can be ranged from operators to engineers, without the preference of experience. This will ensure transparency for the research study. As per the management, the main departments of safety will be chosen for this study. Karkoszka in 2009 stated that a safety organization comprises of legal, quality, and the human resource (HR) management as a team.[11] Therefore, this model formation will include the team effort from the legal, quality, and the full management organization.

Model validation is critical as the concern to test the accuracy of the model forecasts the data from which it was learned is vital. Bias-Variance Trade-Off method will be used to validate the proposed model for this study. Since the target values for the data were used to train a model, it is even more necessary to understand a model's robustness and capability when required to model new variables with the same specification and features as the training set but with separate individual values.[12] The analysis generates the training and validation score according to the proposed model. If the number of parameters in a model increase, the model becomes more dynamic, and variance becomes the primary concern, while bias gradually decreases. In other words, as model complexity increases, bias has a negative first-order derivative, while variance has a positive slope.[13]

Agrawal et al. in 2009 studied the reliability, integration, and availability of the "Earth Pressure Balance Tunnel

Boring Machine" (EPBTBM) when operating to bore a tunnel in mixed ground.[14] They applied the "Markov Modelling" by using the health and safety factors and developed the reliability block diagram system for the EPBTBM as shown in Figure 2.[14]

After performing the simulation, they found a 40% decrease in the reliability of EPBTBM within 1.5 hours of working. This failure occurred due to different factors which were summarized as leakage in the hydraulic system, fused rock zones, different rock conditions, and cutter head jamming. They further found that it needs at least 20 hours to get its initial condition back if any breakdown occurs. They introduced preventive maintenance (PM) and proper planning to the system and found a significant difference in the system; according to their results, the reliability decreased by 40% after 6 hours of work and increased by 400% after implanting PM of 10 hours. While PM's application also increased the availability by 9%, whereby before the PM application, it was 61%, and after the PM implementation, it became 70%.

Rajaprasad et al. in 2018 analyzed the reliability, integrity, and availability of a paper machine. The machine utilizes 120 tons of paper pulp per day.[15] In order to fulfill the required processing requirement, it is necessary to get the higher availability of the machine. To improve the availability, reliability, and integrity, a failure analysis is needed where the time taken when a machine processes its task, the unwanted breakdown, and restarting the task are seen. The authors have performed all the appropriate methods to make the "reliability, integrity, and availability" analysis, including System and Data collection, evaluation of data, data analysis, failure analysis, and goodness of fit test. The machine on which the authors have experimented has five sub-parts, as shown in Table 1.[15]

After performing the analysis, it was found that at the time of 200 hours, the reliability of the system was reduced to 0.408, and after 400 hours, it reduced to 0.090. On the other hand, the paper plant's integrity shows that after five hours, the WP, PP, DY, CL, and PA were 0.535, 0.42, 0.96, 0.99, and 0.99, respectively. In contrast, after the 10 hours of breakdown time, the WP shows the integrity of 0.961 while all other subsystems show the integrity of 1. As per the availability of the paper, the author obtained the operation availability and the inherent availability of the inherent availability by using the "Mean Time Between Failures" (MTBF), "Mean Time To Repair" (MTTR), and "Mean Down Time" (MDT) approach.[15] According to their results, the operational and inherent availability of the paper machine is mentioned in Table 2.[15]

According to the authors, the wire paper machine required a 4% improvement for integrity, while a 1.5% improvement was related to availability. The other parts required improvements of 0.5% for availability. However, Yaqun et al. in 2020 have done the "dynamic reliability analysis" of the thrust chamber of the reusable "rocket engine".[16] They selected the random variables of geometrical dimensions, working loads, and properties of the material in order to analyze the reliability of the inner wall of the thrust chamber under the "cyclic cumulative damage," "multi failure modes," and "static strength failure." For this purpose, they used the "Dynamic Multiple Response Surfaces" (MRS) and "Coupled Thermal Structural Finite Element" models.

Furthermore, Lazakis et al. in 2015 conducted a study on a ship machinery components' reliability.[17] They collected the raw data and performed the risk/reliability analysis to decide on the purpose of component replacement. The "Condition Based Maintenance" (CBM) was used in this approach where the upcoming problems of the components of machinery were investigated based on on-going conditions. In this experiment, the ship's six crosshead bearings were observed for two days and fifty readings were taken. Based on this performance, the reliability performance forecasting took place and found a very low decrease in reliability. As shown, the crosshead bearing 1 starts from 98.905% on day one, which shows 97.89% reliability. A similar trend for other crosshead bearings can be seen, and that is certain that there is no purpose to replace this equipment until the forecasted date. As the piston liners' data were obtained for two days and modeling was done for four days, it showed a similar trend for the crosshead bearing. In contrast, three air systems were also checked for reliability in the same manner, and that showed almost constant results with no change in the reliability. This reliability analysis shows high reliability of 90%, and there is no purpose to replace the components.

The underground exploitation is a difficult engineering labor, and the machinery used for the extraction of coal remains unfit to perform the operations until their expected lifetime due to poor maintenance[18]. Brodny et al. in 2017 made an availability analysis for coal mining machinery.[19] The data collection for this analysis was collected by an industrial automation system.

After performing the availability analysis for each of the mentioned components, they found the results shown in Table 3,[19] and it can be concluded that the availability of their mining machinery is not satisfactory due to poor safety measures in the workplace. It is observed that there is no other part of a machine that passes the average daily availability of more than 75%.

Mohamed et al. in 2018 made a study on the implementation of a risk-based inspection approach of reliability and safety through pressure equipment in Malaysian industries.[20] The authors determined the possible benefits of adopting the risk method as well as the potential problems connected with its implementation. The research survey found that the risk associated with reliability is reduced upon major inspection done by the employees. Surveys, however, found that the lower reliability of the machineries contributed to major accidents in the workplace.

Results

A summary of the works and the analysis are shown in Table 4.

The pre-research study on the elements of reliability, integrity, and availability gave an extended insight into the level of machinery safety in a workplace. Agrawal et al. and Rajaprasad et al. have received a positive change through their research studies, where the elements of reliability, integrity, and availability have substantiated the machinery safety in the workplace.[14,15] However, Lazakis et al., Brodny et al., and Mohamed et al. concluded a negative remark on their research, without proceeding to come up with a correction action to curb the issue.[17,19,20] The research studies did not have proper communication with the management for suitable corrective action as well. Besides, machineries without proper reliability, integrity, and availability can affect the state of machinery safety, thus causing machinery accidents to peak in a workplace. This shows that there is an absence of employee and management team effort to enhance the machinery safety level of the workplace. Therefore, a combinational approach that involves the management and employee is fundamental in strengthening a workplace machinery safety standard, which also is the key contributor for the model development.

Table 1: List of Sub-system of Paper Machine

Subsystem	Code
Wire Section	WP
Press Section	PP
Dryers Section	DY
Calendars	CL
Pope Reel, Primary & Secondary Arms	PA

Table 2: Results of Availability Analysis

Sub System	Inherent Availability	Operational Availability
WP	0.997	0.986
PP	1	0.998
DY	0.998	0.997
CL	0.998	0.998
PA	1	0.998

Table 3: Results of Availability Analysis

Part	Average Daily Availability %	Maximum Daily Availability %
Longwall Shearer	66.60	77.36
Crusher	62.06	77.43
Beam Stage Loader	71.25	82.65
Armored Face Conveyor	70.36	82.45
Combined	67.56	82.65

Table 4: Summary of Pre-Research Work Review

Author	Element	Safety Analysis
Agrawal et al.[14]	Reliability, Integrity, and Availability	Preventive Maintenance reduced leakage failure.
Rajaprasad et al.[15]	Reliability, Integrity, and Availability	The strength failure approaches increased machine reliability, integrity and availability tremendously.
Mohamed et al.[20]	Reliability	Lower reliability of the machineries contributed to major accidents in the workplace.
Brodny et al.[19]	Availability	Availability of their mining machinery is not satisfactory due to poor safety measures in the workplace.
Lazakis et al.[17]	Reliability	Machinery used for the extraction of coal remains unfit to perform the operations due to poor maintenance.

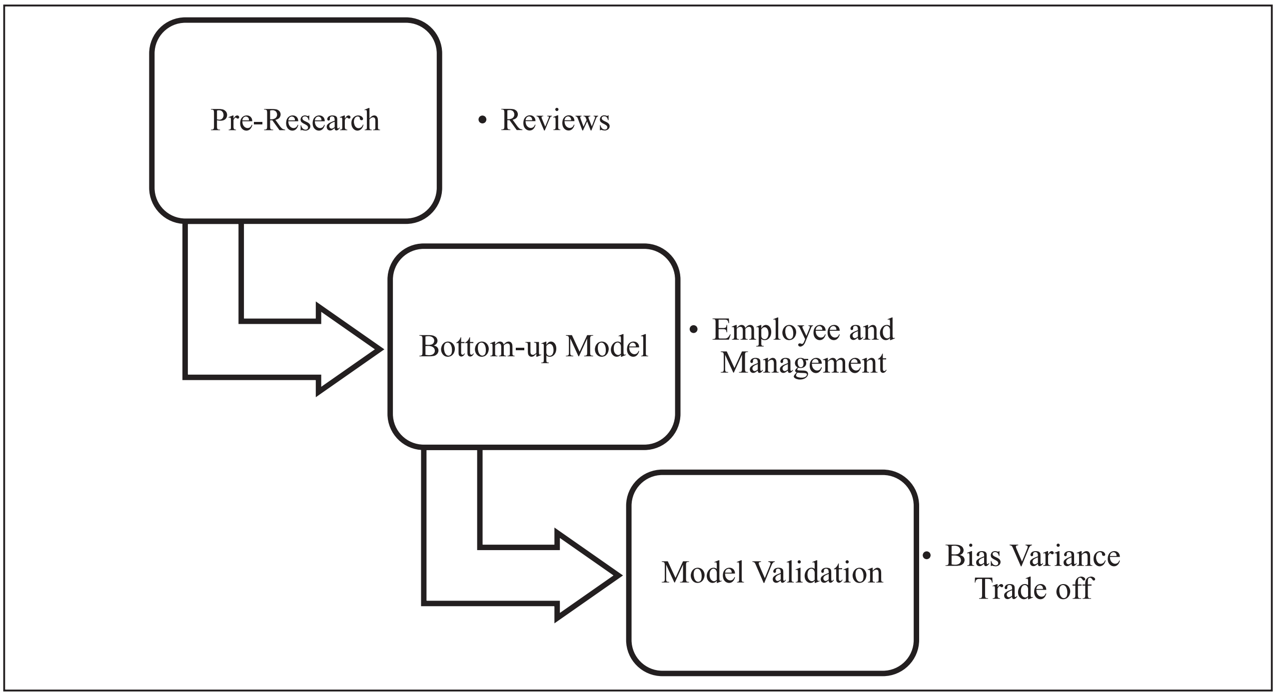

Figure 1: Flowchart for framework of research study

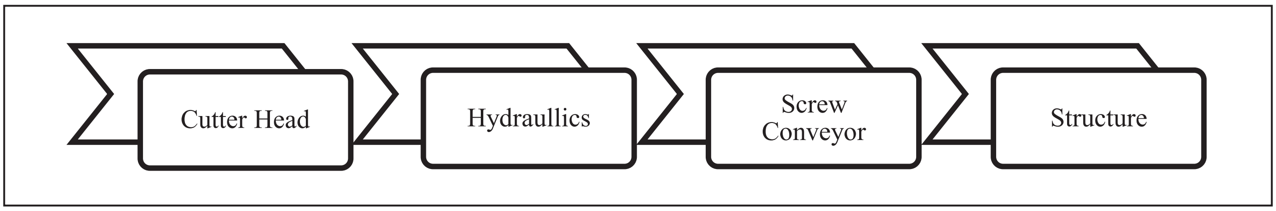

Figure 2: Reliability block diagram of EPBTBM

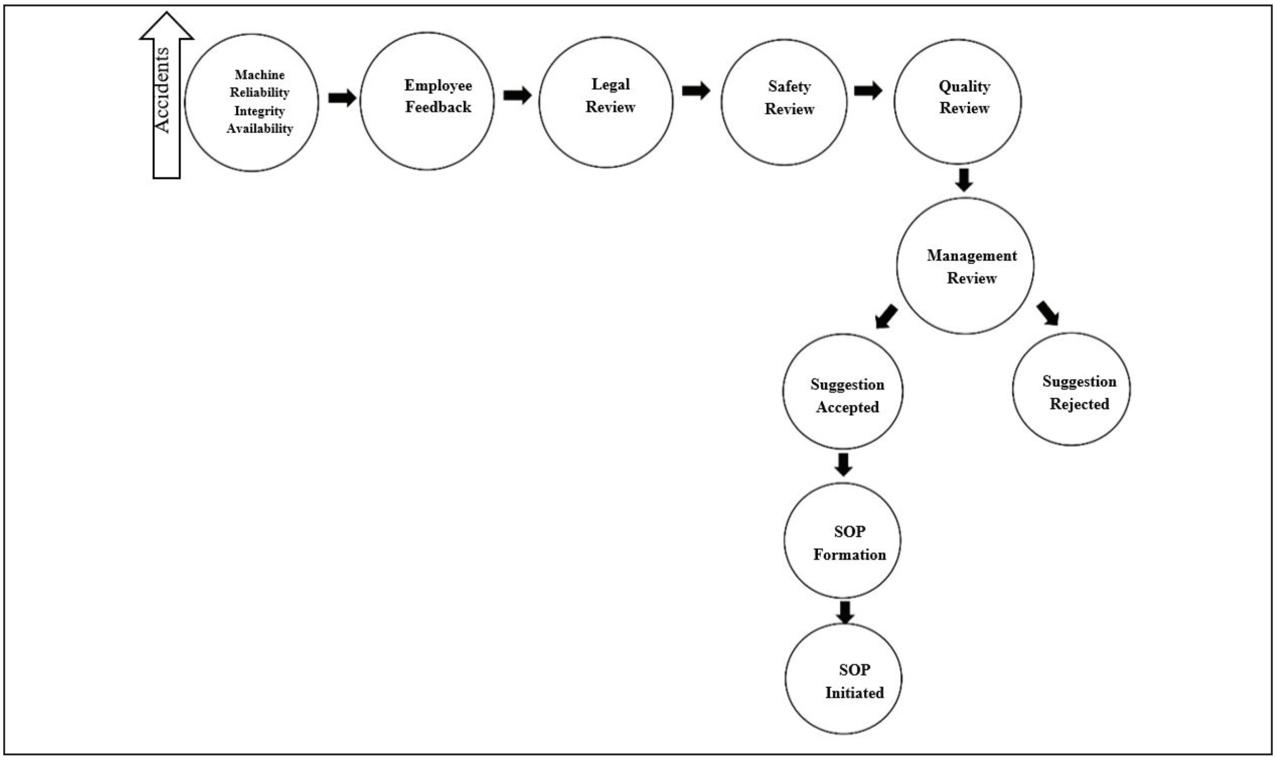

Figure 3: Scientific Model Representing an Improved Bottom-up Approach.

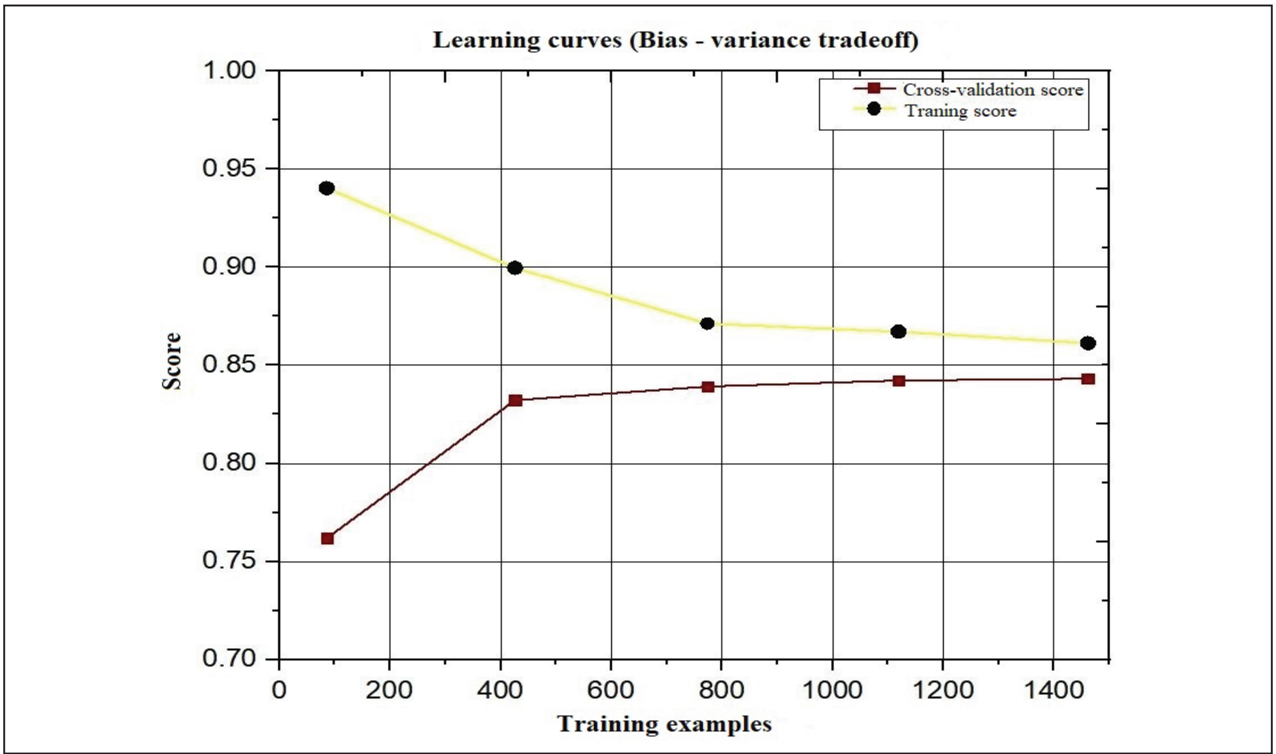

Figure 4: Bias-Variance Trade-off Analysis for Model Validation Graph

Discussion

Machinery Accidents are common everyday issues faced by industries over the years and a number of precautionary steps have been taken into account to curb the accidents. Colombo et al. in 2020 recommended a method to curb machinery accidents by adding regression-based finite elements to fine-tune Weibull parameters and found that the FEMaR-based method was accepted to attain top outcome and learn the characteristics of time to failure in terms of the downhole safety valves.[21] However, this approach does not include the addition of the management and employees' approach to curb the accident.[22] Wu et al. in 2020 investigated real-time updates of the recurring neural network model through process measurements of chemical reactor machines and found that the assistance of online education of RNN models in terms of enhanced closed-loop solidity is achieved but did not fully curb machinery accidents from the core.[23]Innovative ideas in the field of safety can increase the safety performance level of a company.[24,25] A scientific model that initiates an improved Bottom-up approach would reduce machinery accidents at an early age. Figure 3 shows the proposed scientific model design for this research study. The rise in machinery accidents from the elements of machinery reliability, integrity, and availability would be an issue to be addressed in the industry. The collected cases are categorized based on the root cause factors to improve the accuracy of the cases. The first step of the model is to acquire the employees' feedback on the accident issue. Employees who were directly involved in the affected machinery accident will be interviewed and given the chance to provide feedback on how to prevent occurrences of the accident in the future, as they are intimately familiar with the affected machine's functionality. The employees working in the same line of field are also interviewed to reduce partiality and to improve the suggestions for the issue.

The next step is to collect the suggestions received from the employees and convert them into a report to be given to the legal team for certification. Upon receiving the suggestion, the engineer on duty would re-write the suggestions and convert it into an official report to be sent to the legal advisor of the company. The suggestions are filtered and processed by the legal team to verify their compatibility and to check if those suggestions are against any laws of the company and the government. If the suggestions are not on par with the objective and the laws of the company, the idea would be rejected and no further steps would be taken.

Once the suggestion is certified by the legal team, the report goes to the safety department for review. The safety engineer would then have a meeting within the team to discuss the suggestion if it has been proposed previously and improve the suggestion to accommodate the safety rules according to the company's safety policy. The suggestion then goes to the quality department for screening purposes. The quality engineer on duty would perform a final checking of the suggestion to sort out unconventional suggestions and screen for operational methods compatibility. This step is vital in order to have an effective and substantial report before heading towards the upper management.

The upper management would later discuss the report findings in the monthly management review and make a decision based on budgeting and objective factors. If the suggestion is rejected, the report would be kept under records by the management team for reference and as evidence for future purposes. If the suggestion is accepted, the suggestion would then be given to the quality team to develop a precise and extensive Standard Operating Procedure (SOP) based on the suggestion and a briefing would be given to employees on the new SOP formed in order to initiate the new element for the company. The employees who contributed the suggestions would later be given certificates as a token of appreciation.

In order to validate the proposed model, a linear regression analysis through Bias-Variance trade-off method is performed. The proposed model is validated by performing a short case study in a 27MW power plant in Kuala Lumpur, Malaysia. Power plant is chosen for this study as a power plant mainly comprises of safety-critical equipment, which is important and beneficial for the aim of the validation study. Upon approval, fifty employees and twenty management representatives according to the model were selected for the study. Fifty employees working with safety critical equipment were chosen, which comprises of engineers and operators. The age and experience of the selected case study team were not taken into account to avoid discrepancies. The proposed model is thoroughly explained and the power plant was given a total of two months to follow the model process and record the output of the process. The management review and the feedback process were classified as training and the total validation score is generated in accordance with the software attributes of the analysis. The training examples that comprise of the legal, quality, and management review were recorded and the changes in the accident rate were later analyzed for this study. The Bias-Variance Trade-off analysis was carried out as a method of model validation for this study. The graph output from the analysis is shown in Figure 4.

Note that the analysis shows a small gap at the end of the learning curve, which indicates a good fit for the study. The model also has a high-test score and a high validation score, which also indicates a low error rate in the formation of the model for the effectiveness of the study. Mehta et al. in 2019 state that combining a number of simple hypotheses (vertical or horizontal lines) is preferable to using an arbitrary linear classifier.[13] This, of course, comes at the cost of adding more elements to our learning process. However, if the problem cannot be solved with a basic hypothesis, there is no reason to resist using a more complicated model. As ensemble approaches reduce variance, they're a good choice for the study, which follows the combinational training aspects as explained in the methodology. The accident rate in the workplace was also recorded to reduce from twenty-two cases to fourteen cases for the duration of a month after the model was initiated in the workplace.

This improved scientific model proposed by the author that starts from the bottom, all the way to the top management instead of the reverse is vital to tackle the issue from the core of the problem that can minimize accidents easier. This model is a simpler form of Management of Change (MOC) element with mechanical integrity sub-elements included in it, but with a more diverse approach to include multiple steps that inculcate the responsibilities of employees and management. It is an effective method to prevent machinery reliability, integrity, and availability accidents from an early stage.

Conclusion

The objective of the study was met in this study, The Bottom-up approach model was able to reduce the machinery accidents in the workplace through the team effort of employees and the management. The experience of employees who are handling the machineries from all corners of the workplace is beneficial for an effective preventive action to uphold the machinery safety of a workplace. The model is also capable to be one of the solutions to restructure the management review in the field of safety by involving a combinational effort to the performance of the workplace. However, the limitation of the study is restricted to machinery safety in the workplace. The model can be further studied to fit to chemical and biohazard safety in a workplace for future directions.

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