Discrete-Event Simulation of a Maintenance Policy with Multiple Scenarios

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Abstract. The current study offers a discrete-event simulation algorithm developed to reveal the effects of different maintenance work packages on the failure and the cost profiles of the mining systems. The algorithm is stochastic with two possible optimization criteria as maximizing system availability and minimizing maintenance cost for a given period. A numeric example is also provided to highlight how the effectiveness of a maintenance policy may differ with its content. In the example, 42 alternative maintenance policies were applied to an earthmover where corrective maintenance, preventive maintenance in regular inspections and opportunistic maintenance were located combinatorially for different inspection intervals. The total maintenance cost was dropped to $913,481 with an achievable production of 7,304 h for the optimal policy that included only corrective and opportunistic maintenance in the system-level, and excluded regular inspections.

Keywords: Maintenance policy · Mining machinery · Discrete-event simulation

1 Introduction

Increasing rate of production and the technology adapted to systems have evolved maintenance policy requirements in the recent decades. Corrective maintenance, which stands for run-to-failure approach and repair after component failure, had a high priority in maintenance policies a couple of decades ago. Corrective repairing or replacement of components may be performed immediately after the failure or with a delay when the defect is not major. However, global industrial competition motivated especially after the world wars has necessitated preventive actions in maintenance policies in such a way that high production rates and system health can be satisfied simultaneously. In addition, improvements in sensor technology have enabled the utilization of remote monitoring systems that can warn operators and managers about the approaching failures. These systems continuously check some indicators such as vibration, heat, pressure, tension, and revolution in the related components so that predetermined thresholds for each indicator may give a notice about the minor defects that can turn to failures. These systems are called condition-monitoring systems, and categorized under preventive maintenance. Since condition-monitoring is not always

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applicable, its financial and operational benefits need to be inquired. One another branch of preventive maintenance is predetermined maintenance where calendar-clock or engine hour counter is taken as a basis in defining which components need to be replaced or repaired with which intervals. The last type of preventive maintenance is opportunistic maintenance. In case that any mandatory or pre-scheduled maintenance activity for any component in the system creates any opportunity time, and the required resources, i.e. spare parts and crew capacity, are good enough, then, an opportunistic maintenance may be performed for the operable but deteriorated components in the meanwhile.

Maintenance work packages frequently applied for production systems can be viewed in Fig. 1. Single or multiple of these activities may be included in a maintenance policy if applicable. Although the implementation of preventive maintenance increases scheduled system halts, it decreases unplanned downtimes due to component failures and the resultant system deterioration. In this basis, properly located preventive measures in a maintenance policy may have a reduction in total maintenance cost by 8 to 12% [2].

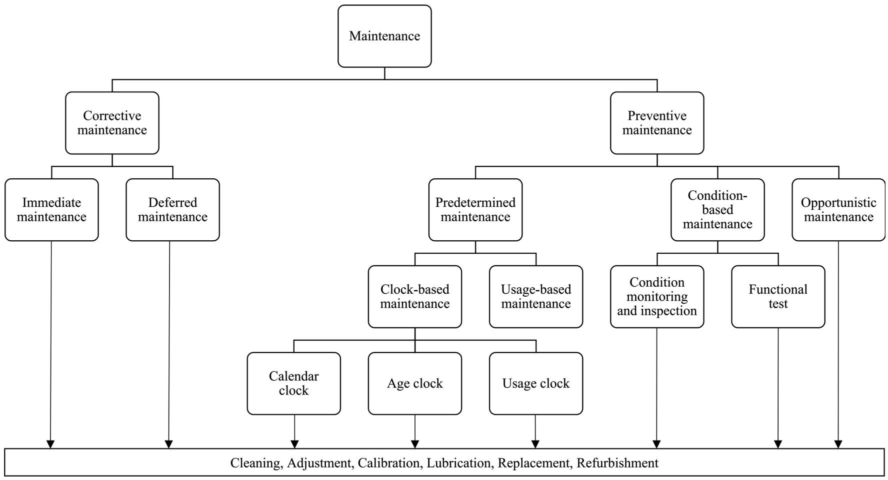

Fig. 1. Sub-branches of a maintenance policy for production systems [1]

A vast majority of the literature studies concentrates mainly on predetermined maintenance while corrective maintenance has a remarkable weight in industrial applications (Fig. 2). In this sense, future researches need to evaluate more than one maintenance type to have more applicable and comparable results with the industry. In addition, there is still a lack of enough literature about which maintenance work packages need to be selected specific to mining machineries, and what the overall benefit or loss for different policies is. The current study offers a discrete-event simulation algorithm that is capable of calculating annual availabilities and overall maintenance costs of mining machines sensitive to the scopes of maintenance policies.

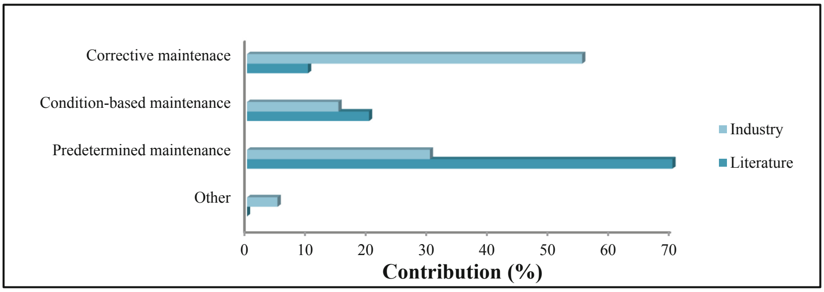

Fig. 2. Weight of maintenance activities in the US industry [2] and the literature researches [3]

2 Multi-scenario Maintenance Model

This study intends to develop a dynamic maintenance model to reveal the sensitivity of system outputs to the scope of applied maintenance policies. System outputs will be system availability, production rates, failure profiles of components or subsystems and total maintenance cost including physical maintenance cost and the value of production loss. The developed model regards stochastic behaviors of operating times and failure downtimes when deciding on the changes in system status that can either of (i) under corrective maintenance, (ii) under preventive maintenance in a regular inspection, (iii) under opportunistic maintenance, (iv) production interruption due to a scheduled break, and (v) no maintenance required and production resuming. Using the study methodology (Fig. 3), three different scenarios can be generated as follows:

- 1st Scenario - Corrective maintenance and preventive maintenance in inspections: This policy assumes that the failed components will be recovered with corrective maintenance during production shifts. Second, any deterioration detected during regular inspections will be fixed preventively. The deterioration levels of all components are determined with an approach called delay-time. Delay-time assumes that some components may give some preliminary warnings for various anomalies and these anomalies happen after a while from components' certain lifetime. After the appearance of such an anomaly, it becomes detectable when the crew makes a visual check on that component during any system halt.
- 2nd Scenario - Corrective maintenance, preventive maintenance in inspections, and opportunistic maintenance in system level: Corrective and preventive maintenance parts of this scenario are same as the first scenario. Additionally, opportunistic maintenance will be applied for the deteriorated components if corrective maintenance of any other failure gives enough time for the opportunistic maintenance of any non-failed but deteriorated component in the system. For instance, let's suppose that a component called Comp01 fails and the algorithm assigns a random corrective repair time of 1.5 h. Here, the algorithm also performs a simultaneous check for the deterioration levels of other components. If a component called Comp04 is detected to be deteriorated and its required maintenance time is less than 1.5 h, this component is also maintained opportunistically.

- 3rd Scenario - Corrective maintenance, preventive maintenance in inspections, and opportunistic maintenance in subsystem level: All the policy items work in the same way with the second scenario. Only difference here is that opportunistic maintenance is applied in sub-system level. It means that the algorithm checks the probability of performing an opportunistic maintenance for the components of subsystem where a failure happens. The second and the third scenarios assume that there is not any restriction for crew capacity and competency, and inventory level.

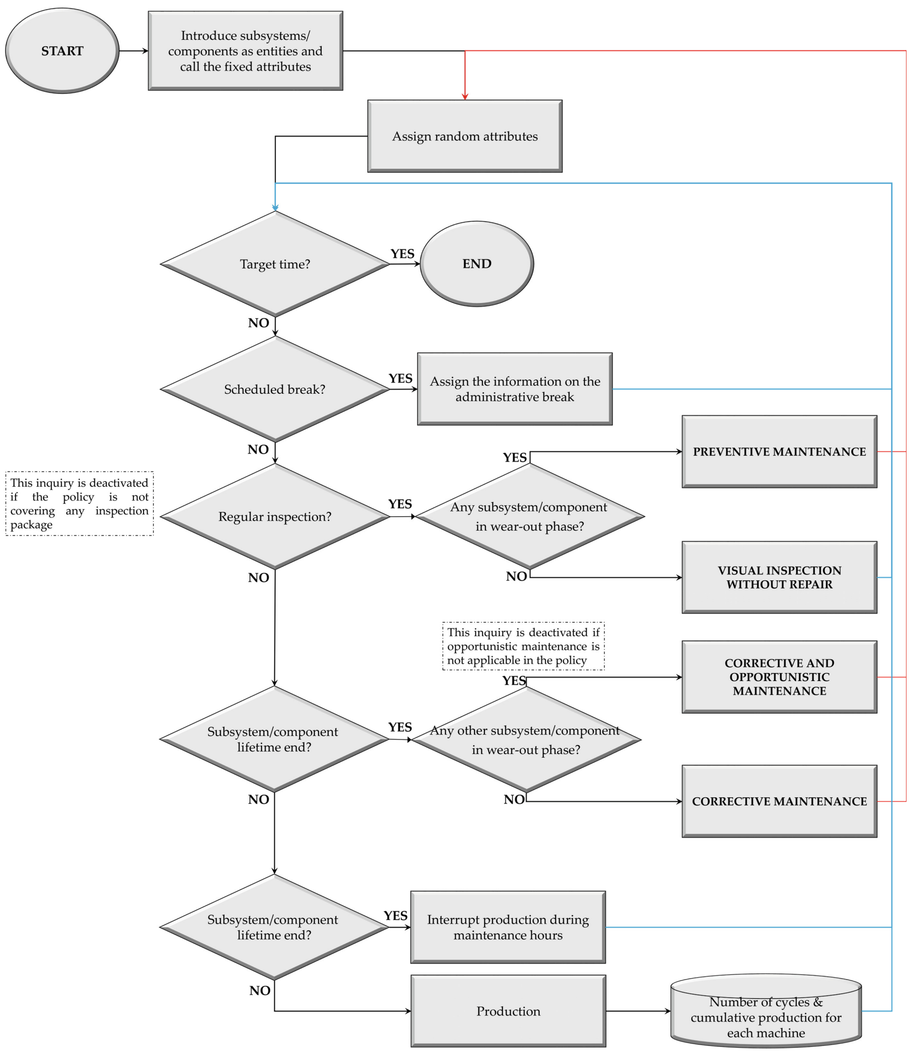

Fig. 3. The algorithm methodology

The algorithm briefly discussed in Fig. 3 is implemented in Arena® software, which is a discrete-event simulation software used in various industries to reveal the resource allocation and production flow in a cycle. In this basis, the current model requires an earlier acquisition and determination of some random and deterministic attributes. Since the model output can be either of maximizing availability or of minimizing cost, data requirement may show a change. As given in Fig. 4, an application just on system availability can be carried out if there is an available knowledge about component failure and repair times, scheduled breaks, times and durations of planned maintenance activities, and component deterioration rates. In case that cost values are also available, the algorithm can compute to see the best maintenance policy that minimizes the total maintenance cost including direct and indirect cost values.

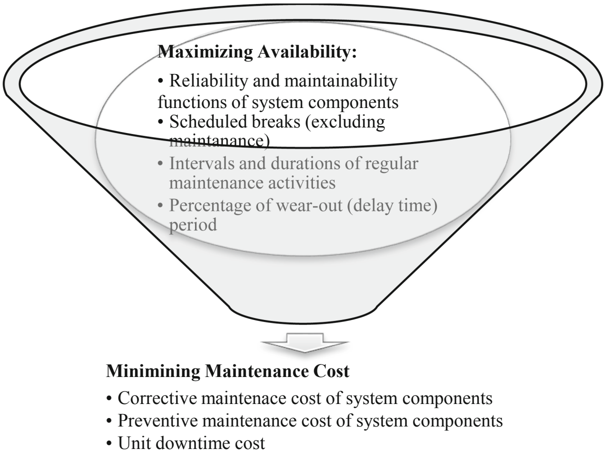

Fig. 4. The data requirement depending on the model objective

3 A Case Study for an Earthmover

The algorithm was implemented for a dragline with a bucket capacity of 30 yd^3. Three main parameters of the model, which are time between failures (TBF), time to repair (TTR) and the starting time of wear-out phase (TSW) were retrieved from a research study by [4]. In that study, a dragline was decomposed into twenty-seven components that have at least five failure records for an operating period of 11 years. The components were clustered under six main subsystems with a serial dependency: Machinery house (MH), rigging (RI), dragging (DR), bucket (BU), movement (MO), boom (BO). In the simulation, TBF, TTR and TSW values were generated randomly from the reliability functions, maintainability functions, and delay-time percentages of the components, respectively. Since the cost values are also available, the algorithm computes for both availability and cost predictions that variate depending on the maintenance policy type.

As discussed in the previous chapter, all three scenarios cover corrective maintenance and inspection that are the work packages observed in mining areas frequently. Here, the algorithm allows not just comparing three policies, also tries to find out the inspection interval that minimizes the total maintenance cost. In this section, all three policies are evaluated for an inspection interval changing between 16 h and 320 h with an increment of 24 h. Therefore, 14 different alternatives in each scenario, 42 alternatives in total, are evaluated and compared. According to the simulation results, the best alternative in each scenario is given in Table 1.

Table 1. The best alternatives for each scenario in terms of the total maintenance cost.

Scenario ID	TBI (h)	Direct cost ($)	Indirect cost ($)	Total cost ($)	Production time (h/year)
1	208	112,088	869,650	981,738	7,157
2	Very large	121,272	792,209	913,481	7,304
3	304	113,516	861,159	974,675	7,174

The results show that, in the first scenario where only corrective maintenance and regular inspections are applied, time between inspections (TBI) with a value of 208 h will drop the total maintenance cost to $981,738 where a total production time of 7,157 h per year will be achieved. In the second scenario where opportunistic maintenance in system level is applied additionally, the algorithm minimizes the total cost to $913,481 with a decision of no inspection. Here, the algorithm takes a comparatively very large value for TBI to eliminate the inspection package from the maintenance policy. Therefore, the second scenario is reduced to a policy including corrective maintenance and opportunistic maintenance alone. The third and the last scenario decides to apply an inspection interval of 304 h to minimize the total maintenance cost to $974,675. It should be remembered that the third policy is separated from the second one with its application area such that opportunistic maintenance is applied only in subsystem levels.

Among all three scenarios and 42 different alternatives, the optimal policy was chosen to have only corrective maintenance and opportunistic maintenance in system level under the second scenario. A representative example of how annual production time and total maintenance cost (includes physical costs and production losses) variate with different inspection intervals for the first scenario can be examined in Fig. 5. In Fig. 5(a), the surface is colored considering the variations in total maintenance cost where the same surface is colored with a legend regarding the changes in annual production hour for different TBI values in Fig. 5(b). The total maintenance cost minimizes and the system availability maximizes at a common point, TBI = 208, for the first scenario. For this TBI value, an annual production of 7,157 h can be obtained with a total maintenance cost of $981,738 per year as highlighted in Fig. 5(b) and (a), respectively.

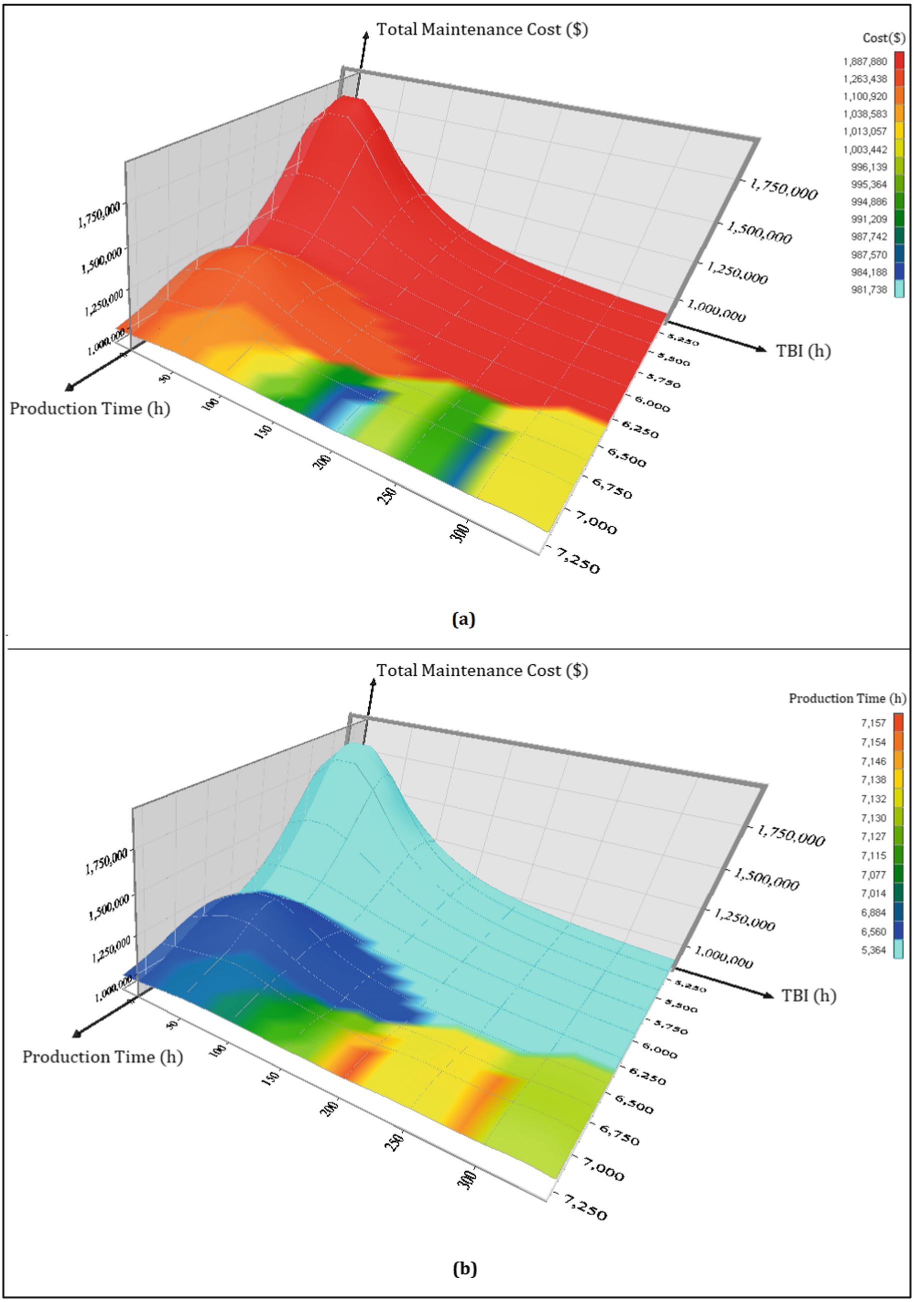

Fig. 5. Variation of annual production time and total maintenance cost with TBI values for Scenario-1: Thematic illustration considering the cost (a) and the production time (b)

4 Conclusions

This study allows a comparative evaluation of multiple scenarios in maintenance policies applied for production systems. Two model objectives, which are maximizing system availability and minimizing total maintenance cost, can be achieved with the developed simulation algorithm if the required datasets are available. Operating and downtime characterization of system components and their responses to maintenance work packages in terms of cost and availability can be observed as model outputs in system, subsystem and component levels. Corrective, preventive (regular inspections) and opportunistic maintenance applications, which are common work packages in maintenance activities, can be analyzed combinatorially with the algorithm for different inspection intervals. In the current paper, three different scenarios with 42 different alternatives were evaluated for an earthmover case study. The results revealed that application of corrective and opportunistic maintenance without inspection might minimizes the total maintenance cost and maximizes the availability in case that maintenance crew capacity and competency, and inventory level are good enough to perform opportunistic maintenance as a preventive action.

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