



Use of Markov Decision Model to Minimize Maintenance and Replacement Cost of Turbines in the Shiroro Hydro-Electric Power Station, Kaduna River, Niger State Nigeria

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ABSTRACT: This paper presents the application of Markov decision model to minimize the maintenance and replacement cost of turbines in the Shiroro Hydro-Electric Power Station, Kaduna River, Niger State, Nigeria. Data obtained reveals that minimum cost of equipment maintenance through the Markov reward model is achievable and able to ascertain long-run maintenance and the repair/replacement of turbine. Information obtained have the potential to assist engineers and utility staff to plan against turbine failure and hence, improve the stability of power generation which will in-turn lead to accelerate the economic growth of the nation.

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Markov decision process models have been applied to a wide range of equipment maintenance and replacement problems. In these settings, a decision-maker periodically inspects the condition of the equipment, and based on its age or condition decides on the extent of maintenance if any, to carry out. Choices may vary from routine maintenance to replacement. Costs are associated with maintenance and operating the equipment in its current status. The objective is to balance these two cost components to minimize a measure of long-term operating cost. Howard (1960) provided a prototype for such models with his “automobile replacement problem”. In it, an individual periodically decides whether or not to trade in an automobile and, if so, with what age automobile to replace it. Subsequently, many variables of the model have been studied and analyzed. Rust (1987) carried out a research on the Madison (Wisconsin) Metropolitan Bus Company maintenance. The result showed that the responsibility of keeping a fleet of buses in good working condition is one; the other aspect of the job is deciding when to replace the bus

engines. The researcher formulated the replacement problem using Markov decision process model as Replacement decisions are made monthly and the system state represents the accumulated engine mileage since the last replacement. Costs include an age-dependent monthly operating cost and a replacement cost. The monthly operating costs include a routine operating and maintenance cost component and an unexpected failure cost component. The failure cost accounts for the probability of breakdown for a bus of a given age and the cost associated with towing, repair and cost goodwill. Chao and Robert (2011) studied the problem of adaptive video data scheduling over wireless channels. They proved that, under certain assumptions, adaptive video scheduling can be reduced to a Markov decision process over a finite state space. Therefore, the scheduling policy can be optimized via standard stochastic control techniques using a Markov decision formulation. Simulation results showed that significant performance improvement can be achieved over heuristic transmission schemes. Hassan-Sheikh Aisha,

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Abdullahi M.U and Ahmad A.Y (2017) Used the Markov decision model for the maintenance problem of deteriorating equipment with value iteration to study a dynamic system which is reviewed at equidistant points of time and each review, the system is classified into a possible number of states and subsequently, a decision has to be made. The economic consequences of the decisions taken at the review times are reflected in costs. These properties of the Markov decision process are employed to study the maintenance condition of deteriorating equipment. The result could be used to study the status of equipment used in various organizations to determine their efficiency and productivity. Hence, the paper use of Markov decision model to minimize maintenance and replacement cost of turbines in the Shiroro hydro-electric power station, Kaduna River, Niger state Nigeria.

MATERIALS AND METHODS

Study Area and Data Source: The data used in this research work, were collected from the Shiroro Generation station. Shiroro hydro electricity generation station has four turbines, they are turbines 411G1, 411G2, 411G3 and 411G4, and each of these turbines generates a maximum of 150MW having a total maximum generation capacity of 600MW. We obtained the daily running data of Shiroro hydro electricity generation station of the four (4) turbines for the period of four (4) years i.e. (2018-2021).

Markov Decision Process: Consider a process that is observed at discrete time points to be in any one of m possible states, which we number $1, 2, 3, \dots$. Consider a process that is observed at discrete time points to be in any one of m possible states, which we number $1, 2, 3, \dots, m$. After observing the state of the process, an action must be chosen, and we let D , denote the set of all possible actions where we assume that D is finite. If the process is in state i at time n and action k is chosen, then the next state of the system is determined according to the transition probabilities ${}^k P_{ij}$ (Howard, 1960).

Following Ross (1989), let X_0 denote the state of the process at time n and K_n the action chosen at time n , then the above is equivalent to stating that

$$P(X_{n+1} = j | X_0 = i, K_0 = k_0, X_1 = i_1, K_1 = k_1, \dots, X_n = i, K_n = k) = {}^k P_{ij} \quad (1)$$

Thus, the transition probabilities are dependent on the present state and subsequent action.

Formulation of the Model: At any given point in time and a state of the process, the Power Holding Company of Nigeria (PHCN) has an opportunity or a privilege to repair or replace the turbine /equipment in order to have a constant operation. The maintenance of turbine / equipments may however, depend on the availability of the equipments, resources available for the maintenance and purchase of the turbine /equipments and the state of the maintenance. To this end, we use Markov decision model to determine the best policy that minimize the cost of maintenance of the turbine in the hydro plant production.

Therefore, we classified the condition of turbine into a four-state model as,

STATE 1 Operating above the average (1800MW and above per day)

STATE 2 Operating below the average (below 1800MW per day)

STATE 3 Short time repair (under repair for a maximum of seven days)

STATE 4 Long time repair (under repair above seven days)

Suppose that the two alternatives exist for each state thus:

STATE 1 Operating above the average (1800MW and above per day)

Alternative (1) Inspection

Alternative (2) Repair

STATE 2 Operating below the average (below 1800MW per day)

Alternative (1) Repair

Alternative (2) Replace

STATE 3 Short time repair (under repair for maximum of seven days)

Alternative (1) Low price equipment

Alternative (2) High price equipment

STATE 4 Long time repair (under repair above seven days)

Alternative (1) part not available in the store

Alternative (2) part available in the store

Costs are associated with each of these alternatives.

Thus, instead of considering the cost of individual repair or replacement, we shall consider the cost of a combination of repair or replacement of turbine at any given state and time.

Let the transition probabilities P_{ij} and the corresponding cost R_{ij} be given as follows

$$P = \begin{pmatrix} P_{11} & P_{12} & P_{13} & P_{14} \\ P_{21} & P_{22} & P_{23} & P_{24} \\ P_{31} & P_{32} & P_{33} & P_{34} \\ P_{41} & P_{42} & P_{43} & P_{44} \end{pmatrix}$$

And

$$R = \begin{pmatrix} R_{11} & R_{12} & R_{13} & R_{14} \\ R_{21} & R_{22} & R_{23} & R_{24} \\ R_{31} & R_{32} & R_{33} & R_{34} \\ R_{41} & R_{42} & R_{43} & R_{44} \end{pmatrix} \quad (2)$$

Let D be the decision set so that in every state of the process we have two alternative decisions available for the maintenance that is, alternative 1 and alternative 2, thus in every state we have $k = 1, 2 \in D$.

Let ${}^k P_{ij}$ and ${}^k R_{ij}$ be the probability of the transition from i to j and the corresponding reward respectively for ${}^k V_i^{(n)}$ the expected total earning in a transition under decision k , we have

$${}^0 V_i^{(n)} = \min_{k \in D} \sum_{j=1}^m {}^k P_{ij} [{}^k R_{ij} + {}^0 V_j^{(n-1)}] \quad (3)$$

Gives

$$= \min_{k \in D} \left[{}^k Q_i + \sum_{j=1}^m {}^k P_{ij} {}^0 V_j^{(n-1)} \right] \quad (4)$$

Where $\sum_{j=1}^m {}^k P_{ij} {}^k R_{ij} = {}^k Q_i$.

Let ${}^0 V_i^{(0)} = 0$, for $i = 1, 2, 3, 4$. Then for $n = 1$, we have

$$\left. \begin{aligned} {}^1 Q_1 &= {}^1 P_{11} R_{11} + {}^1 P_{12} R_{12} + {}^1 P_{13} R_{13} + {}^1 P_{14} R_{14} = \alpha_1 \\ {}^1 Q_2 &= {}^1 P_{21} R_{21} + {}^1 P_{22} R_{22} + {}^1 P_{23} R_{23} + {}^1 P_{24} R_{24} = \alpha_2 \\ {}^1 Q_3 &= {}^1 P_{31} R_{31} + {}^1 P_{32} R_{32} + {}^1 P_{33} R_{33} + {}^1 P_{34} R_{34} = \alpha_3 \\ {}^1 Q_4 &= {}^1 P_{41} R_{41} + {}^1 P_{42} R_{42} + {}^1 P_{43} R_{43} + {}^1 P_{44} R_{44} = \alpha_4 \end{aligned} \right\} (5)$$

We shall now implement the second alternative for the four states. Thus, we have

$$\left. \begin{aligned} {}^2 Q_1 &= {}^2 P_{11} R_{11} + {}^2 P_{12} R_{12} + {}^2 P_{13} R_{13} + {}^2 P_{14} R_{14} = \alpha_5 \\ {}^2 Q_2 &= {}^2 P_{21} R_{21} + {}^2 P_{22} R_{22} + {}^2 P_{23} R_{23} + {}^2 P_{24} R_{24} = \alpha_6 \\ {}^2 Q_3 &= {}^2 P_{31} R_{31} + {}^2 P_{32} R_{32} + {}^2 P_{33} R_{33} + {}^2 P_{34} R_{34} = \alpha_7 \\ {}^2 Q_4 &= {}^2 P_{41} R_{41} + {}^2 P_{42} R_{42} + {}^2 P_{43} R_{43} + {}^2 P_{44} R_{44} = \alpha_8 \end{aligned} \right\} (6)$$

The value of α_i for $i = 1, 2, 3, 4, 5, 6, 7, 8$ will determine which of the alternatives minimizes our cost for $n = 1$. Since we are concerned about minimizing the costs of repair or equipment replacement, the alternative that yields the least value of α_i for $i = 1, 2, 3, 4, 5, 6, 7, 8$ constitutes the best policy for $n = 1$ that is, if the least value occurs between α_i for $i = 1, 2, 3, 4, 5, 6, 7, 8$ then alternative 1 constitutes the best policy.

The method is based on recursively determining the optimum policy for every n that would give the minimum value. One major drawback of the method is that, there is no way to say when the policy converges into a stable policy; therefore, the value iteration procedure is useful only when n , is fairly small.

RESULTS AND DISCUSSION

We shall determine when the Turbine is in good condition for every n using equation 7. Since our interest is to determine the best policy that minimizes the cost of maintenance of the Turbine and maximizes the megawatt generated (mw), the alternative that yields the best policy constitutes the best option for the states and time. The Turbine undergoes state changes based on the following transition probabilities and the corresponding reward matrices in (thousand naira) respectively using equation 2 we have equations 7 and 8.

$$P_1 = \begin{pmatrix} 0.9393 & 0.0387 & 0.0220 & 0 \\ 0.0683 & 0.7337 & 0.1980 & 0 \\ 0.0797 & 0.2122 & 0.6419 & 0.0662 \\ 0.0135 & 0.0223 & 0 & 0.9642 \end{pmatrix}$$

and

$$P_2 = \begin{pmatrix} 0.71 & 0.21 & 0.07 & 0.00 \\ 0.24 & 0.62 & 0.14 & 0.00 \\ 0.53 & 0.30 & 0.10 & 0.07 \\ 0.32 & 0.19 & 0.00 & 0.49 \end{pmatrix} \quad (7)$$

Let the corresponding cost matrices be

$$R_1 = \begin{pmatrix} 1 & 2 & 3 & 4 \\ 2 & 3 & 5 & 0 \\ 4 & 5 & 5 & 1 \\ 3 & 2 & 0 & 4 \end{pmatrix} \text{ in } \text{₦}10,000 \text{ for alternative 1}$$

and

$$R_2 = \begin{pmatrix} 1 & 3 & 4 & 2 \\ 5 & 3 & 3 & 1 \\ 9 & 10 & 5 & 3 \\ 4 & 0 & 2 & 3 \end{pmatrix} \text{ for alternative 2} \quad (8)$$

It is important to mention that the cost matrix (R) is hypothetical. This is because anything finance in the Hydro- Electric Power (H. E. P.) Shiroro is treated as a top secrete therefore the finance records are not accessible to non-staff.

We shall use these values in equations 4 and 9 to determine the best policies for every n. we have

$$\begin{aligned}
 {}^1Q_1 &= {}^1P_{11} {}^1R_{11} + {}^1P_{12} {}^1R_{12} + {}^1P_{13} {}^1R_{13} + {}^1P_{14} {}^1R_{14} = 1.08 \\
 {}^1Q_2 &= {}^1P_{21} {}^1R_{21} + {}^1P_{22} {}^1R_{22} + {}^1P_{23} {}^1R_{23} + {}^1P_{24} {}^1R_{24} = 2.73 \\
 {}^1Q_3 &= {}^1P_{31} {}^1R_{31} + {}^1P_{32} {}^1R_{32} + {}^1P_{33} {}^1R_{33} + {}^1P_{34} {}^1R_{34} = 4.041 \\
 {}^1Q_4 &= {}^1P_{41} {}^1R_{41} + {}^1P_{42} {}^1R_{42} + {}^1P_{43} {}^1R_{43} + {}^1P_{44} {}^1R_{44} = 4.29
 \end{aligned}$$

We shall now implement the second alternative for the four states. Thus, we have

$$\begin{aligned}
 {}^2Q_1 &= {}^2P_{11} {}^2R_{11} + {}^2P_{12} {}^2R_{12} + {}^2P_{13} {}^2R_{13} + {}^2P_{14} {}^2R_{14} = 1.21 \\
 {}^2Q_2 &= {}^2P_{21} {}^2R_{21} + {}^2P_{22} {}^2R_{22} + {}^2P_{23} {}^2R_{23} + {}^2P_{24} {}^2R_{24} = 2.90 \\
 {}^2Q_3 &= {}^2P_{31} {}^2R_{31} + {}^2P_{32} {}^2R_{32} + {}^2P_{33} {}^2R_{33} + {}^2P_{34} {}^2R_{34} = 4.19 \\
 {}^2Q_4 &= {}^2P_{41} {}^2R_{41} + {}^2P_{42} {}^2R_{42} + {}^2P_{43} {}^2R_{43} + {}^2P_{44} {}^2R_{44} = 3.08
 \end{aligned}$$

Let ${}^0V_i^{(0)} = 0$ for $i = 1,2,3,4$. Then for $n = 1$ using equation 4 we find ${}^0V_1^{(1)} = \min_{k \in D} {}^kQ_i$ for ${}^1V_1^{(1)} = 1.08$, ${}^1V_2^{(1)} = 2.73$, ${}^1V_3^{(1)} = 4.19$ and ${}^1V_4^{(1)} = 3.08$ in states 1,2,3,4 respectively. The corresponding alternatives are $d_1^{(1)} = 1$, $d_2^{(1)} = 1$ $d_3^{(1)} = 2$ and $d_4^{(1)} = 2$ for the first iteration.

Then for $n = 2$ using equation 4. We have

$${}^0V_i^{(2)} = \min_{k \in D} \left[{}^kQ_i + \sum_{j=1}^4 {}^kP_{ij} {}^0V_j^{(1)} \right] \quad i, j = 1, 2, 3, 4 \quad k = 1, 2 \quad (9)$$

${}^1V_1^{(2)} = 2.29$, ${}^1V_2^{(2)} = 5.66$, ${}^1V_3^{(2)} = 6.41$ and ${}^1V_4^{(2)} = 6.25$ in states 1,2,3,4 respectively. The corresponding alternatives are $d_1^{(2)} = 1$, $d_2^{(2)} = 1$ $d_3^{(2)} = 2$ and $d_4^{(2)} = 2$ for the second iteration. The iteration is continuous for $n = 3,4,5, \dots, 13$ and the results are summaries in table 1

Table 1. A Summary Result of the Optimal Policies and Costs

n	$d_1^{(n)}$	$d_2^{(n)}$	$d_3^{(n)}$	$d_4^{(n)}$	${}^0V_1^{(n)}$	${}^0V_2^{(n)}$	${}^0V_3^{(n)}$	${}^0V_4^{(n)}$
1	1	1	2	2	1.08	2.73	4.19	3.08
2	1	1	2	2	2.29	5.66	6.41	6.25
3	1	2	2	2	4.83	11.13	10.84	12.62
4	1	2	2	2	10.14	20.90	19.00	25.58
5	1	2	2	2	21.18	39.57	35.29	51.24
6	1	2	2	2	44.05	72.23	74.40	102.46
7	1	2	2	2	91.29	138.02	132.12	205.60
8	1	2	2	2	188.57	259.90	242.25	413.17
9	1	2	2	2	390.97	503.87	469.43	831.03
10	1	2	2	2	913.89	983.30	924.12	1684.21
11	1	2	2	2	1883.63	1953.86	1887.51	3480.75
12	2	2	2	2	3962.89	3992.82	3997.71	7039.84
13	2	2	2	2	7928.90	7967.94	7981.90	14223.50

Table 1 presents the values of summary result of the optimal policies and costs for the turbine

The paper presented the Markov decision model for the maintenance of turbines in the Shiroro hydro generation station. From the above Tables 1, the results represent the best policies for each state and time. That is, $(d_i^{(n)})$ where $n = 1, 2, \dots, 13$ and $i = 1, 2, 3, 4$ in Table 1. Thus, we have obtained the best polices in 13 months for the four states turbine model. In addition to the best policies, the corresponding expected total minimum costs are also provided. From the table, the result shows that $d_1^{(1)} = 1$ with ${}^0V_1^{(1)} = 1.08$ means that the best

policy for state 1 for the first month is to inspect the turbine and the corresponding expected total cost is ₦10,800. The result also shows that there is consistency in the policies. For instance, Table1 shows that the best policy for state 1 is the first alternative for $n = 1, 2, \dots, 11$, whereas for $n = 12$ and 13 the best policy is the second alternative. Similarly, the best alternative for state 2 is the alternative 2 for $n = 3, 4, \dots, 13$. However, for $n = 1, 2$ the best policy is alternative 1. States 3 and 4 have identical second alternative as their best policy for all $n = 1, 2, \dots, 13$. For all the states and their best policies, the corresponding expected minimal

(optimal) costs are provided in table 1. The result also shows that the stable policy for state 1 is alternative 1. That is to embark on regular inspection and it will cost a maximum of ₦1,883.63 in 11 months ($n = 11$). The stable policy for states 2, 3 and 4 is the alternative 2. This means either to make a repair, replacement or acquire high-priced equipment with an optimal cost of ₦7967.94, ₦7981.90 and ₦14,223.50 respectively in 13 months ($n = 13$).

Conclusion: A Markov Decision model for the maintenance of the hydro machine of Shiroro hydro-electric power station, Kaduna River, Niger State, Nigeria has been presented. The model was able to ascertain long-run maintenance and the repair/replacement of turbine in the organization studied. The results from the model are important information that would assist the engineers and utility staff to plan against the failure of turbines, in order to improve the stability of power generation in view to accelerate the economic growth of the nation.

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