Yearly Plant Maintenance Budget Evaluation: A Simulation Approach

Atul Srivastava, Girish Kumar and Piyush Gupta

January 11, 2021

Yearly Plant Maintenance Budget Evaluation: A Simulation Approach

[1]Atul Kumar Srivastava, [2]GirishKumar, [3]Piyush Gupta

Abstract—The main objective of any production unit is profit. It can be achieved by minimizing the maintenance cost without compromising on the lower bound reliability and availability. Maintenance budget markedly impacts maintenance costs so it is crucial to appropriately assess it for an organization to maintain their competitiveness. Precise estimation of maintenance budget is necessary to initiate and complete the maintenance activity as desired. The existing methodologies of budget estimation are all non-scientific and based on plant specific values of budget influencing parameters and contextual in nature. This work attempts to resolve this. Maintenance parameters affect the maintenance budget and this depends upon the level of identified maintenance parameters. In this paper, different maintenance scenarios are described. Monte Carlo simulations are deployed to evaluate steady state value of maintenance budget by assigning random values to the budget parameters within specified range corresponding to a chosen maintenance scenario.

Mat Lab code is deployed for its implementation. Descriptive analysis is carried out on yearly maintenance budget data generated by Monte Carlo simulation for all identified maintenance scenarios. Descriptive tools such as histogram, box and whisker plot, central tendency and dispersion measures are employed to organize and describe the characteristics of maintenance budget data. The results are validated by comparing it with world class and best practices values reported in the literature.

The study shows that maintenance parameters have significant effect on the plant maintenance budget. It is, therefore necessary to take corrective measures on the budget parameters, if the values of these drop below certain levels. This study will avoid using historic data or subjective expert judgments in selection of maintenance budget.

Keywords—: Descriptive analysis, Maintenance Budget, Maintenance Management, Monte Carlo Simulation

I. Introduction

MAINTENANCE budget (MB) is required to initiate and perform the maintenance activities related to arranging spares, tools, maintenance personnel, special equipment, etc. Inadequacy in maintenance budget may obstruct maintenance works and can create situations such as, interruptions in production and insecure plant practices while excess budget can lead to wasteful expenditure. It is, therefore crucial for an organization to appropriately assess maintenance budget to maintain its competitiveness.

Competitiveness can be achieved only by optimum utilization of maintenance resources. Maintenance budget is generally evaluated in percentage of asset replacement value (ARV). High percentage of MB indicates that organization is spending too much on maintenance activities every year and less indicates that plant follows the competitive levels.

Available maintenance budget estimation techniques are wayward and based on past-period data, opinion of expert or using rule based on experience and practices that might lead to wastage of monetary resources. Gupta and Gupta [9] &Gupta et al. [10] estimated the annual maintenance budget by graph theory and matrix approach for the air conditioning plant of a research institute at New Delhi under contextual condition and for the plant that follows world class standards respectively. The suggested methodology is not generalized but depends upon contextual conditions.

In the proposed methodology, Monte Carlo simulation is suggested to evaluate the yearly maintenance budget (YMB) by allocating the value to the budget variable in the specific range according to the maintenance level. The proposed approach is a generalized technique and enables the maintenance managers in decision-making as regards to annual maintenance budget selection. The rest of this paper is organized as follows: Section II & III briefly discusses the parameters influencing the YMB and reviews the maintenance budget as well as the recent developments. Section IV provides the methodology including model description and algorithm. The results are analyzed through descriptive statistics in different maintenance scenarios in section V. Finally conclusion is presented in the last section.

II.PARAMETERS INFLUENCING MAINTENANCE BUDGET

In this section, various maintenance parameters relevant to budget estimation are discussed. Plant availability measures the performance of system. It is a probability that the machine is performing its stipulated operation within time when functioning under stated operating conditions. Decreasing the rate of failure and improving the repair rate leads to increased availability of the plant. More financial resources will be required in the case of unavailability of plant, consequently it increases the maintenance budget. If the availability of a plant

F. A. Atul Kumar Srivastava is Research scholar with the Delhi Technological University, Delhi, India (Phone: 8383043349 e-mail: atchan1@ rediffmail..com).

S. B. Girish Kumar is with the mechanical engineering department, Delhi technological university, Delhi, India. (e-mail: girishkumar@dce.ac.in).

T. C. Piyush Gupta was with Inter University accelerator centre New Delhi, india, (e-mail:piyushiit1980@gmail).

is greater than 90% then the plant will come under the category of world class standard. The industrial plantoperations are intrinsically hazardous and have high risk. Therefore, the requirement of maintenance work will be more to overcome risk of accident. Higher maintenance budget is required to maintain the desired safety of a plant.

Physical environment, complexity of plant, redundancy in-plant system, technology level that leads to operational automation, service duty of plant, plant layout, physical location of plant are the variables associated with characteristic of plant and distinguished as sub-variables [15]. These variables are also considered to decide the maintenance budget.

It is established that condition monitoring techniques optimize maintenance expenditure by avoiding the untimely failures in the plant. Researchers suggested model to estimate optimum intervals to perform preventive and condition based maintenance [21] [22]. It can help in adopting appropriate maintenance strategies related to the schedule of maintenance actions/tasks.

Type of maintenance work is also important variable in quantifying the maintenance budget. Maintenance interventions are needed to upkeep the plant assets. Proactive and reactive maintenance ensures the availability of plant. It is recognized that proactive maintenance reduces the maintenance cost by 15-30%, reduction in downtime by 20-40%, increase in production by 15-25%. More than 80% of maintenance works must be proactive, Gulati and Smith [7].

Kumar and Gandhi [13] reported that majority of equipment of any plant breakdown due to human error. Therefore, skilled manpower should be deployed in maintenance activities of plant.

An efficient inventory management system leads to lower waiting time for spare parts while performing maintenance. Thus, inventory management is significant in reducing maintenance costs. Gulati and Smith [7] reported that maintenance personnel wasted 30 % of time in locating the spare parts in store. Hence, highly effective material management software must be used by the organizations for their stocking decisions to prevent unnecessary delay in maintenance work.

It is widely recognized that procurement of 100 % of spares required for asset maintenance will be uneconomical for any organization. Procurement of the optimal number of critical spare part is a challenging task because the demand for these parts, other than planned maintenance is unpredictable. Therefore, the ordering decision of spare parts should be rational. Condition-based maintenance reduces inventory as the procurement of parts can be triggered by the identification of a potential failure, Louit et al. [14].

Maintenance planning should be based on methodology, technical documentation, work content, safety and special requirements, requisite human/material resources, etc. It reduces the failure probability of system and also helps in improving safety and environment concern. Further, it enables maintenance team to take right decisions regarding employing maintenance resources. This will result in better plant utilization. Intensity of planning, planning response, and quality of planning can be used for quantification of maintenance planning variable.

It is established that planning of production and maintenance simultaneously result in reduced maintenance budget. Scheduling is an interdependent exercise between operation and maintenance. Scheduling intensity, scheduling quality and schedule realization rate are the key indicators to quantify the maintenance scheduling variable Muchiri et al.[15].

Maintenance execution is carried out after the completion of maintenance planning and scheduling according to requirement of operations. This budget variable is determined by considering the value of schedule compliance, percentage of re-work, percentage of completed task over all received tasks, manpower efficiency and number of overdue tasks Muchiri et al.[15].

III. MAINTENANCE BUDGET

Maintenance costs account for significant proportion of today’s manufacturing costs and it is found that a third maintenance budget is wasted due to improper maintenance management. Moreover, break down repairs are usually three times more costly than planned repairs. In United Kingdom maintenance budget ranges from 12 to 23 % of total plant operating cost. Dekker [4] showed that due to automation in the production processes, work force in maintenance department has increased considerably, which has resulted in increased maintenance spending. Appropriate policy for performing the maintenance significantly reduces the maintenance budget. Sarkar et al. [19] recommended that maintenance budget is vitally impacted by the number of age groups and age threshold of components. Topal et al. [20] showed that the optimal scheduling of mining equipment in mining industry reduced 16% maintenance budget in one decade of mining life. Campbell [3] recorded that 40-50 % of the total operating cost in mining industry was on account of maintenance. Condition based maintenance (CBM) approach may be applied to mitigate the yearly maintenance budget of a plant by using condition monitoring data of machines. Maintenance decisions on whole system rather than individual components will be more economical, which results in reduced annual maintenance budget. Nahas et al. [16] optimized the sequence of preventive maintenance actions, which reduces the cost of maintenance along with desired system reliability. Pham &Wang [18] established the optimal maintenance policies to maintain optimum system availability/reliability and safety achievements at the least possible cost of maintenance. When YMB is more than 20% of asset replacement value then it will not be economical to apply maintenance action, but to initiate the process of replacement of existing plant by new one. Industries are not yet giving due importance to maintenance. Efficiency of maintenance may be boosted by applying reliability centered maintenance policies and total productive maintenance. Alsyouf [1] investigated that about 13% of the maintenance time is wasted in maintenance planning and approximately one-third of time is lost on unplanned tasks.

Gulati and Smith [7] reported that, the benchmark for YMB lies between 3 to 9 percentage of asset replacement value if the plant follows best maintenance practices and, the world class organizations spend about 2.5 to 3.5 percentage. Subsequently, Gupta et al. [10] developed a model to calculate the annual maintenance budget (AMB) in terms of percentage of asset replacement value (ARV) by taking considerations of numerous maintenance parameters affecting the budget. The model was validated using several case-studies. Additional validation of this model was also done by Gupta [8] in evaluating the maintenance cost for a particle accelerator system. In another similar work, Gupta and Gupta [9] evaluated the annual maintenance budget (AMB) for an air conditioning plant working in specific contextual constraints. The suggested methodology could evaluate the maintenance budget, without taking the expert opinion. The methodology was based on contextual condition of plant and salvage value of assets, and it enabled the maintenance manager to identify the weaknesses in the maintenance system.

Bahr and Kunnibert [2] developed a practical adaptive budgeting of maintenance to facilitate the transparent and realistic evaluation of maintenance budget, which enables maintenance managers to estimate accurate budget projections for the maintenance. Ottoman et al. [17] estimated the maintenance budget considering the plant replacement value/initial cost, components and systems life-cycle cost, quantifiable characteristics of the plant, and determination of present /projected physical condition of the plant by comparing the available repair and maintenance budget models. Maintenance budget largely depends upon the environment, such as, harsh climatic condition, inadequate and insufficient facilities for maintenance. Kayrbekova et al. [11] showed that maintenance cost increases in low temperature region. These effects must be accounted for accurately using suitable statistical models to achieve competitiveness. Komonen [12] developed a cost model for benchmarking and profitability analysis of industrial maintenance by developing a hierarchical system of identified performance indicators.

Dordevic et al. [5] established an optimization model for maintenance budget, which was based on maintenance plan. The model minimizes the maintenance budget and achieves the required level of reliability. Ferreira et al.[6] formulated a non-linear programming model to solve the problem of maintenance budgeting for a multi-component system. The result optimizes the anticipated value of deterministic and stochastic costs.

IV. METHODOLOGY

This section covers model description and algorithm for evaluation of maintenance budget for different maintenance scenarios. For the system modeling, parameters that affected the plant maintenance budget are identified. The identification of parameters is based on literature and expert discussions. The estimation of budget is done broadly in 8 maintenance scenarios considering the range of budget influencing parameters. (Refer Table I). The variables in the range of higher side will reduce the maintenance budget. The value 100 represents the ideal condition of variable.

Model Description

The proposed work is the extension of the budget model suggested by Gupta et al. [10]. The developed model is based on Graph theory and matrix approach (GTMA)

The main steps followed in the model formulation are discussed briefly in the following:

- Initially the pertinent maintenance parameters are identified.
- Next, the attributes digraph is developed considering the identified parameters and their mutual importance. The number of nodes shall be equal to the number of parameters. The edges and their direction are based on interrelations among the parameters.
- Subsequently, the maintenance budget matrix for the digraph is generated. The matrix is of size x by x with diagonal elements as maintenance parameters and the degree of influence among the parameters are off-diagonal elements. Diagonal elements are determined by assigning the value to each variable in percentage based on operational practices and then take log of that value in order to avoid skewness. Off-diagonal element for each variable is calculated depending upon the intensity of relation with other variable.
- Finally, the permanent function for the matrix is obtained that is called budget function of maintenance (BFM). Permanent is used to avoid loss of information.
- The yearly maintenance budget is evaluated by the following expressions.

YMB $=\{(BIM \times 100) - 100\}$% of ARV).

Where, budget index of maintenance (BIM) is determined by

$$BIM = \frac{BFM(ideal)}{BFM(actual)}$$

- In this work a generic model is introduced in place of contextual model developed by Gupta et al. [10]. Different values within the range of 0-100 are allocated to identify maintenance parameters for different category of plants (S_1-S_8) and MCS is used for estimation of maintenance budget (Refer Table I).

To implement the suggested methodology an algorithm is suggested as follows:

Algorithm

An algorithm is developed for AMB estimation based on MCS and various steps are detailed as.

Step (a): V_1, V_2, V_3……….. V_x are the x maintenance parameter. These variables are diagonal elements of the matrix and input to the model.

Step (b): Off-diagonal elements of matrix for each variable are assigned values depending upon the intensity of relation with other parameters.

Step(c): Allocate the value 100 to all budget influence variable under ideal condition.

Step(d): Generate the ideal maintenance budget matrix.

Step (e): Evaluate Permanent of matrix under ideal condition.

Table I
Categorization of Maintenance scenarios based on parameter range

S. No.	Maintenance parameters	Maintenance Scenarios/Parameter range							
		S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8
1.	Plant availability	90	90-100	90-100	80-100	70-100	80-90	70-80	60-70
2.	Safety aspects of plant	100	100	90-100	80-100	70-100	80-90	70-80	60-70
3.	Characteristics of plant	93	93-100	90-100	80-100	70-100	80-90	70-80	60-70
4.	Optimization tools along with condition monitoring technique	100	100	90-100	80-100	70-100	80-90	70-80	60-70
5.	Type of maintenance	80	80-100	90-100	80-100	70-100	80-90	70-80	60-70
6.	Quality of manpower	95	95-100	90-100	80-100	70-100	80-90	70-80	60-70
7.	Inventory management	98	98-100	90-100	80-100	70-100	80-90	70-80	60-70
8.	Procurement rate of critical spares	99	99-100	90-100	80-100	70-100	80-90	70-80	60-70
9.	Maintenance planning	95	95-100	90-100	80-100	70-100	80-90	70-80	60-70
10.	Maintenance scheduling	95	95-100	90-100	80-100	70-100	80-90	70-80	60-70
11.	Maintenance execution	90	90-100	90-100	80-100	70-100	80-90	70-80	60-70

Step (f): Generate the x random numbers between (0-100) and allocate to x budget variables for plant followed various maintenance scenarios (Refer Table I).
Step (g): Generate the maintenance budget matrix for given scenario.
Step (h): Evaluate Permanent of matrix.
Step (i): Calculate the maintenance budget index.
Step (j): Evaluate the YMB.
Step (k): Repeat the step (f) to step (i) for N number of cycles. Where N is sufficiently large to converge the result.
Step (l): Calculate mean and variance of YMB after each simulation.
Step (m): Simulate the mean for N numbers of cycles using MCS.
Step (n): Perform statistical analysis on model output for various parameters.

V. RESULTS AND DISCUSSION

Descriptive statistics is the procedure that summarizes the data with the purpose of describing what occurred in the sample and detect the characteristics of the sample. In this work histogram, box and whisker plot, central tendency and dispersion measures are used to organize and describe the characteristics of maintenance budget. Descriptive analysis is carried out by budget data collected from 1000 Monte Carlo simulation runs.

The histogram corresponding to maintenance scenario (S_4) with budget parameters values in the range 80-100 is shown in the Fig. 1. Gulati and Smith [7] observed that, the industries following world class standards spend about 2.5 to 3.5 YMB in percent of asset replacement value (ARV) on maintenance and the standard lies between 3 to 9 percent, if best maintenance practices are followed. From the histogram (fig. 1), it is clear that 3% of budget data falls in between 2.5 to 3.5 % (world class) and 83% data are in best practices range. It means that restricting the maintenance parameters in the maintenance scenario S_4 most of the YMB values fall in best practices range. On the other hand, the histogram for Scenario S_2 indicates that majority of plants are in world class category as AMB is less than 3%. In the case of maintenance scenario S_2, the data are centered at 1.67% and have a spread measured by inter-quartile range of 0.76%. The maximum and minimum value of budget is 2.91% and 0.49% respectively. It reflects that plant follows world class standards regarding maintenance expenditures. After analyzing the data for Scenario (S_3), it is concluded from the histogram that approximate 7 % data are

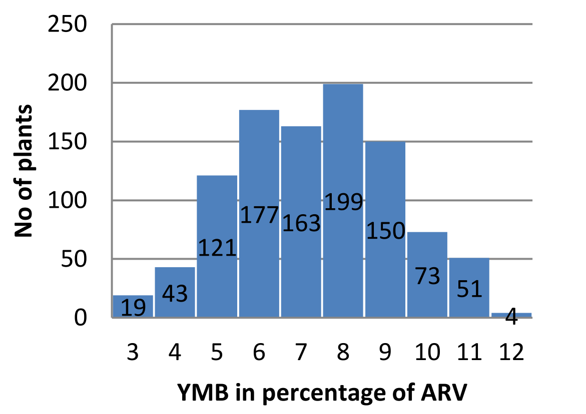

Fig. 1 Histogram for scenario (S_4)

of world class, 93% possibility is that the plant follows best practices. The key feature of maintenance scenario (S_5) is that there are 66% data are in worst practices span, 32% data are in best practices range and only 2% cases are of world class. Such maintenance scenario is critical however the distribution is positively skewed. After analyzing the data for scenario (S_6) it is observed that 93% maintenance budget data are of worst practices range and 7% chances for best practice. Such type of maintenance level is highly critical and there is need for improving the maintenance parameters. A closer look at results for maintenance level (S_7) and (S_8) shows that 100 % data are in worst practices range. In maintenance scenario (S_7), 40% data are those in which maintenance budget is more than 20% of asset replacement value. In such circumstances completely new plant must be procured. For maintenance scenario (S_8) 100% data exhibits maintenance budget more than 20% of ARV, which shows that all the maintenance parameters are working in worst condition and the plant must be replaced.

An overview of the characteristics of maintenance budget data is also presented using Box plots. The box represents the 25^{th} and 75^{th} percentile values of the maintenance budget data, whereas the bar inside the box signifies the median. The whisker attached to the box characterizes the range of the budget data. A data set of 1000 was used to construct the Box and whisker plots for different maintenance scenarios. The plot for maintenance scenario (S_4) is displayed in Fig. 2. It shows that typical budget values are in between inter-quartile range (5.32% to 8.19%). The median value is about 6.9%. It shows a more or less even distribution and the plant is having higher chances of getting best practitioner rank.

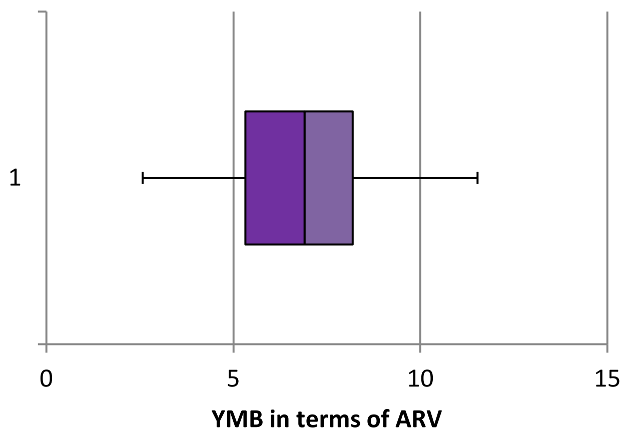

Fig.2 Box and whisker plot for scenario (S_4)

A box and whisker plot was similarly constructed for scenario S_3 and we can instantly conclude that 50% of maintenance budget data has a value in the range of 2.6 to 3.79% and 25% data lies in between 3.79 to 5.83%.The median lies at about 3.15%. Also, more than 50% of possibility is that the plant follows world class maintenance practices and less than 25 % possibility is that the plant follows best maintenance practices. By observing the shape of the box plot, it can be identified that the distribution is positively skewed.

When comparing the box and whisker plot for maintenance scenario (S_5) to (S_8), the scenario (S_6) to (S_8) are having higher chances of getting worst maintenance practices category. Quantitative measures are used to summarize a set of data in a clear and comprehensible manner. Central tendency and dispersion are the two key characteristics of quantitative measures. Mean, median, mode is the major estimates to characterize central tendency & variance and standard deviation are the main measures of dispersion. Skewness and kurtosis gives the idea about the shape of the distribution and how well the distribution can be approximated to the normal distribution. For this work the selected parameters are summarized in table II.

For scenario S_2 in table II, the mean and median value of maintenance budget is 1.7% and 1.67% respectively. 1.46% is the most frequently occurring value in the maintenance budget data set. The value of mean is greater than median. Therefore, the distribution is positively skewed. This is evident from the value of skewness in the table 2 i.e. +0.06. The value of kurtosis is -0.57 which indicates that the distribution is platykurtic. The spread dispersion is 0.27. The small value of spread signifies that the maintenance budget values of the distribution are very close to the mean value of maintenance budget.

However, owing to very small differences in mean, median and mode values it can be concluded that the population from which the sample of maintenance budget was drawn is normally distributed.

Examining the maintenance budget data of (S_3) to (S_5) scenarios, mean is found greater than median in (S_3)and (S_5), therefore, the distribution is positively skewed; on the other hand it is negatively skewed in (S_4) due to lower value of mean than median. The distribution will be platykurtic and moderately skewed in all maintenance scenarios. Moreover, the variance is large in case of (S_5). It signifies that the budget values largely deviate from the mean value of budget (Refer table 2). A closer look at result tabulated in table II for maintenance level (S_6) to (S_8) showed a negative skewness in (S_6) and (S_8)indicated by the tail of the distribution extending to the left side of the curve; conversely in (S_7) the tail of the distribution extends to the right side and positively skewed. Moreover, skewness is very less in (S_6) and (S_7) hence most of the budget data is clustered near the center. The kurtosis is positive in (S_8) shows leptokurtic distribution. And negative in

Table II

Quantitative descriptive measures for different maintenance scenario

		Central tendency measures			Dispersion measures			
Maintenance scenario/ parameter range		Mean	Median	Mode	Variance	Std.	Skewness	Kurtosis
S2(World class range)		1.70	1.67	1.46	0.27	Deviation	0.06	-0.57
S_3	90-100	3.18	3.15	1.79	0.66	0.53	0.02	-0.46
S_4	80-100	6.84	6.9	10.18		0.81	0.04	-0.57
S_5	70-100		10.83	11.90	3.59	1.89	0.14	-0.88
S_6	80-90	10.96	10.51	10.45	10.61	3.26	-0.04	-0.57
S_7	70-80	10.49	19.57	19.29	1.06	1.03	0.05	-0.59
S_8	60-70	19.57	30.72	29.65	1.68	1.30	-0.54	1.73

(S_6) and (S_7) that confirm platykurtic distribution. The variance is 2.38% in S_8 implying that the budget data are not closer to the midpoint in comparison to (S_6) and (S_7) where the budget data is close to the center.

VI. CONCLUSIONS

The result of the analysis shows that the maintenance parameters have a great influence on maintenance budget of a plant. Descriptive statistics is used for summarizing the quantitative data of maintenance budget for various maintenance scenarios.

The study is useful for the maintenance manager who will have a better insight on maintenance budgeting for different maintenance scenarios. The study offers an opportunity to evaluate the maintenance budget scientifically as maintenance parameters have been assigned random values within specified ranges corresponding to the chosen maintenance scenario.

This study is concerned with descriptive analysis, however it can be extended to parameter estimation according to inferential statistics. This paper encourages further research by using additional maintenance parameters that are not incorporated in computation of yearly maintenance budget.

REFERENCES

[1] Alsyouf, I., 2009. Maintenance practices in Swedish industries: survey result. International Journal of Production Economics. 121(1), 212-223.

[2] Bahr, C., and Lennerts, K., 2010. Quantitative validation of budgeting methods and suggestion of a new calculation method for the determination of maintenance costs. Journal of Facilities Management. 8(1), 47-63.

[3] Campbell, D., 1995.Uptime: Strategies for Excellence in Maintenance Management. Productivity Press, Portland, OR, USA.

[4] Dekker, R., 1996. Applications of maintenance optimization models: a review and analysis. Reliability Engineering& System Safety. 51(3), 229-40.

[5] Dordevic, M., Petrovic, S., Peric, S., and Spasic, D., 2012. Maintenance cost budgeting optimization. 5thInternational Scientific Conference on Defensive Technologies *OTEH*, Belgrade, Serbia, 18-19 September.

[6] Ferreira, R.S., Barroso, A., Feinstein, C., and Borges, L., 2013. A non-linear programming approach tomaintenance budgeting for multi-component systems. IEEE Transactions on Power and Energy, 1-5.

[7] Gulati, R., and Smith, R., 2009. Maintenance and Reliability Best Practices, Industrial Press Inc. New York, NY 10018, USA.

[8] Gupta, P., 2017. Maintenance budget estimation for a Particle Accelerator System under its contextualconditions: a case study. International Journal of Systems AssuranceEngineering and Management. 88(Suppl. 2),S1143–S1153.

[9] Gupta, S., and Gupta, P., 2017. Evaluating maintenance budget for an AC plant under its contextualconditions. Journal of facilities management. 15(1), 76-89.

[10] Gupta, P., Gupta, S., and Gandhi, O.P., 2014. Annual maintenance budget estimation for a plant system –Digraph model and matrix approach. Journal of Quality in Maintenance Engineering.20 (2), 193-210.

[11] Kayrbekova, D., Barbadi, A., and Markeset, T., 2011. Maintenance cost evaluation of a system to be used in Arctic Conditions: a case study. Journal of Quality in Maintenance Engineering. 17(4), 320-336.

[12] Komonen, K.., 2002. A cost model of industrial maintenance for profitability analysis and benchmarking.International Journal of Production Economics. 79(1), 15- 31.

[13] Kumar, V., and Gandhi, O. P., 2011. Quantification of human error in maintenance using graph theoryand matrix approach. Quality and Reliability Engineering International, 27(8), 1145-1172.

[14] Louit, D., Pascual, R., Banjevic, D., Jardine, A., 2011. Optimization model for critical parts inventories- A reliability approach. Journal of Operation Research Society.62(1),992-1004.

[15] Muchiri, P., Pintelon, L., Gelders, L., and Martin, H., 2011. Development of maintenance functionperformance measurement framework and indicators, International Journal of Production Economics. 131(1), 295- 302.

[16] Nahas, N., Khatab, A., Ait-Kadi, D., and Nourelfath, M., 2008. Extended great deluge algorithm for theimperfect preventive maintenance optimization of multi-state systems. Reliability Engineering & System Safety. 93(11), 1658-72.

[17] Ottoman, G. R., Nixon, W. B., and Lofgren, S. T., 1999. Budgeting for facility maintenance and repair. I: methods and models. Journal of Management in Engineering. 15(4), 71-83.

[18] Pham, H., and Wang, H., 1996. Imperfect maintenance. European Journal of Operation Research. 94(3), 425–438.

[19] Sarker, B. R., and Faiz, T. I., 2016. Minimizing maintenance cost for offshore wind turbines following multi-level opportunistic preventive strategy. Renewable Energy. 85, 104-113.

[12] Komonen, K.., 2002. A cost model of industrial maintenance for profitability analysis and benchmarking.
International Journal of Production Economics. 79(1), 15- 31.

[13] Kumar, V., and Gandhi, O. P., 2011. Quantification of human error in maintenance using graph theoryand matrix approach. Quality and Reliability Engineering International, 27(8), 1145-1172.

[14] Louit, D., Pascual, R., Banjevic, D., Jardine, A., 2011. Optimization model for critical parts inventories- A reliability approach. Journal of Operation Research Society.62 (1), 992-1004.

[15] Muchiri, P., Pintelon, L., Gelders, L., and Martin, H., 2011. Development of maintenance functionperformance measurement framework and indicators, International Journal of Production Economics. 131(1), 295- 302.

[16] Nahas, N., Khatab, A., Ait-Kadi, D., and Nourelfath, M., 2008. Extended great deluge algorithm for theimperfect preventive maintenance optimization of multi-state systems. Reliability Engineering & System Safety. 93(11), 1658-72.

[17] Ottoman, G. R., Nixon, W. B., and Lofgren, S. T., 1999. Budgeting for facility maintenance and repair. I: methods and models. Journal of Management in Engineering. 15(4), 71-83.

[18] Pham, H., and Wang, H., 1996. Imperfect maintenance. European Journal of Operation Research. 94(3), 425–438.

[19] Sarker, B. R., and Faiz, T. I., 2016. Minimizing maintenance cost for offshore wind turbines following multi-level opportunistic preventive strategy. Renewable Energy. 85, 104-113.

[20] Topal, E., and Ramzan, S., 2010. A new MIP model for mine equipment scheduling by minimizing maintenance cost.Europian journal of operational research. 207(2), 1065-1071.

[21] Kumar, G**.,** Jain, V., and Gandhi, O. P., (2018). Availability analysis of mechanical systems with condition based maintenance using semi-Markov and evaluation of optimal condition monitoring interval. Journal of Industrial Engineering International, 14(1): 119-131.

[22] Kumar, G., and Joel, P. V., (2019), Optimum preventive maintenance policy for a mechanical system using Semi-Markov approach and Golden section search technique, *2018* IEEE International Conference on Industrial Engineering and Engineering Management (IEEM), Bangkok, Thailand, Dec. 16-19, 2018, 232-236.